URBAN ENERGY POVERTY AND POSITIVE ENERGY DISTRICTS

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URBAN ENERGY POVERTY AND POSITIVE ENERGY DISTRICTS

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EDITORIAL
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Editorial: Urban Energy Poverty and Positive Energy Districts

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Editorial on the Research Topic

Urban Energy Poverty and Positive Energy Districts

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Cities are important actors in low-carbon energy transitions. They matter as front-runners, trend-setters and decision-makers. They matter as daily settings for over half of humanity. As cities continue to evolve, urban form is changing and the effects on consumption and climate change are the focus of political debate, governance and urban transformation research. Yet, without careful planning and thought, changing cities can have profound negative impacts on social inclusion. These impacts are felt most acutely by disadvantaged groups such as the urban energy poor. Shifts to positive energy districts (PEDs) and low-carbon urban forms can lead to green gentrification and exacerbate intersecting inequalities, or they can be drivers of inclusive cities that become low-carbon and socially sustainable.

This thematic collection focuses on the contested, varied and dynamic relationship between urban energy poverty and PEDs, which the Joint Programming Initiative Urban Europe defines as "an urban neighbourhood with annual net zero energy import and net zero CO_2 emissions working towards a surplus production of renewable energy, integrated in an urban and regional energy system[1]" The former refers to a lack of access to essential domestic energy services in cities, while the latter highlights the multi-scalar spaces and places of sustainability interventions in urban infrastructure. We feature contributions from a wide range of urban contexts, social science disciplines and novel interdisciplinary methodological approaches that address three cross-cutting thematic domains and suggest a need to include a focus on equity and justice in policy on PEDs.

First, the collection strikes a balance between locally situated understandings of energy vulnerabilities and attention to how these are and can be assessed and addressed. On the one hand, contributions unpack aspects such as territorial vulnerability, deprivation, inequity, insecurity, gendered differences, cultural preferences and practises in relation to richly contextualised perspectives on changing energy systems during low-carbon transitions (Calvo et al.; Boza-Kiss et al.; Cravioto and Mosqueda; Reid and Simatele; Pereira et al.). On the other hand, contributions

[1] See https://jpi-urbaneurope.eu/ped/

delve into the ways in which energy poverty is and can be assessed and addressed at the district scale in relation to low-carbon energy transitions, spanning approaches such as historic district retrofitting and renovation, behavioural change interventions, community scale renewable energy, housing and energy sector intersections and regional scale initiatives (Gouveia et al.; Caballero and Della Valle; Nordholm and Sareen; Antepara; Crowther et al.). Together, this array of contributions constitutes a substantive basis to grasp the multi-dimensional nature of energy vulnerabilities at stake and the multiple pathways and synergies possible in order to attend to them during low-carbon transitions. It also highlights the risks that should be considered in order to avoid exacerbating existing inequalities, or producing new ones, during ongoing systemic changes in energy and related sectors at the district scale.

Second, a number of the contributions advance our understanding and appreciation of the relationship between socio-economic and low-carbon indicators at urban and sub-urban scales. Some foreground perspectives of situated actors; e.g., city regions in England working to shape customised pathways and infrastructures for just transitions (Crowther et al.), social housing providers in Spain grappling with carbon markets and building energy consumption (Antepara), and government initiatives in Portugal aimed at enabling broader social inclusion through community scale solar energy plants (Nordholm and Sareen). Others mobilise comparisons across urban contexts broadly understood (Boza-Kiss et al.), within the same country using Chile (Calvo et al.) and Mexico as apt cases, in a global region such as Southern Africa (Reid and Simatele) and across multiple countries in Latin America (Pereira et al.). The upshot is a convincing demonstration of how complex it is to ensure a socially equitable, cross-sectoral move to low-carbon energy systems in ways that recognise and enrol the diverse needs and perspectives of district-level stakeholders. Yet it becomes clear that this challenge is a shared one, with ample scope for knowledge sharing and cross-fertilisation of approaches and indicators as initiatives are metricised, and existing metrics adapted to new infrastructures.

Third, the global span of the collection underscores the varieties of urban energy transitions that are underway, from retrofitting the built environment as explored in Mexico (Craviato and Mosqueda 2021) to intervening in localised energy practises at the sub-urban scale as unpacked in the case of Italy (Caballero and Della Valle). Equally importantly, the contributions reveal how the impact of such transitions extends well beyond the formal changes targeted through plans, to reshape numerous informal aspects of urban life. The implications are especially significant for disadvantaged population groups, as evident in the insights on energy deprivation and inequities during the pandemic (Boza-Kiss et al.), and through reflections on energy insecurity in the urban livelihoods of female informal workers (Reid and Simatele). Thus, low-carbon energy transformations not only raise a variegated set of social inclusion concerns; planned changes require a novel range of hybrid metrics and measures to assess and address impacts that transcend narrow conceptualisations of transition. As shown in a cross-country analysis (Pereira et al.) and even within complex domestic geographies (Crowther et al.; Calvo et al.) and sub-urban particularities (Gouveia et al.), the national variance and context-specificity of energy poverty drivers limits the value of narrow national parameters to address informal aspects at lower scales. Thus, district and urban scale actors have key roles to play to enable and mobilise hybrid energy poverty metrics and alleviation measures aligned with low-carbon energy transitions.

In closing, we reflect on the relative paucity of energy poverty research that engages directly with PEDs as an object of policy. This is attributable to PEDs mainly being driven from Europe as the only global region with a specific target of realising 100 PEDs by 2025. Yet even among the five contributions that deal with European countries, most engage only tangentially with PEDs as a specific set of infrastructural interventions. A risk we foresee here is that energy poverty considerations will not sufficiently inform this critical low-carbon energy transition ongoing at sub-urban scales in a timely manner. It follows from our synthesis points above that a failure to integrate the two research agendas will result in the sub-optimal customisation of PEDs to socially situated experiences of energy poverty, informed by metrics and impact assessments that inadequately capture the full range of socio-economic concerns, both formal and informal, in all their complexity, nuance and geographical specificities. Consequently, we call for future research on energy poverty to engage closely with PEDs, and vice versa, in order to shape real-world practise beyond European contexts.

AUTHOR CONTRIBUTIONS

SS led the writing. All authors contributed to the article and approved the submitted version.

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Tackling Energy Poverty Through Behavioral Change: A Pilot Study on Social Comparison Interventions in Social Housing Districts

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Behavioral Economics has in recent years played a key role in informing the design of non-price interventions aimed at promoting energy conservation behaviors in residential housing. Some of the most influential contributions of the discipline in an applied setting have centered around the development of norm-based interventions. The success that these interventions have had in specific contexts presents an opportunity to exploit them as tools for tackling a prevalent type of poverty at the EU level: energy poverty. Recent contributions to the literature highlight the role of inefficient energy behavior as a significant driver of this particular type of poverty, which is characterized by an inability to afford the basic energy services necessary to guarantee a decent standard of living. Therefore, the effectiveness of norm-based interventions in vulnerable populations merits further investigation to determine whether this approach can suitably address the behavioral components of energy poverty by promoting efficient energy consumption and conservation efforts. This study reports on a pilot conducted in an exemplary social housing context (located in Bolzano, Italy) with the aim to assess the effectiveness of social comparison interventions in energy vulnerable groups. Our investigated cohort covers an initial small sample of apartments with a large representatives of elderly individuals and other energy-vulnerable groups. Using a design that combines appeals to injunctive and descriptive norms embedded within In-Home Devices (IHD) in recently retrofitted homes, our objective is to set a basis for the assessment of effectiveness of these types of interventions in social housing populations. Our study seeks to provide useful methodological insights to policy makers on how to effectively design behaviorally informed interventions aimed at tackling energy poverty. Despite the current data limitations, our results do seem to suggest that uniformly applied norm-based interventions may have potentially backfiring effects in small-scale implementations. Therefore, they suggest that attention needs to be paid to household composition and pre-existing levels of consumption, when designing behavior-change interventions in these groups.

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1. INTRODUCTION

The field of Behavioral Economics has contributed greatly to informing the design of non-price interventions aimed at promoting energy conservation behaviors in residential housing (Andor and Fels, 2018). Increasingly more applied research has focused on uncovering the effectiveness of the provision of feedback in promoting energy conservation efforts by household occupants. The main methodological contribution of the discipline in this regard has been in expanding the use of Randomized Controlled Trials (RCTs) (Banerjee and Duflo, 2009) to identify causal links between feedback intervention and reduced energy consumption. In addition, behavioral economics has expanded the implementation of feedback interventions by integrating appeals to social norms, that is by designing norm-based interventions that rely on social comparisons to encourage energy conservation.

Norm-based interventions in the energy domain refers to the provision of information to households about how their individual levels of energy consumption compare to that of a reference group of comparable households (Andor and Fels, 2018) (who ideally should be chosen to have lower levels of consumption, signaling to the target household a pre-existing societal norm toward lower levels of consumption). The specific strand of norm-based interventions based on leveraging social comparisons are known in the literature as *social comparison* interventions.

The main objective of social comparison interventions in the energy domain is to promote energy conservation, reducing therefore our dependence on CO_2 emissions. Given our urgent need as world citizens to take action on climate change, as highlighted by the recent IPCC special report (IPCC, 2018), all efforts promoting conservation and decarbonization are of paramount importance. Evidence suggests that behavioral components are key drivers of variation in household energy use (Chen et al., 2015; Huebner et al., 2016), and behavior is more adaptable in the short-run than the appliance stock or building efficiency. Because of these reasons, adopting sustainable energy consumption habits must be a key component in our efforts to mitigate climate change. Furthermore, behavioral interventions of this kind can help reduce the *energy performance gap* (Galvin, 2014), described as the difference between expected energy savings and actual energy savings. Particularly in what concerns retrofitted apartments, these interventions can help align behavior with the technological innovation in order to achieve greater levels of energy savings.

Despite the existence of a large literature testing norm-based interventions in the field, little attention has been given to understanding the effects of these interventions on specific demographics. Evidence by Khosrowpour et al. (2016) suggests the need for tailored interventions for households with different energy consumption patterns, highlighting the fact that different populations may react in different ways to the provision of social information. The issue of intervention success on target demographics is of crucial importance when testing interventions that could be especially beneficial to the energy vulnerable, a group characterized by specific energy needs and potentially sub-optimal energy behaviors (Kearns et al., 2019). This study aims at addressing this gap in the literature, setting a basis for the evaluation of norm-based intervention effectiveness in a *social housing context*.

We present a methodology to study the effects of providing social information through In-Home Devices (IHDs) installed in recently retrofitted social houses, on energy consumption behaviors. More generally, we set the methodological basis for a more extensive evaluation of these interventions in a specific context of vulnerability. We begin to uncover how context-dependent the success of these interventions may be by adopting an experimental approach that allows us to make causal inferences. Finally, we make the case for a wider implementation of this methodology in social housing demographics to advise policy-making.

Previous research on this specific case studies' cohort (DellaValle et al., 2018) uncovered context-specific factors that affect the energy consumption patterns of the sample. These include the high proportion of retirees and older individuals in our sample who are amongst the most energy vulnerable. Furthermore, conditions of resource scarcity have proven to exacerbate behavioral biases such as myopia (Shah et al., 2012), and other context-specific factors, like stigma, play a crucial role in the development of inefficient energy behaviors within the most vulnerable populations (Hall et al., 2014; DellaValle, 2019). For these reasons, studying the effectiveness of a well-known behavioral intervention on the energy behavior of this specific population is of particular interest.

Our study also adds to the literature on interventions aimed at tackling energy poverty. Recent research (DellaValle, 2019; Kearns et al., 2019) has begun to pay attention to energy behaviors as an additional driver of energy poverty, recognizing factors such as use of household spaces and failure to adopt "adaptive thermal comfort" as significant determinants. Our study is unique in its emphasis on using behavior-change strategies to tackle energy poverty by encouraging the adoption of more efficient behaviors and, as a result, improving access to basic capabilities that derive from an efficient use of energy, such as good physical and mental health, education, and social integration (Day et al., 2016).

Our pilot is embedded within a wider EU project called Sinfonia, ran in social housing districts in Bolzano, South Tyrol (Italy). Consenting tenants were provided with IHDs to monitor and better control their energy use, and it is within this technology that we embed the intervention. In this paper, we focus exclusively on the effects of providing social information, not the effects of providing the IHD technology in general.

At the moment, we report preliminary results from the intervention in a subset of 12 apartments within one of the investigated districts. These were the first wave of apartments to receive the intervention. We plan to investigate the effects of the intervention in more districts and over a wider period of time in a follow-up study. While acknowledging the data limitations of our pilot application at the present time (which limits our ability to draw generalisable conclusions), our focus with this study is to provide useful methodological insights to policy makers on how to design successful behavior-change interventions in vulnerable contexts, with the ultimate aim of addressing the behavioral aspects of energy poverty.

The remainder of the paper is structured as follows: section 2 details the theoretical framework we position our pilot study in, with particular emphasis on why social housing tenants make for an interesting and important target group to investigate in the context of energy behavior-change interventions. Section 3 introduces a methodology for the application of social comparison interventions in social housing districts and explains the context and application of our pilot intervention. Section 4 presents the results from our pilot intervention, with a particular focus on the adoption of a suitable analytical accounts for important household characteristics and preferences. Section 5 discusses the results, limitations of the study as well as directions for future research. Finally, section 6 provides preliminary conclusions.

2. THEORETICAL BACKGROUND

2.1. Norm-Based Interventions

Norm-based interventions[1] have proven amongst the most successful non-price interventions to achieve behavior change in applied settings[2]. In a variety of pro-environmental domains, the provision of social information has proved an effective tool in shifting preferences toward more sustainable behaviors. In the domain of recycling (Schultz, 1999), towel reuse (Schultz et al., 2008), household water use (Ferraro et al., 2011), and crucially energy use (Allcott, 2011), norm-based interventions have been shown to affect both intention and actual behavior in the field.

The psychological processes by which the provision of social information affects individual behavior is still a matter of debate in the literature, but prevailing research seems to emphasize the role that normative appeals play is shaping our empirical expectations[3]. When these expectations on other people's behavior condition our own behavior, the resulting behavioral pattern is described as a "descriptive norm" (Bicchieri, 2005). As noted by Bicchieri and Dimant (2019), while the term "descriptive norm" is widely used in the psychological literature to mean a perception of what is commonly done, it is important to clarify that descriptive norms relate to interdependent behaviors, or those behaviors where motivation to undertake is dependent on a person's beliefs of what is commonly done. Our expectations based on unconditional (shared) behavior, therefore, are distinct from descriptive norms (such as our expectation that people will use an umbrella when it is raining). According to these expectations, people may wish to stick to descriptive norms for fear of social disapproval, or seeking social esteem (Farrow et al., 2017a). Eventually, they condition their own behavior based on the empirical observations of other's behavior (Bicchieri, 2005).

It is also important to discern between descriptive norms and injunctive norms. While descriptive norms relate to behavior motivated by empirical expectations on how people behave, injunctive norms are behavioral patterns that are conditional on our perceptions of what is perceived to be desirable or approved from our peers (therefore, like in the case of descriptive norms, also being interdependent behaviors). The key difference are the relevant underlying expectations, whether they are related to what other people are doing or what other people believe "ought" to be done (Bicchieri and Dimant, 2019).

In the context of norm-based interventions therefore, at least two things need to be clearly outlined before designing an intervention. First, we need to diagnose the targeted behavior, whether it is conditional on our expectations of others or not (interdependent or independent) (Bicchieri and Dimant, 2019). Assuming the targeted behavior is interdependent, we then need to define what expectations to target in order to achieve the desired behavioral change, whether expectations on what people do or expectations on what people think is right, therefore appealing to descriptive norms or injunctive norms, respectively (Bicchieri and Dimant, 2019). Here, the answer is likely to be highly dependent on context, but at least in the energy domain there is extensive research that supports appealing to both of these norms simultaneously when designing an intervention, as explained in the following section.

2.2. Norm-Based Interventions in the Energy Domain

Norm-based interventions in the energy domain for the most part rely on allowing energy users to compare their consumption levels with other users, therefore they can be classified as social comparison interventions. Some ambiguity in terminology exists in the literature regarding the use of the term social comparison interventions compared to norm-based interventions. For the purposes of our paper, social comparison interventions are taken to be a subset of applications within a wider set of norm-based interventions.

Social comparison interventions in the energy domain refer to the provision of information to households about how their individual levels of energy consumption compare to that of a reference group of comparable households (Andor and Fels, 2018). This approach is intrinsically linked to the provision of feedback on one's consumption, and, at the same time, also introduces appeals to norms through the provision of social information. As outlined above, the application of a norm-based intervention to target energy behaviors assumes that at least part of people's decisions regarding energy consumption are interdependent with how others behave. This is intuitive (while a certain level of energy consumption is required to meet our needs, a large portion of our daily energy behaviors depend on what we believe to be socially acceptable, as well as the behavior of our peers, Wolske et al., 2020), and further backed by a wealth of empirical research on successful interventions that leverage social norms (Andor and Fels, 2018). Moreover, using the framework of Bicchieri and Dimant (2019), we recognize that a large part of the literature is primarily concerned on appealing to descriptive norms by altering empirical expectations on social behaviors.

The most heavily researched social comparison interventions have been ran by the US utility company OPower, where

[1] i.e., interventions relying on social influence.

[2] For a recent review of the literature (Farrow et al., 2017a; Andor and Fels, 2018).

[3] i.e., how we expect other people to behave.

consumers were sent Home Energy Reports (HERs) through the mail with varying levels of frequency (Allcott, 2011). More recently, digital devices such as "smart meters" and other In-Home Displays (IHDs) have allowed for more flexibility and a higher frequency in the delivery of social information, as well as for the combination of several types of interventions to study their aggregate and interactive effects (Schultz et al., 2015). Our methodology uses IHDs as feedback mechanisms that integrate appeals to social norms in order to obtain a desired behavioral change (i.e., reduction in energy consumption). Despite the great potential offered by IHDs for the implementation of behavioral interventions, their effectiveness as delivery modes in social comparison interventions is still under-researched.

Despite differences in feedback frequency and delivery mode (Farrow et al., 2017a), implementations of norm-based interventions in the energy domain share several commonalities. One common attribute of these interventions is the combination of appeals to injunctive norms and descriptive norms. Evidence suggests that descriptive norms are more effective in encouraging behavior change than injunctive norms, however appeals to descriptive norms in isolation can lead to what is known as a *boomerang effect* (Clee and Wicklund, 1980). The boomerang effect in this context refers to an increase in energy consumption from households initially consuming less than the norm once they have access to the social information. This risks backfiring on the intervention's desired effect, and can have consequences on the net results of the intervention. However, when descriptive norms are used in conjunction with injunctive norms, the boomerang effect has been shown to disappear (Schultz et al., 2007).

Another common aspect is the target demographics that these interventions are aimed at. For the most part, these interventions have been limited to residential energy use, primarily in the private sphere. Their effectiveness on energy use in the public sphere has been largely ignored. In this paper, we start to contribute to this line of research by studying the effectiveness of social comparison interventions in social housing.

There is no general consensus in the literature as to the success of social comparison interventions in the energy domain, but estimates from applications in private households seem to suggest the interventions lead to reduced energy consumption anywhere between 1.2 and 30% compared to a non-intervened control group (Andor and Fels, 2018). However, very few of these studies use IHD devices in their delivery. In comparison, Schultz et al. (2015) finds a reduction of approximately 7% in energy consumption from households receiving norm messages integrated in IHD devices. However, this can vary widely on a case-to-case basis, with some backfiring effects observed in some contexts (Farrow et al., 2017b), particularly with low energy users (Schultz et al., 2007). Furthermore, some evidence from Germany (Andor et al., 2017) seems to suggest these interventions are less effective with European populations, who typically consume less energy on average than the general US population targeted in the OPower trials.

The ambiguity of the existing evidence suggests that these norm-based interventions should be designed carefully, with a clear understanding of what discreetly defined behavior we aim to achieve, what are the underlying expectations we want to affect in order to do this and, most importantly, who we are targeting and how they take energy decisions. For example, some households (particularly those with lower incomes or more restrictive budgets) have been shown to exhibit a "prebound effect" (Sunikka-Blank and Galvin, 2012) wherein they consume less energy pre-retrofitting than expected from techno-centric estimates, at cost to basic quality of life given that they usually live in energy-inefficient buildings. Behavioral patters such as the prebound effect constitute a challenge for behavior-change interventions, but also illustrate why it is so important that technical innovations making the housing stock more efficient are accompanied by a good understanding of pre-intervention behavior.

2.3. Conceptualization of Energy Poverty

By focusing on the specific context of retrofitted social housing our study adds to the literature on energy poverty, particularly in relation to behavioral-change interventions that tackle the issue (DellaValle, 2019). While currently there is no academic or policy consensus regarding the definition of energy poverty, a leading conceptualization that we will adopt for the remainder of this study is the capabilities approach, first applied to the energy domain by Day et al. (2016). In particular, energy poverty is conceptualized as an "inability to realize essential capabilities as a direct or indirect result of insufficient access to affordable, reliable, and safe energy services, and taking into account available reasonable alternative means of realizing these capabilities" (p. 260).

The theoretical basis of this approach is grounded in the link between energy and well-being by explicitly acknowledging the relationship between energy services and the realization of basic capabilities (good mental and physical health, social acceptance, access to education, etc.), more so than other measures discussed in the literature. This is particularly important when considering the social housing context of our study, a demographic typically characterized by vulnerable conditions in socio-economic terms (low-income households, aging populations, large families) and a high level of energy vulnerability (high number of hours at home, troubles in paying energy bills, etc). In these contexts, basic capabilities are not always realized, making it of paramount importance to acknowledge their connection with energy services.

Our study takes the view of recent studies recognizing behavior as a driver of energy poverty. A number of papers have suggested that a key factor determining energy poverty is the interaction between low household incomes and thermally inefficient homes (Bouzarovski, 2014). However, recent literature (Kearns et al., 2019) has begun to pay attention to energy behaviors as an additional driver of energy poverty, recognizing factors such as use of household spaces and failure to adopt "adaptive thermal comfort" as potentially lowering behavioral efficiency in interactions with the dwelling stock. The consequences of reduced behavioral efficiency can have detrimental effects on physical and mental health, which could further contribute to the worsening of energy poverty conditions (poor mental health can lead to the adoption of poor heating regimes, and increasing challenge in a households ability to keep warm/cool).

2.4. Energy Behaviors in a Social Housing Context

A notable feature of our study is the choice of the specific target group for intervention. Social housing tenants are a demographic that is often overlooked in energy behavior-change research (Hafner et al., 2020), yet they present a particularly interesting and important group to study for a number of reasons.

Firstly, due to the very aim of social housing being to provide affordable housing for all, there is usually a high representativeness of vulnerable demographics in social housing populations. This includes low-income households, unemployed individuals, retirees, disabled individuals, and large families. These groups are exposed to a number of energy vulnerabilities, for example low-income groups spend a larger share of their income on energy costs than high-income households (Schaffrin and Reibling, 2015). In some cases tenants may need to make energy-consuming adjustments to the dwelling, or add consumptive appliances for health-related reasons (keeping house warm, medical equipment, etc.). Additionally, social housing is typically energy-inefficient, and even in recently retrofitted housing (as is the case in our pilot study), empirical evidence highlights critical behavioral responses that limit the effectiveness of efficiency upgrades (Sorrell et al., 2007). This all suggests that the failure to adopt efficient energy behaviors can have substantial negative distributional or health-related consequences for social housing tenants. Subsequently, these tenants have the most to gain from an intervention that leverages their behavior to achieve energy savings, while also possessing unique energy needs that have to be considered by policymakers and practitioners. Research carried out on this specific cohort of tenants in Bolzano confirms that vulnerable situations are also apparent in the investigated Sinfonia districts (DellaValle et al., 2018), where the majority of individuals are identified as low educated or retired.

Secondly, there exists a large literature on the psychology of scarcity that points at the potential impacts that living in precarious conditions may have on energy decision-making. For example, scarcity has been shown to focus attention on the most immediate concerns (for the vulnerable this may be paying rent and bills, improving health, caring for children or the elderly), while significantly depleting attention for decisions that are not considered of immediate importance (Shah et al., 2012). Paradoxically, research also shows that this attention depletion leads to sub-optimal decision-making in some domains that would have helped individual combat their existing conditions of scarcity (Tomm and Zhao, 2016). This large body of evidence could also be applied to energy decision-making in vulnerable demographics. In particular, the psychology of scarcity could lead to the adoption of sub-optimal energy behaviors and the lack of interaction with behavior-change interventions, that actually contribute to helping reduce scarcity in the form of lower energy costs.

We should also expect that resource scarcity will worsen the individual tendency toward myopia in the energy domain (DellaValle, 2019). This refers to the over-weighting of present costs and benefits, and the under-weighing of future ones in a time-inconsistent fashion (Loewenstein and Prelec, 1992), leading to sub-optimal choices in the long-run. In the energy domain, such myopic behavior results in the undervaluing of future benefits associated with adopting energy efficient behaviors (Hershfield, 2011). Overall, the literature gives us ample reason to believe that the specific vulnerable conditions that social housing tenants are exposed to will cognitively impact them, leading to the adoption of sub-optimal energy behaviors.

Finally, the cognitive impact of stigmatization, deeply linked with social housing residency, poses barriers to the achievement of several benefits accrued by the adoption of energy efficient behaviors. Stigmatization has been shown to be linked to under-performance (Mani et al., 2013), due to the depletion of executive resources deriving from efforts to suppress negative thoughts and emotions in the service of self-regulation (Hall et al., 2014). Furthermore, stigmatization has also been shown to result in social distancing, whereby individuals distance themselves from a prescribed social identity (Horan and Austin, 2014). These factors pose important barriers to the adoption of energy efficient behaviors.

2.5. Sources of Heterogeneity in Energy Conservation

In order to disentangle the effect of the intervention from other motivations to conserve energy, we need to understand the decision-making process of energy conservation and, subject to data availability, control for ulterior factors that may affect the underlying choice of conserving energy.

Energy conservation can be interpreted as a pro-environmental behavior (Brekke and Johansson-Stenman, 2008). Accordingly, we need to account for heterogeneity of factors underlying the decision-making process to act pro-environmentally. For example, a tenant's decision to act more pro-environmentally by consuming less energy could be motivated by (i) a desire to act in accordance to empirical and normative expectations (targeted by the intervention) (Bicchieri, 2005), (ii) possessing a high-degree of intrinsic pro-environmental self-identity (Whitmarsh and O'Neill, 2010) or (iii) possessing an intrinsic motivation to contribute to a public good (Bénabou and Tirole, 2006); being the environment the most prominent public good (Brekke and Johansson-Stenman, 2008). We thus measure and control for pro-environmental self-identity and a number of primary predictors of contribution to a public good: trust, altruism, and reciprocity (Kollock, 1998), in order to allow us to more closely understand the effects of the intervention.

The decision to conserve energy can be also understood as an economic behavior. Tenants respond to certain market incentives by reasonably adjusting their behavior (retail energy prices, energy bill subsidies, etc.). Lacking data on the specific economic incentives facing each individual tenant, we do not control for these factors econometrically, however we can reasonably assume that they all face the same economic conditions.

Additionally, conservation can be seen as an inter-temporal utility trade-off between present consumption and future financial benefits (in the form of a lower energy bill). A proportion of our population may be intrinsically very patient and willing to sacrifice some consumption now to benefit from lower energy-related expenses in the future. Therefore, the decision to conserve less energy, similarly to the decision to invest in energy-efficient appliances (Newell and Siikamäki, 2015), can be motivated by an intrinsic preference for delayed returns. In our analysis we therefore elicit and control for time preferences.

Finally, the decision to conserve more energy may simply be due to a better understanding on how energy behaviors relate to environmental and financial outcomes. For example, even if an occupant self-identifies as environmentally-friendly, she may not adjust to more conservatory behavior if she fails to recognize the link between her energy behaviors and environmental outcomes. Therefore, following (Blasch et al., 2017), we control for a general level of energy literacy in our analysis.

2.6. Pilot Application Aims

The pilot experiment has been designed to address two main research questions:

1. What are the effects of social comparison interventions, integrated within IHDs, in a social housing context?
2. Can a social comparison intervention applied to a target demographic comprised primarily of vulnerable individuals, help alleviate energy poverty?

To tackle these questions with the accessible set of data, we make a simplifying assumption on the drivers of energy vulnerability in our target demographic, which allows us to study differences in the evolution of energy consumption between groups. In particular, we assume pre-existing energy behaviors are sub-optimal and exacerbating a household's position of energy vulnerability (Kearns et al., 2019). Therefore, if we observe a larger reduction in energy consumption during the investigated period in our treatment group than in our control group, we can take this result as signaling that the intervention was successful in optimizing energy behaviors, and in turn in reducing the energy vulnerability of households. For example, if we assume a negative rebound effect post-intervention which reduced the potential energy savings from the retrofit, a reduction in consumption following our *behavioral* intervention can be interpreted as aligning the technological and behavioral components of energy efficiency.

Of course, these assumptions are limiting and a closer study on energy poverty conditions (whether through indoor temperature monitoring or self-reported measures) would have allowed us to tackle the second question more carefully. Obtaining this data however is impossible in practice at this stage of the project as self-reported measures on the occupant's energy experience are yet to be collected. For the scope of this paper, the assumptions are instrumental to study the impact of the intervention on energy poverty by looking at electricity consumption only.

The success of the intervention faces several barriers deriving from the specific context of social housing, such as a high level of energy vulnerability, and the cognitive impacts of scarcity and stigmatization. On the other hand, it is also because of these contextual reasons that understanding the effects of this widespread behavioral intervention is of paramount importance. It can highlight pathways to the successful implementation of energy efficiency investments that account for and target social aspects by promoting the adoption of more virtuous energy behaviors, thus contributing to drawing social housing tenants out of a situation of energy poverty. If the intervention is unambiguously successful, it can further promote the roll-out of these uniform normative appeals in the context of social housing retrofits. Alternatively, if we find substantial resistance in the intervention success, or encounter unique difficulties that limit the intervention's effectiveness, our results may suggest the importance of targeted feedback programs (Khosrowpour et al., 2016) that address the particular needs and characteristics of the most vulnerable.

Our results unveil practical recommendations for policy makers who wish to maximize the impact of retrofit interventions in social housing settings, mindful of contextual influence. Specifically, behavioral policies in vulnerable demographics should be financially assessed vis-a-vis price interventions in order to choose the most efficient policy instrument to achieve the desired social and environmental objectives. Our focus at this time is not to present generalisable results, but rather provide a practical example of a behavioral approach to tackling energy poverty, underlining advantages and limitations of this approach with respect to context, data availability, and assumptions on pre-existing consumption, and finally proposing a quantitative analytical approach for the creation of more general conclusions.

3. MATERIALS AND METHODS

3.1. Context and Pilot Design

The Sinfonia Smart city project, born from the cooperation between Bolzano and Innsbruck, aims at finding integrated solutions to achieve significant levels of energy savings in social housing districts[4]. As part of this project's activities, a number of apartment buildings in different districts throughout Bolzano were retrofitted to make them more energy efficient. The retrofitting activities took place between July 2017 and May 2019. One of the key aspects of the technical renovation was that they were designed to be completed without the need to temporarily relocate occupants. For this reason, the majority of the work involved external activities: constructing an envelope for the energy improvement of the building by installing prefabricated panels on the external walls, creating a centralized heating system with geothermal heating pump, and installing a solar thermal field, a controlled mechanical ventilation system, and a 20 kWp photo-voltaic system on the rooftop. As the retrofitting was part of a large-scale EU project, the works were financed by the project budget, with the municipality of Bolzano also providing part of the financing. Importantly, the tenants did not personally

[4]Sinfonia website, http://www.sinfonia-smartcities.eu/.

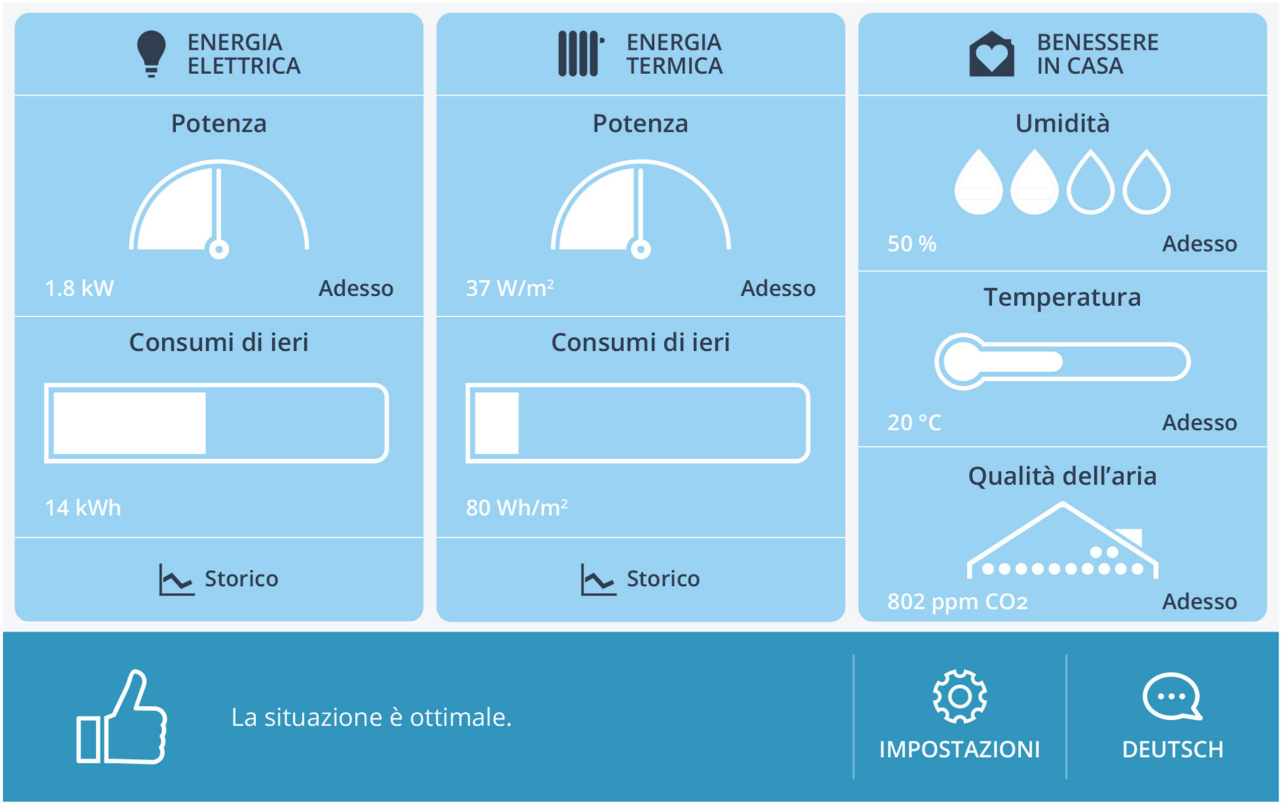

FIGURE 1 | Control group home display.

pay for any of the retrofitting activities. This also meant that the retrofitting decision was imposed in a top-down manner, tenants did not have a say on whether or not they wanted their apartment retrofitted.

After the works finished, a number of consenting apartments were installed sensors and "smart meter" (IHD) technology providing timely feedback about several household characteristics relating to energy efficiency and comfort. These characteristics include humidity, temperature, air quality and, notably, electrical and thermal energy consumption (in terms of kWh and Wh/m^2). Notably, tenants did face a decision here about whether or not to allow for the display's installation, potentially introducing some self-selection bias in our analysis of intervention effects (discussed in section 5).

The home page of the smart meter display can be seen in **Figure 1**. These displays were shown on a tablet installed near the tenants front door, which is being transmitted the information recorded by the sensors. The reason for installation near the front door was technical: the tablets were to be powered by the building electrical grid which is distinct from the apartment electrical grid. In order to connect to the building grid therefore, the displays had to be positioned close to the entrance. While this placement ensures the display is in an area of frequent movement for tenants where it is likely to be seen with some regularity, placement in a m of the intervention.

The sensor technology employed to record this information (installed after the retrofitting works) allows us to collect information and provide feedback with high-level granularity. Users have access to electricity consumption through both the home page of the display, and an additional "consumption history" page which they can access via the home page. In the home page, they receive information on previous-day consumption, as well as information on current consumption levels which is updated with a frequency of 5-min. Once they click the "consumption history" tab, users are brought to a separate page as seen in **Figure 2**. Users can then navigate this page to find information on their past energy consumption aggregated at different levels (daily, weekly, monthly), and they can visualize the evolution of their consumption levels.

3.2. Pilot Study Design

Households with installed IHDs are then randomized into two different groups, the control group and the norm group. The control group receives feedback on their own energy consumption through the home and history pages as described above. The layout of the pages in their display is identical to that shown in **Figures 1**, **2**.

The norm group receives identical information on their own consumption as the control group, but their level of energy consumption is also compared in their display to that of a

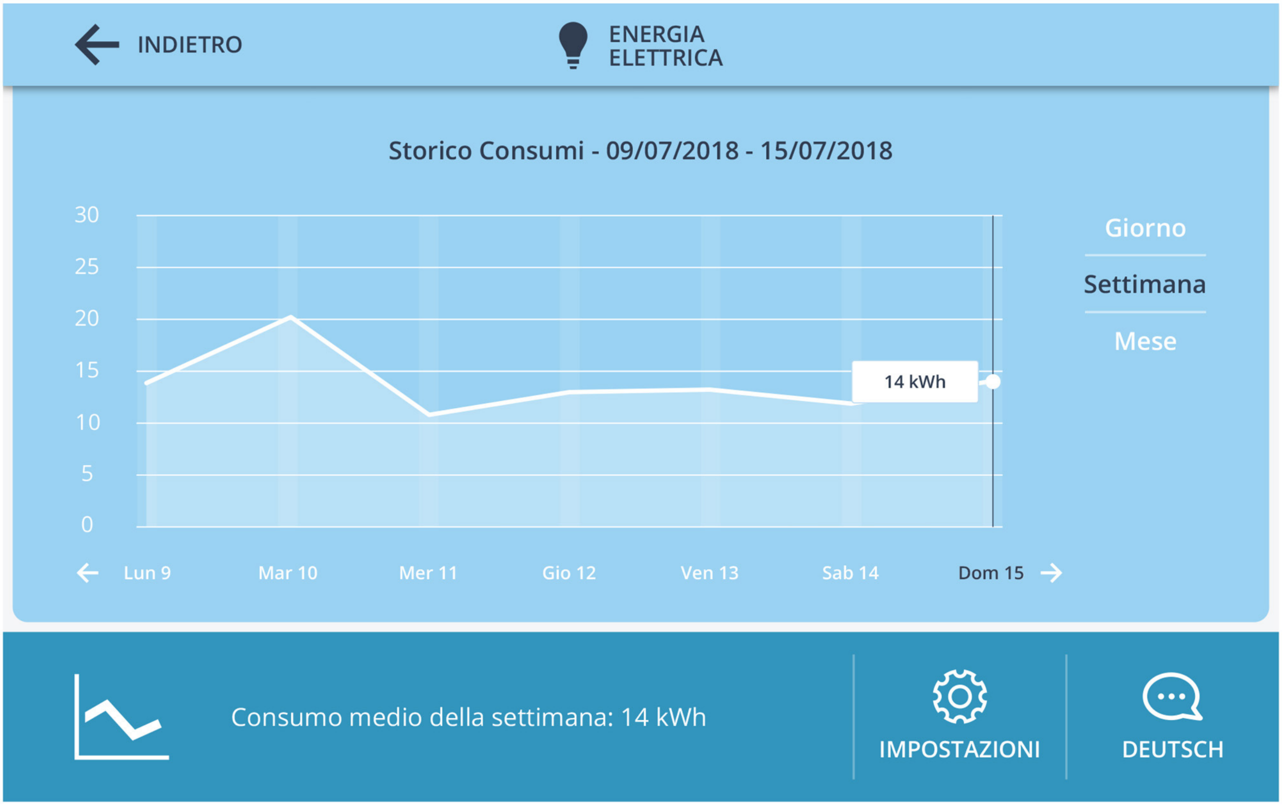

FIGURE 2 | Control group history display.

reference group of neighbors. This comparison is represented both in terms of last-day averages (as shown in **Figure 3**) and in different formats through the "history" tab (shown in **Figure 4**). In short, tenants in the control group receive only information on their own electric and thermal consumption, whereas tenants in the norm group receive own-information as well as social information.

Close attention was paid to the selection of the reference groups from which to generate the displayed social information for apartments in the norm group. Evidence suggests that the choice of reference group is crucial for the effectiveness of norm-based interventions (Abrahamse et al., 2005; Bicchieri and Dimant, 2019). Toward this end, we use a restrictive similarity criterion to cluster households into different reference groups on the basis of observable characteristics which reflect actual energy use. These are: number of household occupants and average number of hours spent at home by household members. This means that two apartments may well be both in the norm group yet receive different social information if they have a household composition which allocates them in different reference groups based on the employed clustering technique.

Furthermore, in line with previous literature (Alberts et al., 2016; Anderson et al., 2017), we choose to compare individual household behavior not to an average of other households in the reference group, but rather the behavior of top performers within the reference group to provide a virtuous example to follow. We were able to create comparable groups comprising of 3-4 households in our investigated apartments, and picked the average energy consumption of the top two highest performers in that group as the shared social information to display to those households in the same reference group who were under the norm treatment.

The high feedback frequency of consumption information is a notable contribution of our study to the overarching literature on norm-based interventions using IHDs. There has been mixed evidence on how the frequency of feedback affects energy conservation efforts. Fischer (2008) argued that frequent feedback on energy consumption was more effective than infrequent feedback due to the closer link it creates between actions and consequences, but later empirical evidence has refuted this claim (Ehrhardt-Martinez et al., 2010), finding real time feedback to result in lower conservation efforts than weekly/daily feedback. In an experimental environment, Casal et al. (2017) also find that the frequency of feedback does not impact individual performance.

For our purposes, the frequency of feedback is only relevant insofar as all tenants have access to information on their consumption (and others' consumption in the case of the norm group) at the same frequency. This is the case in our pilot study. Future research could focus on the effects of increased feedback

FIGURE 3 | Norms group home display.

frequency on energy conservation with a particular focus on social housing.

In our norm-based intervention we appeal to both descriptive and injunctive norms. We employ "smiley face" emoticons similar to those used in the HERs in Allcott (2011). These emoticons are meant to appeal to injunctive norms by suggesting the social desirability of a behavior. If a specific household were currently consuming less than their reference group of neighbors, they would be presented with a smiling face together with the social information, while if the household was currently consuming more than the reference group of neighbors, they would receive a red frowning face.

Our experiment also draws from previous evidence highlighting that social comparison interventions are more effective when complemented with actionable tips (Dolan and Metcalfe, 2013). The technology of the IHDs allows us to suggest targeted actions to reduce consumption of energy in households while maintaining a suitable level of comfort (such as opening a window and turning down heating when the outside temperature is greater than the inside temperature). These tips are available to households both in the control and treatment groups, meaning that in our analysis we only isolate for the effect of exposure to social information, and not the inclusion of the tips.

In conclusion, all consenting apartments were installed with IHD technology. These apartments were then randomized into 2 groups (Control and Norm) with the only difference between the groups being the provision of descriptive and injunctive norm appeals in the form of social information on energy consumption. The social information was generated by clustering households into reference groups based on two observable characteristics (number of tenants, hours spent at home), and choosing the level of energy consumption equivalent to the average of the two best performing households in each reference group to display to the norm group households within each reference group. All other aspects of the display (targeted actionable tips, frequency of feedback, other design features) were kept constant between groups.

3.3. Data Description

To study whether changes in behavior have taken place in the short-term, we studied the effect of the intervention during the first 3 months of implementation. The project has been ongoing past these first 3 months, but to enhance project accountability, it is important to highlight immediate results of the intervention. In a later study, we will analyse also the long-term effects of the intervention for households in the remaining districts. It is also important to note that this study is part of an overarching complex project including dwellings with different technical characteristics and different

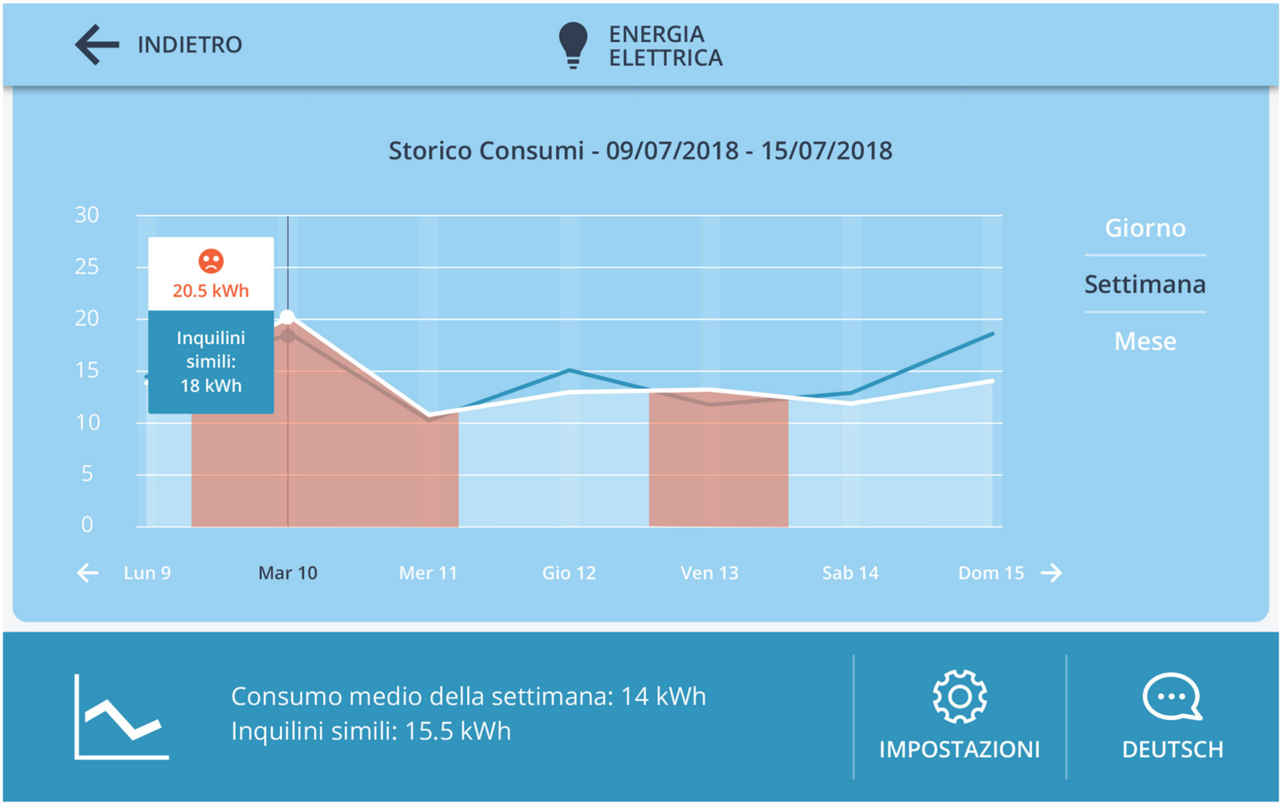

FIGURE 4 | Norms history display.

sets of interventions being implemented across districts. In this study, we are solely interested in studying the effects of the social comparison intervention, and adopt our analytical approach accordingly.

3.3.1. Sample Characteristics

This initial analysis includes only the first consenting apartments to have their displays activated in one of the project districts. The households included in the sample all had their displays activated at the same moment, meaning they were exposed to the intervention for an equal time period. This included 13 apartments initially. Subsequently, one of the tenants asked to have the sensor uninstalled and was removed from the sample. This left us with 12 apartments across 2 groups (Control and Norm group; 6 apartments in each group) analyzed over a period of 3 months, from November 22nd to February 23rd. This included 27 enants.

A descriptive analysis on the observable characteristics of the sample population is summarized in **Table 1**. This data was based on self-reported individual-level characteristics compiled by the occupants present at time of installation of the display. From this data, a number of aggregate household characteristics were measured. The first five rows of **Table 1** describe the distribution of individual categorical characteristics in the sample (defined as dummy variables that take the value of 1 if the individual is part of the defined category, and 0 otherwise) while the last four rows describe the distribution of the aggregated household characteristics.

These descriptive statistics reveal some key points. Firstly, a significant proportion of the tenants in the sample are

TABLE 1 | Descriptive characteristics of sample.

Variables	*N*	Mean	St. Dev.	Min	Max
Female dummy	27	0.518	0.509	0	1
Retired dummy	27	0.259	0.446	0	1
> 65 years dummy	27	0.259	0.446	0	1
40–59 years dummy	27	0.481	0.509	0	1
Children dummy	27	0.0740	0.267	0	1
N. children	12	0.167	0.389	0	1
N. > 65	12	0.583	0.793	0	2
N. retired	12	0.583	0.793	0	2
N. members spending > 12 h at home	12	0.833	0.389	0	1

The first five rows describe the distribution of individual-level characteristics in our sample. These are defined as dummy variables that take the value of 1 if the individual is part of the defined category, and 0 otherwise. The final four rows describe the distribution of apartment-level aggregate characteristics, including Number of Children, Number of over 65 year old, number of retired individuals, and number of members spending more than 12 h at home per day.

retired and over 65 years of age (26% of individuals in the sample for both categories). Subsequently, the majority of the households have one member that stays at home more than 12 h each day. This confirms that the sample prominently features vulnerable individuals, such as the elderly and retired, and that the general energy needs of the our sample might be high.

The sample does not feature a large number of children, meaning the large prevalence of individuals staying long hours at home is not primarily driven by adults staying home with their children. Rather this is likely driven by retirees, or potentially the unemployed.

3.3.2. Energy Consumption Data

Using the sensor technology installed after the retrofitting works, we gathered data on hourly energy consumption for each of the 12 apartments. Taking advantage of both the longitudinal and cross-sectional nature of the data, we created a panel dataset that collected highly granular information on energy consumption across the 12 households. This granular data was aggregated at the hourly level for the sake of tractability.

In this study, we focus only on electrical energy consumption, which was measured in kWh. As anticipated, thermal energy consumption will be investigated in a follow-up study.

It is worth mentioning that we encountered some technical difficulties during the data collection process that resulted in receiving distorted hourly data on electricity consumption. Due to the nature of the sensing technology and a margin of error, for a small proportion of hours and in a limited number of apartments, consumption was recorded but not reported immediately. Instead, the recording system aggregated the results from multiple hours of consumption into the observation for a single hour. This led to some incorrect observations in the dataset, in 4 of the 12 apartments in the sample, which could bias our results. We decided to drop these biased observations (the individual hours with recorded errors) from the dataset before estimating our regression models: whenever there was a gap in reporting of more than 1 h for any apartment, the following observation was dropped. While this makes it so that we lose a small number of observations (hence ending up with an unbalanced panel), it allows the analysis to be unaffected by technical difficulties in the sensor and recording technology, ensuring that every observation in the dataset is indeed collecting consumption during the span of a single hour. It is important to note however that, as the incidence of these errors disappeared when aggregating consumption at the daily level, these observations were not dropped when completing the Difference-in-Differences (DID) analysis.

A notable limitation of the dataset is the inability to access long-term pre-intervention data on energy consumption. This did not allow us to complete a comprehensive DID Analysis. Therefore, a proxy DID approach was adopted, following Bager and Mundaca (2017), as will be explained in the following section.

Summary statistics for this variable can be found in the **Appendix**. The mean hourly level of energy consumption in the overall sample and control group is 0.248 (St. Dev = 0.294).

TABLE 2 | Summary statistics of hourly energy consumption of sample (kWh).

Group	*N*	Mean	Std. Dev.	Variance
Control	13,190	0.248	0.290	0.084
Norm	13,386	0.249	0.298	0.089

3.3.3. Household Preferences

In addition to data on household characteristics and energy consumption, we collected data on a number of household preferences using surveys administered at the time of installing the smart meter. The objective of the survey is to collect valuable information on the individual preferences of occupants in order to control for factors that may affect the underlying decision-making process of conserving electricity, in absence of the intervention. By controlling for these potential sources of heterogeneity in the analysis, we can determine how much of the resulting change in behavior can be attributed to the intervention. The survey-elicited measures are therefore integrated into the estimated regression models as additional explanatory variables.

The survey-elicited data included measures on energy literacy (Blasch et al., 2017), pro-environmental self-identity, altruism, trust, reciprocity, group identity and inter-temporal preferences. The survey items, based on Luhtanen and Crocker (1992) and the experimentally-validated items developed by Falk et al. (2018), were a combination of Likert scales and multiple-choice questions.

It is important to note that many of the items in the survey elicit information on individual characteristic of the respondent, not necessarily the household as a whole. As the survey was conducted on only the one household member present at the time of installation, the collected measures are likely affected by an individual bias and can at best be used as proxies of general household characteristics. This is a limitation of the collected data, that can lead some of the relevant variables to have an individual-level bias.

4. RESULTS

4.1. Descriptive Analysis

Studying differences in overall average energy consumption between the two groups in the short-term (**Table 2**) there appear to be no significant differences at the average level amongst groups, with the control group consuming 0.248 (St. Dev = 2.90) as opposed to the norms group consuming 0.249 (St. Dev = 0.298).

This is confirmed by a cross-sectional Mann–Whitney *U*-test at the household level that fails to reject the null of equal distributions across groups ($p = 0.6310$).

4.2. Difference-In-Differences

Following Bager and Mundaca (2017), we employ a DID approach by measuring relative change in daily electricity consumption from the first to the last week of intervention for both groups, and comparing the changes between

TABLE 3 | Daily average hourly electricity use for households by groups.

Group	First week average (kWh)	Mid-period week average (kWh)	Last week average (kWh)	Change in consumption (δ%)
Control	6.179	6.446	5.176	−16.232
Norm	6.145	5.866	5.588	−9.064

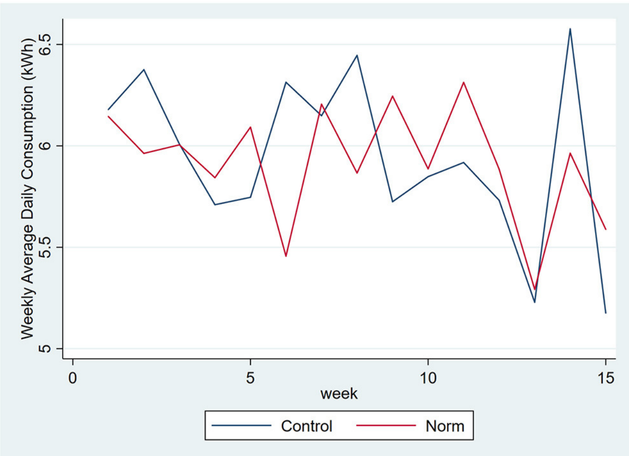

FIGURE 5 | Weekly average daily energy use for households by groups.

groups. The variable of interest is weekly average daily electricity consumption[5].

The results for the weekly DID analysis can be found in **Table 3**, and a graphical representation of the weekly evolution of daily consumption can be found in **Figure 5**.

As is clear from the table, over the relevant period of intervention both groups experience a reduction in their daily electricity consumption. However, there is a larger reduction in the energy consumption of the control group, rather than the norms group (a differential effect of 7.168%), suggesting a backfiring role of the intervention. From **Figure 5** however, we can see there are no marked differences between daily consumption of the two groups throughout the weeks.

It can also be seen from **Table 3** and **Figure 5** that both groups reduced their weekly average daily energy consumption overall in the investigated period. More detailed analysis, taking into account weather effects, is needed to understand why both groups go through a reduction in electricity consumption. We can speculate, based on previous research on the effects of increased feedback on consumption (Faruqui et al., 2010), that the display installation did have an effect in reducing overall electricity consumption, but that the normative appeals were unable to promote further reductions for the treatment group.

[5]This was measured by aggregating hourly energy consumption over a single day. This daily energy consumption measure was then averaged at a weekly-level.

4.3. Regression Analysis

The regression analysis method we present here is intended as a methodological starting point for the complete analysis that will be conducted once data from further districts is collected. It is important to note however that due to the currently low number of households included in the analysis, indications of statistical significance should be considered with caution.

We start by defining a bivariate model to analyse the impact of treatment assignment on hourly electricity consumption levels of individual households:

$$electricity_{it} = c + \beta social_i + \epsilon_{it}$$

The dependent variable is kWh of electricity consumed by household i during hour t in the panel data-set (t = 1–2233). *Social* is a treatment dummy variable that takes the value of 1 if the household is in the norm group, and 0 if the household is in the control group. ϵ is a randomly distributed error term.

We further enrich our model (following Schleich et al., 2017) by adding hourly and monthly dummies in order to control for variations in electricity demand across months (i.e., due to weather conditions) and across hours of the day (i.e., due to variations in household occupancy and activities). The purpose of controlling for these parameters is to study how the intervention performs when this variability is taken into account.

$$electricity_{it} = c + \beta social_{it} + \sum_{m=1}^{4} M + \sum_{h=1}^{24} H + \epsilon_{it}$$

Finally, we define two multivariate models [MV(1) and MV(2)] that separately control for household structural characteristics, as well as the survey-elicited preferences. The two multivariate models are defined separately in order to circumvent potential biases in the results deriving from analyzing data collected at two different levels (household structural variables represent household level characteristics, while survey-elicited preferences represent individually-collected preferences). In defining MV(2), we use the individual preferences as household-level proxies for overall preferences, in order to control to some extent with potential sources of heterogeneity in energy consumption deriving from individual preferences. This approach however suggests treatment effects derived from estimation of our MV(2) model are to be considered carefully, acknowledging this aggregation of preferences.

The two multivariate models then become:

$$electricity_{it} = c + \beta social_i + \alpha latermovein_i + \mu Z_i + \epsilon_{it}$$

and

$$
\begin{aligned}
electricity_{it} = c + \beta social_i + \sigma\, TimePref_i + \zeta\, ReciprocityPref_i \\
+ \rho AltruismPref_i + \delta GroupId_i + \lambda EnvSelfId_i \\
+ \gamma\, TrustPref_i + \theta EnerLit_i + \epsilon_{it}
\end{aligned}
$$

latermovein is a dummy variable that accounts for when the tenants moved into the apartment in the timeline of the retrofitting project. Z_i is a matrix of variables measuring different household characteristics, including number of children, number of males and females, number of people over 65, number of occupants in the household, and average number of hours spent indoors by occupants. We exclude data on dwelling size for this part of the analysis, as it is not expected to be strictly relevant for electricity consumption, but rather will be included in the follow-up study when investigating the effects of the intervention on thermal energy consumption. For the sake of completeness however, we also run all our regressions with the variable of dwelling size (in M^2) included and report the results in the **Appendix** (obtaining qualitatively similar results). We should note that the decision of parameters to include in our estimation was also made on the basis of allowing for replication across different districts, and hence we omitted aspects which would not be replicable in other districts (such as specific geographical or locational characteristics).

Turning to the variables obtained by survey answers, *TimePref*, *TrustPref*, and *ReciprocityPref* are ordinal variables that capture individual-level intertemporal preferences and preferences on trust and reciprocity, respectively, on a scale of 1–7. *AltruismPref* is a normalized variable that captures individual level altruistic preferences from 0 (extremely non-altruistic) to 1 (extremely altruistic). *GroupId* is a measure that captures degree of cohesion to social groups which proxies social distance which, as previously explained, can be a predictor to willingness to contribute to public good. This measure is defined as an average to the answers to four questions relating to the level of identification with specific social groups. Finally, *EnvSelfId* is a measure of pro-environmental self-identity and *EnerLit* is a normalized variable measuring the amount of correct answers out of 4 in a series of questions carefully designed to test the general level of energy literacy of the individual.

All models are estimated via the GLS panel random-effects estimator. In order to understand whether or not there are differences in intervention efficacy during weekends and weekdays, we also estimate all models separately for weekends and weekdays.

The results from the estimated model can be seen in **Table 4**. These results confirm the limited, potentially backfiring role of the intervention. The estimated coefficient in the two bivariate models is positive, confirming that subjects in the treatment group consumed on average more than those in the control group. As expected by the small sample, the results do not reach statistical significance. Estimates of the average treatment effect in the bivariate model range from a positive effect of 0.03–0.07%, with the inclusion of monthly and hourly dummies diluting the positive effect.

TABLE 4 | Results from GLS random effects regression.

Variables	(1) BV(1)	(2) BV(2)	(3) MV(1)	(4) MV(2)
Social	0.000688	0.000331	0.124***	−0.0476***
	(0.0613)	(0.0740)	(0.00587)	(0.00852)
EnvSelfId				0.0205
				(0.0134)
TrustPref				0.0263***
				(0.00347)
ReciprocityPref				−0.0790***
				(0.00455)
AltruismPref				−0.0626***
				(0.00835)
TimePref				0.0506***
				(0.00232)
EnerLit				−0.0520***
				(0.00339)
GroupId				0.0162***
				(0.00293)
latermovein			−0.183***	
			(0.00628)	
OccupantNumber			−0.215***	
			(0.0124)	
HoursAtHome			0.0113***	
			(0.00115)	
MeanAge			−0.00855***	
			(0.000476)	
N children			−0.00759	
			(0.0109)	
N > 65			0.155***	
			(0.00837)	
*N*female			0.238***	
			(0.00849)	
Constant	0.248***	0.160***	0.639***	0.178***
	(0.0433)	(0.0531)	(0.0308)	(0.0655)
Observations	26,576	26,576	26,576	22,160
Number of apartments	12	12	12	10

Standard errors in parentheses.
****p < 0.01, **p < 0.05, *p < 0.1.*
Dependent variable is energy consumption of apartment i at hour t (t = 1–2233). BV(2), MV(1), and MV(2) control also for hourly and monthly variations by including hour and month dummies in the regression (suppressed in output). MV(2) drops observations from two apartments from which we do not have survey data.

Turning to the multivariate models, controlling for household characteristics, we again estimate a positive coefficient for our treatment dummy, but this time the effect of the intervention is statistically significant. On the other hand, when controlling for individual characteristics, not only do the coefficients associated to some individual characteristics (namely trust, reciprocity, altruism, time discounting, and level of energy literacy) turn significant, but also the coefficient of the treatment dummy turns negative. This suggests that heterogeneity in unobserved household preferences might play a crucial role in affecting the efficacy of the intervention.

During weekdays the effects of the intervention are not qualitatively different from the effects we observe using the entire range of data (reported in **Appendix**).

Different results emerge when estimating the model using only weekend data (**Table 5**). The estimated coefficient of the treatment dummy for MV(1) is still positive, further suggesting that socio-demographic characteristics are important determinants of the effectiveness of social comparison interventions in this context. However, the estimated coefficient for the treatment dummy is negative in both our bivariate models, despite being statistically insignificant.

4.4. Interaction Effects

We conducted a study of conditional marginal effects in the model for a subset of significant variables. This was done in order to better understand the direction of treatment effects at different levels of significant covariates in our model. We completed this study separately for models MV(1) and MV(2).

The results of this analysis for the structural variables (**Table 6** and **Figure 6**) are not surprising given earlier results and much of the literature on socio-demographic determinants of energy use (Šćepanovi et al., 2017). The difference in energy consumption of those households assigned to the control group and those assigned to the treatment group increases as the number of females and mature tenants increases. However, only the results relating to the variable "number of females" are significant. These results suggest that (according to the estimated model) the more females in a household, the wider the positive difference in electricity consumption between treatment and control groups, therefore the less the intervention has been effective. This highlights that household family-composition characteristics may be crucial determinants in how effective these interventions are in a social-housing context, and suggests the need for targeted interventions that take into account household gender composition.

Moving on to studying the marginal conditional effects of some of the survey-elicited variables, we are interested in estimating the conditional marginal effects of reciprocity, energy literacy, and willingness to delay (**Table 7**).

The results for energy literacy and time preferences are not significant. Turning to reciprocity (**Table 7** and **Figure 7**), there seems to be a statistically significant difference in electricity consumption between groups at different levels of this variable. This difference also seems to be increasing at higher levels of reciprocity, which counters the predictions of our theoretical framework. The results seem instead to show a diminishing negative difference, and eventually a positive difference in electricity consumption between groups as reciprocity increases, signaling a reduced effectiveness of the intervention for higher levels of reciprocity. While this result might be an artifact of the limited sample, it might also be driven by the reduced sense of agency from living in sub-optimal contexts that generally leads to a deterioration of social preferences (Becchetti et al., 2013).

TABLE 5 | Results from GLS random effects regression including only weekends.

Variables	(1) BV(1)	(2) BV(2)	(3) MV(1)	(4) MV(2)
Social	−0.0172	−0.0181	0.132***	−0.0275*
	(0.0607)	(0.0662)	(0.0111)	(0.0161)
latermovein			−0.175***	
			(0.0119)	
OccupantNumber			−0.270***	
			(0.0234)	
HoursAtHome			0.0134***	
			(0.00217)	
MeanAge			−0.0101***	
			(0.000899)	
N children			0.0114	
			(0.0206)	
N > 65			0.185***	
			(0.0158)	
N female			0.281***	
			(0.0161)	
EnvSelfId				0.00714
				(0.0255)
TrustPref				0.0207***
				(0.00656)
ReciprocityPref				−0.0940***
				(0.00861)
AltruismPref				−0.0814***
				(0.0157)
TimePref				0.0534***
				(0.00441)
EnerLit				−0.0422***
				(0.00640)
GroupId				0.00380
				(0.00555)
Constant	0.269***	0.179***	0.741***	0.430***
	(0.0429)	(0.0497)	(0.0582)	(0.125)
Observations	7,952	7,952	7,952	6,626
Number of apartments	12	12	12	10

Standard errors in parentheses.
****p < 0.01, **p < 0.05, *p < 0.1.*
Dependent variable is energy consumption of apartment i at hour t (t = 1–2233). BV(2), MV(1), and MV(2) control also for hourly and monthly variations by including hour and month dummies in the regression (suppressed in output). MV(2) drops observations from two apartments from which we do not have survey data.

5. DISCUSSION

5.1. Discussion of Results

The results, while acknowledging significant limitations in the data sample size (from only one district) and scope (electricity consumption only), points to the fact that the application of norm-based interventions in vulnerable contexts may not be as straightforward as may seem from the evidence emerging from larger RCTs in more general residential populations. We fail to

TABLE 6 | Conditional marginal effects of household characteristics.

1.Social	***N* female**	***N* > 65**
Delta method		
0	−0.099	−0.047
1	0.011	0.037
2	0.121**	0.122
3	0.231**	0.206

Standard errors in parentheses.
****p < 0.01, **p < 0.05, *p < 0.1.*

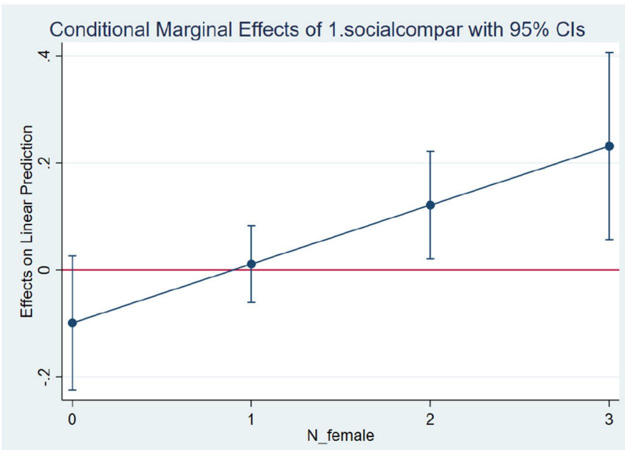

FIGURE 6 | Conditional marginal effects of *N* of females in household.

TABLE 7 | Conditional marginal effects of energy-related preferences.

1. Social	**ReciprocityPref**	**EnerLit**	**TimePref**
Delta method			
1	−0.992**	0.007	0.0555
2	−0.812**	−0.066	0.046
3	−0.633**	−0.139	0.036
4	−0.454**	−0.211	0.026
5	−0.274**	-	0.016
6	−0.094**	-	0.006
7	0.085	-	−0.004

Standard errors in parentheses.
****p < 0.01, **p < 0.05, *p < 0.1.*

identify significant differences in electrical energy consumption between the two groups at the average level, and find statistically insignificant treatment effects in the bivariate regression models. Furthermore, we observe some backfiring effects of the intervention when we control for household characteristics. We do estimate a statistically significant negative coefficient for our treatment effect when controlling separately for survey-elicited characteristics. Given the potential for individual bias however, the estimated results from this model will be corroborated by a future study with data from other districts.

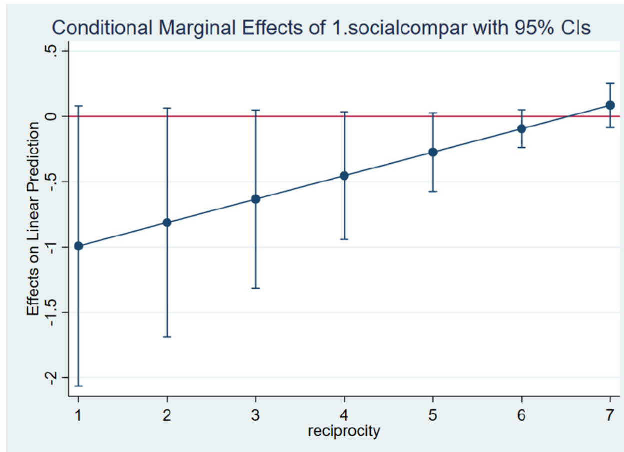

FIGURE 7 | Conditional marginal effects of reciprocity.

A first recommendation emerging from this pilot is that policymakers and practitioners ought to fully consider the characteristics and particular behaviors of the target group before designing an intervention aimed at tackling energy poverty through behavioral change. Even if the low statistical significance and effect size of the intervention is a result of the small sample, the direction of the behavior change suggests that running a small-scale uniform intervention could backfire in vulnerable demographics, particularly if the scope of the intervention is narrow (a small sample limits the capacity to communicate relevant differences in consumption within the sample). It is paramount to take into consideration the specific needs, pre-existing behaviors, motivations, and key reference groups relevant for the demographics being targeted, in order to maximize the effectiveness of the intervention. Drawing on previous findings by Khosrowpour et al. (2016), that highlight the need for targeted feedback mechanisms in behavior-change interventions, similar behavior-change interventions could leverage these contextual features to design more targeted norm-based interventions. Of course, the results do not provide conclusive evidence that these approaches would lead to more successful norm-based interventions, and this remains an empirical question that further research with more targeted approaches should strive to answer.

For this particular demographic, a more holistic behaviorally-informed intervention than one based solely on nudging, might be desirable. As an example, an intervention that provides individuals with basic facts on energy poverty might be implemented to boost skills and knowledge required for identifying and sharing their needs and problems related to home energy comfort and energy consumption (DellaValle and Sareen, 2020). This might not only a way to harness the local experience, thus truly engaging target individuals in the process of betterment of their conditions, but also a way to further increase their capabilities and optimize their energy-use to fit their specific needs. At the stage of analysis furthermore, the integration of more qualitative methods could complement our quantitative approach to better understand experienced conditions of tenants in relation to energy vulnerability and engagement with IHDs (Ambrosio-Albala et al., 2020).

The difference in the direction of the treatment effects between weekdays and weekends is also significant. Given the sample composition being comprised in large part of retirees or other groups that stay a minimum of 12 h at home, we should not observe substantial differences in energy behaviors for these tenants between weekdays and weekends. The fact that the intervention leads to a negative difference in electricity consumption between the treatment and control group when considering only weekend data, could suggest that the composition of occupants in a home at any one time has a moderating effect with the intervention. For example, young adults who are typically away during weekdays might have a higher likelihood to interact with the technology (and therefore see the normative appeals) than some of the older household members who are at home during weekdays. Such an interpretation could support the implementation of remote feedback mechanisms with integrated normative appeals and high granularity information on consumption, such as an app. This more accessible information could lead to the diffusion of more efficient energy behaviors in the home, even when the younger members are away. However, it is important to remark that our findings are not statistically significant, and further research needs to be conducted to support these types of expensive policy propositions.

5.2. Further Research

While our pilot design is not well-suited to identify what specific contextual features limited the effectiveness of the intervention, we propose a number of directions for future research, emerging from patterns in the data and/or supported by preexisting literature, that can further shed some light on the issues we have begun to explore in this study.

Firstly, it could be that the level of cognitive strain associated from being in a condition of income and energy vulnerability is too large to lead to the required level of interaction with the technologies and initiatives designed to achieve behavioral change (due to the contextual-psychological reasons outlined in section 2.4). While this issue is likely to have impacted the effectiveness of the intervention to an extent, it would seem dismissive to assume that it categorically impedes social housing tenants from engaging with a behavior-change strategy. This would also be inconsistent with previous findings that have trialed different forms of behavior change interventions in social housing districts with moderate success (Hafner et al., 2020; Sangalli et al., 2020). It would however be interesting to uncover to what degree different psychological barriers stifle the adoption of more optimal energy decisions, and how each, in turn, could be addressed. A controlled laboratory could prove a suitable environment to provide further knowledge in this direction (Lunn and Ní Choisdealbha, 2018).

Secondly, it is plausible that the lack of effectiveness of the intervention does not derive from the uniform design applied, but rather that tenants are simply not interacting with the IHD technology enough to be exposed to the normative appeals. Certainly increasing the level of interaction with the IHD technology would be unquestionably beneficial, not only to promote energy conservation but also to increase the agency of vulnerable individuals in the control of their energy consumption. The data however does not seem to support this hypothesis as the estimated model fails to identify statistically significant interaction effects when adding Number of clicks as a variable in our Bivariate regression models (**Appendix**). Further researcher on a larger sample would need to be conducted to investigate causality between the level of display interaction and intervention effectiveness. It would also be important to conduct further research that can identify behavioral determinants of interaction with IHDs.

Thirdly, it may be that the integration of the intervention in the context of recently retrofitted homes is affecting its behavior-change potential. Evidence has shown that in social housing districts there exists a particularly high tendency to "take-back" a large proportion on energy savings after efficiency upgrades in the form of increased internal temperatures (Coyne et al., 2018). This behavioral response to retrofitting is likely to be consistent across different forms of energy consumption, including electricity. Taken together with the evidence of a pre-bound effect prevailing in low-income populations (Sunikka-Blank and Galvin, 2012), it seems likely that our group of tenants (who are part of particularly vulnerable demographics and would be consuming below optimal levels of energy pre-retrofitting), increase their consumption post-retrofitting in order to appropriately meet their basic capabilities now that they can financially afford to do so. The impact of this behavioral response to retrofitting on tenants' subsequent willingness to adapt their consumption downwards as a result of normative appeals is hard to measure with the available data (all tenants were subject to retrofits and no pre-retrofit consumption information was available to compare individual apartment behaviors at different stages). However, it seems plausible to assume that tenants who have recently adjusted to a higher levels of consumption thanks to the efficiency upgrades, would be reluctant to then adjust their consumption downwards when presented with social comparison modules, especially if they were previously consuming sub-optimal levels of energy.

To our knowledge, there currently is no literature studying the impact of rebound and pre-bound effects on the effectiveness of subsequent behavior-change interventions, so it is challenging to discern how important these effects are to the observed results. An interesting direction for further research would be to study social comparison interventions in a social housing context not having recently undergone refurbishment, and see if the results differ.

It is important to note that just because the intervention did not lead to statistically significant differences in electricity consumption during the time-period investigated, this does not mean that the households were not consuming energy at an optimal level. Their current consumption levels may well have been conducive to them achieving their basic capabilities. Studying how changes in behavior following the retrofit affected the achievement of basic capabilities would be necessary in order to evaluate the success of the intervention from more of a capabilities perspective. This would require a longer period of observation and a more qualitative study of household outcomes as the optimal levels of energy consumption needed to satisfy basic capabilities are likely to be highly subjective.

5.3. Pilot Study Limitations

Due to the field nature of the pilot study, there were a number of limiting factors during implementation and in the scope of the study which should be addressed in future research. These limitations are worth discussing in order to better interpret the study's outcomes and outline future approaches to more closely determine the effect of social comparison interventions in social housing contexts.

The scope of this study is narrow, as the focus is on electricity consumption only, over a 3 month period and in a limited number apartments. This narrow scope was taken for three reasons: (i) existing data limitations as there was a delay of apartment display installations following COVID-19, (ii) in order to focus on short-term effects as these are the most relevant for behavior change and (iii) to emphasize the methodological and analytical aspects of our study, so as to serve as a reference point for a larger, more extensive analysis once more data is available. While it is plausible that expanding the scope of analysis by including more apartments, studied over a larger period of time, and additionally considering thermal behavior would result in the identification of significant differences in energy consumption between groups, we have no reason apriori to believe that this will be the case. These concerns however are certainly valid from an analytical point of view and a more exhaustive analysis of the available data will be carried out in a forthcoming study in order to draw rigorous conclusions that can direct policy-making. Moreover, further research could look at how similar interventions affect energy profiles throughout the day, as it may be that the intervention does not reduce overall energy consumption but rather shifts energy habits and consumption patterns across the day, which could have associated environmental and financial benefits for a society (especially in the case of variable energy tariffs).

A common implication of field studies such as ours is that participation is voluntary, creating the possibility that our sample is non-representative of the wider population we intend to study as there may be some systematic relationship between participation and some unobservable characteristics, leading to a self-selection bias. The potential for a positive self-selection bias is well-researched in field experiments (Gautier and Klaauw, 2012), as well as in the case of our specific type of intervention (Allcott, 2015).

In our study it is possible that the households which self-select to allow the display installation are particularly prone to have a higher pro-environmental attitude (the mean for the elicited measure of pro-environmental self-identity is 6.58, considerably higher than the median of 4.5) or be more likely to be willing to take control of their energy consumption. This is indeed a limitation of the study as it threatens to reduce the external validity of our findings.

Additionally, the apartment-level randomization that took place within the district has the potential of leading to negative spillover effects, arising from social interaction between tenants, which violate the "stable unit treatment value assumption" (SUTVA), an assumption routinely invoked in order to draw causal inferences from experimental effects (Rubin, 1986). These spillover effects could occur as a result of communication between tenants in different groups. For example, if tenants in the control group become aware that other tenants have displays that show social comparison modules, or even observe each other's displays, this could potentially affect the way they behave, obfuscating the potential causal inferences to be drawn from the results. While a better option would have been to randomize treatment assignment at the building or district-level, the existing timeline of the project as well as other technological considerations made this impossible.

Finally, some issues when running the regression analysis. As previously explained, a number of the variables included in our full regression model are based on individual-level measures obtained from survey responses. This was done because it proved too intrusive and methodologically complex to try and obtain survey answers from all occupants in the dwellings. We opted instead to get answers from one of the occupants present at time of installation. These variables were treated in our analysis as proxies for household-level preferences. This approach is certain to produce household-level measures which are subject to the individual bias in preferences of the occupant answering, introducing this bias to the results. Moreover, despite basing the survey items on experimentally validated items following (Falk et al., 2018), there is still scope for hypothetical bias in our survey answers. Finally, there is little variation in the answers to some of the survey items (ReciprocityPref St. Dev = 0.674, TimePref St. Dev = 1.794, EnerLit St. Dev = 1.128), which together with the relatively small sample, limits the significance of our survey-elicited variables and the results obtained from the corresponding model estimation.

6. CONCLUSIONS

In this study, we have presented a methodology designed to integrate a popular behavior-change intervention in the context of social housing retrofits, with the aim of addressing social and behavioral elements of energy efficiency improvements that are often overlooked in a social housing context. We introduced our pilot field study, based on a wealth of previously successful social comparison interventions in the energy domain, and discussed why social housing tenants make for a particularly interesting and important case study, due in part to their high level of energy vulnerability and potential to fall in energy poverty. Our primary aim throughout has been to uncover whether this intervention could be applied in a standard way within a social housing context, with its unique difficulties and characteristics.

The results suggest prudence on the part of policy-makers when applying these behavior-change interventions in vulnerable demographics. Interventions of this kind, especially if delivered using the IHD technology, can be costly to implement. If their effectiveness in social housing are miscalculated and overstated based on the evidence of RCTs on a more general residential area, the costs of the intervention could far outweigh its actual benefits. This echoes findings from Andor et al. (2017) who find that the benefits of social comparison interventions may be overstated in European populations, making their indiscriminate implementation potentially unfruitful when the costs and benefits are fully accounted for. Policy-makers might alternatively wish to initially implement more cost-effective interventions that are less cognitively taxing for vulnerable demographics to engage with, and instead boost the competencies of vulnerable individuals, so as to empower them to make more optimal energy decisions. Of course there may be benefits related to the use of the display, other than reduced energy consumption caused by social comparison modules, which would make their installation cost-effective. Further research could take a more holistic approach and study the benefits of IHD devices on different dimensions to better evaluate the effectiveness of the display installation as a whole.

Overall, while results at present are somewhat limited from data availability and a narrow research scope, the methodological basis we introduce with this study enriches the emerging field of applied behavior-change interventions in social-housing districts. This field not only has immense practical importance for policy-makers wishing to leverage virtuous behavior in the context of efficiency upgrades of the social housing dwelling stock, but is also deeply important for discussions on energy justice and the tackling of energy poverty. If research in this area can identify ways that behavior-change interventions could be designed to be mindful of the contextual situations of the most vulnerable, we could ensure that behavior is effectively leveraged together with technical upgrades, in order to improve the capabilities of the most vulnerable and tackle energy poverty.

DATA AVAILABILITY STATEMENT

Data generated as part of EU Project Sinfonia, Grant Agreement No. 609019. Requests to access the datasets should be directed to nicolas.caballero@eurac.edu.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Eurac Research. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Both authors provided input into the draft and final manuscript, including conceptualization, and writing-original draft preparation. NC compiled the literature review and was in charge of the data curation and formal analysis. ND was in charge of overall supervision.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2020.601095/full#supplementary-material

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Scalar Containment of Energy Justice and Its Democratic Discontents: Solar Power and Energy Poverty Alleviation

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The threats climate change poses require rapid and wide decarbonization efforts in the energy sector. Historically, large-scale energy operations, often instrumental for a scaled and effective approach to meet decarbonization goals, undergird energy-related injustices. Energy poverty is a multi-dimensional form of injustice, with relevance to low-carbon energy transitions. Defined as the condition of being unable to access an adequate level of household energy services, energy poverty persists despite the emergence of affordable renewable energy technologies, such as solar photovoltaics (PV). Historical injustices and the modularity of solar PV combine to offer new possibilities in ownership, production and distribution of cost-competitive, clean and collectively scalable energy. Consequently, emerging policy priorities for positive energy districts call into question the traditional large-scale modality of energy operations. We report from a case study of solar power in Lisbon, a frontrunner in urban energy transitions while also home to high energy poverty incidence. The study focuses on scalar aspects of justice in energy transitions to investigate whether and how solar PV can alleviate urban energy poverty. It features 2 months of fieldwork centered on community and expert perspectives, including semi-structured interviews and field observations. We mobilize a spatial energy justice framework to identify justice aspects of multi-scalar solar PV uptake. By showing how energy justice is shaped in diverse ways at different scales, we demonstrate ways in which scale matters for just urban energy transitions. We argue that small- and medium-scaled approaches to electricity distribution, an integral component of positive energy districts, can address specific justice concerns. However, even as such approaches gain attention and legitimacy, they risk structurally excluding socio-economically vulnerable users, and proceed slowly relative to large-scale solar rollout.

Keywords: solar PV rollout, energy transitions, multi-scalar governance, energy justice, national energy and climate plans, carbon democracy

INTRODUCTION

The Intergovernmental Panel for Climate Change (IPCC) has indicated the importance of limiting global warming to 1.5°C to avoid catastrophic climate change (IPCC, 2018). Congruently, the World Energy Outlook Report 2019 called for "a laser-like focus on bringing down global emissions" and highlighted that "deep disparities define today's energy world" (IEA, 2019). Alongside the necessity of a rapid and deep global transformation away from fossil fuel sources, there is increasing awareness of the need to transition away from injustices traditionally associated with energy production and distribution. Fossil fuel sources usually entail a physical distance between extraction, management and distribution, and energy end-users. "Carbon democracy" is characterized by fossil fuels which are characteristically concentrated in limited geographic locations; a spatiality that limits ownership and control (Mitchell, 2009). Scouting for and extracting deposits requires heavy financial assets, technology, and equipment. Energy security has long been critical for development. Thus, energy governance is bound up with international negotiations, power posturing, and war (Mitchell, 2009; Behrens et al., 2016). The ability of nation-states to secure adequate energy resources to industrialize and modernize is instrumental in their economic development (Mitchell, 2009). The transition away from fossil fuels, then, goes beyond decarbonizing energy systems. Energy resources interact recursively with geopolitics and national development, and low-carbon energy transitions can potentially reshape these dynamics.

The need for a response to the climate crisis, the geopolitical challenges listed above and expanding renewable energy technologies call into question the traditional scale of operation and ownership in energy systems, through initiatives such as positive energy districts. Critiquing the spatial containers in which we analyze, politicize, and operationalize phenomena such as energy is not new. Fraser (2009) questions the modern territorial state as the default point of policy, control, and analysis. These emerging policy priorities highlight a justice aspect to the scales at which energy transitions take place. Large-scale, centrally controlled energy sectors have been historically riddled with injustices. In solar irradiation rich countries, like Portugal, the tangible proximity of solar energy being "right there" to capture and use inspires social imaginaries about improved energy futures (Szolucha, 2019). Renewable energy sources, like solar photovoltaics (PV), have become affordable and accessible, and increasingly able to compete with fossil fuels. Globally, solar PV has experienced substantial sectoral growth, with 119 GW global capacity installed in 2019 alone, due to its "unique ability to cover most market segments; from the very small household systems to utility-sized power plants" (IEA, 2020).

Despite the affordability and modularity of solar PV, people remain in energy poverty: a socio-material injustice characterized by a household's inability to secure sufficient energy services to meet basic needs (Horta et al., 2019). This suggests that the narrow points of control, as called out by Mitchell (2009) and Fraser (2009), may persist despite transitions to this renewable energy source, regardless of its distinctly different spatial characteristics. Global efforts to eradicate energy poverty are notable in governmental efforts in China, Vietnam, Nigeria, South Africa, Chile, Brazil, Bangladesh, Senegal, and Kenya (Aklin, 2018) and the United Nations' (UN) Sustainable Development Goal (SDG) 7, namely universal access to affordable and clean energy (UN, 2018). Energy poverty is often linked to lack of infrastructure to deliver energy services but can persist despite ubiquitous energy infrastructure due to entrenched inequalities. It constitutes a significant challenge in the European Union (EU), with high concentrations in southern and eastern Europe (Bouzarovski, 2018). In Europe, energy poverty often has socio-economic roots, but can be socio-material, due to poor-quality, energy-inefficient buildings (Bouzarovski, 2018). It persists despite the existence of clean, affordable energy sources. Indeed, studies show that low-carbon energy transitions can exacerbate existing inequities (Behrens et al., 2016; Delicado et al., 2016; Peña et al., 2017). Such energy injustices prompt constructive opposition and public efforts to imagine improved energy futures (Szolucha, 2019). Imagination is "the faculty that allows the extraordinary person to see beyond the limits of constraining reality" (Jasanoff, 2015, p.5). Emergent social imaginaries, notably positive energy districts, are often characterized by scalar changes such as small-scale, decentralized solar PV energy communities. But what potential does solar PV actually hold to alleviate energy poverty? Can solar PV enable people to transcend the entrenched narrow control of the carbon democracy?

Addressing this concern gets to the core of ensuring affordable and adequate energy access as a human right. In recent years, the EU has officially recognized access to affordable and reliable energy services as essential to human life (Hesselman et al., 2019). This is in keeping with established recognition of energy as a necessity for citizenship in one's society because it enables one to stay clean, maintain good health, exercise political rights, and support adequate living temperatures (Day et al., 2016; Brand-Correa and Steinberger, 2017). However, as Walker (2015) notes, the notion of a right to energy is complex and can be "slippery" to pin down. People have different ideas of what the right to energy entails. Contestation over imaginaries often plays out along scalar lines. Perhaps the right to energy implies governmental responsibility for large-scale infrastructure that harnesses economies of scale to provide energy services, or perhaps it means clear legal and affordable pathways to privately owned energy systems for individuals and collectives. This implicates questions of limits and balance. If energy services are free, people may use them sub-optimally, complicate grid management, and compromise a stable low-carbon energy transition. If energy costs escalate, households may be unable to secure requisite energy for wellbeing. Clearly, energy costs require balancing between such extremes. This raises the question of who influences and makes decisions that affect costs, such as fixing electricity surcharges. The governance of energy determines how an energy transition happens and to what degree various actors are involved. Decision-making for energy systems is historically deeply centralized. Emergent social imaginaries regard decisions about energy futures as delegated to decentralized, small-scale nodes, and as thereby involving end users of energy—energy citizens—who are affected by such decisions (Szolucha, 2019). The right to energy debate highlights the prominent role scalar issues play in considerations of just energy transitions.

Consequently, attention to energy justice has spawned a vast subset of energy transitions research (Heffron and McCauley, 2017; Hiteva and Sovacool, 2017; Sovacool et al., 2017; Bouzarovski, 2018; Jenkins, 2018; McCauley, 2018; Sareen and Haarstad, 2018). The important role of scale is increasingly recognized (Bouzarovski and Simcock, 2017; Hiteva and Sovacool, 2017; Sovacool et al., 2019a). Furthermore, previous conceptualizations aim to make sense of the complex relationship between energy and people. Brand-Correa and Steinberger (2017) argue for decoupling human need satisfaction from energy use for more humane approaches to energy analysis. Day et al. (2016) seek to account for geographical and other variations by defining energy poverty through a capabilities approach which highlights context and location as important factors in availability and consumption of energy. Such conceptualizations offer means to better understand the impacts of scale on energy use and participation, a key aim in this article which extends work along these lines. Specifically, we address the energy justice effects of solar energy transitions at multiple scales. The right to energy debate makes evident that energy future contestations are frequently scalar in nature. While governments and large, long-standing energy companies have the resources to enable the rapid and broad-reaching low-carbon energy transition that the climate crisis necessitates, this transition must simultaneously address continuing energy injustices (Sovacool et al., 2019b). We therefore ask what role scale plays in energy justice, and focus our empirical enquiry on the urban spatial context where decisions are mobilized.

This paper contributes to expanding research on energy poverty, energy justice, and multi-scalar analysis through a case study in the Portuguese capital of Lisbon. It aims to present new insights into the role of scale in renewable energy transitions in terms of their implications for energy justice. We examine the potential of solar PV for energy poverty alleviation through a scalar lens: What role does scale play in low-carbon energy transitions and what is its impact on energy justice? We employ a conceptual framework of energy justice that features four mechanisms: distributive justice, procedural justice, cosmopolitan justice, and justice as recognition (Bouzarovski and Simcock, 2017; Sovacool et al., 2017, 2019a). Additionally, we focus on spatial justice in order to integrate scalar aspects.

We proceed as follows: Section Conceptual Framework draws on literature from socio-technical transition studies, features a multi-scalar focus from energy geographies, and combines this with a socio-spatial approach to energy justice in order to elaborate our conceptual framework. Section Methods describes our methods for data collection and the scope of the case study in Section Findings. The empirical analysis first reports findings on the participation of institutions and actors in multi-scalar solar PV rollout in Lisbon (in section Multi-Scalar Participation in Solar PV Rollout in Lisbon), then devotes explicit attention to scalar aspects of energy justice (in section Distinctive Scalar Aspects to Energy Justice). Section Scalar Energy Justice, Energy Poverty Alleviation, and Solar PV Rollout discusses the role of solar PV to alleviate energy poverty in relation to scale and energy justice. Finally, Section Conclusion offers concluding reflections on implications for policy and research on just multi-scalar transitions.

CONCEPTUAL FRAMEWORK

Transition Studies, Justice, and Energy Geographies

The contextual dynamics of an energy transition affects its justice outcomes. Scholarship shows that low-carbon energy transitions can amplify existing socio-economic inequalities (Bartiaux et al., 2016; Behrens et al., 2016). For instance, feed-in tariffs can increase renewable energy use, but this cost may be passed on to consumers while large energy companies profit (Peña et al., 2017). The field of transitions studies challenges simplistic notions of shifts from fossil fuels to renewable sources. Bridge et al. (2013) make a case to examine energy transitions as geographical processes. Climate change and energy security needs are reworking established patterns of scale and distribution. Transitions studies also links energy production and distribution with democracy. Moss et al. (2014) observe how a supply-oriented logic persisted through dictatorial, state-socialist, and democratic regimes in Berlin, and argue for long-term perspectives on path dependencies. Labussière and Nadaï (2018) argue for examining energy transitions in relation to democratic ideals, as many cases do not offer people a genuine chance to exercise a stake in their energy futures. In his seminal work, Mitchell (2009) explores how democratic and undemocratic processes relate to carbon-heavy energy sources.

In essence, a democratic energy transition must help transform spatial patterns of socio-economic activity to bring about a more just energy system. This entails governance challenges to shift energy systems away from reliance on remote, large-scale energy production and transmission and centralized management models. Solar PV in particular challenges the spatial embeddedness of energy production and distribution practices due to scalar flexibility and accessibility to collectives and individuals. In solar rich geographies like Portugal, studies of energy transitions emphasize participatory approaches (Campos et al., 2016) and action at the municipal scale (Campos et al., 2017), and call for stronger accountability in environmental governance in response to the climate crisis (Sareen, 2019).

Spatial Justice and Multi-Scalar Analysis

The need for multi-scalar analysis in energy transitions and environmental governance has gained traction in research on energy justice (Späth and Rohracher, 2012; Newig and Moss, 2017; Sovacool et al., 2017; Bouzarovski and Haarstad, 2018). Bouzarovski and Simcock (2017, p.642) argue that a spatial approach is vital for recognizing energy injustices, saying that "whether patterns of spatial inequality are revealed, and the forms these take, will depend on the scale of analysis employed and the material sites that are considered."

Notably, Fraser (2009) has problematized the nation-state as the traditional scale where justice is evaluated. She critiques this

Keynesian-Westphalian framing as a vehicle of injustice and argues that such a territorial approach can lead to misrecognition and misrepresentation of important justice issues. She asks: which scale of justice is truly just? The typical scale of production and distribution of energy is at the national level. Globalization has called into question the territorial nation-state as the standard scale of measurement, as this partitions political space in ways that block vulnerable groups from challenging oppressive forces. Energy technologies such as solar PV afford new flexibility and accessibility, leading people to imagine and build energy systems that challenge the national scale of operation. These lower-scale systems are often associated with idyllic descriptions like "community," "socially responsible," and "independent," terms closely intertwined with emergent positive energy districts. Yet as urban contestation reveals, drivers for energy justice are localized and contextually dependent (Hiteva and Sovacool, 2017). Bouzarovski and Haarstad (2018) argue that mainstream discussions seldom reflect an in-depth, theoretical understanding of scale in relation to rapid decarbonization strategies. Thus, multi-scalar analysis is a growing approach in energy studies and calls for explicit attention to how scalar aspects modulate the impact of energy transitions on justice.

Späth and Rohracher (2014) critique the prevalence of binary spatial characterizations in European debates on energy transitions. In Germany, government and industrial actors have argued that a transition to renewable energy sources essentially constitutes a sustainable energy system. Others hold that the German Energiewende must increase distributed generation capacity to allow for more electricity from small-scale solar PV and other projects. Beyond reducing transmission needs, they view decentralization as the only way to counter oligopolistic power over energy systems. Another study of the Energiewende reveals that social movements to strengthen local control over energy policy have created energy collectives and initiatives to re-municipalize energy utilities (Moss et al., 2015). Debates on re-municipalization often transcend legal and material ownership, and espouse spatially localized control, procedurally just participation and distributional justice (Cumbers, 2012).

A pertinent analysis of energy justice offers a framework featuring three scales: macro (transnational), meso (national and sub-national), and micro (local, proximate to energy infrastructure) (Sovacool et al., 2019a). The authors argue that energy injustices are not limited to fossil fuels or large-scale energy systems, and problematize the justice impacts of potential low-carbon energy transition technologies such as solar PV. They point out that the impacts of transitions can extend beyond single geographic territories and that such impacts become recognizable through a multi-scalar, spatial energy justice lens. Our article mobilizes these three scales of analysis in relation to a specific form of injustice: energy poverty. Like Sovacool et al. (2019b, 583) who point out that "One cannot identify and manage what they do not (currently) measure, and here, we maintain there is empirical novelty in documenting these injustices," we operationalize energy injustice based on what participants report as perceived injustices and energy poverty concerns.

Energy Justice

Energy justice is rooted in environmental justice, a field of scholarship that emerged in the 1980s and points to the uneven and thus unjust distribution of environmental effects such as climate change and pollution (Agyeman et al., 2002, 2003). For example, historical emissions by some people in rich countries impose 200–300 times more health damage on others than they experience themselves (Sovacool et al., 2016). However, environmental justice scholarship has been critiqued for inadequate influence on decision-making to address environmental failures (Jenkins, 2018). By contrast, Jenkins argues, energy justice scholarship has a targeted systems focus that aids policy uptake, and is better suited for real-world impact. A coherent analytical framework is essential to address complex challenges such as energy transitions and energy poverty. Historical energy usage has made visible a tension between top-down and bottom-up approaches to policy and participation. For wellbeing, the energy poor often need to increase energy use, whereas global environmental justice requires overall decreased energy consumption. Rolling out renewable energy presents an opportunity to deviate from traditional top-down decision processes in order to increase participation and recognition of traditionally underrepresented stakeholders. Therefore, a framework must systemically account for such conflicts and a variety of needs in energy transitions. This is in keeping with the situated and pragmatist approach to justice that Galvin (2019) proposes in his conceptualization of moral claim-making. We employ an established definition of justice as distributive, procedural, cosmopolitan, and recognition.

Distributive justice deals with how social benefits and disadvantages are allocated across society (McCauley, 2018; Sovacool et al., 2019b). Additionally, Bouzarovski and Simcock (2017) argue that the understanding and recognition of geographic disparities in energy vulnerability are key components of energy justice. They challenge "the artificial production vs. consumption binary that characterizes much energy poverty research" (Bouzarovski and Simcock, 2017, p.640), and identify mechanisms that increase energy injustices at multiple scales: landscapes of material deprivation, geographic underpinnings of energy affordability, vicious cycles of vulnerability, and spaces of misrecognition.

Landscapes of material deprivation highlight that energy poverty is spatially uneven both at supra-national (Bouzarovski and Tirado Herrero, 2017) and sub-national scales (Gouveia et al., 2017). Place-specific environmental features like housing stock quality and energy use patterns shape household vulnerability to energy poverty; thus, the scale at and spaces in which energy justice is assessed have implications for what injustices are revealed. The geographic underpinning of energy affordability implies that some countries are more pre-disposed to incidence of energy poverty due to high rates of inequality (Bartiaux et al., 2016). For instance, gentrification has changed where people live in Lisbon (Lestegás, 2019; Sequera and Nofre, 2019). Vicious cycles of vulnerability implicate the multi-dimensional nature of energy poverty, with medically disadvantaged people often at increased risk of experiencing energy poverty, and those with pre-existing conditions more vulnerable to winter mortality (Healy, 2003). As Graham (2007, p.xi) notes, "inequalities in people's health are intimately and inextricably connected to inequalities in their material and social circumstances." We discuss spaces of misrecognition later, under justice as recognition.

Procedural justice concerns fairness in how transitions are implemented (Yenneti and Day, 2015). It helps evaluate whether decision-making is democratic. According to Sovacool et al. (2019b, p.582), "all major socio-technical transitions require open and democratic participation by a wide range of actors (including firms and consumers, as well as civil society groups, media advocates, community groups, city authorities, political parties, advisory bodies, and government ministries) to minimize unwanted impacts." We draw a distinction between institutional and non-institutional actors. An institution comprises any organized body with the capability to govern, whether formal or informal (Lund, 2016). Thus, institutions have control over energy resources and can disenfranchise or empower. Non-institutional actors are persons or groups actively involved in the promotion, production or use of solar energy, and who are thus materially affected by it. These actors hold socio-technical imaginaries, or "collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific, scientific, and/or technological projects" (Jasanoff and Kim, 2009, p.120), that may differ from existing institutional practices.

Cosmopolitan justice is a globalized approach that recognizes the equal worth of all human beings commonly bound and protected by certain moral principles (McCauley et al., 2019). It also recognizes their collective morality beyond borders, regardless of national affiliation (Sovacool et al., 2019a). While its aspects can in principle be covered by the other dimensions of justice, we see value in ensuring explicit attention to a global perspective given the global material nature of solar energy modular supply chains and the climate challenge (Newell and Mulvaney, 2013).

Justice as recognition identifies vulnerable people at risk of worsened exposure by transitions to renewable energy sources (Sovacool et al., 2019a). It recognizes that certain populations, such as the chronically poor, ill, or the unemployed may need affirmative action, and "seeks to ensure the acknowledgment of marginalized and/or disadvantaged groups in relation to energy systems" (Lacey-Barnacle, 2020, 3). One group subject to energy injustice is the energy poor (Sovacool et al., 2016), as recognized by both the EU and the UN defining access to affordable, reliable clean energy as a human right (European Union, 2012; UN, 2018). In a spatialized sense, spaces of misrecognition refer to patterns of risk that remain overlooked, typically due to stigmatization or victim-blaming that neglects underlying drivers and patterns of injustice, leading to lack of targeted support to at-risk groups (Bouzarovski and Simcock, 2017). This offers a focused means to identify injustices of recognition.

METHODS

We apply the above analytical framework that brings together spatial and conventional dimensions of energy justice with specific reference to energy poverty and solar PV rollout in Lisbon. To do so, we draw on empirical material based on 8 weeks of fieldwork spread across two visits during November–December 2018 and May–July 2019, in the framework of a Master thesis project conducted in line with institutional guidelines and ethics requirements at the University of Bergen. The first 2-week scoping visit—funded by the European energy poverty network ENGAGER as a Short Term Scientific Mission—allowed for trialing and subsequently adjusting data collection protocols. The main 6-week stretch—funded through a Meltzer Foundation award—enabled detailed stakeholder interviewing and some participant observation with a clear interest in issues of scale in the governance of solar rollout. This ethnographic approach matches case complexity at the intersection of energy poverty, low-carbon transition, and scale. Fieldwork targeted experts and engaged citizens in solar PV rollout, in line with the multi-scalar focus, which dictated speaking to informants with various experiences of solar PV deployment. Email and telephone requests both in advance of and during fieldwork, along with snowball sampling, were used to recruit participants, who received a written overview of the project and signed consent forms prior to being interviewed. We also drew on a co-author's existing knowledge of institutions and networks relevant to solar energy in Portugal, based on a larger research project commenced in 2017 with extensive fieldwork.

Interviewing decision-makers and small- and large-scale solar PV actors and institutions provided the context for who participates and who is absent (notably the energy poor) in the solar PV rollout in Lisbon. Materials include 24 interviews with 20 different informants (some were interviewed twice) and field observations from two sectoral events: a national Roadmap to Carbon Neutral 2050 meeting on 4 December 2018 and a prosumer business model workshop at the University of Lisbon on 12 June 2019. Informants included researchers, energy community professionals, proponents and members, government officials, and three renewable energy investment firm representatives.

Interview recordings were transcribed to text and then qualitatively coded using the NVivo data analysis software. These primary data were complemented by desk study of peer-reviewed and gray case-specific literature, and a journal record featuring observations on everyday energy practices during fieldwork that served the function of cross-validation and contextualization. For a comprehensive description of methodology, please see Nordholm (2020, 38–55).

Informant selection was skewed to actors engaged in small-scale solar PV projects. Securing responses from larger actors including governmental institutions was challenging, as typical when studying elite groups (Kezar, 2003), especially as a junior field researcher. Difficulty in reaching these large institutions reveals socio-economic dynamics when "studying up" (Aguiar and Schneider, 2016). Interviewed informants shared many reflections about large institutional solar stakeholders.

FINDINGS

Multi-Scalar Participation in Solar PV Rollout in Lisbon

We first describe the relevant stakeholders and analyze their agency in solar PV rollout. A key tenet of procedural justice is to identify participating and missing actors, and to characterize the allocation of benefits and burdens across them (Yenneti and Day, 2015; Sovacool et al., 2019b).

Institutional participants in solar PV feature governmental institutions such as the Ministry of Environment and Energy Transitions (MATE), the Directorate General of Energy and Geology (DGEG), the Energy Services Regulatory Authority (ERSE), and Lisbon's municipal energy agency Lisboa E-Nova. DGEG was the only governmental institution that responded and participated in an interview for this study; the participation of the others was determined from the readily available information due to their public roles. MATE, ERSE, and DGEG operate at the macro-, meso-, and micro-scales of solar PV rollout. They handle transnational operations in Portugal and are responsible for laws, regulations, and taxes that apply to energy infrastructure, production, and distribution. Lisboa E-Nova operates within the urban context of Lisbon with some transnational urban networks. During the study period, policymakers and regulators enabled community energy legislation, notably a collective self-consumption law that came into force in January 2020 to allow individual and collective self-consumption of renewable energy (Diario Da Republica Electronico, 2020). Other prominent institutional participants are energy companies, notably Energias de Portugal (EDP). EDP participates in and benefits from solar PV uptake across scales. At the macro-scale, the transnational company has a presence in 14 countries. At the meso-scale, it is Portugal's largest producer, distributor, and supplier of energy, and has the resources to aid a low-carbon transition for cosmopolitan justice. At the micro-scale, EDP offers a solar PV package for individual and collective self-consumption that allows users to acquire panels without common logistical, financial and temporal barriers.

Other institutional participants include civil society organizations and non-profits that represent interest groups. A notable non-profit institution is Coopérnico, Portugal's first renewable energy cooperative, located at the meso- and micro-scale. It crowdfunds solar PV installations and partners with a supplier to sell virtual solar electricity to members at competitive rates. A notable impact investing institution is GoParity, which facilitates ethical profitable investments such as small-scale solar PV projects that address SDGs such as SDG7. Finally, academic institutions play an important role, with researchers holding knowledge and legitimacy, and often called upon by policymakers to inform energy transitions. They serve to connect large- and small-scale stakeholders. This study secured participation from a representative of a renewable energy civil society group, two representatives of Hyperion investment group, two Coopérnico representatives, and a representative of GoParity. Additionally, this study had participation from nine energy poverty and solar PV researchers at University of Lisbon, NOVA University Lisbon, and the European funded research initiative PROSEU.

Non-institutional participants include investors of Coopérnico and GoParity, energy citizens who invest in small-scale solar PV projects despite a low return relative to conventional investments. Coopérnico also has non-investing members who buy its virtual solar electricity due to a good price. Five members of Coopérnico participated in this study.

Missing actors are those of lower socio-economic standing. Citizens who are not environmental or renewable energy enthusiasts are unable and/or unwilling to spend money on home solar PV or to crowd-fund solar PV projects. Our analysis found that participation was generally missing from this group without deliberative top-down action, such as an initiative led by the municipal energy agency Lisboa E-nova for a low-income housing solar PV community (Franco, 2018). This study purposefully did not seek to include these actors due to a potential injustice of recognition that could result from seeking them based on their potential "poverty" status, which entails a risk of stigma unless carried out with greater local sensitivity and concomitant resource demands than our scope of study allowed for. Work on this theme is, however, emerging (Horta et al., 2019). **Table 1** sums up participation by actors at various scales.

Distinctive Scalar Aspects to Energy Justice

Several actors expressed the idea of changing the scalar configuration of energy consumption, taxation, power, and capital as a strong motivating factor for solar PV uptake. For them, changing the scalar configuration meant more fairness in energy. For example, a member of Coopérnico stated that "The state needed to get money. So basically, over the last 20 years, citizens are paying for that need of the government" (interview dated 17.06.2019). He proceeded to talk about the "murky and very obscure" story behind energy prices in Portugal, in which the state energy company increased revenues in order to sell at a higher price (see: Silva and Pereira, 2019). He continued: "If you can do a system that the objective is not to give profit to big managers... but to use those profits to lower the cost of energy for people and for companies, I think that's fair." He gravitated to Coopérnico because the cooperative offers energy modalities other than the "big," national level incumbent industry.

Coopérnico's model shifts the distribution of energy benefits and burdens from meso- to micro-scale. Informants of this study, such as this Coopérnico member, preferred solutions that avoided bureaucracy, which suggests they were weary of traditional energy institutions. His repeated use of the word big in relation to what he saw as the systemic problems with energy suggests a mistrust of meso-scale energy operations. Several informants (four of the five Coopérnico members) also identified redistribution of capital away from large incumbent industries toward community and other micro-scale energy as a relevant

TABLE 1 | Scalar participation in solar PV by various institutions and actors in Lisbon.

	Stakeholders	Macro-scale participation	Meso-scale participation	Micro-scale participation	Participation in this study
Institutional	Governmental actors (DGEG, ERSE, REN, Lisboa E-Nova)	Regulates transnational solar stakeholders within Portugal, such as the solar auction participants.	Energy policy, renewable energy tariffs.	Lisbon low-income housing project solar community, collective self-consumption law.	Two participants from DGEG. All other governmental institutions listed here were contacted but did not respond.
	EDP	Transnationally owned and operated. Solar PV in multiple countries.	Portugal's largest energy supplier.	Offering solar panels to individual households.	Did not respond to request for interview.
	Civil society (APREN, ADENE)	APREN advises on e.g., interconnection with Morocco for trade in solar PV electricity	Important for national transition to renewably sourced energy. Coordinates large-scale public and private interests.		Three participants, two from APREN, two from Hyperion.
	Coopérnico		Supplier of 100% renewably sourced energy in Portugal.	Crowd owned and funded projects for small-scale, community-oriented projects.	Two participants.
	GoParity	Funds SDG focused projects also outside Portugal which include small-scale solar PV.		Crowd funded projects, most of which are small-scale and solar PV is a big focus.	One participant.
	Researchers		Provide actionable knowledge on solar PV rollout to governmental actors.	Growing body of research on municipal- and small-scale solar PV.	Nine participants.
Non-institutional	Coopérnico members			Environmentally focused people with keen interest to invest in community level solar.	Five participants.
	GoParity members			Environmentally focused people with keen interest to invest in community solar.	One participant (also a member of Coopérnico.)
	Ordinary citizens		Opportunity for inclusion from Coopérnico due to low energy cost. EDP solar panels.		No participants by design.
	Energy vulnerable households		Opportunity for inclusion from Coopérnico due to low energy cost. EDP solar panels.	Limited opportunity for participation via Lisboa E-Nova.	No participants by design.

theme. The flow or stagnation of capital finances the location and scale of low-carbon energy transitions, deciding which of these projects lives on and succeeds. GoParity's investment criteria put this idea to work; their capital sourcing criteria provide a low €20 entry point to investment in solar PV. The GoParity representative stated "we are giving access to everyone. To [a] community of investors" who fund social impact projects as small as €10,000 net worth, making possible many micro-scale, decentralized ambitions. "Traditional commercial banks don't fund that. We fund that" (interview dated 25.06.2019).

Problems with the built environment, and the national administration's response to this issue, were prominent iterative themes in discussions about energy poverty during interviews. Government efforts to address this material deprivation, and thereby energy poverty, included tax breaks for efficient housing upgrades. A researcher critiqued this by arguing that "they are giving the incentives and the privileges to ones who already have money and knowledge to change" (Researcher six, interview dated 19.06.2019). The government also offered financial reimbursement for energy efficiency enhancing building renovations, such as the installation of insulating double-glazed windows. However, informants argued that the national execution of these well-intentioned policies resulted in prohibitive knowledge and bureaucratic hurdles, rendering these programs inaccessible to the neediest households.

A researcher from NOVA University Lisbon (interview dated 18.06.2019) imagined a solution to the difficulty in rolling out these policies and proposed nation-wide decentralized deployment of knowledge in the form of municipal information hubs that would assist citizens in home renovation, solar panel procurement, and energy sector bureaucracy navigation. He explained the multi-scalar administrative approach as one in which "there is a central office that works with the municipalities, so they go for the programs and plans on energy efficiency together." He argued for knowledge and programs that can improve people's lives to be easily accessible and enabling across groups with a broad range of educational and socio-economic attributes. Another researcher (Researcher two, University of Lisbon, interview dated 28.06.2019) elaborated that the energy tariff program for energy vulnerable households at most assists poverty alleviation, but not energy poverty alleviation. It lowers home electricity bills, but residents do not necessarily increase thermal comfort, which is essential for good health. Spared income is often redirected to other needs like food and medicine. Effective solutions must focus on achieving thermal comfort regardless of financial means and he mentioned solar energy communities as one possibility.

The same researcher highlighted the problem of spatially remote energy production and consumption. Lisboa E-Nova runs a citizen training program on energy efficiency, where residents of an affordable housing neighborhood solar PV community meet to discuss energy efficiency practices and behaviors, receive knowledge to decrease their energy bills, and access available support schemes. The researcher pointed out that "I would be very surprised if we could replicate this at larger scales" (Researcher two, interview dated 28.06.2019), emphasizing the scalar mismatch between improving local participation and large-scale electricity generation and distribution. He proposed a community solar peer-to-peer regulatory scheme as another means to address energy poverty, rather than a large distribution service operator. The peer-to-peer system would let owners sell energy in their community or make aggregated grid sales.

Around half of Portuguese housing stock requires extensive renovation (Palma et al., 2019). The above mentioned building renovation scheme was labeled a failure by several informants and came up unprompted in over a third of interviews. A researcher (Researcher six, interview dated 19.06.2019) flagged the "centralized point of view" of the overly demanding scheme design to illustrate how the narrow, national level, central control of these policies, and resources has been ineffective. A decentralized peer-to-peer model, like the one suggested by Researcher two, requires community cooperation and can utilize a third-party institution to access benefits usually limited to higher-scale operations. A third-party can aggregate excess solar energy and trade it on the wholesale market, removing technical barriers that hinder small-scale solar PV adoption. Two informants (see **Table 2**) highlighted the importance of networks within and across urban contexts, citing intermunicipal communities in regions as vital enablers of energy policy implementation and resource sharing. The NOVA researcher observed that of the municipalities, "most of them are small. So they cannot act alone... in some regions there is a combination of like 15 municipalities" (interview dated 18.06.2019). Thus, networks are important for small-scale solar PV actors since they allow for the aggregation and sharing of resources and knowledge. Through these networks, small-scale actors acquire and share valuable assets resulting in risk-sharing and an increase to their project's security, longevity, and potential for success. Risk sharing is part of the thinking behind the PROSEU prosumer solar PV communities as brought forth by the PROSEU representative: "The families with already installed systems, would use the savings they have to then help [vulnerable] families... that people with no money could have access to solar energy" (interview dated 17.06.2019). **Table 2** sums up the main findings above, backed by especially pertinent quotes.

SCALAR ENERGY JUSTICE, ENERGY POVERTY ALLEVIATION, AND SOLAR PV ROLLOUT

The Potential of Solar PV to Alleviate Energy Poverty

The Lisbon case gives a glimpse into the complex nature of energy justice within energy transitions. Specifically, it shows us that the scalar containers used in analysis and execution of energy operations and transitions matter for justice outcomes. For example, to exercise the potential of solar PV to alleviate energy poverty, the energy poor must be able to participate in its rollout. They must be able to experience the monetary savings and self-deterministic effects that many solar PV proponents speak of. Participation is intertwined with procedural justice, as policy and implementation processes, and the modularity of the energy technology, determine who participates and benefits. Solar PV has a broader socio-economic and scalar composition of stakeholders than fossil fuel energy sources due to flexible modularity which shapes new socio-material assemblages of energy and gives wider options for ownership and control. In Lisbon, emerging stakeholders, empowered by the accessibility of solar PV, represent constructive opposition to incumbent operators. Energy democracy, characterized by large amounts of distributed generation and less capital-intensive energy production, is a possible outcome of the tensions that shape the trajectory of emergent socio-material assemblages (Calvert, 2016). However, technological progress and resource availability do not suffice to materialize pro-poor energy futures. In Lisbon, procedural tensions facilitated networked engagement among new solar PV actors, but maintained limited opportunity for participation from energy poor households.

Building quality featured often without prompting during interviews as a leading problem in addressing energy poverty. Poor housing quality constitutes landscapes of material deprivation (Bouzarovski and Simcock, 2017), a distributive consequence that renders addressing energy poverty with solar PV challenging, based on the built environment's poor interaction with climate effects. One study found that building renovation measures provided long-term sustainable effects over energy subsidies (Gouveia et al., 2018). The 2010 government-implemented building renovation strategy, that allows residents to apply for cost reimbursement of energy efficiency-enhancing features, was rolled out nationally to be available to all citizens. Theoretically, this approach would address a root cause of energy poverty while increasing the feasibility of solar PV. Unfortunately, informants revealed the prohibitive complexity of the building renovation program in Portugal, which inadvertently limits the benefits to those in a position to acquire extra help and afford bureaucratic delays for renumeration. Two well-educated and well-connected informants (interviews

TABLE 2 | Main findings and quotes.

Finding	Details	Supporting quotes
Energy justice has distinctive scalar aspects	Changing scalar distribution of energy consumption, taxation, power, infrastructure, and capital.	"We are currently embracing self-consumption and [energy] communities."—Representative of DGEG "The state needed to get money. So basically, over the last 20 years, citizens are paying for that need of the government."—Member, Coopérnico, and GoParity "We hopefully want to (bring) a bit more power to…local communities as consumers and producers of energy."—Representative, PROSEU (European research initiative to mainstream prosumerism) "We are giving access to everyone. To [a] community of investors" and "traditional commercial bank don't fund that. We fund that."—Representative, GoParity
	Increase distributed generation and distributed knowledge.	"The public policy instruments in place, they are not tailored for low income persons or families. At all."—Researcher at the Center for Environmental and Sustainability Research (CENSE) "We are living almost in a monopoly. We have EDP and they are very strong."—Researcher six, University of Lisbon "Centralized is doing the same we have done so far, but with a different source. It's the same regime, same structure, and the same paradigm. Just changes the source… we will have the same inequalities in distribution."—Representative, PROSEU "Distributed generation…happens in many different places and there is no way of centralizing the generation."—Researcher two, University of Lisbon
Networks are important for small-scale solar actors	Small-scale solar actors aggregate in different ways to acquire benefits usually reserved for large, meso-scale operations.	"The families with already installed systems, would use the savings they have to then help [vulnerable] families…that people with no money could have access to solar energy."—Representative, PROSEU "Most of them are small. So they cannot act alone…in some regions there is a combination of like 15 municipalities…there is a central office that works with the municipalities so they go for the programs and plans on energy efficiency together."—Researcher three, NOVA University Lisbon

dated 19.06.2019 and 5.09.2019) stated they were unable to complete the paperwork themselves and had to utilize their administrative connections to finish the process. In addition, residents usually had to buy the equipment and deal with the technical requirements themselves (an additional consultation cost if they did not possess appropriate technical skills). This constitutes an extra temporal boundary as those who most need the assistance likely do not have the money to invest upfront, and even if they do, few can wait for the bureaucratically long reimbursement schedule. This can hardly be called a solution for those most vulnerable to energy poverty and this example was used by this study's informants to argue for new, small-scale configurations of energy access. Procedural and temporal complexities represent barriers for energy vulnerable households.

The Role of Scale in Energy Justice

Community and expert perceptions collected during this study indicate that the scale of solar energy rollout matters for energy justice. According to a representative from PROSEU: "Centralized is doing the same we have done so far, but with a different source. It's the same regime, same structure, and the same paradigm. Just changes the source…we will have the same inequalities in distribution" (interview dated 17.06.2019). This striking claim merits closer examination: while meso-scale, centralized energy provision has historically led to injustices, this is not inevitable. Consider the effects of Portugal's low-carbon energy transition to wind power since the 2000s, which decreased its fossil-fuel dependence "from 64% of total electric power demand in 1994 to 36% in 2014" (Peña et al., 2017, p.201). A renewable energy feed-in tariff with public subvention facilitated this massive shift (ERSE, 2020). Studies confirm that the large growth in wind power increased the price for end users (Peña et al., 2017; Prata et al., 2018). This constitutes inequitable distributional effects and supports many of the informants' claims.

The case is illustrative of distributional injustice in that it shows how the burdens of transitioning to renewable energy were distributed unfairly to end users, many of whom struggle with energy poverty. Yet, the case aids in parallel cosmopolitan justice through large-scale decarbonization at the national and global scale. This demonstrates that it is possible to have both an increase and a decrease in justice effects, depending on the scale of and spaces of recognition. It points to the potential blindspot or trade-off that can result from limited scalar containers of action and analysis. What is good for the country, may not be good for greater notions of cosmopolitan climate justice; a contestation that reveals how political trade-offs happen and the importance of acknowledging and analyzing them (Newell and Mulvaney, 2013). Deploying meso-scale energy transition addresses the global need for vast and rapid decarbonization (cosmopolitan justice) but facilitates this at the expense of end users, causing procedural and distributive injustice at the micro-scale.

Perceptions of respondents indicate a desire to address distributional injustice by changing how national energy markets function. A study of the distributional costs of Portuguese wind energy under the liberalized Iberian market regime supports this perception, showing an asymmetric benefit at play for ratepayers. It notes that the rate increase for end users "suggests some kind of welfare transfer that policies should avoid" (Prata et al., 2018, p.508).

Thus, large-scale operations have caused injustice. However, up-and-coming small-scale approaches sometimes rely on traditional, large-scale approaches to gain influence and legitimacy. Our research indicates that small-scale actors recognize that there is more control and legitimacy at larger scales of energy operations, yet their experience tells them that just and democratic effects are happening at smaller scales. By establishing networks, they work within and match the established socio-technical structures that yield better resource access and greater control over their energy futures while maintaining the inclusivity of small-scale solar PV communities. For example, Coopérnico amalgamates small-scale community solar PV systems into a larger cohort and has become an energy supplier to secure market access. PROSEU draws on 11 prosumer, renewable energy communities across the EU and has secured competitive research funds from the European Commission. This enables the empowerment and amplification of a small-scale solar community in Portugal toward its goal of energy autonomy. In both cases, solar collectives and networks increase salutary justice outcomes through procedural, distributive, and recognition effects. Through collectives that exercise broad claims of a right to energy, energy users take on institutional and state effects through a multi-scalar identity. This widens the narrow points of control that were previously limited to a carbon-only democracy (Mitchell, 2009), creating new openings for energy justice in an explicitly spatialized, socio-economic sense.

Paradoxically, the solar panel program EDP targets to individual households presents the best current example of a horizontal solar PV rollout, by removing technical, logistical, temporal, and monetary barriers. However, there are real justice issues with the final distribution of benefits from adoption, and also in the supply chain for solar panels, which often extends beyond national borders (Barnes, 2017). It is unclear where EDP sources solar panels from, and which standards procurement complies with. By contrast, Coopérnico employs a rigorous certification process to ensure the complete lifecycle of the panels used in their projects is sustainable and humane (interview dated 14.06.2019) but they do not possess the resources at this stage to roll out a solar PV program as comprehensive as EDP's. Thus, at the macro-scale, Coopérnico's approach explicitly embodies cosmopolitan and recognition justice by taking measures to acknowledge and ensure that, for example, materials do not come from conflict zones. In this way, they ensure that their contribution to the renewable energy transition does not result in unjust global externalities. Yet, EDP utilizes its commanding multi-scalar influence to enable a horizontal diffusion of individual solar that transcends typical adoption barriers to procedural and distributive justice.

If energy transitions are mono-scalar, spaces of misrecognition are liable to arise (Bouzarovski and Simcock, 2017). Healy and Barry (2017) emphasize that national transition strategies should facilitate coalitions, consider local contexts, and include communities and citizens in policymaking. The fact that energy poverty has not been effectively addressed through either micro- or meso-scale solutions suggests the need for alternative approaches at these scales. Two interviewed researchers effectively made the argument for improved multi-level governance by positing that national-scale governance should equip and task municipalities with adjusting and implementing energy policy for horizontal diffusion of solar PV to their constituents. They argue that this would allow for location-specific distribution and greater efficacy, an argument that resonates with academic literature about multi-scalar approaches to governance. Späth and Rohracher (2012) argue that multi-level governance that integrates and implements socio-technical configurations, and differs from traditional, dominant regimes, may be advantageous for the long-term success of an energy transition. Since municipalities embody generally even territorial coverage, they argue that such micro-scale delegation of control and responsibility can enable spatial and energy justice.

Thus, national governments and large-scale institutions can and do play an essential role, both to facilitate rapid and substantial decarbonization of energy systems for cosmopolitan justice as well as to coordinate multi-scalar action. An economy built on carbon requires decarbonization efforts of massive proportions on the scale of—and layered on top of—existing carbon infrastructure to avoid the worst effects of cataclysmic climate change. The trade-off between the urgent need for large and rapid decarbonization, and ongoing injustices associated with large-scale approaches to energy provision, further underscores the need for a coherent vision and explicit commitment to energy justice across scalar approaches. Our study suggests rich scope for alternate modalities of solar PV rollout that require diverging from traditional top-down implementation in favor of policies that explicitly enable energy justice at lower scales through socially situated approaches.

There is a consequent need to consider and allow for variation in "regime structures" during transition (Späth and Rohracher, 2012). Engaging renewable energy actors across scales has a vital place in deliberate strategies for accelerated decarbonization (Calvert, 2016). Portugal's world record setting solar auctions in 2019 and 2020 saw massive participation by foreign players. A competitive market mechanism spurred rapid uptake premised on a globalist approach that more narrowly targeted, localist approaches would have unduly limited. Community energy and other small-scale approaches can and should complement a robust, multi-scalar low-carbon transition. However, as cautioned earlier, mono-scalar focuses to energy transitions appear to have their disadvantages, and micro-scale energy, favored by many participants in this study, is no exception. For instance, scholars caution against the disadvantages of localism (Späth and Rohracher, 2014; Sturzaker and Nurse, 2020). Stokke and Mohan (2001) point out how localist approaches can be mobilized by various ideological stakeholders, for instance to undermine the role of state or transnational authority. Such a tendency can hold back the critical multi-scalar role energy governance needs to play for an effective and just low-carbon transition.

CONCLUSION

Twentieth century democracy was both created and limited by fossil fuels (Mitchell, 2009). In the 21st century, we are unpacking how renewable energy recursively shapes democracy and what new limits and injustices this governance dynamic creates. Is it the same democracy with the same limits and injustices as carbon democracy, albeit with a different socio-spatial configuration? Are these democratic maladies unavoidable as states transition to renewable energy sources? The Lisbon case illustrates how a particular approach to low-carbon energy transitions enacts complex justice outcomes and the recognition of those outcomes depends on the scales at which action takes place. Our analysis reveals how an action or policy can be simultaneously just and unjust, underscoring that comprehensive consideration of just energy transitions must be rooted in an explicitly multi-scalar perspective. It also signals the way forward for more democratic energy transitions that are mindful of how approaches selectively encourage or hinder participation. As Mitchell (2009, p.401) states: "Understanding the relations between fossil fuels and democracy requires tracing how these connections are built, the vulnerabilities and opportunities they create and the narrow points of passage where control is particularly effective." These narrow points of passage ensured that a limited group of people experienced the profits and power of fossil fuel energy sources. How does solar PV stack up? Solar PV, unlike fossil fuels, is inherently scalable from large solar parks down to the household unit, inspiring socio-technical imaginaries for more democratic energy futures. Is it inherently more democratic, or do established forms of carbon democracy overpower any potential changes? Is solar PV more democratic at some scales than others? The Lisbon case shows us that solar PV has many more "points of passage" than fossil fuels, a socio-material artifact that limits possibilities of central control and opens up to more democratic energy futures. We see emergent small-scale energy actors empowered by the modularity and affordability of solar PV. We see these actors laying claim to their energy, and exercising authority over it, by forming networks and coalitions. We see how policy enables or hinders their ability to act on their claims. Despite citizens' attempts to take decisive steps to overcome perceived shortcomings of energy governance, we note spatial variation where large-scale material shifts only sporadically accommodate local contextual aspects. This results in "islands" of increased democratic effects. Without targeted policy, landscapes of material deprivation persist despite the existence of affordable clean energy sources, and manifest as lingering energy poverty and socio-spatial patterns of exclusion in small-scale solar PV rollout.

Further investigation could explore multiple paths. First, scalar notions of energy justice would benefit from the inclusion of more voices from large institutions and governmental agencies, to examine aspects such as changing roles of electricity suppliers. Second, scalar research could interrogate interactions across scales in a single study, despite a spatial focus on the urban, as in our case study. Scholarly treatment of spatial energy justice tends to utilize different cases for each scale. Third, our study brings to the fore instances of practical approaches to energy justice that are spatially limited, such as the social housing renewable energy project of Lisboa E-Nova. Future work could explore how such innovative projects impact energy poor households and develop guidance for how to scale out and replicate these in diverse contexts.

Future studies can address the mainstreaming of energy justice in energy policy, taking point of departure in rapidly proliferating multi-scalar energy transitions. Energy justice "needs to be taken out of the abstract and placed into the realm of the practical" (Hiteva and Sovacool, 2017, p.638). A spatialized energy justice approach could help policymakers recognize the variations of injustices that can occur across various scalar configurations of the energy policy they enact. With a better understanding of the potential political trade-offs between the different types of energy justice, they can execute more inclusive energy policy. In this way, they may be able to decrease negative externalities, such as energy poverty, that can readily manifest from or be exacerbated by renewable energy transitions. It may help them better manage the complex nature of ensuring a just energy transition to create more democratic socio-technical energy futures. Finally, further research could pick up the torch on this very case, the nature of which is quickly changing. A statement by an interviewed researcher captures the complexity and rapidly evolving nature of the studied context: "And uh, if we had this conversation in 6 months' time, I would probably say a few different things." While real-world change makes for moving targets, there is clear and significant scope for impact-oriented research.

Like the Energiewende in Germany (Moss et al., 2015), aspects of escalating energy transitions are contested in Lisbon and Portugal. These contestations, and the potential of solar PV, have produced a diverse range of stakeholders with varied socio-technical imaginaries about the energy futures at stake. Who gets to realize those futures, and how, is a rapidly unfolding challenge for energy justice, and one where scale plays a central role—in communities, in Lisbon, in Portugal, and globally.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AN led the conceptualization, framing, data reporting and writing, and data collection. SS contributed to all aspects of the paper other than data collection. All authors contributed to the article and approved the submitted version.

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Deprivations and Inequities in Cities Viewed Through a Pandemic Lens

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The COVID-19 pandemic brought a halt to life as we knew it in our cities. It has also put a magnifying glass on existing inequalities and poverty. While everyone has been facing the pandemic's risks, the lived challenges of the lockdowns have been felt most acutely by the poor, the vulnerable, those in the informal sector, and without savings and safety nets. Here, we identify three ways that the COVID-19 pandemic and related containment measures have exacerbated urban inequalities and how subsequent recovery measures and policy responses have tried to redress these. First, lockdowns amplified urban energy poverty, while recovery measures and policies offer an opportunity to address entrenched inequalities in shelter and energy access. Second, preexisting digital divides even within well-connected cities have translated into inequalities in preparedness for living through the lockdown, but digitalization strategies can enhance equity in access to e-services, online work and education for all in the future. Third, slum dwellers in the world's cities have been particularly hard hit by the pandemic and lockdown measures, but the spotlight on them provides further impetus for slum upgradation efforts that through improved access to infrastructure can improve living conditions and provide more secure livelihoods.

Keywords: COVID-19, cities, inequality, urban poor, energy poverty, slums, informal settlements, digital divide

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INTRODUCTION

The COVID-19 pandemic is a combination of a global health crisis, an economic recession, and a social crisis. It has held up a magnifying glass to existing inequalities and deprivations. While it is claimed that "the disease does not differentiate between poor and rich," the immediate and long-term impacts are being felt by vulnerable populations disproportionately. COVID-19 has manifested more visibly in urban areas in terms of vulnerability, pandemic management, and counter-measures (UN, 2020). Higher population density in cities has increased the risk of spread of the disease, especially in cases when distancing and hygiene requirements have been difficult to meet. This has required more stringent measures to be implemented in cities, which in turn have triggered additional social and economic repercussions (Chen and Chen, 2020). A new World Bank report estimates that the new poor are likely to be more urban (World Bank, 2020). The actual vulnerability to COVID-19 and resilience to the related social transformation in cities depends on numerous conditions, including age, gender, socio-economic status, the place, quality and size of dwellings and workplace, access to public services, reliable energy and clean water, access to digital services, and urban governance. Deep-rooted inequalities in cities have influenced how seamless and workable a transition to the new realities of life under the pandemic has been, and how resiliently populations have been able to adapt, in both the global North and South.

In this work, we highlight three instances of how inequalities in housing infrastructure, access to Information and Communication Technologies (ICT) and digital services, and access to modern energy services have impacted the ability of urban inhabitants to cope with the lockdowns, curfew measures, and subsequent economic and social fallout. With the COVID-19 pandemic still ongoing and entering its second year, data on impacts, response measures, and lessons learnt are still emerging. Information on select shorter-term impacts is increasingly available, while medium- and longer-term effects are deducted from the lessons of comparable past disruptive events or other similar evidence.

For this Perspective, we undertook a literature search of peer-reviewed and other commercial and government documents across multiple disciplines, to identify illustrative examples of issues, impacts, and responses relevant to the intersection of urban energy poverty, the pandemic, and the three thematic focus areas mentioned above. After identifying the immediate impacts of the pandemic and containment measures, we critically synthesized the reported experiences and measures to assess the potential effectiveness of short-term measures and some implications of these for longer-terms strategies. We conclude each of the following three sections with a discussion of how a conscious implementation of recovery to a post-pandemic world could alleviate inequalities and poverty based on multiple dividends, embedding this also within the pre-pandemic literature on longer-term sustainable development transformation strategies.

DISPARITIES IN HOUSING CONDITIONS AND ENERGY USE

Time at home has increased considerably during the pandemic with implications for energy use at home, especially in urban areas, where dwellers had been spending more time inside already before COVID-19 than rural communities (Matz et al., 2015). The growth in thermal energy demand in 2020 compared to 2019 has been estimated at around 18 and 6% in the global North and South, respectively (Kikstra et al., 2021). Similar changes were observed in electricity demand due to more use of ICT, cooking, cooling, lighting [e.g., 26% increase in Indian cities, and 6.7% increase in Bhutan compared to 2019 according to Chhetri (2020)].

Higher energy use means increased energy costs, that generate a serious burden particularly on poor households, especially in buildings with low energy standards. Low energy quality buildings are often inhabited by lower socio-economic groups (Weinsziehr et al., 2017), whose heating costs in Europe can be €2,000 higher per year than the best performing buildings even in normal circumstances (Government of the UK, 2019). Spending more time inside and in poor housing conditions also affect the lives of disadvantaged populations in a number of other ways (Patel et al., 2020). Low quality buildings perform poorly on temperature and humidity control, which can result in a room climate that is either too cold and damp, or too hot, associated with higher incidence of respiratory problems (Awada et al., 2021).

In parallel, the pandemic has led to contracting markets and closure of industries and services that have resulted in high rates of unemployment, reduced working hours (and thus, incomes) with enormous differences within and across countries. On average, there has been a 10.7% loss of labor income during 2020 compared to 2019 (ILO, 2020) and as high as over 50% in some countries, like Peru. Urban populations have been hit harder, with low quality job-holders, younger workers, and women more likely to lose jobs (Cueva et al., 2020; ILO, 2020).

As a result, energy poverty has been aggravated in many countries, with residents finding it difficult to pay energy bills, e.g., households in European cities spending an additional €18–25 per month for energy. Unaffordable energy bills have also had an impact on mental health (Goyens, 2020).

Shortly after introducing containment and stay-at-home orders, many countries announced measures to mitigate the impact on households and businesses (Mastropietro et al., 2020b). The immediate value of emergency policies has been to enable marginalized families and individuals to continue to earn a salary while staying at home. Traditional poverty measures in electricity provision, such as purchasing prepayment meters have been supported in a number of EU countries (Goyens, 2020). After the pandemic, many counties prohibited disconnection from energy supply in case of non-payments (Mastropietro et al., 2020b). To make this measure specific for vulnerable citizens, some countries applied limitations, such as registration (Government of the UK, 2019), and providing support for first homes only (Goyens, 2020). These bans have been linked to deferral plans, payment extension solutions, and or zero-interest rate loan solutions (Mastropietro et al., 2020b). Sri Lanka set up a special fund for containment, mitigation and social welfare spending, and special energy tariffs were created for vulnerable households in Mali and Togo (IMF, 2020). The validity and eligibility of social tariffs has even been extended in some nations (Spain, Italy and Ukraine) (IMF, 2020; Mastropietro et al., 2020a).

In the longer term, placing buildings in the center of recovery measures and efforts could bring several social, health and economic benefits (Zangheri et al., 2020). Experiencing the hardships of low-quality buildings and energy poverty even more acutely during 2020 can increase the popularity of deep energy renovations. Drastically increasing the energy performance and quality of buildings can provide co-benefits for the resilience and living conditions of vulnerable groups, the environment, and the labor market. Several countries (for example, the UK, Germany) have added building refurbishments to their recovery and stimulus packages, hoping to improve also local employment and economic activity.

Municipalities are among the largest landlords for social housing in many cities (e.g., Vienna), and are responsible for retrofitting housing for vulnerable groups, while providing impetus for the renovation industry and leading into an energy transition (IEA, 2020). Today it is possible to build or retrofit almost any building to produce more energy than what is consumed inside (Ürge-Vorsatz et al., 2020), ensuring almost zero costs for occupants even in lockdown conditions.

DIGITAL DIVIDES AND DIGITAL PREPAREDNESS

The digital divide is not only a global North-South, urban-rural, generational or gender divide (ITU, 2020). It also exists within well-connected cities, megacities, and regional centers across socio-economic strata. Through the COVID-19 pandemic and responses, the divide in digital preparedness to deal with the impacts on everyday life has become visible at multiple levels: for information, schooling, work, social connection, daily chores, entertainment, religious, health and government services.

The pandemic is exposing the lingering inequalities underpinning the digital divide, adding a new dimension of urgency. Multiple barriers exist that hamper digital inclusion: access to digital technologies due to high costs (for devices, Internet, and electricity connections) and unreliable services (again both for electricity and Internet), low digital literacy and support (Beaunoyer et al., 2020). In deprived urban areas, households, schools, and businesses suffer from unaffordable, weak, or non-existent Internet connection (Wamuyu, 2017), leading to falling behind further during lockdowns, missing out on education and income. Improved Internet access in poor urban neighborhoods increases telecommuting and home education opportunities during lockdowns. The poor, young and women are least likely to have jobs that are fit for teleworking (Brussevich et al., 2020), doing the essential work that maintains and sustains urban life: public transport, healthcare, refuse collection, deliveries, or food service and supply. Those with the lowest incomes have also found it hard or impossible to isolate at home, leading to higher risk of COVID19 exposure (McFarlane, 2020).

In such circumstances digital services become a privilege. Sir Tim Berners-Lee, inventor of the World Wide Web, called for access to the Internet to be considered a human right (Web Foundation, 2014). This notion is being supported by the initiative "Cities for Digital Rights" that promotes and defends digital rights in urban settings. Digitalization offers great opportunities to improve access to services, accelerated through COVID-19 related measures (e.g., e-governance, e-health services) (TWI2050, 2020) and to provide opportunities for home schooling and telework. This requires cities to embrace digital solutions and innovation in their planning and management processes, while being cognizant of the digital divide. Many digital public health technologies previously deemed unacceptable are now being tested in cities worldwide to reduce the spread of COVID-19 (Bragazzi et al., 2020). Increasing digitalization of urban life could perpetuate or break the cycle of health inequalities (Hoernke, 2020).

The longer-term impacts of the pandemic and digitalization on cities and their infrastructure remain to be seen. Peak-urbanization (at least for large cities) and the comeback of the country-side or regional centers has emerged as a new demand. With the amenities of city-life, such as entertainment and culture, having come to a halt, affordability of housing and closeness to nature speak for the countryside, if telework is possible. The demand for office buildings and certain types of housing and related services and jobs could shift. First impacts on the housing markets have already been witnessed. This could impact the future of city composition (migration and segregation), urban planning (e.g., sprawl), municipal budgets and sustainable development objectives. To achieve digital inclusion, cities first need to understand and identify where digital divides persists (geographically and demographically).

Digitalization is an autonomous trend that is impacting nearly every aspect of our lives. It offers many opportunities to improve our lives through better service quality, harnessing of efficiency potentials, facilitating communication and information exchange, and creating new opportunities. At the same time, it comes with challenges for sustainable development for which strong governance at all levels is needed (TWI2050, 2019).

Inequalities in access to technology and services could be addressed by providing reliable, ubiquitous Internet, raising digital literacy rates (Ahmed et al., 2020) and facilitating access by providing electronic devices to those in need, e.g., for educational access for home schooling (Quaintance, 2020). Else digital technologies risk excluding and further disadvantaging those already left behind (Seah, 2020). This requires time, resources, and capacities that not all cities have readily available. Mobile Wi-Fi hotspots (e.g., on buses) for underserved areas or public spots for dense areas are a quick short-term solution (Samms, 2020). The focus should be on what is there already: Bogotá, for example, uses a multi-channel approach including TV and radio to provide education to children during home-schooling (UCLG, 2020).

In the long-run, city-development strategies should build around improved digitalization that ensures inequality aspects, also in partnership with other actors such as the private sector. Cooperation with the private sector needs strong governance (e.g., in procurement strategies) to deliver social value beyond business value alone (Wray, 2020). Municipality owned affordable and reliable Internet (and electricity) is an option that allows connectivity at home in addition to the traditional public places (e.g., libraries, community centers) (Samms, 2020). Lastly, training and empowering users to take advantage of digital technologies is key (What Works Cities, 2020). Given that reducing the digital divide will take time, cities need to continue providing complementary offline services.

SLUM AND INFORMAL SETTLEMENT VULNERABILITIES

Slums, peri-urban, and informal settlements have been disproportionately impacted by the COVID-19 pandemic and its aftermath and have had to face distinctive risks. This is because these are characterized by precarious and overcrowded housing conditions, lack of basic infrastructure and amenities, and a high concentration of the socioeconomically disadvantaged (Buckley, 2020; Corburn et al., 2020; Tampe, 2020). Lockdown measures that were the first response in many countries to deal with the pandemic were difficult to implement and unsuited for such settlements because overcrowding made social distancing physically impossible, and these measures undermined survival opportunities of slum dwellers (Chirisa et al., 2020; Wasdani and Prasad, 2020). A lack of access to adequate energy and ICT services, a critical issue for most slums even prior to the pandemic, exacerbated the multiple vulnerabilities of populations living in these areas.

Slum dwellers make a significant contribution to urban economies in many developing countries. However, most slum dwellers face asymmetries in access to labor market opportunities, livelihood advancement, and occupational mobility, with a vast majority predominantly employed by the informal sector (Ghosh et al., 2020). While the nature of the informal sector varies from country to country, unregulated working conditions and wages, insecurity of jobs, and lack of social safety nets or protection and low to no savings characterize urban informality more broadly. The pandemic and lockdowns left many informal workers either without jobs and income or compelled to work in precarious and unsafe conditions to survive. The loss of income also had knock on effects, making the payment of regular expenditures for rent, water, electricity, and other utility services difficult and forcing many to continue to work, since a lack of access to adequate energy services and ICT amenities precluded these populations from remote education or teleworking. In some instances, evictions increased, as a vast majority of urban homes are rented rather than owned and lost incomes made regular rental payments difficult.

Women within these settlements have been disproportionately impacted by the pandemic, being overrepresented in the informal economy, and more likely to be engaged in invisible work, such as home-based or domestic and care work (WIEGO, 2020). Already overcrowded homes with additional anxious family members confined indoors have also resulted in increased rates of gender-based violence under lockdowns [Gender in Humanitarian Action Working Group (GiHA WG), 2020; Mittal and Singh, 2020]. A lack of street lighting and unreliable electric supply in urban slums, in addition to the cramped living conditions, has increased the vulnerability of women to domestic violence (de Duren and Ruth, 2020), and put abusers in closer proximity to their victims making it harder for women to seek help too.

A growing concern has also been the potential health associations of cooking with biomass in cramped indoor quarters and COVID-19. Many slum dwellers already depend on biomass or charcoal for cooking, and women and children are more exposed to the smoke from these kitchens. The pandemic increased exposure to indoor smoke through several channels. For some, who were able to afford cleaner fuels before the pandemic, economic insecurity and income losses forced a move down the energy ladder to the use of cheaper and more easily available solid fuels or kerosene (Shupler et al., 2020). In other evidence, slum and unorganized floating residents were found to use more biomass and other solid fuels not only to offset the financial burden but because cooking activity increased significantly due to the shutdown of hotels, restaurants, and street vendors (Beig et al., 2020). Efforts to increase access to clean cooking services have included either extending pay for service financing options or potentially discussing the extension of government schemes like India's Ujjwala targeted to rural areas to also include poor urban households (Hindustan Times, 2020).

Recent trends indicate that in many developing and emerging economies urbanization has to a large extent proceeded unplanned, with many of the urban poor ghettoed in slums and informal settlements. The pandemic provides an opportunity to rethink how we develop and plan cities. Strengthening community organizations within slums can be an important means of enabling local action. Partnerships between such community groups and local governments and municipalities, private sector, non-governmental agencies, and social organizations can help in designing locally developed strategies to protect slum inhabitants from the immediate impacts of the pandemic. Several examples of such initiatives have been documented in many countries. One such is the case of the city of Bengaluru, India, where Swiggy, a food delivery platform partnered with commercial kitchens, NGOs and the state government to provide daily meals to thousands of underprivileged, daily wagers and stranded migrant labor during the lockdown (Deccan Herald, 2020).

In the longer term, for cities to remain places of opportunity, a broader structural transformation of slum and informal settlements to provide decent housing and shelter as well as access to basic amenities, secure employment, and safe public green and open spaces is necessary (Patel and Shah, 2020). Future slum rehabilitation programs need to consider integrating concerns regarding effective urban governance and formalization of informal spaces (Van Belle et al., 2020). This also means cities need to take a more dynamic and inclusive approach to planning to enhance equity and resilience (Bhide, 2020). Universal access to basic services including health, education, water, energy, digital services, sanitation, and waste collection, with targeted interventions for vulnerable groups also needs to be ensured (UN, 2020). Many cities have realized that resilience, equity, and access to basic public services and green public spaces are essential for their citizens well-being (C40 Cities, 2020). Broader strategies for more just relationships between employers and workers, educators and students are needed to address preexisting inequalities and ensure long-term security of jobs and livelihoods.

CONCLUSIONS

The COVID-19 pandemic has transformed some short and long-term dynamics in our cities (Sikder, 2020), but the impacts are unevenly spread across populations, often aggravating previously existent inequalities. Therefore, recovery measures need to ensure immediate relief, but also point toward long-term solutions that contribute to the redistribution of wealth, and new urban development through tapping the benefits of improved housing, more

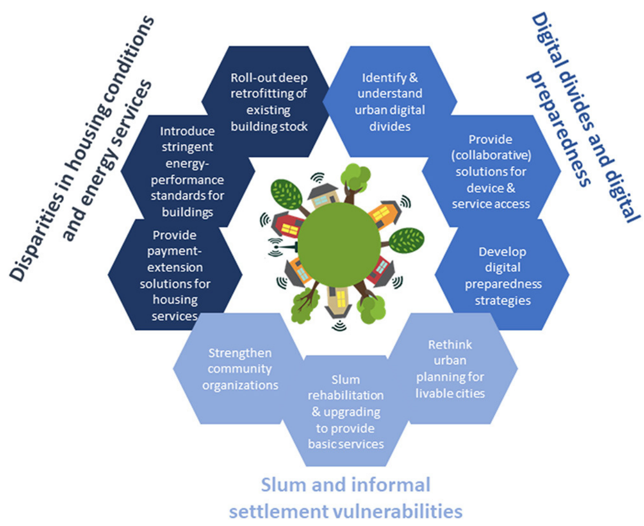

FIGURE 1 | Select mid- to long-term recommendations for future cities under a COVID-19 recovery.

inclusive infrastructure, and better access to basic amenities and services.

In this perspective, we sketch out key focus areas for governments to work on to improve living conditions and preparedness of the urban poor (**Figure 1**).

Local policymakers are called upon to address the three issues that are underlined in this paper: disparities in housing conditions and energy services, digital divides and digital preparedness, and slum and informal settlement vulnerabilities. Urban green recovery plans that include large-scale home renovation programs could ensure warm, healthy homes and affordable energy bills for all. In the shorter-term, alleviation of payment defaults on rents and utility bills of the energy poor should continue. In parallel, urban digital preparedness, more equal access to virtual delivery of essential services, provision of opportunities for virtual working and education for all in the future need attention. COVID-19 can be a wakeup call to increase efforts to close the digital divide and push for structural change. The crisis has increased the urgency to redesign and improve informal settlements and for providing adequate and efficient services that address the diverse needs of poor urban residents. This requires partnerships between urban municipalities and planners and stakeholders, as well as strengthening local communities for inclusive planning strategies (PSUP University Politecnico di Torino, 2020). More immediately, direct support to slum and informal settlement populations for income support, adequate nutrition, energy, water and other basic infrastructure and services is necessary.

All in all, the COVID-19 pandemic has been a "test of societies, of governments, of communities and of individuals" (Bachelet, 2020). Solidarity and cooperation are our tools to tackle the virus, to mitigate the effects of the pandemic, and to develop more sustainable, resilient, and livable cities. In this context, we treat digital technologies, home renovation, and slum rehabilitation as means, not the end (UCLG, 2020) to improve conditions for all, and the specific needs of the most deprived, in particular. We need more egalitarian policies to enhance access to modern infrastructures and decent living services for all and to ensure reliance to future shocks for the most vulnerable.

DATA AVAILABILITY STATEMENT

The data that support the analysis and findings of this study are publicly available from sources that are referenced in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SP conceived the research. BB-K, SP, and CZ analyzed and wrote parts of the perspective and conclusions. All authors contributed to the article and approved the submitted version.

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Toward Regional Low-Carbon Energy Transitions in England: A Relational Perspective

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Re-scaling energy systems and governance to the local level is increasingly necessary to transition to a low-carbon society. City region devolution in England enables city regions to develop their own approaches to low-carbon transitions that reflect the context in which they are situated. The approaches associated with these transitions support the localization of the energy system, the involvement of a diverse range of actors and institutions and the establishment of new supporting infrastructures. This paper considers the interactions between, and influence of, different actors, infrastructures and institutions and how these impact the nature of approaches developed by applying a relational perspective. Relational perspectives are increasingly prevalent in research on low-carbon transitions, although they have not been used to consider how different components of the transition influence the approaches developed—which is the focus of this paper. By understanding the influence of the different components, it supports the establishment of appropriate mechanisms to facilitate low-carbon transitions at the localized scale. This paper analyses the approaches to low-carbon transitions developed by three city regions with devolved powers in England. The approach developed by each of the city regions orientates around a different scale of focus—from the whole city region to strategic hubs to individualized, siloed activity. These different scales of focus reflect the influence held by the actors, institutions and infrastructures located within each city region. The context of the city region itself also influences the actors, institutions, and infrastructures present. By adopting a relational perspective, it unpacks the complex interrelations, the multiple points of interaction and influence, and the multi-scalar nature of low-carbon transitions at the city region level. Although the approaches to low-carbon transitions developed by the different city regions suggest a re-scaling of transition processes, the associated actors, infrastructures and institutions associated with these processes are not isolated from broader contexts and particularities of place. There are multi-scalar interactions and influences which impact the nature of approaches developed, demonstrating the value of relational and heterogeneous perspectives when developing localized approaches to low-carbon transitions.

Keywords: city regions, decentralization, infrastructure, relational understanding, low-carbon energy transitions, devolution

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INTRODUCTION

Transforming toward a low-carbon energy system is a key contemporary challenge, with the pressures of climate change and energy security enhancing its necessity (Bolton and Foxon, 2015). Establishing a low-carbon energy system requires a transformation of the socio-technical systems that form the basis of our everyday lives; involving shifts in "technical infrastructure, social practices, regulations, institutions, information, cultural meanings and economic networks" (Lennon et al., 2020 p. 184). There is the need to "create different systems or transform existing ones" (Kemp and Loorbach, 2005, p. 125), that incorporate a diversity of actors across different local, national, and international levels of activity. Consequently, energy transitions can be considered the product of dynamic interconnections between multiple scales, including the national, regional, and local, and their respective environmental, social, economic and historical contexts (Lemon et al., 2015). Cities and urban areas are positioned as critical spaces for this transformation as they are the site where the systems of provision that require transformation coalesce, and provide the opportunity to establish and initiate localized visions and strategies of change, at a quicker pace than national and global actions (McCormick et al., 2013).

A range of initiatives have been developed to support low-carbon transitions at the localized scale of cities and urban areas, including Positive Energy Districts (PEDs). PEDs are areas developed within city boundaries that have net zero emissions (SET-Plan TWG, 2018) as a result of optimizing energy efficiency, flexibility and production (Gollner, 2019). Central to PEDs is the interaction and integration of different components including buildings, energy users and regional energy systems—this is facilitated by political vision, governance frameworks, the active involvement of a range of actors, the integration of energy and urban planning, and use of ICT (Gollner, 2019). Through PEDs the city is positioned as a key site for achieving energy and climate targets (Gollner, 2019) as it "can play a unique role as a host, facilitator and incubator of new technologies and solutions" (Build Up, 2020).

Action supporting energy transitions at the city and urban level has been accompanied by a trend of devolution; increasingly sub-national governments globally are being awarded a mix of powers that vary from place to place (Rodríguez-Pose and Wilkie, 2017)—many countries that were previously centralized are becoming more decentralized in nature (Li et al., 2016). The decentralization of energy services to cities and urban regions provides opportunities to establish sustainable energy systems by changing governance structures so that ownership and management of energy systems are more localized (Nolden, 2013). Decentralization enables localities to establish development plans which reflect their local socioeconomic and institutional contexts (Rodríguez-Pose and Wilkie, 2017). Policies developed at the subnational level are contextualized in a way that makes them more pertinent and tangible to the individuals they are aimed at, thus supporting the establishment of more effective policies (Coutard and Rutherford, 2010). This is particularly important in the context of energy policy, as unlike traditional centralized modes of energy generation and distribution whereby energy consumers played a passive role, more localized approaches to energy generation and distribution support the integration of a greater variety of actors that are able to actively engage with the energy system (Lennon et al., 2020). The networks of actors associated with the energy system differ between locations (Lemon et al., 2015) demonstrating the need for context-dependent localized approaches to energy system transformations.

The devolution of power from national government to sub-national governments can be seen in the context of city region devolution in England. Through the "Cities and Local Government Devolution Act 2016" the management of certain governmental responsibilities is devolved to city region combined authorities, alongside additional powers and budgets. A range of responsibilities typically held by national government can be devolved, such as transport, skills and jobs, housing, public services, health and social care, children's services, and offender management. Each devolution deal is bespoke with different responsibilities being devolved reflecting the context of the area and providing opportunities to develop localized strategies (Randall and Casebourne, 2016). Devolution deals are dynamic agreements, with modifications in powers possible. The bespoke nature of devolution deals, and the autonomy given to combined authorities in decision-making and planning, results in a diversity of approaches to transforming the energy system to a low-carbon one. Within the energy strategies developed by the city regions, different actors are assumed to undertake certain roles in order to support the energy transition. Although city region energy strategies are not officially defined as Positive Energy Districts (PEDs) the motivations, intentions and foci of the energy strategies developed by the city regions reflect those of PEDs. Each devolved city region's energy strategy focuses on utilizing local resources, creating opportunities for a range of actors to participate in the energy transition and establishing a cost-effective, sustainable energy system. Actions are developed that reflect the local context, and demonstrate an awareness of the interconnected components that need to be acknowledged. Although, the actions undertaken at this scale also impact and are impacted by other scales of governance, including global, national and sub-regional.

The decentralization of energy can be considered to strengthen democracy and increase participation as a result of the shifting of power from central government to regional and local levels (Ziervogel et al., 2019). The re-scaling of energy actions to the localized level of cities and urban areas results in a greater number and breadth of actors being involved. To ensure the effectiveness of action at this localized level, there is a need for collaborative action between these different actors (McCormick et al., 2013). Consequently, new modes of localized governance have been established in response to the increased complexity of relations within the energy system. However, the decentralization of energy systems has also been critiqued for a number of reasons. There are arguments that decentralization can be considered a move toward a further neoliberalization of the state (Featherstone et al., 2012) through the marketization and privatization of resources and services.

Furthermore decentralization can potentially reinforce existing exclusionary patterns of local power, meaning that democratic and participatory intentions may not be achieved (Brown et al., 2015). Consequently, energy decentralization can foster and reproduce social and spatial inequalities.

The social and spatial aspects of energy systems have been explored in a range of ways—including how space is produced in energy transitions, the processes of re-scaling associated with energy transitions in terms of both governance and actions and the associated cross-scalar interactions, and the spatial materiality of energy transitions in terms of energy landscapes and physical infrastructures (Becker et al., 2016a). A range of lenses have been applied when researching these social and spatial aspects of energy systems, including relational understandings as these enable the consideration of how the "creation and deployment of newer, low carbon energy generation technologies co-evolves with socially, politically, and physically heterogeneous terrain" (Cowell, 2020, p. 73). These relational understandings have also been applied to research on place-based approaches to energy by considering the broader relations associated with these actions. Re-scaling energy approaches to a local scale facilitates the involvement of local decision makers that are able to draw upon local knowledge when designing, implementing, and monitoring energy strategies (Pike et al., 2016), with this bringing both economic and social advantages. Yet, within research there is little acknowledgment of the broader contexts in which these localized practices are embedded, and the consequential cross-scale relationships. Despite a breadth of research engaging with the scale and relativity of energy systems, there is limited research that considers how scale impacts the politics and governance of energy systems (Baka and Vaishnava, 2020). Within the literature there has been little consideration of how different actors and infrastructures are presented in low-carbon transitions re-scaled to the local level, their interrelations and the influence they have on the approaches developed. Transforming to a low-carbon energy system is not as simple as allocating different actors certain roles to undertake; as shown through this paper, there is the need to consider the cross-scalar interrelations between actors, infrastructures and contexts. By developing these understandings, it provides insight to support the establishment of mechanisms that facilitate effective low-carbon transitions as the different components will be accounted for.

This paper focuses on the approaches developed when re-scaling low-carbon transitions to the city region scale, drawing upon relational understandings to unpack the potential factors that have contributed to the approaches taken. Analysis will consider the actors included within these approaches, the roles they are assumed to undertake and the infrastructures that exist to support their completion of these activities. The focus will be on city regions with devolved powers in England, considering their approaches to low-carbon transitions. By adopting a relational understanding of energy transformations it draws attention to the co-constitutive cross-scalar interactions that exist between different actors, contexts, and infrastructures. These relationships are central to energy transitions, influencing and being influenced by the different practices being implemented. Despite focusing upon a specific national context, the global trend of localization and devolution and the focus on the diversity of actors and configurations associated with these processes enables the insights from this research to be applied to strategies of energy transformation globally (Li et al., 2016).

The structure of the paper is as follows: it opens with a literature review that outlines current spatial and relational understandings of energy systems (section Toward Multi-scalar Relations: Spatial and Relational Understandings of Energy Systems) and the relational nature of the infrastructures to support low-carbon transitions (section The Relativity of Infrastructures: How Material and Institutional Infrastructure Influence and Are Influenced by Low-Carbon Transitions). section Methodology outlines the methodology adopted as well as a brief overview of the policy and governance context that the research is situated. The key insights from the existing literature will be used to frame the analysis of the approaches developed by three devolved city regions in England to support low-carbon transitions. The analysis considers the complex relativity associated with low-carbon transitions that are re-scaled to the city region level (section The Role of City Region Governments in Low-Carbon Transitions and the Impact of Multi-scalar Influences), the need to incorporate relational and heterogeneous understandings when developing localized approaches to low-carbon transitions (section Considering the Heterogeneity of Actors—contextualized Actions vs. Blanket Suggestions), and how innovation is facilitated within each city region (section Innovation in City Regions: Who, What, How, and Why?). The paper concludes with reflections on the impact that multi-scalar relations can have on localized approaches to low-carbon transitions, the nature of innovation and the value in the methodology adopted (section Conclusion).

LITERATURE REVIEW

Toward Multi-Scalar Relations: Spatial and Relational Understandings of Energy Systems

The recent spatial turn in energy research acknowledges the diversity of energy challenges that emerge as a result of differing geographies, the impact that energy systems have on the practices of everyday life, and the dynamic, uneven and contested spatiality of energy systems (Bridge, 2018). Embedded within this spatial turn is an appreciation of the relational processes associated with the social, political, economic and infrastructural aspects of energy systems. However, within analyses of sustainable energy transitions the importance of spatial, political, and temporal aspects of transitions tend to be underplayed (Roelich et al., 2018). The re-scaling of energy systems to more localized configurations provides the opportunity to unpack the spatial and relational processes that influence this transformation.

The interconnectedness between scales is increasingly considered within urban and energy research (Bulkeley, 2005; Goldthau, 2014; Goh, 2020); scales are understood in relation to other scales and the socio-spatial processes that produce them (Howitt, 1998). This relational perspective means that scale is seen to be produced through the relationships between actors and the contexts in which they are situated—despite the urban scale being materialized and territorialised in certain ways, it is also made and remade as a result of interactions with other scales (Bouzarovski and Haarstad, 2019). Even when energy policy focuses on making localized changes to infrastructures and practices at the city and municipal scale, the actions implemented are related to and influenced by actions at other scales and levels (García-Sánchez and Prado Lorenzo, 2009); cities and municipalities are not isolated entities.

Furthermore, cities and municipalities are not "rigid and passive physical containers" for change, but are "key nodes within vibrant socio-technical networks that operate across multiple material sites" (Bouzarovski and Haarstad, 2019, p. 257). The networks and information loops within cities facilitate communication between different actors, enabling complex physical and organizational systems to be developed and instituted (Sassen, 2013). There are "multiple scales and diverse socio-physical ecologies" within cities (Sassen, 2013, p. 238), with low-carbon initiatives being increasingly embedded within multi-level governance arrangements as part of a wider political project (van Veelen, 2019). Consequently, these initiatives are often "closely connected to policies, institutions and resources at other scales" (Grandin and Sareen, 2020, p. 74). These relations between scales facilitate change at the urban level, as a range of actors at different levels of governance are able to be drawn upon to support and facilitate the processes of change (Bouzarovski and Haarstad, 2019). There is a need to understand how the politics of scale shapes and is shaped by transitions in particular contexts, and how actors within scales are constructed in the social, political, and economic relations associated with these transitions (Silver and Marvin, 2017).

Actors and initiatives at the global scale influence, and are influenced by, actions at the regional and urban scale. This is encapsulated in the UNFCCC's Paris Agreement, as it acknowledges and advocates for action at the sub-national scale as this can support the achievement of reducing greenhouse gas emissions and the mitigation of climate change impacts (UNFCCC, 2015). However, gaining this recognition was partly the result of actions undertaken by these sub-national actors, with collective groups coming together to demonstrate the value they bring to achieving climate goals, such as the covenant of mayors (Poon, 2016). Individual actors are a core component of the energy transition that significantly influence the outcomes of different initiatives, as it is the cumulative impact of the actions undertaken by these different actors that underpin transition processes (Lennon et al., 2020). Without engaging with individual actors, encouraging and supporting them to shift their behaviors to align with the different strategies developed, evoking change would be difficult. The sustained interconnections between multiple actors at different scales when developing energy transition strategies at the regional and urban scale demonstrates the value of considering these strategies from a relational perspective. By applying a relational perspective it helps unpack the connections between, and influence held by different actors, components and institutional structures.

The Relativity of Infrastructures: How Material and Institutional Infrastructure Influence and Are Influenced by Low-Carbon Transitions

Energy practices and transition processes within cities and urban areas are facilitated by the infrastructures present. These infrastructures can be both material infrastructures such as technical components of the energy system, or institutional infrastructures relating to the governance of energy systems. Infrastructures influence and are influenced by the contexts in which they are situated; different infrastructural technologies, systems and networks enable different practices, and differ over time and based upon the context they are situated (Shove, 2017). Infrastructures are not a passive entity upon which something operates, rather they become in relation to organized practices. As infrastructures do not exist stripped of use (Star and Ruhleder, 1996) this highlights their inherently relational nature. The practices enabled by infrastructures are the product of cross-scalar interactions and influences, with these practices also influencing the nature of infrastructures developed.

In the context of energy transitions, infrastructures and innovation are products of institutional change, but also produce political pressure for institutional change (Silver and Marvin, 2017). As commented by Bridge et al. (2013, p. 336) "the spatial diffusion of energy technologies is culturally contingent," with multi-scalar systems of signification and cultural routines influencing the integration of these technologies. Introducing new energy technologies and their associated practices highlights the embeddedness of energy systems in the socio-environmental particularities of place (Bouzarovski and Haarstad, 2019). Energy infrastructures dictate human action but also catalyze action in terms of socio-ecological change (Bennett, 2010), thus experiences of energy are shaped by material infrastructures with these material infrastructures being shaped by social processes (Lennon et al., 2020). Urban energy infrastructure is informed by and shaped through multi-scalar governance, with the local context as well as national policies and global institutions contributing (Silver and Marvin, 2017). The socio-political infrastructures that support energy transitions are also important to consider when discussion localized approaches, especially due to the greater range of actors that are involved in the energy system (Hall et al., 2013). New forms and scales of governance are developed in response to, and to facilitate, localized energy transitions. These governance institutions are "multi-layered and interlinked social structures that create, mediate and allow society to be formed" (Becker et al., 2016b, p. 22), with this framing and directing agency and consequently determining the extent to which practices and organizations change (Becker et al., 2016b). Institutions are dynamic and relational, they are "created, maintained and changed through action" (Barley and Tolbert, 1997, p. 112). Alongside formal institutions, intermediary organizations exist within energy governance practices; these organizations intend to mediate between the diversity of actors now present within the energy system (Creamer et al., 2018). Intermediaries support the exchange of knowledge and skills, connect different actors, support innovation, and facilitate transformational change (van Veelen, 2019). A range of actors can undertake the role of intermediary including individuals, public bodies, non-governmental organizations, consultancies, or trade bodies. Intermediaries are not isolated entities as their capacities and functions are influenced by the wider set of socio-political relations in which they are situated (van Veelen, 2019). These socio-material relations and the associated outputs are also influenced by the practices and approaches of the intermediaries, which further reinforces the relativity embedded within processes of and actors associated with energy transformations.

In considering literature relating to the relativity of energy transitions and their associated infrastructures, a number of key understandings are highlighted:

- The agency of individuals, both independently and collectively, is a key component of the energy system as shown through the increasing number of actors associated with localized energy systems and the approaches to energy transitions (Hall et al., 2013; van Veelen, 2019; Ziervogel et al., 2019; Lennon et al., 2020).
- There is a need for a heterogeneous approach when analyzing the energy system, due to the influence that specific contexts at the urban and individual scale have on energy practices (Bridge et al., 2013; Bridge, 2018; Cowell, 2020).
- Both technical and socio-political infrastructures influence and are influenced by energy practices—transformations are not solely about implementing new technologies, they also require shifts in practices and expectations of energy consumers (Uzzell, 2008; Shove, 2010).
- There are multiple points of interaction and influence within the energy system, between actors, infrastructures and overarching contexts including social, economic, political, technological, and environmental—these are cross-scalar, and include a diversity of actors and energy system components (McFarlane and Rutherford, 2008; Sassen, 2013; Lemon et al., 2015; Bouzarovski and Haarstad, 2019).

Drawing upon these understandings, this paper will now consider the approaches developed when low-carbon transitions are re-scaled to the regional level focusing on the experiences of three English city regions with devolved powers. A relational lens will be applied to help unpack the interactions between and influence held by the different actors, material and institutional infrastructures involved, as well as the impact these interactions and the city region context has on the approaches developed.

METHODOLOGY

Before outlining the methodology of this paper, we will briefly summarize relevant policies and governance structures relating to city region devolution in England to contextualize the approach undertaken.

In recent years, a range of legislation has been introduced that facilitates the devolution of power within the UK and the creation of more localized governance structures. The "Cities and Local Government Devolution Act 2016" supports the creation of more localized governance structures and localized initiatives, by devolving greater power and resources to combined authorities in England. Through devolution, combined authorities undertake responsibilities typically overseen by national government (Paun et al., 2020). Combined authorities are formed of at least two neighboring local authorities (local government areas), and typically encapsulate city region areas. A total of 10 combined authorities have been established in England, with eight of these being mayoral combined authorities with devolution deals (Paun et al., 2020). A visual representation of the different political entities and scales associated with sub-national devolution to combined authorities in England is provided in **Figure 1**.

Sub-national devolution has influenced low-carbon transitions as combined authorities have developed localized transition strategies; each devolved combined authority (apart from Tees Valley) has declared a climate emergency, and many have outlined ambitions to become zero-carbon ahead of the national government's 2050 target. However, despite processes of devolution appearing to enable the localized re-scaling of low-carbon energy transitions, the practices undertaken by devolved combined authorities need to align with national government spending to receive funding (Paun et al., 2020). Thus, national government is able to maintain overarching control of the activities undertaken within the devolved city regions. This paper focuses on the energy strategies and low-carbon transition approaches developed within the context of this sub-national devolution by using a document review to reflect upon the strategies developed to facilitate a low-carbon transition by three combined authority city regions with devolved powers in England will be explored. The city regions of Greater Manchester, West Midlands and Sheffield have each situated their approach to transition at a different scale, ranging from the whole city region (Greater Manchester) to strategic hubs (West Midlands) to individualized/siloed action (Sheffield) with responsibility being diffused between associated actors in different ways. The location of these combined authority city regions, and the local authorities that they are composed of are shown in **Figure 2**. By focusing on a defined urban context, it enables a more critical reflection of the interactions between actors by acknowledging the particularities of that place (Hodson and Marvin, 2009). The different ways in which localized energy has been operationalised by the different city regions highlights the fluidity of the term "local" within energy systems, and how this can be considered an umbrella term for a range of activities. These different scales influence the institutional and material infrastructures developed within the energy transition. Although this paper discusses experiences within English city regions with devolved powers, it is hoped that the understandings can be drawn upon in other contexts as the focus is on the actors involved with localized energy transitions and the networks that exist to support this.

Within existing literature, document reviews have been used to develop understandings of policies and strategies from a range of perspectives, including the overarching policy itself such as governmental support programmes for community energy (Park, 2012), the impact of policies on behaviors (Doggart et al., 2020), and how the enactment of these policies and approaches can facilitate processes of transition, such as passenger mobility (Geels, 2018). This research undertook a document review to

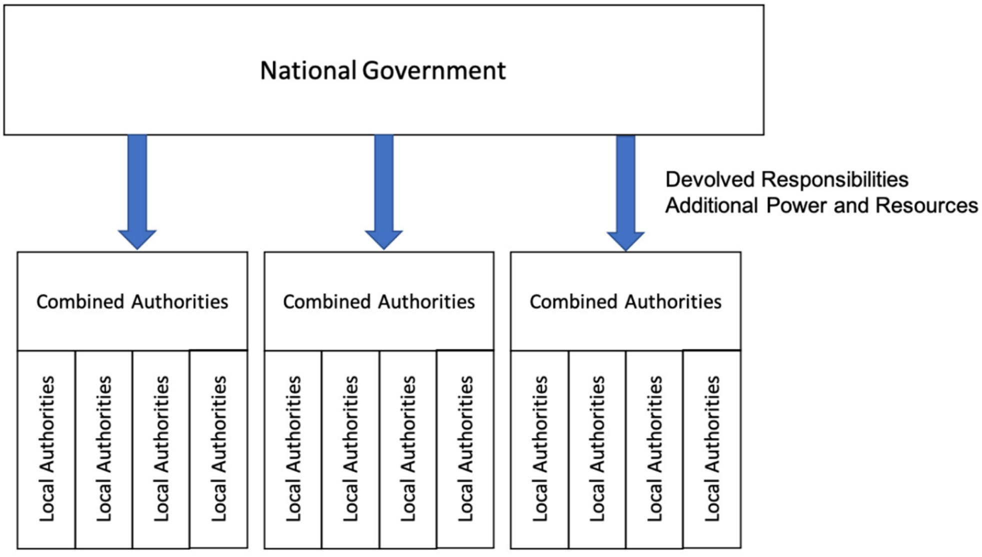

FIGURE 1 | A graphical depiction of the key actors associated with sub-regional devolution, showing the shifting of responsibilities, powers, and funding from central government to devolved combined authorities that are comprised of two or more local authorities.

develop understandings of the strategies developed by each of the city regions to support a low-carbon transition, focusing on the scale of action, the actors involved and how responsibility was diffused between these actors.

In order to retrieve documents for the review, three different methods were adopted: (1) Key terms and phrases were entered into a search engine, such as the particular city region (Greater Manchester, West Midlands, or Sheffield City Region) followed by low-carbon transition, low-carbon energy transition, net zero or zero carbon (2) The websites of key actors and organizations (identified through readings and the SNA outlined below) were searched using the key phrases used within the search engine searches or any specific policies identified through other readings, and (3) Relevant documents cited in other documents included within the review were retrieved. These different retrieval methods resulted in documents produced by a range of actors associated with each city region's low-carbon transition being collated for the review, including city region government actors and their strategic partners, public institutions, private companies and national organizations. This variety of actors producing documents relating to each city region's low-carbon transition approach and strategies is reflected in the different types of documents present in the review, including: official strategy and policy documents, press releases, meeting minutes, oral presentations, policy proposals, policy appraisals, promotional documentation, and website sections. The perspectives, motivations, and intentions of these different actors are embedded in the documents they produce, with this bringing an additional dimension to the analysis of the policies and strategies developed to facilitate city region low-carbon transitions. Through the document review, a narrative of the current situation within the city regions, the approaches they have developed to facilitate a low-carbon energy transition, and the actors involved with this was developed by combining the different information and perspectives present in the different documents. However, only documents that are publicly available were included within the review; additional internal documents may exist which could bring additional understanding to the approaches developed or the process of their development. By focusing on documents produced by those involved with each city region's low-carbon energy transition, it highlights the practices and relationships that were intended to be present within the approaches developed, and the imagined impact of the policies without external factors influencing outcomes. This is of interest as it highlights the priorities of the different city regions and how they believe these can best be achieved.

Analysis of the documents was supported by an analytical framework which focused on the scale of the actions within the strategies, the actors that were included, how these actors were understood and presented within strategies, and the roles the different actors were assumed to undertake to support the energy transition (**Table 1**). Having this analytical framework provided structure to the analysis of documents and helped ensure that relevant details were being extracted; the different components of the analytical framework were designed to pick out details relating to the perspectives and interactions that influenced the low-carbon energy transition approaches and strategies developed by the city regions.

Alongside the document review, Social Network Analysis (SNA) was undertaken. SNA is a method for mapping and analyzing the connections between individuals and organizations and provides the opportunity to include diverse voices (Scott, 2015). By mapping these connections and networks it translates messy 'behaviors into things' (Murdoch, 1997, p. 327) providing something that can be analyzed. There is a focus on "the structure of relationships among social entities, as well as

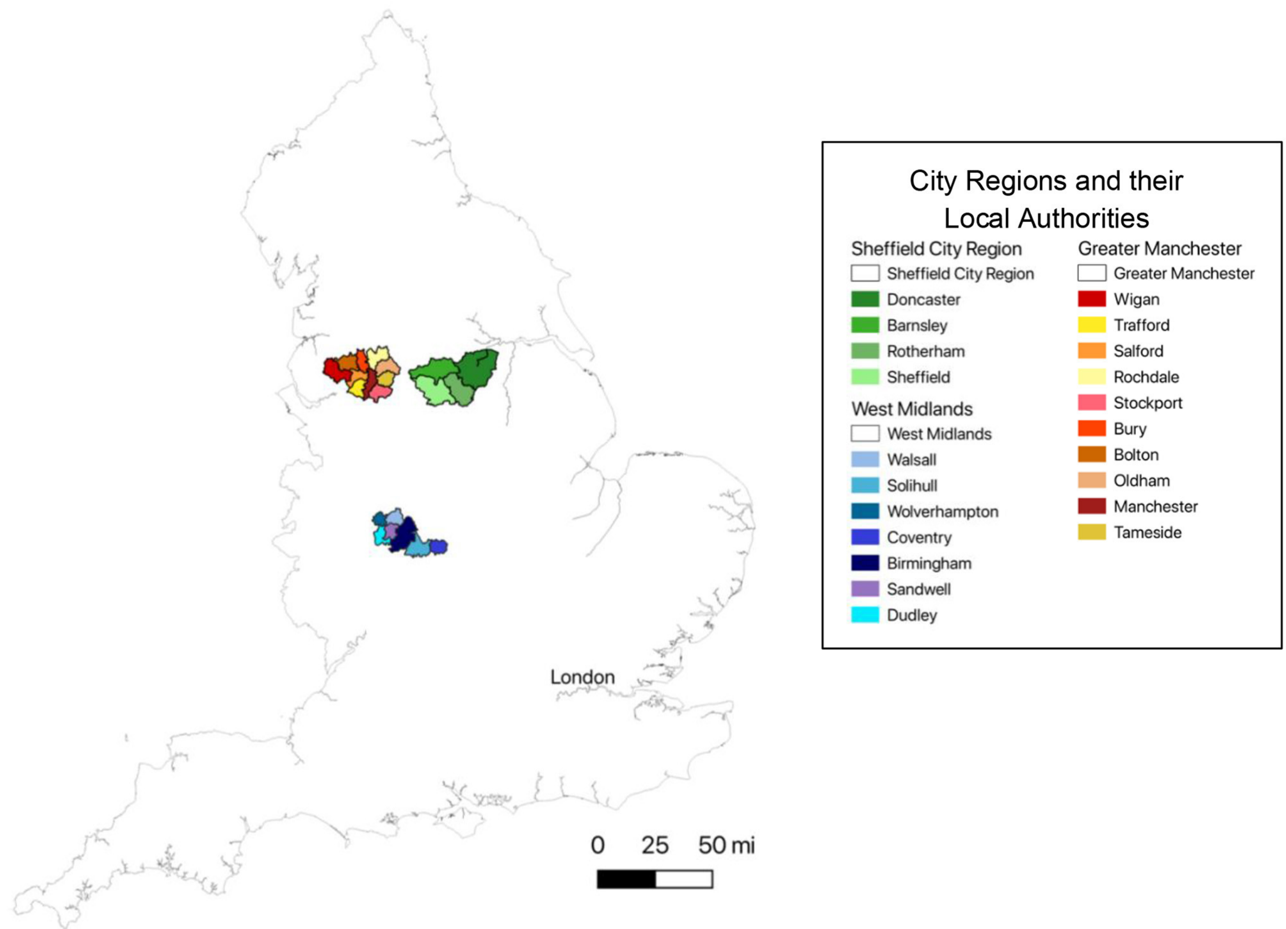

FIGURE 2 | A map showing the combined authority city regions of Greater Manchester, West Midlands, and Sheffield including the local authorities that they are comprised of (Authors Own).

the impact of said structure on other social phenomena" (Butts, 2008, p. 13). Developing these understandings can support the achievement of goals or help identify and remove barriers (Mischen and Jackson, 2008). Social Network Analysis has been conducted in a range of research including energy efficiency projects (Zedan and Miller, 2017), multi-scalar energy networks (Martinus et al., 2015), actors and technologies associated with innovation (Van Der Valk and Gijsbers, 2010), social movements (Saunders, 2007) and natural resource management (Prell et al., 2009). Within this research, SNA was conducted to highlight the different actors associated with the city region's approaches to low-carbon transitions, the scales at which these actors were situated, and the relations that existed between actors. The SNA was conducted by drawing upon the document review, picking out the key actors mentioned within these documents and the relationships presented. By mapping the actors in this way it complements the relational approach taken in the analysis, as a visual representation of these interactions and associated influence is provided.

The insights obtained through the document review and stakeholder analysis were combined, with overarching themes relating to the scale of activity, the actors involved and the infrastructure to support them being highlighted. Relational understandings were applied to these themes to further unpack the processes and relationships embedded within the energy strategies developed by city regions. The themes highlighted provide the structure for the analysis section which follows—there is a discussion of the role undertaken by the city region's municipal government, the extent to which actors are considered heterogeneous, and how innovation is incorporated into the low-carbon transition approaches.

ANALYSIS

The analysis of the paper will focus on the different approaches undertaken by the three case study city regions when re-scaling action on energy transitions to the city/urban scale. Relational understandings will be drawn upon to unpack the

TABLE 1 | A breakdown of the analytical framework used to support the analysis of each city region's approach to a city region low-carbon transition, developed by the authors.

CITY REGION CODING FRAMEWORK	
Who?	
What actors are present within the City Region and associated with implementing energy strategies	
What Capacity?	
Component in System	***Knowledge Holder***
The actors are viewed as being part of the system and process, but are not drawn upon for insight or information when developing the plans—this doesn't undermine their legitimacy	The actors are able to provide information and insight that will facilitate the development/establishment/maintenance of energy strategies and the transition to low-carbon society—able to break down into the different types of knowledge held by actors (Experiential, technical, bureaucratic etc.)
How are they presented?	
Heterogeneous	***Homogeneous***
There is an understanding of the diversities, subtleties and complexities within the group, with an acknowledgment that referring to the group as a single entity doesn't capture this	Actors are presented as a homogenous group, there is not distinction between the different actors within the group or the different experiences/knowledge bases/
Active	***Passive***
Actors actively engage with the planning, development and establishment of different elements of the energy strategy, they are shown to have agency and the ability to influence outcomes for themselves and/or the actions undertaken	Actors are involved in the activities associated with the energy strategy/plan but don't influence the direction or really contribute to decision-making processes—they are guided by the decisions of others
What is understood about them and when?	
Experiences	***Viewpoints***
There is engagement and interest in the everyday, embodied and/or historic experiences that actors have had in relation to energy and/or the approaches adopted Consider at what point throughout the project's lifecycle this is drawn upon i.e., planning, developing, implementing, functioning, maintaining	There is interest in what actors think about the situation or the proposals for action to be implemented = Consider at what point throughout the project's lifecycle this is drawn upon i.e., planning, developing, implementing, functioning, maintaining
How is knowledge obtained?	
Assumptions	***Engagement***
Actors are not directly consulted about their understandings, perceptions, and/or views, rather external actors make assumptions of these based upon the data and evidence available to them	Actors are directly asked or given the opportunity to share their views, understandings are presented by the actors in their own words

potential factors that have contributed to the approaches taken, considering the actors involved, the roles they are assumed to undertake and the infrastructures that exist to support their completion of these activities. **Table 2** provides a brief overview of the approach developed by each of the city regions, outlining the vision, scale of action, the institutional vehicles developed, governance and main actors involved.

The Role of City Region Governments in Low-Carbon Transitions and the Impact of Multi-Scalar Influences

Each city region's municipal government is positioned as a key actor in, and co-ordinator of, the local low-carbon transitions, with institutional infrastructures being established to facilitate the actions required.

For both Greater Manchester and Sheffield City Region, existing governance configurations at the city region level have been expanded to incorporate responsibility for the city region's low-carbon transition. Greater Manchester has established the GM Green City Region Board to support the city region's low-carbon transition, with challenge groups being established to oversee particular action including "Sustainable Consumption and Production," "Low Carbon Buildings," "Energy Innovation," and "Natural Capital." Greater Manchester's vision of an Energy Transition Region (ETR) comes under the Energy Innovation Challenge Group. The ETR focuses on a place-based approach to low-carbon transitions at the scale of the city region by developing appropriate infrastructures and shifting practices—there is the intention to establish a smart energy system that draws upon local assets and innovative approaches (Owen, 2019). Sheffield City Region's Energy Strategy, which outlines actions related to low-carbon transitions, is part of the Mayor's Climate Response Framework. The documents that comprise the Mayor's Climate Response Framework outline how the city region intends to achieve environmental sustainability and address the climate emergency (SCR Mayoral Combined Authority, 2020). There is an emphasis that the intended approach requires strong leadership from the public sector (SCR Mayoral Combined Authority, 2020), in order to facilitate and support the involvement of local residents and businesses (SCR, 2019). By drawing upon existing governance structures it helps integrate the low-carbon ambitions with existing priorities across the city regions, brings it to the consciousness of key decision-makers and helps ensure relevant actors are involved by drawing upon existing networks. Unlike Greater Manchester and Sheffield City Region who allocated responsibility for facilitating low-carbon transitions to existing entities, the West Midlands established a new body called Energy Capital to support the city region's low-carbon transitions. Energy Capital is responsible for the coordination of changes in the West Midlands' energy system, with the intended outcome being a modem, clean competitive and secure energy system (Climate-KIC, 2020). Energy Capital is embedded within the city region's governance structure and is accountable to the municipal government (WMCA, 2018). The main outputs that Energy Capital are utilizing to support the low-carbon transition are Energy Innovation Zones (EIZs). EIZs

TABLE 2 | A table outlining the approaches developed by each of the city regions, summarizing the overarching vision, the scale of action, the governance structure and key actors/actions.

	Greater Manchester City Region	West Midlands City Region	Sheffield City Region
Vision	To develop a city-region energy system that is smart, fit for the future, low-carbon and sustainable Become a zero carbon city region by 2038	To become Zero carbon by 2041 through a range of actions across multiple sectors	To have a clean, efficient and resilient energy system, which supports a healthier environment for people to live, work and visit, and which drives our transition to a low carbon economy Become zero-carbon by 2040
Scale	City region—Whole Systems Approach	Strategic Hubs	Individualized/Siloed Activity
Vehicle	Energy Transition Region (ETR) and Energy Innovation Agency (EIA)	Energy Innovation Zones (EIZs)	Mayor's Climate Emergency Response Framework
Governance	Building upon and extending existing governance structures within Greater Manchester	Developed Energy Capital, a body responsible for overseeing energy transition in the city region that is embedded in regional governance structure	Action lead and initiated by regional government
Main Actors	Greater Manchester Combined Authority (GMCA), Local Authorities (Bolton, Bury, Oldham, Manchester, Tameside, Wigan, Trafford, Salford, Rochdale and Stockport), Energy Innovation Agency (EIA), Businesses, Academia, Communities	West Midlands Combined Authority (WMCA), Local Authorities (Walsall, Solihull, Wolverhampton, Coventry, Birmingham, Sandwell, and Dudley), Energy Capital, Local Enterprise Partnerships, EIZ Partnership Boards, Businesses	Sheffield City Region Mayoral Combined Authority, Local Authorities (Doncaster, Barnsley, Rotherham, and Sheffield), Local Enterprise Partnerships, Businesses, Communities
Main Actions	Innovative projects to energy challenges in the city region are supported through the ETR, the cumulative impact of these considered to support transition	Strategic hubs of activity within the city region are established through EIZs—action dependent upon the context, motivations, priorities and actors present within the area	Range of actions to be taken by individual actors and groups with cumulative impact on the transition to a low-carbon city region

are geographically-bounded hubs within the city region that aim to stimulate local and democratically accountable clean energy innovation (Energy Capital, 2018). EIZs are also embedded within the regional governance structure—Energy Capital and WMCA provide regulatory support, funding and expertise to the EIZ, whilst the local authority in which the EIZ is considered responsible for the coordination and management of these strategic hubs (WMCA, 2018). The creation of a new body to coordinate progress to a low-carbon energy transition provides the opportunity to focus attention on the actions that need to be undertaken, and develop internal processes and mechanisms that are tailored to these actions specifically. The approach taken by each city region—whether that be integrating responsibility for the low-carbon transition into existing governance structures or establishing new bodies to facilitate progress—reflects the context of the city region, its existing structures, its resource and its perceptions of how best to support change.

The different approaches developed by the city regions to support low-carbon transitions, and the institutional infrastructures accountable for their implementation, not only influence the actions that will be undertaken within the city region but are also influenced by the city region's context. The nature of the approaches and associated institutional infrastructures are a reflection of the context of the city region itself, its ambitions, resources and priorities. The context in which strategies are to be implemented impacts decision-making processes, determines the feasibility of actions and the likelihood of their success; each city region has different networks of actors engaged in low-carbon activities and different resources available to them (Lemon et al., 2015). Not only does the context of the city region influence the approaches taken, but the approaches themselves have an impact on the configuration of the city with regards to both material infrastructures and non-material circumstances. The embedded social and cultural dimensions of the approaches developed, such as power, politics, and entrenched inequalities influence the dynamics of transitions and impact the contextual setting (Lawhon and Murphy, 2012). The West Midlands region is an industrial and manufacturing hub reflecting its geographical location and historical legacy (HM Government, 2019). These factors contribute to the nature of innovations being implemented through the city region's EIZs—there is a bias toward manufacturing and supporting these industries. The Sheffield City Region approach to a low-carbon transition predominantly focuses on demand side action with this reflecting the city region's current lack of localized generation assets (SCR, 2020). A range of action is outlined including making better use of infrastructure for energy efficiency, low carbon energy generation, or sustainability, accelerating the uptake of Ultra-Low Emission Vehicles by developing the required infrastructure and upskilling the workforce to support future energy systems (SCR, 2020). Local energy generation is to be supported through community energy schemes (SCR, 2020). Greater Manchester's Energy Transition Region concept intends to support the testing of innovative energy approaches at scale by "bringing together academia, industry, community energy and the public sector" (GMCA, 2019). This collaboration-focused mechanism included in the city region's approach to the low-carbon transition is only possible due to the diversity of resources and knowledge situated within Greater Manchester.

Furthermore, the approaches developed by the different city regions are a product of broader contexts and cross-scalar relationships. Actions situated at the city-region level that intend to support low-carbon transitions are influenced and constrained by actors and infrastructures at other scales, including national government and individuals within the city region (García-Sánchez and Prado Lorenzo, 2009; Silver and Marvin, 2017; Bouzarovski and Haarstad, 2019). For each city Region, receipt of funding is dependent upon aligning with central government spending (Paun et al., 2020) demonstrating the influence the central government is able to exert despite having devolved powers to the city region. Low-carbon transitions are also dependent upon individual actors engaging with the approaches developed in order to make progress; a diversity of actors are embedded within these approaches including industrial actors, local communities, businesses, academic institutions and non-governmental organizations. When considering these multi-scalar influences it highlights the complexity embedded within localized low-carbon transitions; there is a need to establish a narrative and supporting infrastructures that engage individuals at the sub-regional level but also align with broader national intentions.

Considering the Heterogeneity of Actors—Contextualized Actions vs. Blanket Suggestions

Despite the municipal governments of the devolved city regions coordinating the localized approaches toward a low-carbon transitions, they emphasize that they are not solely responsible. As outlined in the Sheffield City Region Energy Strategy "collective change requires collective action" (SCR, 2020). The low-carbon transition approaches developed by each of the city regions are dependent upon the engagement of a range of actors, with these actors being assumed to undertake specific roles and support the energy transition in particular ways. There is an expectation that a range of actors will engage with initiatives, shift their behaviors and adapt their practices. Re-scaling low-carbon transitions to the local scale supports the engagement of a range of actors (Ziervogel et al., 2019), with the opportunity to draw upon local knowledge being considered an advantage of localized energy approaches (Pike et al., 2016). The interaction with a range of individuals, understanding their situation, contexts and priorities is considered a benefit of localized approaches to energy transitions (Lennon et al., 2019). Being able to situate low-carbon transition initiatives in the specific context of the city region supports place-based approaches that reflect the diversity of actors present and aligns with their contexts. However, within the city region's approaches to low-carbon transitions, only the Energy Innovation Zones (EIZs) developed by the West Midlands appear to acknowledge the diversity of needs, priorities and capabilities of different actors. Both Greater Manchester and Sheffield City Region appear to take a more "blanket" approach to actions providing high-level outlines of what is to be done by actors, and not acknowledging the specificities of individual actors' contexts.

Each of the EIZs developed in the West Midlands is a product of the context in which it is situated, with this influencing the priorities and configuration of the EIZ; they are portrayed as reflecting "the local needs and perceptions of energy system opportunities and challenges" (King, 2018). The EIZs provide the opportunity to implement activities that align to specific local goals (Climate-KIC, 2020), with local market and customer needs driving the approaches developed (King, 2018). Currently there are four pilot EIZs underway—Black Country, UK Central, Birmingham Central and Tyseley, and Coventry—with each EIZ focusing on developing strategies that reflect the context and the actors present. The influence context has on the actions undertaken within an EIZ is shown in the case of Black Country EIZ. Black Country EIZ encompasses an industrial area that has the motivation to attract further advanced manufacturing companies to the area, particularly aerospace, automotive and high added value engineering (Energy Capital, 2018). These industrial actors require an affordable, reliable and high-quality supply of energy to power their manufacturing processes. Consequently the EIZ is focusing on developing a modern, clean energy system that can deliver energy at globally competitive costs (Energy Capital, 2018) demonstrating how the socio-economic context of an area can influence the nature of energy projects undertaken. Tyseley and Birmingham Central EIZ provides another insight into how context can influence the nature of energy developments. The geographical location of Tyseley and Birmingham Central EIZ has influenced the energy innovations being scaled-up. As the EIZ is located in close proximity to the city center which is attempting to tackle its air pollution problem through a "Clean Air Zone" and the electrification of transport vehicles including buses and taxis (Energy Capital, 2018), the innovative technologies being developed through the EIZ focus on supporting this. Thus, as part of Tyseley and Birmingham Central EIZ a low-carbon refueling station powered by a waste to energy plant are being developed (TEP, 2019).

Although each of the 4 pilot EIZs have been developed in consideration of the local context, there remains a focus on manufacturing and industrial actors across the four pilots with this reflecting the broader context of the West Midlands. The West Midlands is a manufacturing and industrial hub as a result of geographical location, good transport links and historical legacy (HM Government, 2019). However, the reason for focusing on manufacturing and industrial actors may extend beyond this geographical context to include the influence of broader actors and institutions on plans developed—EIZs are not isolated entities within city regions, rather they are part of a multi-scalar political ecology that makes up the city (Sassen, 2013), and are influenced by actions at other scales as well. Energy Capital, the body established by the devolved West Midlands government to coordinate the city region's low-carbon transition, supports the development of EIZs and depends upon these strategic hubs to achieve the low-carbon ambitions (Energy Capital, 2018). Consequently, the understandings, preferences and priorities of Energy Capital feed into the EIZ plans. The Energy Capital Board is composed of range of actors including local government, local academic institutions, BEIS, and Energy Systems Catapult (WMCA, 2018). An Industrial Advisory Board supports Energy Capital and includes representatives from Jaguar Land Rover, Liberty Group, Western Power Distribution and the National Grid (King, 2018). The priorities of Energy Capital are likely to reflect the actors that are associated with the body, which include large industrial actors, manufacturers and innovators, with the views of these actors reflecting the nature of EIZ approaches. This highlights the impact that the institutional infrastructures can have on approaches to low-carbon transitions—if Energy Capital were to also have an Advisory Board made up of actors focused on more socio-political issues then perhaps different approaches would be present in the EIZs. Thus, ensuring advisory groups and institutional boards are representative of the interests of a range of actors and organizations within the city region could be considered a critical component of ensuring an equitable low-carbon energy transition that reflects the needs of a range of different groups. The focus of EIZs are not only influenced by institutions at the city region level but also national incentives. The UK Industrial Strategy intends to support economic growth by encouraging investment in skills, industries, and infrastructure (HM Government, 2017). As part of this, emphasis is placed on the potential for UK manufacturing industries to increase their share of the global market as a result of shifting to clean energy sources and efficient new materials (HM Government, 2017). This shows how EIZs align with the national focus and as previously mentioned, aligning with National priorities is critical for city regions as this ensures they receive their funding.

The approaches developed by Greater Manchester and Sheffield City Region to support low-carbon transitions appear to show less consideration of the heterogeneity of the actors involved. Theoretically, by re-scaling transitions to the city region level it means approaches can be adapted to reflect the particular context in which they are to be implemented. However, the approaches developed by Greater Manchester and Sheffield City Region do not appear to consider the diverse contexts and relationships that different actors have with the energy system as both city regions provide blanket suggestions for the actions different actors are to undertake. There is little consideration of issues relating to "unequal access to energy, limited financial resources, educational privilege and expertise, or differential levels of control over one's environment and practices" (Lennon et al., 2020, p. 189). Consequently, these issues could manifest as barriers to the achievement of low-carbon ambitions; if the differential abilities of actors engage with low-carbon transitions is not acknowledged with appropriate mechanisms being implemented to support these individuals then equitable low-carbon transitions will not be achieved. As the approaches developed by each of the city regions to achieve a low-carbon transition emphasize the importance of collective action, there is a need to ensure that this diversity is appreciated.

The lack of consideration given to the different contexts of actors can be seen in Sheffield City Region's intention to double the number of community energy organizations in South Yorkshire by 2040 (SCR, 2020). There are multiple factors that affect a communities' ability to participate in local energy schemes including varying interests and knowledge about local energy technologies, different financial situations, different priorities and different renewable energy potential as a result of geographical location (Eadson et al., 2019). Within Sheffield City Region, 11.5% of residents live in flats and 34% live in rented accommodation (ONS, 2016), with these housing types and tenures potentially restricting the ways in which individuals can contribute to community energy projects, especially if there is the intention to install Solar PV on individual properties. This highlights how the built environment can constrain action that supports low-carbon transitions—there is a need to consider the context in which energy technologies are being implemented, including the renewable potential, building type and building tenure (Pehnt, 2006). Thus, despite community energy theoretically empowering individuals through the localization of energy, by not adapting these suggested actions to reflect the different contexts of actors, it can have the inverse effect and leave individuals feeling disempowered and disenfranchised (Lennon et al., 2019). Furthermore, despite actions being undertaken by individual actors, the driving force behind these actions is ultimately the municipal government; there is a top-down implementation of actions that are normally established through bottom-up approaches. The driving forces behind community energy in Sheffield City Region highlight the relationship between the broader regional scale and individual actions—and demonstrate that it is the cumulative impact of sub-regional actions that is intended to underpin the low-carbon transition of the entire city region. To support the achievement of these individualized actions, there is the need for effective communication between the different actors involved in Sheffield City Region's energy sector. This need for communication could be facilitated by intermediary organizations who work "in-between" the different actors, supporting interactions, and illuminating areas where practices could be changed to better reflect the situation (Moss, 2009; Creamer et al., 2018; van Veelen, 2019). In doing so, it offers the potential to have more bespoke approaches to the low-carbon transition that better reflects the contexts of the actors involved and acknowledges the heterogeneity of these actors.

Similarly in Greater Manchester, Demand Side Management (DSM) is advocated within the city region's approach to the low-carbon transition. Within this, there is the assumption that all energy consumers within the city region will be able to make the required shifts in their energy practices, and become a "more responsible consumer" (GMCA, 2019), yet the different contexts of individuals may mean that engaging with DSM practices may not be possible for some. An individual's energy practices cannot be separated from the broader temporalities of their daily life and their specific context (Blue et al., 2020). As discussed by Shove and Walker (2017), energy demand is a product of the daily rhythms of life—for some, these rhythms and the contexts in which they are situated offer greater flexibility in energy practices, whilst for others they are constrained by them. Daily rhythms are the product of multi-scalar influences such as occupation and working hours, housing type, and household composition (Powells et al., 2014). There is a need to acknowledge and accommodate for the diverging daily rhythms of different groups within society, and how this impacts their flexibility in energy practices.

As shown here, the heterogeneity of different actors associated with low-carbon transitions is considered to varying extents in the approaches developed by each of the city regions. Understanding the contexts and characteristics of the different actors associated with low-carbon transitions is important as it enables appropriate support mechanisms to be developed. Applying relational understandings can help appreciate the diversity of characteristics held by actors supporting low-carbon transitions, as this theoretical lens draws attention to the different aspects that influence actors including geographical factors, institutions, and existing infrastructures.

Innovation in City Regions: Who, What, How and Why?

Within the low-carbon transition approaches developed by the city regions particular emphasis is placed on innovation. Each city region has developed different infrastructures, both material and institutional, in order to facilitate innovation that will support its low-carbon transition. This focus on innovation could be seen as a product of the scale at which the approaches are developed, as often experimentation and living labs are conducted at sub-national scales. Through experimentation and living labs it is possible to test out new approaches within a defined context (Frantzeskaki et al., 2017; von Wirth et al., 2019). The notion of experimentation and living labs are implicitly present in the approaches developed—for the West Midlands the EIZs provide the space to scale-up innovations (Energy Capital, 2018) whilst the Energy Innovation Agency (EIA) developed in Greater Manchester intends to provide a mechanism to bring together research and act as a resource to different actors within the city region (Owen, 2019). In the approach developed by Sheffield City Region innovation is woven throughout the different individualized actions outlined (SCR, 2020). The way in which each City Region supports innovation reflects its context, motivations and resource.

The establishment of EIZs demonstrates the centrality of innovation to the West Midlands' low-carbon transition. EIZs are a product of the context in which they are situated, resulting in a range of actors being involved across the different EIZs (King, 2018). This diversity of actors has implications on governance and management as it is not possible to establish an one-size-fits-all approach to designing, implementing and maintaining EIZs. This is particularly evident when considering the different ways in which actors embedded within the context of the EIZs can influence the outcome of the EIZs—the businesses and industries present, local residents, the city region government actors and national government can impact the nature of the EIZs, as is shown in the examples of Black Country EIZ and Birmingham Central and Tyseley EIZ discussed in the previous section. The diversity of actors present and the influence they can have demonstrates the importance of ensuring there are appropriate mechanisms in place to help ensure these influences are channeled constructively into the project. As part of this, the Local Authorities (LAs) and Local Economic Partnerships (LEPs) in which the EIZs are situated undertake a myriad of roles to support the innovation processes (King, 2018; WMCA, 2018). The LAs and LEPs interact with a diversity of actors associated with the EIZs who are situated at different scales and influence the innovation process in different ways. The LAs and LEPs coordinate and facilitate the interaction between the industries and organizations that are undertaking the innovation in the EIZ, they also collate and communicate the viewpoints of local residents through their local government role and liaise with the city region government over the EIZ development (WMCA, 2018). Thus, the LAs and LEPs could be considered as key intermediaries that facilitate communication, support collaboration and help share the experiences of different actors (van Veelen, 2019). Having the LAs and LEPs as intermediaries within the EIZs is advantageous for a number of reasons. Firstly they are established and recognized components of the local government framework meaning that individuals are likely to draw upon them as a resource. Secondly they will have an established network and communication methods that they can draw upon when undertaking this intermediary role—LAs are able to interact with their constituencies, and the LEPs have established links with local business. Finally, as they are situated in the context of the EIZ they have a contextual awareness that will facilitate interactions. The range of actors associated with, and able to influence, the innovation process of EIZs demonstrates the benefits of rescaling this action to a local scale as this enables the context and associated actors to be considered when developing the required support mechanisms. The roles undertaken by the LAs and LEPs demonstrates the importance of having key intermediaries that are able to work in-between the other actors, and bring together the different actors associated in constructive ways.

The role of the LAs and LEPs in the West Midlands is comparable to that of the Energy Innovation Agency (EIA) in Greater Manchester. The intention of the EIA is to support collaboration and engagement between different actors associated within Greater Manchester's energy sector to foster innovation that supports the transition to a low-carbon city region (GMCA, 2020). Similarly to the LAs and LEPs, the EIA is embedded within the city regional governance structure—it is a collaborative endeavor between the local universities, local government and industry (GMCA, 2020). By having these different actors engage with Greater Manchester's low-carbon energy transition through a formal mechanism it could increase the efficiency of innovative developments due to the high levels of resource and knowledge held, as well as the range of networks they are a part of. However, the actions undertaken and innovative approaches developed through the EIA, are likely to reflect the priorities and interests of these academic, governmental and industrial actors as these priorities and interests will be embedded within the resources they are able to provide. Unlike the EIZs, which focus on a defined strategic zone within the city region, the EIA is to be an overarching resource for the entirety of Greater Manchester (Owen, 2019). The broad city region focus of the EIA could foster greater collaboration amongst a wider range of actors to further innovative approaches across a range of contexts—by covering a greater geographical area there is the possibility to interact with a greater range of actors that can influence support the low-carbon transition. However, there is the potential that by having the EIA operate at the city-region level, despite providing support on a case-by-case basis, the heterogeneity of the actors embedded in different contexts may not be fully captured if adequate resources are not allocated to support.

Both the West Midlands and Greater Manchester established formal mechanisms that intend to support innovation by providing a space to scale-up technologies and facilitate collaboration between different actors. For Sheffield City Region, innovation is included as a goal in the city region's energy strategy—"Promote investment and innovation in low carbon energy generation, distribution and storage technologies" (SCR, 2020) but unlike Greater Manchester and the West Midlands there is no formal vehicle to support this. Rather innovation is woven throughout the different areas outlined in the strategy. For example, one area of focus is to "Encourage clean and efficient growth in local businesses and increase the number of jobs in the low carbon energy sector," although on the surface this appears to be economically focused, activities considered to support the achievement of this include "supporting SMEs to become aware of, and apply for, low carbon innovation funding provided from the UK Government and elsewhere" and "establishing South Yorkshire as an innovation incubator where energy innovations can be taken from concept, to prototype, to trial, through to full-scale production" (SCR, 2020, p. 10) thus demonstrating the intention for innovation to occur. The lack of formal innovation mechanism is not to say that there is no collaboration between different knowledge holders within the city region. Sheffield City Region has developed a strategic partnership with the University of Sheffield, Sheffield Hallam University and a range of experts called SCR:NZ which focuses on identifying ways to progress toward net zero (SCR, 2019). As with both West Midlands and Greater Manchester, the actors involved within these partnerships, their interests, motivations and priorities are likely to influence the innovation that occurs.

By considering how innovation is presented and facilitated within the different city regions, it highlights the different influences that act upon approaches to low-carbon transitions—the actors involved, institutional configurations and broader socio-economic context of the city region can influence the actions undertaken.

CONCLUSION

Re-scaling low-carbon energy transitions to the city region level enables a greater diversity of actors to participate in the energy system and provides the opportunity for different infrastructures and institutions to be developed. This paper has applied relational understandings to the approaches developed by three devolved English city regions to support their low-carbon transition—focus was placed on the actors, infrastructures and institutions involved, the networks of interactions they are embedded in and the influence they have on the approaches developed. Each of the approaches developed by the city regions reflects the different motivations, priorities and resources within the area. Consequently, the different energy strategies are situated at different scales within the city region—within Greater Manchester there is a focus on a whole systems approach, the West Midlands identify strategic hubs within the city region, and for Sheffield City Region the focus appears to be on individualized and siloed activity—highlighting how the "local" scale of energy systems is an umbrella term for a range of activities. The relational lens adopted throughout this paper demonstrates the complexity associated with low-carbon transitions, the inability to develop one-size-fits all approaches to low-carbon transitions, and the importance of considering and accounting for context when developing approaches.

By undertaking a document review and SNA to understand the low-carbon energy transition approaches developed by the different city regions, it provided insight into what the authors producing the documents believed the intended outcomes to be; the strategies are presented in the author's own words, reflecting their perspectives, motivation and intentions without any external influence. By combining insights obtained from different documents it enables areas of consensus and contestation to be highlighted, as well as potential gaps in understanding or where strategies may not be as effective when implemented in the real world compared to devised in a policy document. Also, by considering who is not producing documents relating to these issues it can illuminate actors that are not necessarily as involved. The document review methodology could be drawn upon in a range of research contexts, not only those relating to energy transitions or devolution, as it provides rich insight into the motivations, intentions, priorities and perspectives of different actors embedded within processes. Through the document review it possible to identify how policy is understood by different actors within the system, and by unpacking the interlinks between different actors' understandings it illuminates underlying motivations, intentions, priorities and perspectives.

The approaches developed within each city region are both enabled and constrained by actors, infrastructures and institutions situated at scales both above and below the region. Despite having devolved powers, the city regions need to align their overarching priorities with that of the national government in order to receive funding, which could either hinder their ability to undertake certain actions as they are not considered a priority or provide additional support and funding to undertake actions. This demonstrates the impact that national government priorities can have on the approaches developed to achieve a low-carbon energy transition—a shift in priorities would lead to different outcomes. Furthermore, individual actors within the city region need to be incentivised and supported to undertake the actions required from them. Appreciating this complexity that emerges through multi-scalar interactions is critical when developing approaches to low-carbon energy transitions as they are an external influence which can impact the outcomes of strategies developed. Re-scaling governance to the city region scale and developing localized initiatives has the potential to enable consideration of how these interactions manifest at the city region level and develop appropriate strategies. The strategies developed would reflect the context of the city region, including its actors and infrastructures, and in doing so would support the achievement of a more equitable low-carbon energy transition. Yet, this potential is not being fully captured in existing approaches, as shown through the blanket suggestions provided by Greater Manchester and Sheffield City Region, as well as the industrial focus of the West Midlands' EIZs; there is a need to greater acknowledge the diversity within city regions and dedicate enough support/develop appropriate mechanisms to ensure an equitable change occurs. When developing city region approaches to low-carbon energy transitions, there is a need to appreciate the diversity of contexts at the sub-regional scale and incorporate these understandings into tangible actions so that the needs of different actors are recognized—particularly as there is an emphasis on everyone playing a role in the transition.

Within each of the low-carbon transition approaches developed by the city regions, emphasis has been placed on the role of innovation. This again can be considered to be a product of re-scaling low-carbon transitions to the city region level as there is the opportunity for experimentation and living labs. The mechanisms established to support innovation can be considered institutional infrastructures that facilitate the collaboration between actors—the nature of these institutional arrangements is a product of the context they are situated, and the institutions themselves influence the innovative activities undertaken. Each of the city regions support collaboration within their approaches to innovation, with the nature of this collaboration, the priorities, and actors involved being a product of the local context whilst also being influenced by international, national, and sub-national contexts. The actors involved with the collaboration also influences the outcomes and action undertaken demonstrated the complexity of relations associated with low-carbon transitions. However, it is critical that everyone is able to participate in the innovation process or engage with the innovations developed, otherwise there is the risk that innovation could become a vehicle of exclusion. The range of actors and resources associated with transitions has the potential to help overcome this exclusion but appropriate structures are required to co-ordinate efforts. This further emphasizes the critical role of infrastructure in low-carbon energy transitions, not only in terms of facilitating progress but also as a mechanism to support an equitable transition being developed. Situating infrastructures, particularly those which are institutional, at the regional scale helps ensure that they reflect the needs of the actors within that context, and can adapt if the context changes.

The localization narrative, reinforced through processes of devolution, highlights the benefits of developing approaches to low-carbon transitions that consider the context in which they are situated. Consequently, different geographical, economic and socio-material contexts mean that a one-size-fits-all approach to low-carbon transitions is not feasible. The different low-carbon transition approaches developed by the city regions discussed in this paper have started to engage with the need to develop bespoke contextually-situated approaches, but additional resources and infrastructures are required to implement strategies that enable an equitable low-carbon transition. The context within which city region low-carbon transitions occur, and the actors involved are not isolated from broader contexts and particularities of place—there is interaction between these different scales, with each scale influencing and being influenced by other scales. This highlights the complexity embedded within low-carbon transitions, and the need to develop further understandings of the different components involved in order to develop appropriate mechanisms to facilitate transitions. Reflecting upon how these multi-scalar relationships and influences have impacted existing approaches provides insight that can be drawn upon when developing future iterations of approaches to facilitate low-carbon energy transitions.

AUTHOR CONTRIBUTIONS

AC, SP, and JE developed initial concept of paper. AC conducted the research analysis and wrote first draft and final draft based upon comments from co-authors. SP and JE supported continued development of paper concept, highlighted theoretical perspectives, supported editing, and helped refine paper. All authors contributed to the article and approved the submitted version.

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Positive Energy District: A Model for Historic Districts to Address Energy Poverty

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The Positive Energy District (PED) concept has been pointed out as key for cities' energy system transformation toward carbon neutrality. The PED may be defined as an energy-efficient and flexible urban area with net-zero energy import and greenhouse gas emissions, aiming toward annual local surplus of renewable energy. Most of the studies and practical experiences about PEDs are based on newly built districts, where the planning and integration of innovative solutions are less complex and more cost-effective. However, to achieve Europe Union's 2050 carbon-neutral ambition, we argue that the transformation of the settled districts is essential, including historic districts, which present common challenges across European cities, such as degraded dwellings, low-income families, and gentrification processes due to massive tourism flows. This paper aims to discuss how the PED model can be an opportunity for historic districts to reduce their emissions and mitigate energy poverty. The historic district of Alfama, in the city of Lisbon (Portugal), is used as a case study to show the potential of energy renovation measures and solar PV production in households, cornerstones of a PED. The annual energy needs potential reduction due to building retrofit is 84 and 19% for space heating and cooling, respectively, while the integration of building-integrated PV technologies in rooftops and windows potentially generates up to 60 GWh/year. At the district scale, these two components of the PED concept could require an investment of 60M€ to 81M€ depending on the PV technologies in the rooftops, a sensitive aspect in historical districts. Unlike other mechanisms to tackle energy poverty, like the social tariffs, the adoption of structural measures like building energy efficiency retrofit and renewable energy integration will contribute to solve the energy poverty problem, which is significant in Alfama, in both the winter and summer. The highlighted investments require an innovative financial scheme to support not only buildings' owners but also tenants, as these are among the most vulnerable to energy poverty. However, the social benefits of that investment, on the health system, air quality, climate resilience, labor productivity, and social integration, would be invaluable.

Keywords: renewable energy, Portugal, Alfama, fuel poverty, energy performance of buildings, energy efficiency, Lisbon

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INTRODUCTION

It is estimated that 55.3% of the world population lives in urban settlements, and projections state that by 2030 one third of the global population will live in cities with at least half a million inhabitants (UNDESA, 2019). Cities have a relevant environmental impact and are estimated to be responsible for 2/3 of the global energy consumption and 70% of the global carbon dioxide (CO_2) emissions (Satterthwaite, 2008). On the other hand, they have a large potential to drive global action against climate change and develop innovative solutions to reach the Paris Agreement Goals (UNFCCC, 2016) of limiting global warming. Moreover, cities are a fundamental player to reach the Sustainable Development Goals (SDG). SDG 11 explicitly states that cities should become inclusive, safe, resilient, and sustainable by 2030 (UN SDGs, 2015), and its sustainable development is critical for other SDGs and target achievement (Frischmann et al., 2020).

In the last decade, efforts to develop solutions to reduce the environmental impacts of cities have multiplied, with the smart city concept being a promising one to cut greenhouse gas (GHG) emissions. Smart city solutions are a set of integrated and holistic cutting-edge urban development strategies, often based on ICT (information and communication technologies) applications, which contribute to urban sustainability and citizen welfare (Mosannenzadeh et al., 2017). Embedded in this concept, the smart energy city strategy focuses on site-specific transition toward sustainability, self-sufficiency, and resilience of energy systems, which should ensure accessibility, affordability, and adequacy, through optimized integration of energy conservation and energy efficiency (EE) measures, local renewable energy sources (RES), and promotion of energy flexibility (Mosannenzadeh et al., 2017).

To accelerate the decarbonization of urban areas and foster the scalability potential across cities, the Positive Energy District (PED) concept was developed as part of the smart energy city strategy. JPI Urban Europe (2021), the hub for urban transitions in Europe, defines the PED as an energy-efficient and flexible urban area that has net-zero GHG emissions and actively manages to generate an annual local surplus of renewable energy. It also specifies that the PED requires the integration of different systems (e.g., buildings, energy, mobility, ICT) and interactions between different stakeholders while optimizing the liveability of the urban environment (Bossi et al., 2020). Besides technical aspects, it is widely recognized that social aspects play an essential role in successfully implementing the PED. These districts are innovative frameworks for the development of cities toward clean energy consumption and increased energy security while contributing to improve the quality of life of the population within the city. They are a fundamental part of creating a comprehensive approach toward sustainable urbanization; dealing with the technological, spatial, regulatory, financial, legal, social, and economic perspectives (Alpagut et al., 2019); and paving the way toward the goal of 100 climate neutral cities in Europe (European Commission, 2020a). The PED concept plays a relevant role in the vision of climate-neutral cities, which are an essential step on the way to the Green Deal goal of a climate-neutral Europe by 2050 (European Commission, 2019).

In the last years, many feasibility studies and pilot projects about PED implementation have been conducted in many cities across Europe. The action 3.2 of the EU's Strategic Energy Technology Plan (European Union, 2018) supports the planning, deployment, and replication of 100 positive energy districts by 2025 (Bossi et al., 2020). Most studies and practical experiences about PED are based on projects in newly built districts, where the planning and integration of innovative solutions are less complex and the ambition is usually higher (Bossi et al., 2020). However, to achieve Europe's 2050 decarbonization challenge, a transformation of the urban systems is required, including the already settled districts. Therefore, as part of the urban transformation, a renovation wave of the existing building stock is pursued in the next years (European Commission, 2020b), aiming to improve the energy efficiency of the current European building stock, estimated to be around 75% energy inefficient (European Commission, 2020b). According to Mckinsey (2020), the European Union (EU) buildings' emissions must be reduced by 29% by 2030 and the sector should achieve climate neutrality (i.e., net-zero (GHG) emissions) by 2050 (C40 cities, 2020). The bulk of this reduction could be achieved by retrofitting and replacing the heating systems in existing buildings, which will still account for 75–90% of EU building stock in 2050 (Mckinsey, 2020).

Within the existing building stock, buildings in historic districts present particularly challenging characteristics to ambitious energy refurbishment and therefore are usually not considered in PED projects (Bossi et al., 2020). The combination of characteristics of many historic districts, like those located in southern Europe (e.g., narrow streets with few green public spaces, ancient and degraded heritage buildings, elderly population, high tourism dependency), negatively impacts the quality of life of its inhabitants and exacerbates problems such as reduced climate resilience; low energy performance and poor thermal comfort of buildings (Gouveia and Palma, 2019), energy poverty vulnerability (Gouveia et al., 2018, 2019), and congested streets with negative effects on air quality and noise. These environmental and well-being problems, coupled with severe regulatory limitations to implement EE measures and to integrate RES in historical buildings, represent serious restrictions to unlock the potential interventions (Gregório and Seixas, 2017) aimed at implementing the PED concept, which has the potential to improve the inhabitants' quality of life. Nevertheless, historic districts could profoundly benefit from the integration of PED solutions being a promoter of dynamics of change (Eurocities, 2020).

One of the critical socioeconomic issues in historic districts, especially in Southern and Eastern Europe, is energy poverty. Energy poverty generally refers to a situation in which households are not able to adequately heat their homes or meet other necessary energy services at an affordable cost (Pye et al., 2015). This phenomenon is mainly due to high energy prices, low incomes, and poor energy efficiency in buildings (Dobbins et al., 2019). The negative impacts on the affected households are health problems, enhanced poverty risk, increased inequalities, inadequate participation in society due to stigma, reduced climate action ambitions, and lower quality of life (e.g., Bouzarovski and Petrova, 2015). Some of the key measures previously identified to achieve a PED could potentially address energy poverty, such as an increase of decentralized RES generation and a larger integration of EE measures (European Commission, 2020c).

The connection between energy poverty and PED is still scarce in most studies and EU projects, with only a few (e.g., MAKING-CITY, 2018, launched in 2018, and POCITYF, 2019, started in 2019) including in the project KPIs the reduction of energy poverty during the project. However, it is considered as a consequence of the PED implementation and no direct relationship is described. Therefore, in the integration assessment of PED solutions, it is important to include energy poverty reduction targets and extensive citizen engagement for better identification and support of the most vulnerable households, while certifying that PED solutions do not amplify inequalities and increase vulnerabilities. Thus, there are no studies the authors are aware of in the current published literature linking the PED potential to a solution model to reduce energy poverty in historic districts.

This study aims to cover two key questions of the PED concept implementation, applied in historic districts in southern Europe Mediterranean cities: (i) what is the potential of building energy efficiency retrofit measures and solar energy generation and (ii) how these solutions could potentially drive the reduction at scale of energy poverty. The analysis is performed within the framework of the Sustainable Historic Districts project (2018–2020), co funded by EIT Climate-KIC, which addressed the challenges of historic districts in five Mediterranean European cities for a holistic and sustainable transformation pathway (Lisbon, Savona, Sassari, Ptuj, Nicosia) (SUSHI, 2020). In this paper, the historical district of Alfama will be used as a case study. This assessment advances the state of the art by presenting valuable knowledge on critical components of PED development within a historic district, through a high spatial scale analysis of building retrofit and solar energy integration potential (i.e., for over 120 statistical subsections of the district). It also brings together an integrative discussion between PED implementation and energy poverty mitigation. The case study application improves the understanding of the energy retrofit and solar photovoltaic (PV) specificities for a European Mediterranean city with a deep need for both building stock renovation and solar integration at a large scale, aiming to identify where efforts to mitigate energy poverty should focus.

The paper is structured into four sections. The next section presents the case study of the historical district of Alfama (Lisbon) and describes the methodologies used to estimate the techno-economic potential of both EE and RES generation at district scale. The results are described in section Results, whereas section General Discussion unfolds a critical discussion and conclusions on the role of PEDs in historic districts and its potential for energy poverty mitigation.

METHODS

In an effort to deliver key defining aspects of the PED framework as an embedment of an urban energy system, driven by a high level of EE and RES, the methodological approach of this study was divided into three major steps: (i) a case study analysis and identification of the energy poverty vulnerability, setting the scene for further detailed assessment; (ii) a spatially explicit analysis for 121 statistical subsection levels for buildings' renovations (windows, walls, roofs), and (iii) building-integrated photovoltaic (BIPV) electricity generation, considering the best measures and technologies to be integrated within a historical district context.

Case Study Location and Characteristics

Portugal receives some of the highest levels of solar irradiation in Europe and also boasts a high number of solar hours, with values between 2,200 and 3,000 h of sunlight per annum, and as such makes it an excellent candidate for solar energy projects (Cavaco et al., 2016).

The case study location is the Alfama historic district, in the city center of Lisbon. It is a traditional district with an important role in the cultural heritage and identification of the city of Lisbon. It is one of the oldest districts, with unique history and characteristics; it spreads between São Jorge Castle and the Tagus riverfront (in the civil parishes of Santa Maria Maior and São Vicente). Resembling a typical Arab medieval city, Alfama is known for its morphology due to its maze-like narrow streets, being one of the few areas of the city that has survived the 1755 earthquake. For these reasons, it is one of the main touristic locations of the city.

Historically, its population came from an important rural exodus during the middle of the last century. This rural origin is embodied in a way of life, characterized by strong neighbor relations and a sense of solidarity, reproducing the practices of the population origins. Still today, Alfama has an aging population that remains in the neighborhood, maintaining active commercial establishments. The Alfama population has been shrinking over the years. Despite its decrease in population, however, its population density is still very high (13,854 persons/km^2) when compared to Lisbon's average population density (5,477 persons/km^2). The high-density areas occur since the streets are very narrow and thus the buildings are very tight with each other (INE, 2011).

Due to their social culture and habits, the traditional inhabitants of Alfama are an important asset of Lisbon intangible heritage. However, gentrification and mass tourism are putting Alfama and its inhabitants under pressure, due to real estate needs, which tends to replace traditional low-income inhabitants with local accommodation schemes (e.g., Airbnb) and hotels. Currently, tourist accommodations represent 26% of the total available households (Gago and Cocola-Gant, 2019). If all the tourist accommodation houses are at full capacity, they can accommodate almost the same number of tourists/visitors as local inhabitants.

The cultural profile of the district and the tourism play a major role in the selection of building renovation measures and renewable energy technologies in the district, with public opinion having a considerable weight in what technologies should be integrated, e.g., reluctance to change the building façade or to install solar panels and/or small wind turbines on roofing. These aspects are regulated in specific guidelines that limit the rollout of building retrofit interventions and renewable technologies in the district.

Energy Poverty in Alfama

In connection with the building stock thermal performance and energy use in homes, energy poverty stands out as a serious issue affecting the Portuguese population. According to the EU SILC indicators, the estimated energy-poor population ranges approximately between 2.0 and 3.7 million inhabitants, which is between 18.8 and 35.7% of the total Portuguese population (Eurostat, 2021a,b). This issue is particularly serious in historic districts such as Alfama, due to the socioeconomic profile of the inhabitants and the underperforming building stock. **Figure 1** depicts the Energy Poverty Vulnerability Index (EPVI) developed by Gouveia et al. (2019), zoomed in on the Lisbon municipality region and highlighting the Alfama district, for the purpose of this paper. The EPVI is an aggregated assessment of the dwelling stock's energy performance, households' energy consumption (DGEG, 2021), and the ability of the population to implement alleviation measures, defined by a set of socioeconomic indicators from INE (2011).

The Lisbon Municipality is one of the least vulnerable municipalities of the country, due to high levels of alleviation measure implementations, determined by a favorable combination of socioeconomic indicators, such as average monthly income and share of the population with a University degree, as well as its location in milder climatic zones, particular for winter. Nevertheless, the energy poverty vulnerability index levels of the municipality still point to a significant energy poverty issue among the population. Within the municipality, the most vulnerable civil parishes in winter are located in the southeastern region, including Santa Maria Maior and São Vicente, where the Alfama district is located. These are the civil parishes with the oldest building stock, as well as a higher concentration of elderly people, with lower incomes and education level. In the summer, although not being in the highest interval of vulnerability, Alfama's civil parishes still present significantly high indexes of vulnerability.

An important cause of the high index levels is the existent energy performance gap, described by Palma et al. (2019), which consists in the difference between the real energy consumption for space heating and cooling, and the energy that should be consumed to guarantee the thermal comfort inside the dwellings. These gaps (expressed in percentages) are high across the whole country, and Lisbon's civil parishes are not the exception, presenting space heating and cooling energy performance gaps above 80%. These gaps stem from the combination of the low energy performance of buildings, which leads to high building energy needs (common in older buildings) and the low real energy consumptions for climatization, related to the energy affordability issue. For instance, in the first semester of 2020, Portugal had the highest price of natural gas for households in the EU, considering the purchasing power standard (PPS) (Eurostat, 2021c), while the electricity price was ranked fourth highest (Eurostat, 2021d). Furthermore, while ownership rates of cooling systems are historically low (18.7% in the metropolitan area of Lisbon), the ownership of decentralized low-efficiency heating systems is generalized (INE, 2017), including a significant share of electric oil heaters (ADENE, 2017). Coupled with low incomes, these indicators point to potential difficulty in affording adequate energy services. In a survey conducted by the national energy agency (ADENE, 2017), the participants claimed to spend on average 87€/month, which can represent a considerable burden for certain groups, such as elderly people who receive low pensions. The majority of the interviewed claimed to be worried about energy efficiency, in the perspective of reducing burdening energy bills. Additionally, cultural conditioning is also partially responsible for low consumption as people resist to heat or cool their homes, not only due to energy prices but also because thermal comfort is not a priority compared to other basic needs; it

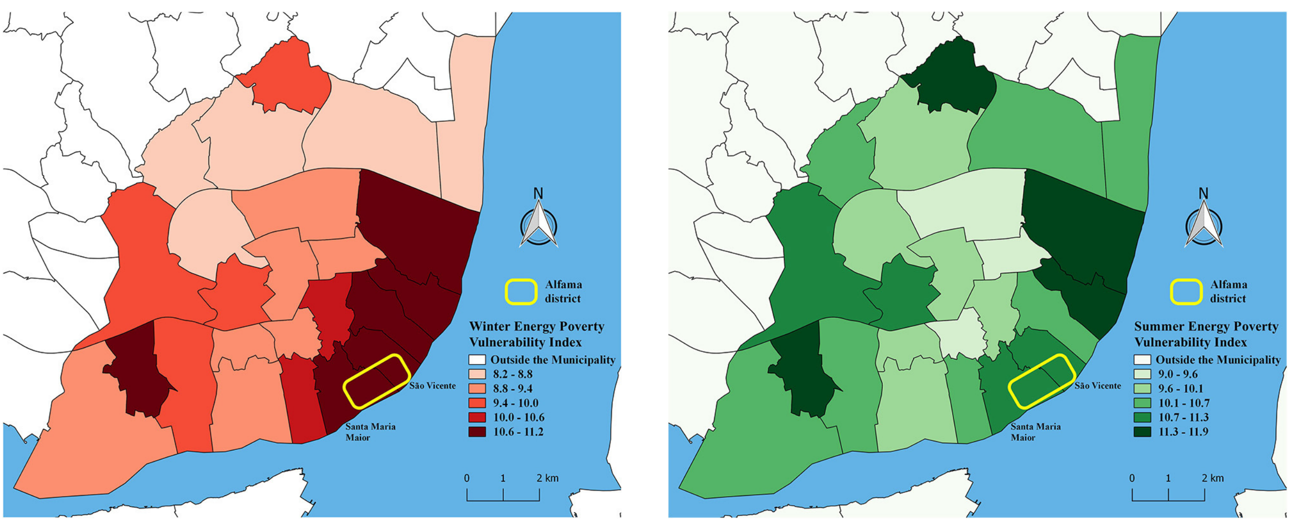

FIGURE 1 | Winter (left) and Summer (right) Energy Poverty Vulnerability index in Lisbon's civil parishes [adapted from Gouveia et al. (2019) and CML (2020)].

can be considered as a waste of money, particularly among elderly people, as evidenced by Horta et al. (2019).

From the policy perspective, the social tariff for electricity and natural gas use is the only measure that directly addresses the energy vulnerability of the population. Moreover, there are several policy instruments and schemes providing support for building renovation, in the form of soft loans and non-refundable grants. However, these options are not viable for low-income families. Nevertheless, the annual energy renovation rate of buildings in Portugal is ∼0.01% (INE, 2019), well below the EU average, which is around 1% (European Commission, 2020b). This difference raises questions about the effectiveness of these schemes, strengthened by the persistently high results of the energy poverty proxy indicators each year.

Representative Building Typologies

The first step of the methodology was the identification of representative building typologies of the residential building stock in the Alfama district, based on the predominant building characteristics obtained with the CENSUS 2011 (INE, 2011). The analysis focuses on the characteristics that are potentially relevant for the purpose of this study, such as construction period, building form, number of floors, and roof type (as developed in Gouveia et al., 2018). The census data (INE, 2011) portrays details for 1 863 buildings in the district. The majority of the buildings are multi-apartment buildings (62%) followed by terraced houses (24%), semidetached (5%), detached (5%), and other types (4%). For this category, all types of houses were combined since their differences and impact on energy needs would not considerably differ in such an urban-dense area. The year of construction is used as a proxy for material types and construction techniques. About 48% of the buildings were built before 1919 and 30% between 1919 and 1945. Overall, around 89% of buildings were built before 1960, before the application of energy efficiency and thermal performance regulations (i.e., 1990), evidenced by the energy inefficiency levels of all typologies. The number of floors and roof type influence the overall height of the building, and together with the height of surrounding buildings, these characteristics are important to compute the space heating and cooling energy needs. As almost all roof types (97%) are sloped roofs with ceramic or concrete tiles, this criterion was not considered relevant for further distinguishing building typologies. However, the number of floors has a wider variety, with the bulk of the buildings having up to 2 floors (42%) or 3 to 4 (42%); therefore, three classes were kept for characterizing the building typologies, i.e., "1 or 2," "3 or 4," and "equal or >5" floors. These criteria, combined with the analysis of the available data, enabled to identify six building typologies (TP), as illustrated in **Table 1**, accounting for 1 585 buildings in the Alfama district, which represents 85% of the total buildings in the area. The remaining 15% of the buildings have very distinct features, are not significantly widespread, and therefore are not considered in the analysis. A relevant criterion for the selection of typologies was the frequency of more than 7% representation in each civil parish of Alfama and the availability of data for its characterization.

Energy Efficiency Retrofit Potential of Residential Buildings

Several authors, such as Lazzeroni et al. (2017), Liang et al. (2018), and Asdrubali et al. (2019), have assessed the effects of retrofit in the energy needs or consumption of buildings, spanning various geographical contexts and spatial scales, as well as considering different types of buildings and measures.

Herein, detailed information from 4,142 energy performance certificates (EPCs) available for the district (ADENE, 2019) was used to characterize the energy performance of each residential building typology. Based on the main characteristics of each typology (**Table 1**), each energy certificate was associated with a specific building typology and the housing envelope elements (windows, walls, and roofs) corresponding to each EPC were analyzed. The parameters of interest were recorded, such as the total area of each component, the type of element, and the coefficient of thermal transmittance (U-value). After analyzing all the certificates associated with each typology for each building component, the average thermal transmission coefficients and the average total area of each component were used to estimate the nominal space heating and cooling energy needs. These were estimated before and after potential retrofitting interventions were estimated as well as the investment costs of the renovation measures applied to the building envelope. The energy needs were estimated following the methodology defined in the current

TABLE 1 | Main characteristics of the representative residential building typologies for Alfama District.

Typology	Construction period	Building type	Roof type	N° of floors	Number of buildings	Number of dwellings	Number of linked EPCs	Average area (m^2)	% EPC ≤ C class
TP1	Before 1919	House/multi-apartment building	Sloped	1/2 floors	330	619	65	45.3	100%
TP2	Between 1919 and 1960	House	Sloped	1/2 floors	321	552	122	48.0	100%
TP3	Before 1919	Multi-apartment building	Sloped	3/4 floors	409	1 316	656	54.0	97%
TP4	Between 1919 and 1960	Multi-apartment building	Sloped	3/4 floors	261	1 320	1 182	52.5	90%
TP5	Before 1919	Multi-apartment building	Sloped	5+ floors	133	946	1 091	77.4	90%
TP6	Between 1919 and 1960	Multi-apartment building	Sloped	5+ floors	131	1 251	1 126	66.4	96%

National Energy Performance Regulation (Ordinance, N°349-B/2013), which derives from the EN ISO 13790 approach. The requirements set in the regulation were adopted, namely, the nominal conditions regarding the maintenance of an optimal indoor temperature of respectively 18°C in the heating season and 25°C during the cooling season, for the whole useful area of the dwelling and during the total duration of the respective season. The equations for calculating the space heating (N_{ic}) and cooling (N_{vc}) useful energy needs, both in [kWh/m^2 .$year$], are the following:

$$N_{ic} = (Q_{tr,i} + Q_{ve,i} - Q_{gu,i})/A_p \qquad [kWh/m^2 .year] \quad (1)$$

$$N_{vc} = (1 - \eta_v).Q_{g,v}/A_p \qquad [kWh/m^2 .year] \quad (2)$$

$Q_{tr,i}$ is the heat transfer through conduction between the building and the surroundings in [kWh]; $Q_{ve,i}$ is the heat transfer through ventilation [kWh]; $Q_{gu,i}$ represents the total useful heat gain in the heating season in [kWh]; A_p is the building's indoor pavement useful area in [m^2]. η_v is the utilization factor of the heat gains [-]; and $Q_{g,v}$ represents the heat gains in the cooling season [kWh]. This process was carried out for the dwellings of all the subsections of Alfama. A subsection represents urban blocks within a civil parish to help identify distinct areas within.

Subsequently, a database with renovation measures was created using a market-based budget generation tool (CYPE, 2013), taking into account the type of materials that are traditionally used in the construction sector, as well as its suitability for the Portuguese buildings. For each measure, information on the physical and thermal properties, as well as its investment costs, including material and estimated man-hours for implementation was collected. Six measures were identified for windows (e.g., aluminum and PVC framing with/without a thermal cut, low emissivity, and standard double glazing), 29 for walls (internal and external), and nine for roofs (e.g., ETIC systems, engineered polyurethane, agglomerated cork, expanded polystyrene). For more information about the considered technologies, see Duarte (2020).

The energy efficiency potential in the district was then assessed through a building fabric improvement scenario for each of the construction components (windows, walls, roofs). This scenario includes a selection for each component of the retrofitting measures that complies with the thermal performance requirements set in the regulation while involving the lowest investment costs. The following suitable options were identified: insulation of expanded polystyrene (EPS) and mineral wool (MW). EPS has a good insulating capacity and is permeable to water vapor. Mineral wool is an incombustible material and completely permeable to air and water vapor but does not absorb water. To estimate the impact of retrofitting measures in the district, the following options were selected as most adequate for being applied: mineral wool 10 mm thick (MW10) for the roof, PVC window frames with standard double glazing (CX PVC STD) for the windows, and expanded polystyrene 6 millimeters thick (EPS6) for the walls, through internal insulation. Historic listed buildings and buildings within historic districts often have façades worthy of preservation (e.g., with tiles or other important visual features) (Build Up, 2020). In Lisbon historical districts, it is very common to have stonework on the door and windows which do not allow the use for example of ETICs (in external insulation) which would be more prominent than these visual details. With ETICs, buildings are more uniform on the outside with impacts on the existing aesthetic beauty in such districts being lost. For these reasons, the internal insulation of walls was selected, despite reducing thermal inertia and the internal floor area.

For walls and roof, insulation material is added to the existing structure; thus, for each building typology the two thermal resistances were summed, and the resulting value represents the final thermal resistance after the retrofit. For windows, the retrofit is a replacement of solutions; therefore, the resulting thermal resistance is equal to the one of the newly implemented solution. **Table 2** shows the selected measures for each building component and its associated costs, where lambda (λ) is the thermal conductivity of the material and the R-value is a measure of resistance to heat transfer of the material, for the given thickness. A detailed description of the full methodology can be found in Duarte (2020).

Distributed Solar PV Potential

One of the key measures identified in PED projects is solar power integration in buildings (Derkenbaeva et al., 2020). This technology can provide a carbon-free energy source while increasing socioeconomic development by generating new investment opportunities. The goal herein is to evaluate the techno-economic potential of solar photovoltaic technologies, in terms of total electricity production and associated costs, to determine the feasibility of the Alfama district transformation, coupled with an opportunity to mitigate energy poverty through reduction of energy costs and larger use of sustainable energy in vulnerable households.

For the estimation of the electricity generation potential for PV projects, there are three approaches: sample, multivariate

TABLE 2 | Selected measures for buildings retrofit.

Building component	Selected improvement measures	Lambda [W m^{-1} K^{-1}]	*R*-value [m^2·K W^{-1}]	Investment costs [€/m^2] CYPE (2013)
Roof	Thermal insulation with mineral wool (MW10)	0.042	2.38	7.21
Windows	PVC window frames with standard double glass (CX PVC STD)	–	0.45	350.60
Wall	Expanded polystyrene (EPS6) through internal insulation	0.031	1.94	35.23

Windows investment costs consider a window with a size of 1.5 m^2.

sampling, and complete census (Byrne et al., 2015). On *the Sample-based*, three simple steps are taken: (a) a survey is conducted to obtain data on the available roof area; (b) average annual solar irradiation on inclined surfaces is determined; and (c) yearly PV production is calculated. It is a fast methodology to implement; however, the lack of variables makes this approach more attractive when calculating estimates rather than accurate and precise electricity production values (Byrne et al., 2015). *Multivariate sampling-based* has a higher difficulty level and consists of five steps: (a) geographical division of the region; (b) rooftop sampling; (c) extrapolation through the use of rooftop area and population relationships; (d) calculations of constraints and detriments (shading, orientation, etc.), and (e) conversion of data into power and energy outputs. Although this method is generally seen as having a lower cost of implementation, the calculation of some variables such as the shading is extremely difficult to conduct, meaning this method is extremely time-consuming and less accurate (Byrne et al., 2015). *Complete census* relies on the computing of the entire available rooftop area, usually performed through the use of innovative cartographic data sets that offer a digital model of the study region, or through the use of existing statistical data sets containing building information. One technique often used to measure solar radiation levels is Light Detection and Ranging (LiDAR) software (Huang et al., 2015). This approach produces extremely accurate results. However, the increased amount of data makes this method the most time-consuming. A few examples of such application of methods are presented, e.g., by the National Renewable Energies Laboratory (NREL) which provides a PV estimation tool PVWatts (NREL, 2020), using hourly meteorological data per year from the National Solar Radiation Database. The work by Hong et al. (2017) using a sampling method calculated the rooftop solar PV potential for the city of Seoul. Phap et al. (2020) assessed the rooftop solar power technical potential of the city of Hanoi by using high-resolution remote sensing images technology. Eslami et al. (2021), utilizing a rich spatial dataset of solar irradiation augmented with electricity bills at the building level, estimated the cost and benefit of installing rooftop PV systems for each building of the city of Beirut (Lebanon).

The methodology used in this part of the work to assess the solar power integration potential follows a multivariate sampling-based approach, bringing together different tools and methods (PV GIS, energy performance certificates, Google Earth, CENSUS data) for achieving a spatially detailed ballpark figure of production and investment needs for the district scale PV integration, and it can be broken down in several parts: investigation and characterization of the buildings; solar irradiation assessment; available areas and orientation; and calculation of electricity production and costs for PV technologies.

The methodology considers the same six-building typologies used for EE assessment (see **Table 1**), with roof type, number of floors, and year of construction being the key characteristics of interest. Year of construction is an important characteristic since BIPVs need stable structures and building envelope to have a secure installation. BIPV includes the replacement of the traditional construction elements with multifunctional elements that generate electricity. This enables the dual function of producing renewable electricity through the use of PV and to provide a construction element for the finished building (Ritzen et al., 2016). The installation of certain PV technologies as façade PV may cause structural problems on older buildings that have not been renovated but are an important structure for solar PV potential of Mediterranean cities as described in Brito et al. (2017). The number of floors influences the overall height of the building, thus being a critical factor to determine levels of shading from surrounding buildings. The slope of the roof is also a major feature in determining if a mounting system is needed, or if solar tiles can be used. Closely related, available roofing surface and orientation are the most important factors in determining solar energy generation capacity. To ensure the maximum potential, the available roof surface should have access to sunlight and face the optimal direction to secure the optimal irradiation angle.

Solar Exposure

The software Photovoltaic Geographical Information System (PVGIS) (JRC, 2021) was used to calculate the average monthly solar irradiation estimates for Lisbon (latitude 38.712° north, longitude−9.131 east) for direct normal irradiation, irradiation at an optimal angle, and diffuse solar radiation. The satellite CMSAF data for the year 2016 was retrieved and used for the assessment.

PVGIS is a free online tool that estimates the solar irradiation, taking into consideration shadowing. The solar irradiation information provided by PVGIS is the average direct solar irradiation at an optimum angle for Lisbon (31°) and optimal orientation (south-facing). Diffuse solar irradiation was used to calculate the annual generation of solar window-type technologies. **Figure 2** shows a high fluctuation for irradiation levels with lows of about 60 kWh/m^2 for January and highs in the summer of about 205 kWh/m^2 (JRC, 2021).

Orientation and Rooftop and Windows Area

Building orientation and rooftop availability determine the angle of solar exposure and the total surface available to install the modules. Those features were assessed through a visual analysis of the buildings in different regions of Alfama using Google Earth. The satellite images were used to evaluate rooftop characteristics. The main orientation of the buildings was gathered to identify a significant trend that could be assumed for the majority of the buildings. Little to no variation was found in the orientation of the buildings; in fact, most of them are facing south. Therefore, all the calculations were done based on the assumption that the buildings are south-facing. The next step was the matching between the orientation and rooftop availability information to the respective building typology (see section Representative Building Typologies).

From the energy performance certificate (ADENE, 2019) sample of the district, we retrieve data on the floor surface, number of floors, and total window surface. The average surface of rooftops was computed for each building typology, using the building's footprint area as a proxy indicator. Three classes of

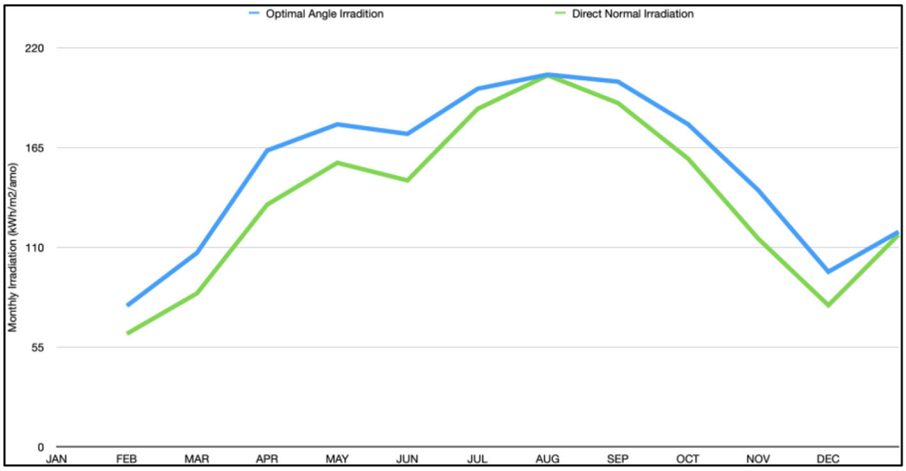

FIGURE 2 | Lisbon monthly solar irradiation estimates (2016) (adopted from JRC, 2021).

rooftop surfaces were defined (i.e., "I: 0–150 m^2," "II: 150–350 m^2," and "III: >350 m^2") as well as for window surfaces (i.e., "A: 0–30 m^2," "B: 30–60 m^2," and "C>60 m^2"). These categories enable the identification of outliers, which have areas that are too large or too small in comparison to other buildings, indicating a fault in data recording or a building that has a completely different typology from the defined categories. Outliers are then removed from the assessment.

However, PV technologies will not be installed in the whole rooftop area. This is because only part of the rooftops will be exposed to sunlight, and there may be existing restrictions that prevent the installation of modules in certain areas. For the rooftop availability, a Google Earth visual inspection was done, taking an overview of the district and then taking a building's sample from each one of its subsections. Identified restrictions could include things like chimneys, water collectors, and parabolic antennas (e.g., for television). Another constraint is that as the rooftops are pitched, one side of the rooftop could be privileged with more access to solar irradiation. This is especially true for the study at hand, as most of the buildings are south-facing. This means that only half of the total rooftop area will be facing the sunlight, so only half of the rooftop is suitable for PV technology installation. The calculation of the half-roof was done through the use of trigonometry following other studies such as Moreira (2016). **Figure 3** clearly shows a multitude of situations that limit the potential of PV integration; for example, there are roofs completely unrestricted (in green), while others have shadowing (in orange) due to surrounding buildings, and roofs have high levels of restrictions (in red).

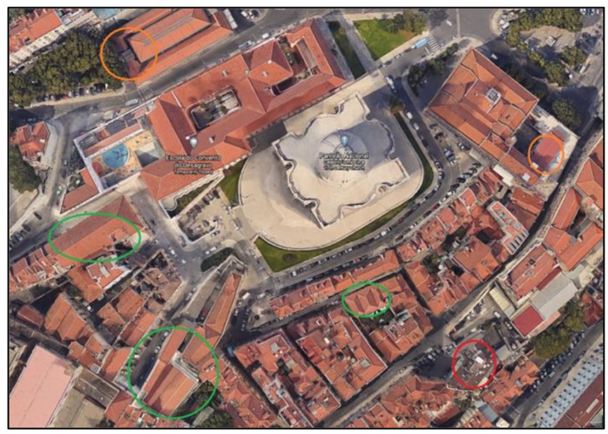

FIGURE 3 | Aerial view of the rooftop availability in the district area of São Vicente de Fora (northeast) (adopted from Google Earth).

Solar PV Electricity Generation

The total solar PV electricity production was estimated considering the average rooftop and window surfaces in Alfama district for the six residential building typologies based upon the results of the previous methodological steps, with varying PV technologies with different levels of maturity and adoption but that are already available on the market. Eight rooftop PV technologies (i.e., building-integrated (BI) and tiles) and two window PV technologies were assessed, as depicted in **Table 3**. For each technology, total investment costs, annual and lifetime electricity production, and levelized cost of energy (LCOE) were calculated. The installation costs of the modules of an additional 5% and O&M of 3%/year were included in the total investment costs, and a total lifetime of 25 years was considered for lifetime calculations. An average 10% discount rate was used. Finally, for the purpose of this paper's PED conceptual overview, the best technology in terms of overall costs, historic district applicability, generation, and LCOE were selected for each application (window and rooftop). Further details of the full methodology can be found in Luz (2020).

TABLE 3 | Key characteristics and prices of the considered module types.

Module name	Module type	Application	Efficiency (%)	Price [€ m^{-2}]	Module area (m^2)
TALLMAX[a]	Panel	Rooftop	17.50%	50.18	1.94
BLUESUN[b]	Solar tile	Rooftop	15.00%	117.94	0.35
PERC 60 305W[c]	B. I. panel	Rooftop	18.35%	97.98	1.66
PERC 60 320W[d]	B. I. panel	Rooftop	18.94%	116.32	1.69
BRAS PREMIUM[e]	Solar tile	Rooftop	17.16%	562.22	0.54
HCM60X9[f]	B. I. panel	Rooftop	19.56%	48.62	1.69
PERC 72 375[g]	B. I. panel	Rooftop	18.89%	115.53	1.99
PERC 72 385[h]	B. I. panel	Rooftop	19.11%	98.22	2.01
Onyx Solar[i]	Thin strip	Window	-	0.73 (€/W)	0.1–8.28
FY Solar[j]	Thin strip	Window	-	62.88	1.32

[a] *https://www.alibaba.com/product-detail/China-supplier-TALLMAX-72-cell-module_62056188419.html?spm=a2700.9099375.35.9.ff96jl Accessed on: 20/08/2020.*
[b] *https://www.alibaba.com/product-detail/Bluesun-solar-roof-tile-hook-2019_62183837021.html?spm=a2700.7724857.normalList.39.73992dacJGelGs Accessed on: 20/08/2020.*
[c] *https://www.solaris-shop.com/mission-solar-mse305sq5k-305w-mono-solar-panel/ Accessed on: 20/08/2020.*
[d] *https://www.solaris-shop.com/mission-solar-mse320sr8t-320w-mono-solar-panel/ Accessed on: 20/08/2020.*
[e] *https://www.baustoffshop.de/dach/mehr-fur-dach-fassade/solar/braas-solarsysteme/braas-pv-premium.html Accessed on: 20/08/2020.*
[f] *https://www.secondsol.com/en/anzeige/25513/pv-module/kristallin/mono/dah-solar/hcm60x9-330w Accessed on: 20/08/2020.*
[g] *https://www.foreverpureplace.com/Mission-Solar-MSE-PERC-72-Solar-Panel-375-Watt-PV-p/mse375sq9s.htm Accessed on: 20/08/2020.*
[h] *https://www.thepowerstore.com/mission-solar-mono-perc-365w-72-cell-silver-white.html Accessed on: 20/08/2020.*
[i] *https://www.onyxsolar.com/product-services/faq Accessed on: 20/08/2020.*
[j] *https://www.alibaba.com/product-detail/customizable-glass-transparency-solar-panel-BIPV_60361886776.html?spm=a2700.7724857.normalList.48.73992dacJGelGs Accessed on: 20/08/2020.*

RESULTS

The results of this study set the scene for the conceptualization of two of the major PED solutions to contribute to energy poverty mitigation in Alfama district while reducing GHG emissions and supporting the transition toward a carbon-neutral city. This section depicts the results for a highly detailed spatial assessment of building EE retrofitting measures and RES integration, unfolding the energy savings' potential of window, roof, and wall retrofit by district subsections and building typologies, as well as roof available surface and solar irradiation, enabling the identification of rooftop PV electricity generation potential for the historic district.

Residential Building Energy Efficiency Potential

The lion share of buildings in this historic district was built before 1960. Before 1930, the use of construction systems such as stone masonry walls, wooden beams in one direction between walls, and pottery floors nailed perpendicular to the beams (i.e., masonry reinforced with wood), without insulation and with lime mortars bringing the stones together, was common. In the period 1930–1950 with the appearance of concrete, there was a constructive evolution but still very poor as no regulation was setting quality standards for thermal performance. Due to climate, culture, and lack of money, there was not much need for improved quality since it would increase costs; thus, roof slab serves as "insulation" and the buildings have wooden windows. All these characteristics set the scene for structural problems and low indoor thermal comfort, with significant potential for improvements (thermal, acoustic, against earthquakes).

Table 4 presents the nominal heating and cooling needs for a dwelling in each building typology before and after the application of the selected retrofitting measures. The current energy needs are generally higher in the dwellings of TP1 and TP2 typologies due to higher thermal transmittance of the building envelope, and because the roof is directly connected to the outside, which does not happen for most dwellings in multi-apartment buildings. The energy needs obtained for the retrofitting scenario were compared to the current needs.

Retrofit measures are more effective in reducing space heating energy needs, as the reduction of energy losses related to the improvement of thermal performance directly reduces the need for energy provision, whereas, for space cooling, this relation is not so straightforward. These needs are determined by a ratio between energy gains and losses, and retrofit can magnify energy needs if the reduction of losses is higher than the reduction of gains. The implementation of the combined set of measures shows a significant reduction of space heating energy needs, equal to 84% of the energy needs before the retrofit. On the other hand, space cooling energy needs are reduced by 19% (**Table 5**). The impact values on windows reflect the trade-off between the application of renovation measures to improve thermal comfort during both seasons (heating and cooling) in a Mediterranean climate, which is an aspect that should be evaluated carefully at the implementation stage. Although space heating energy needs are significantly reduced in all typologies, buildings built before 1919 have slightly lower reductions per dwelling (TP1 with 79.7% and TP3 with 78.2%, and TP5 with 74.8%), as the thick stone walls provide better thermal inertia and consequently a better energy performance from the start. Between the several building typologies, the difference between the higher and lower reductions of the heating energy needs is

TABLE 4 | Annual nominal heating and cooling dwelling energy needs before and after the retrofit.

Building typology	Current nominal heating needs (kWh/m^2.year)	Current nominal cooling needs (kWh/m^2.year)	Nominal heating needs after full retrofit (kWh/m^2.year)	Nominal cooling needs after full retrofit (kWh/m^2.year)	Heating need reduction (%)	Cooling need reduction (%)
TP1	167.7	57.6	34.1	41.8	79.7	27.4
TP2	120.1	33.1	12.8	17.9	90.2	46.1
TP3	89.8	35.8	20.6	30.3	78.2	15.4
TP4	76.8	14.9	10.9	11.6	85.8	22.3
TP5	75.5	31.7	19.0	30.3	74.8	4.6
TP6	55.5	12.9	7.7	12.7	86.1	1.6

TABLE 5 | Energy needs for space heating and cooling, and the impact of different individual renovation measures for each building components.

Current total energy needs (GWh/year)		Building component retrofitted	Total energy needs after retrofit [GWh/year]		Energy need reduction [GWh/year (%)]	
Heating	Cooling		Heating	Cooling	Heating	Cooling
34.3	10.9	Roofs	25.2	8.0	9.1 (27%)	2.9 (27%)
		Windows	30.8	11.5	3.5 (10%)	–0.5 (–5%)
		Walls	18.0	11.2	16.3 (48%)	–0.3 (–3%)
		All measures combined	6.3	9.0	28.9 (84%)	2.1 (19%)

up to 15.4% (between TP2 and TP5), demonstrating that the building typology plays a relevant role in the efficacy of the retrofit. Space cooling energy need reduction is mostly connected to house typologies as the application of roof retrofit significantly reduces energy gains in those dwellings. Building orientation is also considerably relevant—dwellings with walls and windows facing south have higher energy gains and increased space cooling needs, explaining the low TP5 and TP6 space cooling energy needs reduction, respectively 4.6 and 1.6%.

Table 5 shows the energy needs for space heating and cooling and the impact of different individual energy renovations for each building component. Improved roof insulation resulted in an average reduction of space heating energy needs of 27% per dwelling (ranging from 14% on TP5 to 50% on TP2), 10% due to window replacement (ranging from 6% on TP3 to 13% on TP6), and 48% due to walls (ranging from 32% on TP1 to 60% on TP6). Regarding space cooling energy needs, roof measures enable a potential average decrease of 27% (ranging from 10% on TP5 to 58% on TP2). On the other hand, window replacement would increase energy needs by 5% (ranging from −2% on TP3 to −9% on TP6) and wall retrofit would lead to an increase of 3% for space cooling (ranging from −10% on TP6 to 1% on TP1).

Figure 4 depicts the spatial analysis of the resulting energy needs for space heating (left panel) and cooling (right panel) per dwelling in each subsection after all building components are retrofitted. From the analysis, 28% of subsections include dwellings with energy needs after retrofitting over 8.8 MWh for space heating and 15% of subsections with over 10.8 MWh for space cooling (two upper classes of the maps). The two categories where energy needs per dwelling are lower account for 39% of all subsections (i.e., 53). The maps of **Figure 4** also highlight that most of the subsections with lower heating energy needs after renovation measures are also the same where cooling needs are lower, probably due to the building typologies present in the subsection. Lower energy needs might translate into reduced energy consumption requirement and thus potentially lower vulnerability to energy poverty in these subsections. On the other hand, subsections that have higher energy needs after the building retrofit would need additional measures to reduce energy poverty, e.g., a relevant integration of decentralized RES.

Figure 5 discloses different levels of impact of the overall set of measures. This representation highlights the locations where the EE measures are most impactful, contributing to tackle the related thermal comfort and energy poverty problems. Subsections at the north and center south of the district have higher potential for energy need reduction. Most subsections have potential for space heating energy need reduction, whereas the dwellings of only a few subsections, especially in the western regions of the district, have potential for space cooling energy need reduction through building fabric retrofit. The subsections with high impact might be considered as priority hotspot locations for a cost-effective renovation, toward reducing the gap between energy needs and energy provision, while being also valuable locations for energy poverty mitigation. It is interesting to notice that the subsections with the highest heating energy need reduction are still the subsections that have higher energy needs. This highlights where the biggest vulnerability to energy poverty is present, and where a more detailed retrofit plan should be designed.

PV Integration Potential in Residential Buildings

Rooftop and Windows Area

Figure 6 illustrates the composition of each building typology, in terms of the average rooftop area category and window area category. These are displayed as a cumulative bar chart for each

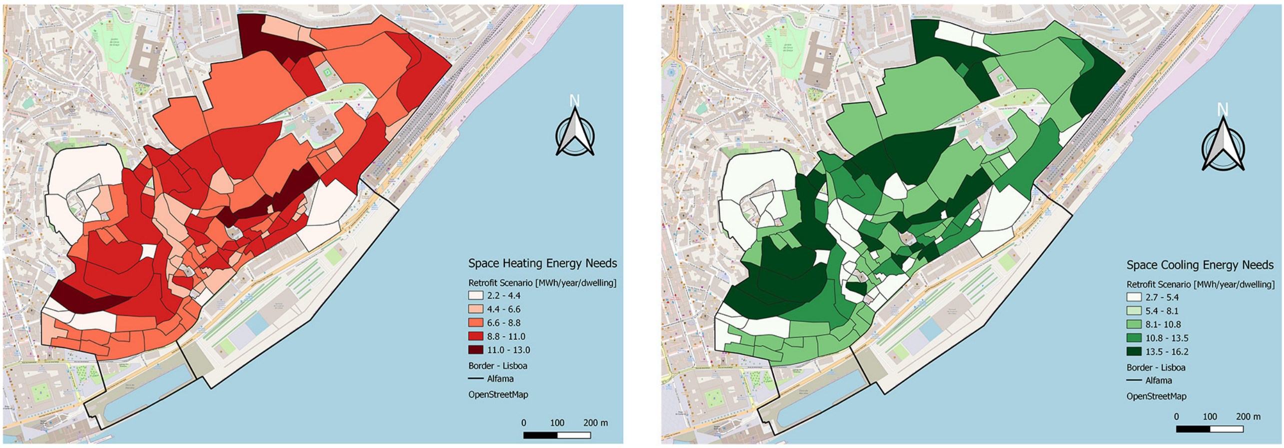

FIGURE 4 | Space heating (left) and cooling (right) energy needs per average dwelling in Alfama subsections after retrofitting measures.

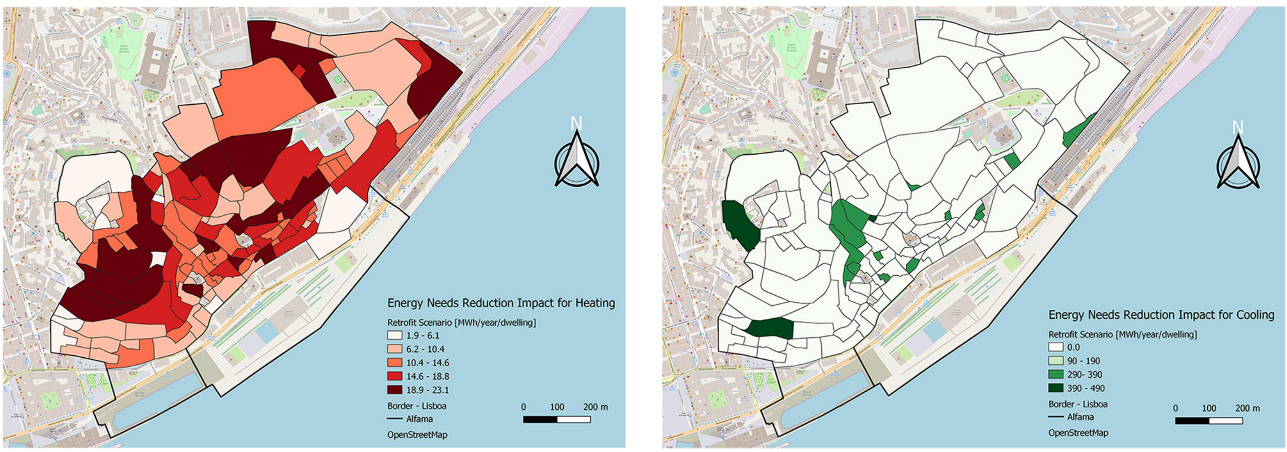

FIGURE 5 | Space heating (left) and cooling (right) energy needs reduction impact per average dwelling in Alfama.

building typology. The data shows trends for both these features in the different building typologies. Assessing the range for the window areas, the vast majority (96% and over) of buildings have an average window area in category A. Negligible amounts of buildings have average window areas in the range of categories B and C, evidently displaying that all the building typologies considered have relatively small available areas for the installation of window PV technologies.

The rooftop area, however, shows a different trend. For TP1 and TP2 buildings, which represent houses/apartments with one or two floors, most of the buildings fall in the roof category I (0–150 m^2), whereas for building TP3 and TP4, it is spread almost evenly between categories I and II (150–350 m^2), providing a varied spread of average areas. For TP5 and TP6, which represent the tallest apartment buildings with 5+ floors, over half of the buildings have rooftop areas belonging to category II. Once the trends have been analyzed, the average half roof area (without taking rooftop restrictions into account) and average available window area for each building typology were calculated.

The roof availability analysis for each building typology revealed roof restrictions as follows: 0% for TP3; 5% for TP1, TP2, and TP4; and 15% for TP5 and TP6. A single roof availability area for each building typology is assumed. This approximation is due to the lack of detailed data on roof characteristics.

Solar PV Electricity Generation

Individual technological evaluation results for investment costs, electricity generation, and LCOEs are depicted in **Table 6**. For window technology, the selected choice was FY Solar was the one enabling a continuous unbiased approach, as the source of information for solar irradiation is the same as the ones used for the rooftop PV technology calculations (i.e., PV GIS) and not the manufacturer estimations. For the rooftop technology, the selection process was more complex since two different module types were chosen to be potentially implemented (solar tiles

FIGURE 6 | Distribution of rooftop (I, II, III) and window area categories (A, B, C) by building typology for Alfama.

TABLE 6 | Electricity generation, investment costs, and LCOE of solar PV technologies.

Module name	Type	Electricity generation (1st year) (GWh/year)	Lifetime electricity generation (GWh)	Module investment costs (M€)	Total investment costs (M€)	LCOE (€/kWh)
TALLMAX	Panel	63	848	12	14	0.04
BLUESUN	**Solar tile**	49	651	30	35	0.12
PERC 60 305 W	B. I. panel	24	316	24	28	0.20
PERC 60 320 W	B. I. panel	61	819	28	33	0.09
BRAS PREMIUM	Solar tile	55	744	137	161	0.49
HCM60X9	**B. I. panel**	63	845	12	14	0.04
PERC 72 375	B. I. panel	61	817	28	33	0.09
PERC 72 385	B. I. panel	62	826	24	27	0.62
Onyx solar	Thin strip	0.06	0.83	0.99	1.1	3.20
FY solar	**Thin strip**	0.05	0.68	0.91	1.0	3.57

and building integrated panels). From the data gathered in the previous steps, it is shown that for solar tile technologies, the best choice is the Bluesun solar tile. Although the total production is less than if the BRAAS solar tile were to be used, the costs are significantly lower. These lower costs significantly impact the LCOEs, with 0.12 €/kWh for the Bluesun solar tile compared to a four-fold figure of 0.49 €/kWh for BRAAS solar tile. For building-integrated panels, more choices were available. After the analysis of the different electricity production levels, investment costs, and LCOEs, two technologies are seen to be better than the other ones—HCM60X9 and Tallmax. Due to the large area of each module for the Tallmax, HCM60X9 is the better choice as it is more adaptable to smaller rooftops or rooftops with a high level of restrictions.

For an integrated analysis of PV integration potential in different building parts, we concluded the two best combinations of window and rooftop technologies—FY-solar strips for window and HCM60X9 modules—which resulted in a combined electricity production of 63 GWh per year and a total lifetime of 846 GWh. The combination of FY-solar strips and the BLUESUN solar tiles has a potential of 49 GWh of generated electricity per year, with a total lifetime production of 652 GWh. The latest combination was ultimately selected as the best option for this district context, because the solar tiles have lower visual impact, reducing the influence on the aesthetics of the historic district, thus increasing public acceptance. If compared to the current electricity generation levels in Portugal (2019), these annual figures would represent 0.09–0.012% of total gross electricity generation and 3.7–4.7% of PV generation. **Figure 7** shows the potential of solar energy generation for this combination, mapped at the district subsection level. The map highlights that 83% of the subsections have a potential electricity generation lower than 0.6 GWh/year, while ∼17% have values in the range from 1.2 to 2 GWh/year (darker purple). There is a higher potential for PV production in the subsections located in the northeast part of the district where most TP2 typologies have higher rooftop areas and also because it is the area in the district with more residential buildings. Lower potential for electricity generation is in the northwestern region where the castle and walls are located.

Investment Costs

This section summarizes the investment costs necessary for deep retrofitting measures and the RES generation through the integration of BIPV technologies in the buildings' windows and rooftops. The analysis provides insights into the relation between energy need reduction and the capital investment necessary to achieve that reduction, for different types of retrofit intervention and solar PV technologies (**Figure 7**).

The evaluated retrofitting measures for all residential building stocks in Alfama requires an estimated investment of 45M€, with 2.9M€ for roof retrofitting, 26M€ for window retrofitting, and 17M€ for wall retrofitting. The left panel of **Figure 7** shows the total investment costs of building retrofit at the subsection level. Wall improvement is the most impactful measure for energy need reduction, with overall investment needed being the second. Roof retrofit has a cost-effectiveness of 0.32 and 1.0€/kWh for energy need reduction for space heating and space cooling, respectively. The retrofit of walls and windows results in 7.4 and 1.0€/kWh, respectively, regarding space heating. Considering only space cooling-related improvements, these interventions are not cost-effective. Overall roof retrofit is the most cost-effective measure for Alfama for both space heating and cooling and should be the first option to be pursued under a limited budget. As discussed in multiple publications (e.g., Howden-Chapman, 2015; COMBI, 2018; Bisello, 2020; Reuter et al., 2020), energy efficiency renovations spawn far beyond direct impact on the environment (e.g., energy consumption and GHG reduction) which should be acknowledged (for health, economy, social welfare) in district-scale ambitious energy efficiency transformations.

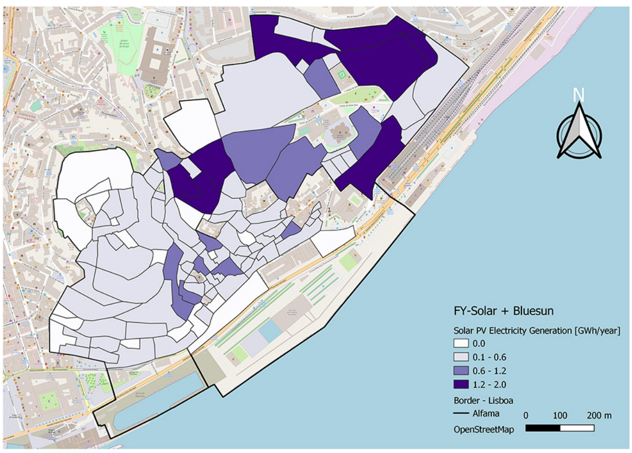

FIGURE 7 | Total solar PV electricity generation technical potential (rooftop and windows) for residential buildings in Alfama.

As for the PV production, however, the combination of FY-solar strips and HCM60X9 panels was found to be the most cost-effective choice, totaling 15M€ of needed investment with an LCOE of 0.04 €/kWh. The combination of FY-solar strips and the BLUESUN solar tiles were selected, as explained in the previous section, as more suitable to be applied in a historic district with several associated building regulatory restrictions. This combination requires a total investment cost of 36M€ and has an aggregated LCOE of 0.13 €/kWh. The right panel of **Figure 8** illustrates the spatial distribution of the total investment costs for the integration of the selected set of PV solutions. It is found that 10% of the subsections entail a potential investment higher than 0.6M€. Locations with high investment costs are mostly found in the eastern part of the district due to their building types and higher presence of residential buildings. Approximately 46% of the subsections depict investments lower than 200k€.

GENERAL DISCUSSION

The work presented in this paper provides a first approach to implement a vision of a Positive Energy District in the Alfama historical district, focusing on two key components of the PED framework—EE measures to reduce energy needs and decentralized locally produced RES electricity. We argue that these two components entail a strategy for a structural and sustainable energy poverty mitigation, paving the way for a holistic and systemic district change (technically and socially)

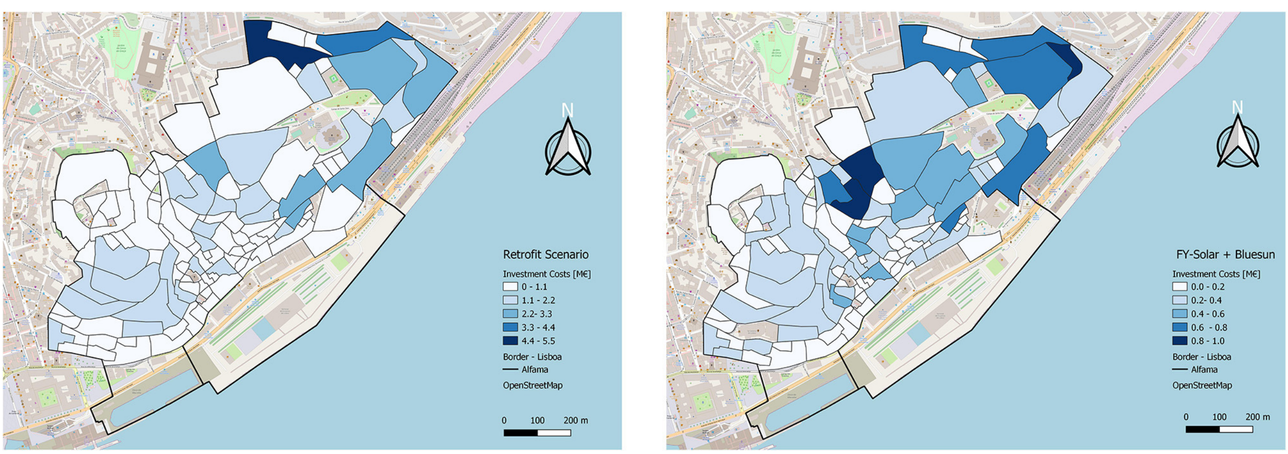

FIGURE 8 | Investment costs needed for full buildings retrofit (left) and solar PV integration (right) in Alfama subsections.

toward a sustainable energy transition. The case study highlights the common problems occurring in the Mediterranean historic city districts, and the methodology can be applied to evaluate the potential of PED implementations in many Southern European cities. Considering the current literature, this paper presents two key novelties that should be underlined: the technical and economic feasibility to adopt some key components of a PED concept in a historic district, while most projects focus on the design of newly built districts (Bossi et al., 2020); and the exploration of the PED model as an opportunity to tackle and mitigate energy poverty.

The majority of European cities have buildings or blocks of historical interest, which have great potential to reduce their energy consumption and to cut GHG emissions (Eurocities, 2020), applying the PED concept. However, they present severe challenges to implement integrated PED solutions, either due to regulatory restrictions or due to standard financial bottlenecks that often limit the integration of RES and EE measures. Moreover, the social acceptance of interventions in historical districts may create barriers to the transition toward more sustainable cities. In many cases, the public opinion for the installation of PV panels or small wind turbines is extremely negative as the infrastructures built are considered to be damaging to the district's overall architecture and charm. Therefore, addressing these conflicts and barriers, developing innovative and creative solutions or designs (e.g., technologies, financing schemes), and, on social features, educating the local population toward the benefits of using RES are of vital importance when transitioning the energy usage in historic districts unlocking their full potential.

The results achieved herein aimed to illustrate the high technical potential of historic districts to contribute to carbon neutrality and sustainable cities. For the case of Alfama, the oldest historic district of the city of Lisbon, energy efficiency measures on the dwelling's structure, including the renovation of the roof (i.e., thermal insulation with mineral wool), windows (i.e., PVC window frames with standard double glass), and walls (i.e., expanded polystyrene, EPS6, through internal insulation), may reduce the energy needs around 84% for heating and 19% for cooling, when compared with the energy needs before the retrofitting measures. The required investment totals 45M€ for the full set of EE retrofitting measures in 6 004 dwellings and 15–36M€ for the two combinations (windows plus rooftops) of decentralized solar electricity generation. The investment for the retrofit of the building may represent between 56 and 75% of the total investment for the district, depending on the solar technologies selected. All these results unfold the importance of a deep-scale full package retrofit for reduction of energy needs while improving the living conditions of the occupants throughout the dwelling stock.

We argue that these levels of energy need reduction which enable to keep the thermal comfort at the set reference indoor temperatures in winter (18°C) and in summer (25°C) have a direct impact on energy poverty reduction, meaning that even if a family does not have the financial resources to heat or cool the household up to the ideal temperatures, the significant reduction of energy losses due to EE measures can increase the thermal comfort of the households. These results stress the need for acting first in the building's components, simultaneously with ventilation, which increases the building airtightness through insulation and better windows, while renewing the indoor air for good air quality conditions. Only then, under a PED concept, should the integration of technical systems (PV systems, boilers, heat pumps, etc.) be considered.

Nevertheless, we concluded a significant technical potential for solar electricity generation in the historic district, for two combinations of window and rooftop technologies. The most cost-effective technology combination is FY-solar strips for windows plus HCM60X9 BIPV panels for rooftops. However, due to its visual impact on the historic district rooftops and the potential low public acceptance, the combined solution of FY-solar strips for windows and BLUESUN solar tile for rooftops was spatially assessed. This combination has higher total lifetime costs; however, the aesthetic of the historic districts would be preserved since the solar tiles have a smaller profile and are designed to simulate rooftop tiles. This trade-off illustrates one of the current challenges historic districts are facing regarding locally produced electricity: the visual perception of PV panels.

The role of locally generated electricity in mitigating energy poverty should be underlined, as it brings an opportunity to lower energy bills. In particular, this could be especially relevant when the most adequate subsections for RES integration are closer or the same as the subsections that have high energy needs for space heating and cooling. In these cases, the PED model is an opportunity for a renewable energy community, a priority for the Portuguese government, as evidenced by the approval of the Decree-Law, 162/2019, which establishes the legal framework for the self-consumption of renewable energy and the constitution of energy communities, with potential positive spillover to the most vulnerable inhabitants through sharing surplus electricity generation. Furthermore, it is understood that the integration of renewables within the scope of, for example, Net Zero energy buildings is not profitable when it is performed building by building (Shehadi, 2020). Cost-effectiveness is much higher at district-scale interventions compared to individual buildings and should be explored moving forward to more ambitious renovation strategies.

The barriers that hinder the integration of PED solutions in historical city districts also affect the opportunities to tackle energy poverty. Although EU Directive sets minimum requirements of the energy performance of retrofitted buildings (European Parliament, 2012), legally protected buildings and buildings of historical interest are excluded from complying with energy efficiency requirements (Caro and Sendra, 2020). Therefore, a significant portion of the existing building stock is not covered by energy efficiency ambition (Dol and Haffner, 2010). Moreover, other practical reasons such as the heterogeneous geometry, peculiar materials, conservation strategies, and variety of protected elements (e.g., façades, indoor finishes) of listed buildings are not suited to standardized values and procedures that are usually used by the construction industry, adding complexity to retrofit plans (Caro and Sendra, 2020). As a consequence, residents in historic districts are potentially more vulnerable to energy poverty than residents in newly built districts, therefore confronted with the related health, economic, and climate change risks. However, most of the EE measures and RES technologies do not comply with the specific regulation in Alfama. In this study, only technical constraints (such as building orientation and rooftop surface availability) were taken into account. In future research, the trade-off between compliance with local heritage regulations and compliance with the building's thermal component should be evaluated, to enable effective large-scale renovations. With the increasing availability of smart meters in the country providing more details on energy consumption profiles, a wider analysis including other important PED components such as energy flexibility with smart controls, as highlighted in IEA (2020) and JPI Urban Europe (2021), should be conducted. This research shows the technical potential hidden in historic districts, aiming to disclose the necessary policy, social, and financial discussion around the role of historic districts in the energy transition of cities.

The viability and sustainability of the business model behind EE measures is the biggest identified barrier, being more difficult to overcome than the existing technical limitations. For instance, split incentives, lack of capital financing, high upfront investment, lack of information and awareness about the costs and benefits, difficulty in the decision-making process, and lack of expertise (Vogel et al., 2015; van Oorschot et al., 2016; Bertone et al., 2018; Bertoldi et al., 2020) are limiting the regeneration of historic districts. For RES implementation, intermittency of sources and uncertainty of market subsidies add to the factors driving out investors (European Commission, 2014). In Portugal, the lack of available capital for upfront investment, together with ineffective, mostly loan-based support schemes, is a relevant obstacle preventing homeowners from investing in their assets. The energy gap between the energy needs for thermal comfort and measured energy consumption in Portuguese homes, as demonstrated by Palma et al. (2019), represents an increased challenge for an investment opportunity, especially for EE measures, since the capital return gains linked to energy savings are reduced or inexistent.

Despite the recent trend of fast-decreasing costs of PV, which is expected to proceed in future years opening a window of opportunity for this type of building PV applications, the highlighted investment numbers will require an innovative financial scheme to support not only building owners but also tenants, as these are among the most vulnerable to energy poverty. We argue that the social benefits of the investment should be evaluated, including benefits on health costs, air quality, climate resilience, and productivity. The quantification of potential social co-benefits (e.g., reduction of energy poverty, community building, reduction of gentrification) from the adoption of the PED model could increase the ambition of the project and accelerate the implementation of these solutions in existing districts, and especially in historic districts, which usually present a more pressing need to solve the beforementioned social issues.

The European Commission through the Clean Energy for all Europeans Package (2019) brought a solid basis for renewable deployment and energy efficiency promotion, improving the regulatory structure and funding instruments, but the impact is still not enough, with renovation works only rarely addressing energy performance of buildings, and uptake of RES remains low (Arístegui, 2021).

In conclusion, the PED model is part of the pathway toward the goal of 100 climate neutral cities in Europe, which relate to the final goal of a climate-neutral Europe by 2050. The PED research field is at the beginning; however, it is important to include existing districts in the assessment, through analysis that covers the entire scale of the district, to achieve a relevant impact for a holistic and sustainable transformation. At the moment, the aspiration to be energy positive is difficult to reach in historic districts; however, high ambition is necessary to push research forward and enable to obtain a momentum of innovation and positive impacts. Moreover, historic districts generally have deep social problems and they play a relevant role in the European cultural landscape: deep demonstration projects that show the efficacy of the PED framework in historic districts could accelerate the energy transition in Europe and increase the value of sustainability.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JG: conceptualization, overall methodology, analysis of results, and writing—original draft preparation. JS: analysis of results and writing—original draft preparation. PP: writing—original draft preparation and support on energy efficiency analysis. HD: building energy efficiency retrofit methodology and analysis. HL: building solar PV methodology and analysis. GC: writing—original draft preparation. All authors have read and agreed to the published version of the manuscript.

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Capturing Multidimensional Energy Poverty in South America: A Comparative Study of Argentina, Brazil, Uruguay, and Paraguay

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Roughly 789 million people have no access to energy, and around 2.8 billion people lack access to clean cooking solutions according to the World Bank, and so we also find many people that cannot afford energy (reliable and clean) at the current prices. In the literature, accessibility, availability, and affordability are underlined as the key drivers of energy poverty. In South America, these aspects have not been studied in depth. This research is relevant because it provides a standardized, cross-country, and comparable analysis of multidimensional energy poverty in the region. The study of energy poverty is critical for the development and well-being of countries, especially in regions such as South America, where this issue can be affected by geographical, cultural, infrastructure, and/or socio-economic differences. In this study, we measured the magnitude of energy poverty in Argentina, Brazil, Uruguay, and Paraguay. This methodology is based on the analysis of energy poverty through a multidimensional approach, considering three parameters as drivers of energy poverty in the countries: accessibility, availability, and affordability. Through a two-step process, first, we calculate the Weighted Average Energy Poverty Index (WAEPI), based on three proposed scenarios (W_1, W_2, and W_3), and finally, through the Composite Energy Poverty Index (CEPI), we measure the existing gaps, based on the selected indicators, between the countries under study and the benchmark country. Additionally, we decided to focus our analysis on the country that has shown the highest level and gaps on multidimensional energy poverty in the region, as a case study to validate the results obtained through the chosen methodology. The results show that during the period of analysis (2000–2016), Paraguay has been the most energy-poor country among the countries under study, while Argentina has been the least energy-poor country. At the local level, we observed that, Paraguay, despite being one of the largest producers and exporters of clean hydroelectric energy in the region, still presents high levels of consumption of biomass or coal for cooking, while electricity only represents 17% of the total final energy consumption in the country (biomass and fossil fuels account for 83%). These results could lead the design of energy policies, projects, and programs to reduce the multidimensional energy poverty, nationally, also at the common platform: MERCOSUR. Finally, this study includes an analysis of policy implications and alternative solutions to eradicate energy poverty in the region.

Keywords: energy poverty, energy poverty index, South America, multidimensional energy poverty, WAEPI, CEPI, Paraguay

INTRODUCTION

The evolution of technology and the lifestyle of human beings resulted in energy becoming an unavoidable element for the prosperity and well-being of people and enterprises.

As mentioned by "Red de Pobreza Energética" [Red de Pobreza Energética (RedPE), 2018], energy allows people to satisfy two main types of energy needs: *fundamentals* and *basics*.

The fundamental energy needs include those related to human health and well-being, while the basic energy needs are linked to the minimum needs that are required to satisfy a minimum standard of life, considering the social, climate, geographic, economic, and socio-cultural characteristics of each community or territory under evaluation.

In this context, if these needs cannot be satisfied or if there is a lack of sufficient, reliable, and clean energy supply to satisfy those needs, we can consider it as a situation of energy poverty (Reddy, 2000; Access to Energy in Developing Countries, 2002; Crentsil et al., 2019).

The study of energy poverty has taken two main methodological approaches: unidimensional and multidimensional analysis (Nussbaumer et al., 2012). Independently of the method, three kinds of indicators are commonly used to evaluate energy poverty: *energy accessibility* (indicators related to the number or % of people who have access to final energy sources—electricity or fuels for cooking—to satisfy their needs), *energy affordability* (indicators related to the levels of final energy consumption), and *energy availability* (indicators related to the availability of primary energy sources in a given place) (Boardman, 1991; Hills, 2011; Moore, 2012; Bouzarovski and Petrova, 2015; Legendre and Ricci, 2015).

We observe an evolution in the analysis of energy poverty from international and multilateral institutions. Historically, at the beginning, the Millennium Development Goals (MDG)[1] proposed by the United Nations (UN) for the period 2000–2015 did not include energy poverty as one of the main challenges to be overcome by the humanity (Gwénaëlle et al., 2009; González-Eguino, 2015).

Nevertheless, from 2015 with the adoption of the 2030 Agenda and the commitment of the 193 UN country members, the 17 Sustainable Development Goals (SDG)[2] have been established, including the SDG7 that highlights the challenges of the energy sector, especially those related to grant the accessibility, affordability, and availability of clean and reliable energy.

In this context, the joint report from the World Bank and other agencies (IEA, IRENA, UNSD, World Bank, WHO, 2020) reports that, even though in the last decade relevant improvements have been accomplished worldwide, there still persist important challenges: 789 million people without access to electricity, 2.8 million people without access to clean energy for cooking, 82.3% share of total final energy consumption from non-renewable energy, and the need of improvements on energy efficiency from electronic apparels and buildings, in addition to the enormous gaps in the flux of investments to mobilize investments and innovation in clean energy sources in the least developed countries.

As underlined by the BID (2020), in Latin America and the Caribbean (LAC), important improvements have been accomplished in energy accessibility, but it represents only one of the drivers of energy poverty. Other issues, such as non-reliable and insufficient energy services, can also lead to the use of alternative energy sources that are usually less clean, more expensive, and unsafe.

Additionally, according to the BID (2016), the challenge of universal access to clean and modern energy remains, especially to satisfy cooking and warming needs. The authors estimate that in LAC, there are ∼22 million people that have no access to energy, observing more difficulties in Central America and the Caribbean.

Added to access to the energy variable, the relevance of the affordability and availability in the multidimensional analysis of energy poverty must also be underlined. Then, considering these three variables, in the literature, we can identify three main groups of energy poor (Khanna et al., 2019): people that have no access to energy but can afford it; people with access to energy but not affordable; and people who have neither access to energy nor enough income to afford it.

Most of the literature focused on analyzing energy poverty have been oriented to study the last group (no energy access nor affordability), principally in Sub-Saharan Africa, while the situation in LAC mainly concerns people with no access to energy (first group) or with affordability issues (second group).

The methodology we utilize is derived from the multidimensional energy poverty measures proposed by Khanna et al. (2019) and have been implemented for the case of South American countries (Argentina, Brazil, Uruguay, and Paraguay). This study has been made through a top-down approach, and it has the objective of presenting a wider vision of multidimensional energy poverty in the selected countries. This study provides a starting point for the analysis of energy

[1] Millennium Development Goals (MDG): https://www.un.org/millenniumgoals/
[2] Sustainable Development Goals (SDG): https://sustainabledevelopment.un.org/?menu=1300

poverty from a general perspective, but not limiting the analysis to the particular context of each country. The multidimensional measures offer a general perspective of the problem of energy poverty in the region, allowing the identification of the challenges of each country and the comparability of the results.

The main contribution of our research is the systematization of the process of measurement of energy poverty based on a multidimensional approach. Moreover, we offer a new perspective to the analysis of energy poverty in South America, through a cross-country, comparable, standardized, replicable, and proved methodology. Then, we also provided a complementary analysis, at the domestic level for Paraguay, which is the country that has shown greater energy poverty gaps in the region. We consider that this research is a valuable contribution to the analysis of energy poverty in the region, considering the reduced number of studies in this topic, as well as approaches considering the regional level or cross-country comparisons.

In section Literature Review, we find the literature review related to the different methods used to measure energy poverty and the conceptualization of energy poverty adopted by their authors.

Then, in section Methodology, we explain the methodology to measure multidimensional energy poverty, considering the limitations of the previously reviewed methods available.

In section Result, we present the results, describing the improvements, challenges, and gaps on energy poverty indicators for the four countries under study during the period of analysis (2000–2016), with a special focus in the three main energy indicators: access, affordability, and availability. Section Limitations highlights the research limitations.

Finally, in section Conclusions and Policy Implications, we present the conclusions and policy implications that should be considered.

LITERATURE REVIEW

The study of energy poverty had its origin in Europe, during the 90's, with the analysis mainly focused on fuel poverty as a problem of households to satisfy their needs of energy for heating. In this context, Boardman (1991) defines energy poverty as "*the inability to afford adequate warmth because of the inefficiency of the home*." The author analyzes energy affordability as a driver of energy poverty, arguing that poor households normally live in less thermally efficient and not well-insulated homes, spending a higher proportion of their incomes in heating (energy).

Next, from the 2000's, energy poverty literature started to grow as policymakers recognized its impact in the population's well-being, and consequently, the first methods and energy poverty indexes appeared.

Then, as mentioned by Nathan and Hari (2020), at the international level, it was not until 2002[3] that the International Energy Agency (IEA) measured energy poverty for the first time. In 2010, during the review of the MDG, the IEA, UNDP (United Nations Development Program), and UNIDO (United Nations Industrial Development Organization) published a joint product, redefining energy poverty and its elements (IEA, UNDP, and UNIDO, 2010).

Additionally, the UNGA (United Nations General Assembly), through the 65/151 Resolution, declared 2012 as the international year of "*Sustainable Energy for All*"[4], reinforcing its commitment that same year, declaring the period 2014–2024 as the "*Decade of Sustainable Energy for All*"[5].

Moreover, in 2015, energy has been officially included as one of the main challenges for humanity through the Sustainable Development Goals (SDG 7), considering energy indicators covering access, affordability, reliability, and efficiency.

The analysis of energy poverty has evolved in the last decades, passing from mainly unidimensional approaches (Boardman, 1991; Foster et al., 2000; Practical Action, 2012) focused on fuel poverty, to bidimensional or multidimensional approaches, recognizing energy poverty as something more than only the lack of income for energy or energy services (energy affordability).

For example, Nathan and Hari (2020) propose a method based on deprivation in modern cooking and lighting fuels to assess energy poverty in India. The methodology proposed in this study is limited to the access-based approach and it is only focused in urban areas in India; however, it allows the categorization of poor in three groups (extreme, moderate, and transitional energy poor) and the consideration of depth and severity of energy poverty. The results show that between the two selected variables, the access to modern cooking is a more fundamental need and a critical variable in the definition of energy poverty.

Then, Pachauri et al. (2004) propose a bidimensional measure of energy poverty and energy distribution, the so-called Energy Access Consumption Matrix (EACM), providing insightful information of the relation between energy poverty and changes in energy distribution for Indian households. The results show that higher levels of access to energy sources are often associated with higher levels of well-being and expenditure levels, and the evidence provided in the paper suggests that improvement and provision of energy services could be relevant drivers of the development of the countries.

In the last decade, energy poverty measures have also included methods based on the construction of indices, considering different variables such as energy use, lack of energy, household size, energy deprivation, energy service quality, and many others.

In this context, Mirza and Szirmai (2010), through the results of Energy Poverty Survey (EPS) conducted in Pakistan, have constructed the Energy Poverty Index (EPI), which considers variables such as energy use, energy shortfalls, and household size. According to Culver (2017), in comparison to other indexes, the EPI is very sensitive to energy poverty in cooking fuels, underlining the usability beyond access but limiting the analysis of the household's energy needs.

Furthermore, Nussbaumer et al. (2012) propose the Multidimensional Energy Poverty Index (MEPI), focusing

[3]World Energy Outlook Report (IEA, 2002).

[4]UN (2012): https://www.un.org/en/events/sustainableenergyforall/#:~:text=Sustainable%20Energy%20for%20All,-UN%20Home&text=Recognizing%20the%20importance%20of%20energy,of%20Sustainable%20Energy%20for%20All

[5]UN (2012): https://www.un.org/press/en/2012/ga11333.doc.htm

on the deprivation of access to modern energy services through the use of different variables including type of cooking fuel, cooking technology, electricity access, and the possession of other household appliances. The MEPI has been widely used in several studies, including developing and developed countries (Okushima, 2017; Sadath and Acharya, 2017; Santillán et al., 2020). However, the MEPI is often criticized because it does not include, because of the indicators used for the measurement of the index, the energy for productive uses and energy use beyond the household. Additionally, the energy variables are selected and classified in a top-down manner, which might not reflect local priorities and needs. In contrast, the MEPI has the advantage of focusing on energy services and energy deprivation, which allow capturing the incidence and the intensity of multidimensional energy poverty in countries.

Moreover, as mentioned by Khatib (2011), the IEA[6] has also developed an index to measure energy poverty, the so-called Energy Development Index (EDI), which relates energy to human development. The EDI considers the following variables: per capita commercial energy consumption, per capita electricity consumption in the residential sector, share of modern fuels in total residential sector energy use, and share of population with access to electricity. From a methodological perspective, we can observe that the EDI focuses on the energy system transition toward modern fuels, while the MEPI focuses explicitly on energy poverty (Nussbaumer et al., 2012). The EDI is often criticized because it does not consider how energy deprivation of households explains how the energy system is maturing (Culver, 2017).

Then, Bhatia and Angelou (2015) have proposed the Multi-tier Energy Access Method or Multi-Tier Framework (MTF), which considers a set of attributes to estimate the household's energy poverty, allowing the classification of households according to the levels of energy poverty intensities. The considered attributes include capacity (electricity consumption), duration (hours of electricity availability per day), reliability of electrical services, quality, affordability, legality, and health/safety. The core assumption of these methods is that energy service requires a certain level of energy quality, described through the different selected attributes. Additionally, the method received several critics, including the complexity of its implementation, the difficulty to access to reliable data in the different dimensions and attributes, the indefensible mathematic of the model, and the unintended implications of the methodology (Culver, 2017).

In recent years, some methods focused on energy affordability have emerged. For example, Teller-Elsberg et al. (2016) propose the Energy Burden (EB) indicator, which measures the extent and severity of fuel poverty, considering energy affordability variables (household's income and energy costs) as the drivers of fuel poverty. Some limitations of this study include not identifying, appropriately, households as fuel poor if the household fails to spend over the limit of 10% of its income on energy, and also counting households as fuel poor, even if the reason of spending above the limit of 10% is a result of trying to maintain their home at a higher temperature.

[6]International Energy Agency (2011).

More recently, Betto et al. (2020) have also proposed a method related to the energy affordability dimension, called Hidden Energy Poverty (hEP), which considers variables as energy efficiency of buildings, poverty situation, energy consumption and climate sensitivity. This method has been first used in Belgium and then later adopted by the European Commission's EU Energy Poverty Observatory (Bouzarovski et al., 2020). The study shows that policymakers, aiming to decrease the impact of hEP, should consider the heterogeneity of the different regions of the country (climate zones) and the proposal of social bonuses only for energy-poor households. Most of the critics on this method are based on the limited access to reliable data needed to implement it, such as energy efficiency of buildings and the identification of climate zones (at regional and provincial level).

Then, Herrero (2017) analyzes the existing methods for energy poverty measurement, highlights the limitations of unidimensional metrics, and advocates for the implementation of multidimensional approaches, which reduces biases and the risk of omitting alternative understandings of the nature and factors behind energy poverty. In the same vein, Pachauri and Spreng (2011), underline the need of widening the scope of metrics, the design of energy poverty indicators, and the evaluation of policies.

Finally, as mentioned by Culver (2017): "*There is no one metric for energy poverty because there is no single, universally-accepted understanding of what it is to be below the energy poverty line*." The author finds that energy poverty metrics can be classified into four main approaches: energy access [including the Energy Access Method (EAM)], energy inputs (including the EACM), outcomes of energy use, and quality of energy delivered (including the MTF).

Energy Poverty in Latin America

Poverty not only implies a low level of income but also encompasses many more dimensions. Addressing poverty from a multidimensional approach, where, for example, aspects of education, health, and quality of life standards can be addressed (including the access to electricity), allows a more comprehensive study of the deprivations and difficulties that the population experiences every day (Bronfman, 2014). Considering the aforementioned, Latin America is one of the richest regions in clean energy in the world.

In this sense, García Ochoa (2014) discusses the social aspects of the use of energy in Latin America and its impact on human development, sustaining that energy poverty is real issue and that it has implications in the field of economy, society, and environment. This directly affects the quality of life of the population. It is important to analyze the relationship between poverty and energy, which is the focus of analysis that must be considered for the creation of public policies in Latin American countries. This has been the starting point for the process of development of a conceptual and methodological framework for the study of energy poverty in the region.

In the last decade, studies related to energy poverty have increased in Latin America. The country case studies have taken various approaches over time. Groh (2014) carried out a study in Arequipa, Peru in which she obtained, as the main result, a close relationship between energy poverty, the isolation of communities, and the implications for people's development opportunities. This was achieved based on an analysis that included not only the classic income analysis but also the multidimensional approach and concepts of penalization for energy poverty that is based on the principle that people with less income suffer more the impact of expenses in energy. In this way, the discussion about the relationship between economic development and the quality of energy service in the low-income strata of the different countries began.

Additionally, Giannini Pereira et al. (2011) have studied the impact of economic and social policies, with a focus on the programs intended to expand the supply of energy to the most vulnerable people in Brazil. The authors have used a wide range of economic analytical indicators to analyze and define an energy poverty line for the case of Brazil. Then, they evaluated the efficiency of the policies implemented at the time in Brazil, finding that both energy poverty and energy inequality were reduced significantly.

In 2016, García Ochoa and Graizbord (2016a) proposed the method "*Meeting of Absolute Energy Needs*" (MAEN) as a metric of energy poverty in households, and Mexico was taken as a case study, where it was identified that ∼43% of Mexican households were classified under the condition of energy poverty. This method is based on the fact that, when people do not satisfy their absolute energy needs, which are related to a series of satisfiers and economic goods that are considered essential in a certain place and time, they present the condition of energy poverty.

Then, an energy poverty indicator has been estimated for households in urban regions of Argentina, in the period 2002–2018, based on the indicator of 10% (Expenses/Income). The main result was that, between 2002 and 2015, there was a sharp decrease in energy poverty, reaching levels of <1%. After 2015, there was a relevant increase in energy poverty in the country, reaching levels even higher than 15% of households (Durán and Condori, 2016). Additionally, in the study made by Jacinto et al. (2018), the authors found that for the northeastern region, which has the lowest electrification rates and does not yet have access to natural gas through the network, an alternative to maximize energy inclusion could be, in addition to increasing the electrification rates and the access to natural gas networks, combining distributed renewable energy with grid electricity or liquefied petroleum gas (LPG).

Several studies addressed the analysis of energy poverty at the subregional level. García Ochoa and Graizbord (2016b) presented a subregional analysis based on the method of "*Meeting of Absolute Energy Needs*" (MAEN) in Mexico. The main result was that 36.7% of Mexican households are in a situation of energy poverty. It was possible to show, among other variables, as the geographical factor is very important in this analysis, always highlighting the focus from the satisfaction of needs.

Other cases of subregional level studies are those of Argentina and Colombia (Durán and Condori, 2016; Hernández et al., 2018), in which they were addressed from a multidimensional approach, based on the work of Nussbaumer et al. (2012), both with local databases (with their respective difficulties of quality and data reliability). In both cases, it was possible to identify national subregions where energy poverty is experienced, especially in rural and isolated areas.

On the other hand, Villalobos Barría et al. (2019) analyzed the consequences of the use of different energy poverty metrics for the case of Chile. Consequently, the EPI was estimated based on the Boardman 10% rule, in addition to the use of MEPI. Based on local databases, both indices had similar results of energy poverty, although in subregional terms, there are discrepancies between the two methods, which are mainly explained by territorial factors. The main point of analysis was that the use of one or another indicator should not be used as a substitute but as a complement.

Quishpe et al. (2019), based on several indicators proposed by the European Union Energy Poverty Observatory (EPOV), used the MEPI to analyze the case of Ecuador. This was carried out taking into account local data, yielding a result that shows the presence of energy poverty in households in Ecuador.

Regarding a global and comparative analysis between Latin American countries, Santillán et al. (2020) recently carried out a study where the use of the MEPI is proposed. Seven Latin American countries were selected for this study (Mexico, Colombia, Dominican Republic, Guatemala, Haiti, Honduras, and Peru). The selection of the countries was not an easy task, mainly due to the lack of reliable information, considering that the ideal would be that all Latin American countries were analyzed for a clearer and more comprehensive vision. This selection of countries was mainly due to the availability of data that allowed the analysis, with some considerations and arrangements in the missing and discontinuous data of some of the selected countries.

The advances in energy poverty line have been quite important. For example, the MEPI of Nussbaumer et al. (2012) has been a tool successfully implemented in Africa and several Latin American countries; however, an element that has not been considered is thermal comfort. To achieve greater inclusion and design of more effective public development policies in the countries, it would be very important to consider thermal comfort and regional climatic aspects (Santillán et al., 2020). Another aspect that has been addressed by Amigo-Jorquera et al. (2019) is the relationship between energy poverty and gender inequality for the case of Chile.

Given that the study of energy poverty is growing in Latin America, the Organización Latinoamericana de Energía (OLADE) made a methodological proposal to develop a set of indicators that take into account approaches to social inequality and gender as conditioning elements for energy access and use. It represents a very interesting effort that would allow the evaluation of the degree of social inequality produced from the point of view of energy. It was possible to identify data sources and useful variables in several Latin American countries, which allowed a clear vision of the difficulties in terms of comparability between these variables, due to the high heterogeneity of the data (Rocha and Schuschny, 2018).

In the framework of the Latin American debate regarding Energy Poverty, Urquiza et al. (2019) address the different dimensions and approaches used for the analysis of energy poverty and present Chile as a sample case study that represents the case of developing countries. Despite the large number of definitions and indicators proposed for the study of energy poverty, most of which were originally intended for developed countries, these can underestimate or overestimate the real situation of energy poverty in Latin American countries (which are mostly they are under development). We must underline that we have presented only some of the most relevant studies on energy poverty for the region; however, we are not presenting a full literature review for each of the countries under study.

The great territorial, economic, and cultural heterogeneity existing in Latin America is a huge challenge for standardization and analysis metrics. Urquiza et al. (2019) propose a three-dimensional framework sensitive to different contexts that can be useful to assess energy poverty for different case studies. The discussions about energy poverty issues in the different Latin American countries continue, but there is still a long way to go.

METHODOLOGY

This paper aims to present an overview of energy poverty in selected South American countries with a multidimensional approach. To achieve this objective, a six-step structured methodology has been implemented.

1. Selection of Indicators
2. Country Selection
3. Selection of Data Sources
4. Data Normalization
5. Analysis of results
6. Validation of the Results

Next, each step carried out in the proposed methodology is presented in detail.

Selection of Indicators

The indicators selected in this work are based on the multidimensional metrics of energy poverty proposed by Khanna et al. (2019), who have measured energy poverty considering three main parameters: energy availability, energy access, and energy affordability. The main advantage of this approach is that the selected parameters represent relevant and quantifiable energy indicators, with a well-established, standardized, and internationally approved methodology for data collection and reporting.

TABLE 1 | Variables of analysis.

Parameters	Indicators	Sub-indicators
Accessibility	Access to electricity	% Population with Access to electricity
	Access to clean fuels and technologies for cooking	% Population with Access to clean fuels and technologies for cooking.
Availability	Total primary energy supply	Total primary energy supply per capita
Affordability	Total final energy consumption	Total final energy consumption per capita

Then, in **Table 1**, we identify the parameters, indicators, and sub-indicators for the analysis:

For the implementation of the metrics proposed by Khanna et al. (2019), and that were selected for this work, it must be structured in two main phases:

- Measure of the Weighted Average Energy Poverty Index (WAEPI).
- Measure of the Composite Energy Poverty Index (CEPI).

Weighted Average Energy Poverty Index

To measure the WAEPI, we need to define some scenarios for energy poverty analysis, which can be determined through the different weight sets (W_1, W_2, and W_3) assigned to the sub-indicators identified as relevant to evaluate multidimensional energy poverty. It is important to highlight that the assignment of the weight sets used for this study was carried out based on Khanna et al. (2019), and these are the initial assumptions for calculating the CEPI. These weight sets allow us to analyze potential scenarios in Latin America and establish reference scenarios for methodological comparability of the results obtained in the different countries and regions.

In **Table 2**, we can observe the three scenarios (W_1, W_2, and W_3) that will be analyzed in this study. Next, we describe each scenario and the hypothesis assumed in each case.

In scenario 1 with the weight set W_1, only the energy access variables have been considered. In this scenario, energy poverty is evaluated through a unidimensional approach, where energy poverty explained exclusively as an issue related to energy access. Historically, this approach has been widely used by international organizations [International Energy Agency (IEA), 2011, 2017; Culver, 2017] through the EAM.

This method has the advantages of a relatively easy implementation and access to standardized and fully available data, but fails to incorporate other indicators (availability and affordability) in the analysis of an eminently multidimensional issue.

In scenario 2 with the weight set W_2, we change to a multidimensional approach for the analysis of energy poverty, assuming the hypothesis that the four indicators corresponding to the three mentioned dimensions analyzed in this paper (availability, access, and affordability) have an equal, proportional, and relevant role in explaining energy poverty.

Finally, in scenario 3 with weight set W_3, we continue with the multidimensional approach for the analysis of energy poverty, but in this case, a greater weight is given to energy access variables (40% each), assuming the hypothesis that this indicator plays a greater role determining multidimensional energy poverty. The availability and affordability indicators are included in the analysis with an equal and proportional weight of 10% each, playing a secondary role as explicative variable of energy poverty.

We must underline that, as stated by Nussbaumer et al. (2012), even though the issue of weights has been in the center of the debate in the analysis of the different energy poverty indices and considering that the different authors assign these weight sets, either explicitly or implicitly, the arbitrary nature of those and the need to adjust the weighting sets depending on the analysis and/or the context must be recognized.

According to Khanna et al. (2019), the WAEPI can be expressed as follows:

$$\begin{aligned} \text{WAEPI}_{\text{x,year}} = \ & \Sigma\,(W_1 * \text{Access to electricity}_{\text{n}} \\ & + \text{W}_2 * \text{Access to modern fuels}_{\text{n}} \\ & + \text{W}_3 * \text{TFEC px}_{\text{n}} + \text{W}_4 * \text{TPES px}_{\text{n}} \end{aligned}$$

Where:
x = Country
n = Normalized Indicator.

The WAEPI measures the level of fulfillment of the energy needs of the population of a country x, considering the three drivers of energy poverty previously identified: access, affordability, and availability.

As mentioned before, energy poverty is a challenge that requires an analysis from different approaches and scenarios, taking into account the characteristics of the population under study. Those different scenarios (including availability, access, and affordability) are shown in **Figure 1**.

From **Figure 1**, we observe that most of the literature on energy poverty have been oriented to the left branch of this energy poverty scenario analysis schema, where we assume no difficulties on energy availability, but limitations on energy access and/or energy affordability.

For this study, the selected South American countries follow that reasoning, considering that at the present, energy availability is not a main problem in those countries, but the challenge is clearly focused on energy access and energy affordability, especially in rural areas and isolated communities.

The diagram in **Figure 1** is a proposal made in order to systematize the multidimensional analysis of energy poverty at the regional, national, or subregional level. It can represent a basic guide to analyze the different case studies that can be addressed in the future.

Composite Energy Poverty Index

The CEPI, which uses the WAEPI results as an input, considers the four sub-indicators as well, which are mentioned in **Table 1**. The CEPI measures the existing gaps (in terms of energy poverty indicators), comparing the situation of a country x in the period of time y, with the baseline from the reference country (EEUU), functioning as a benchmark.

According to Khanna et al. (2019), the CEPI can be expressed as follows:

$$CEPI_x = 100 - WAEPI_{x,y}$$

Where:
x = Country
y = Year of analysis.

Country Selection

The process of selecting countries, in studies as proposed here, is not an easy task, and it would have been ideal to carry out a study for all the countries in South America, but this process is limited both by the availability of data and by the specificities of each country in the region. Santillán et al. (2020) recommend that the selection of countries, for this type of studies, should be based on shared common characteristics (social, energy, economic, etc.).

Within the framework of this study, we have decided to evaluate multidimensional energy poverty in a group of four South American countries: Argentina, Brazil, Uruguay, and Paraguay. These selected countries are members of the *Mercado Común del Sur*[7] (MERCOSUR) and represent an interesting starting point for a future general analysis of all South American countries. This is also due to the fact that the Rio de la Plata area (Argentina, Paraguay, and Uruguay) and the Paraná-Paraguay basin (Argentina, Brazil, and Paraguay) present very similar social, cultural, and energy conditions.

MERCOSUR (a multilateral economic agreement with more than 30 years of life, initiated between the four countries mentioned, and currently with associated countries such as Bolivia, Venezuela, and Chile) provides one of the most solid bases of economic integration in Latin America that can be used for the analysis, discussion, proposal, and implementation of regional development policies in various areas.

It is important to highlight that, among the four selected countries, there are very close and practically indivisible energy relations. Brazil and Argentina represent a large portion of the South American continent and with the highest population density and therefore require greater energy resources to meet the needs of their inhabitants. Paraguay and Uruguay, both smaller, in terms of territory and population, are linked to their neighbors not only by proximity but also economically and energetically

[7]Southern Common Market official website: https://www.mercosur.int/

TABLE 2 | Weight sets for WAEPI scenarios.

Indicators	Sub-indicators	W_1	W_2	W_3*
Access to electricity	% Population with Access to electricity %	0.5	0.25	0.4
Access to clean fuels and technologies for cooking	Population with Access to clean fuels and technologies for cooking.	0.5	0.25	0.4
Total primary energy supply	Total primary energy supply per capita	0	0.25	0.1
Total final energy consumption	Total final energy consumption per capita	0	0.25	0.1

A sensitivity analysis could be applied to evaluate the different results that could be obtained according to different criteria.

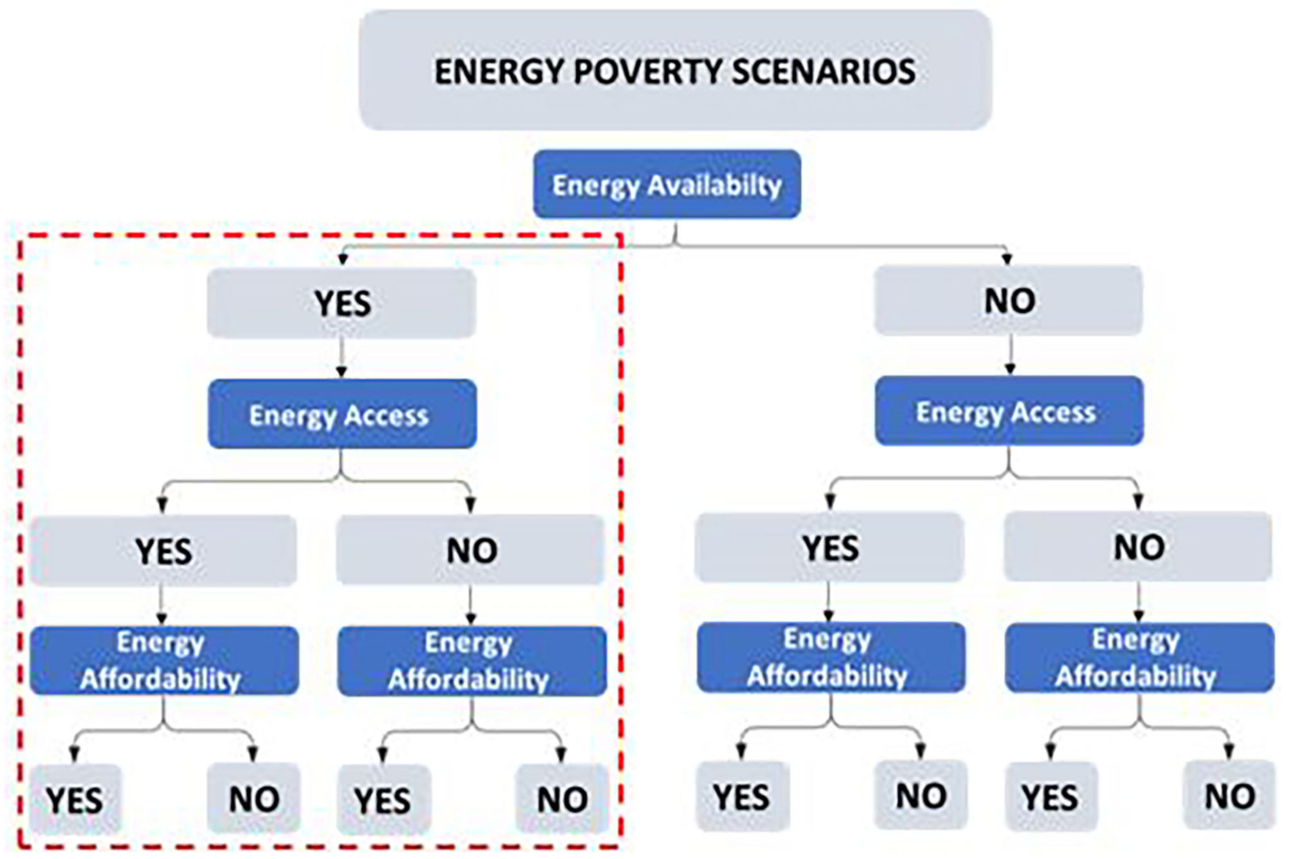


FIGURE 1 | Energy poverty scenario analysis.

and present a higher probability of satisfying the energy needs of their population.

The selected countries present, in terms of multidimensional energy poverty, similar difficulties and challenges, being an interesting case study to evaluate national and regional measures and policies that could be implemented to improve the well-being of the most vulnerable people (Durán and Condori, 2016; Contreras, 2019; Dehays and Schuschny, 2019; Santillán et al., 2020).

It is important to highlight the efforts to study, analyze, and start the debate on energy poverty in the selected countries. No reference on energy poverty could be found in the social and energy policy of the countries under study. For these reasons, it is urgent to address the problem in the simplest, most traceable, and flexible way possible.

The approach proposed by Khanna et al. (2019) presents an interesting methodological perspective to carry out a multidimensional and comparative analysis of energy poverty in the region. Then, to implement this methodology, it is necessary to use a regional benchmark (some Latin American country that presents a good performance in the area) or an international benchmark outside the region.

In this sense, we have considered the United States as the reference country for methodological purposes, serving as a reference to measure the gaps between an ideal scenario (baseline = 100) on the selected energy indicators and the real situation of the South American countries. We are aware that we could have taken the option of using other countries in the region, such as Chile or Mexico, but we decided to take the United States as a reference due to its high performance in the indicators of the different dimensions.

Through this process, we can obtain a clear vision of the regional situation, given the standardized and relatively reliable available data used in the CEPI and WAEPI metrics at the national level.

Selection of Data Sources

Database

The data used in this study come from different secondary data sources that are detailed in **Table 3**. These data have been compiled from publicly available databases from international organizations such as the World Bank (WB) and the IEA.

This research analyzes the data from the period 2000–2016, considering the previously identified parameters and indicators explaining multidimensional energy poverty.

Additionally, it must be underlined that we have also adopted the definitions of the parameters and indicators provided by the

TABLE 3 | Data sources for energy poverty indicators.

Indicators	Sub-indicators	Source
Access to electricity	% Population with Access to electricity	https://data.worldbank.org/
Access to clean fuels and technologies for cooking	% Population with Access to clean fuels and technologies for cooking.	https://data.worldbank.org/
Total primary energy supply	Total primary energy supply per capita	https://www.iea.org/data-and-statistics
Total final energy consumption	Total final energy consumption per capita	https://www.iea.org/data-and-statistics

international organizations (WB and IEA) in charge of updating the above-mentioned databases.

Data Normalization

In section Selection of Indicators, we identified the selected indicators and sub-indicators for the analysis of multidimensional energy poverty for this study, describing different types of information, expressed in different units (%, MJ, etc.). In order to study the data and drawing conclusions, these variables should be expressed in a common footing, so we proceed to the data normalization as expressed in the following formula:

$$x = \left(\frac{x_{c,n}}{x_{EEUU,\, n}}\right) * 100$$

x: normalized score of an Energy Poverty Indicator for a specific indicator.

$x_{c,n}$: score of an Energy Poverty Indicator for a specific indicator n in country c.

$x_{eeuu,n}$: score of an Energy Poverty Indicator for a specific indicator n in EEUU (reference country).

The data normalization consists, as mentioned by Khanna et al. (2019), in "*restructuring of a relational database in accordance with a series of so-called normal forms to reduce data redundancy and improve data integrity.*"

Assuming the reference country (EEUU) as the baseline for all variables (**Table 4**), the following interpretation rules should be considered:

- Indicator values greater than the baseline (100) upon normalization reflect a better performance than the reference country.
- Indicator values lower than the baseline (100) upon normalization reflect a performance worse than the reference country.
- This interpretation rule does not apply to the variable "Energy Use per $1000 GDP," where the reasoning is inverse (+ energy use, − energy efficiency).

In this study, we decided to make an analysis for four specific points during the period of analysis (2000–2016). This extensive analysis gives us a wider vision of the evolution of the performance of the countries in the different indicators and sub-indicators related to the multidimensional energy poverty.

The normalized data for the countries under analysis are presented in Appendix 2, specifying the results for each selected year (2000, 2006, 2012, and 2016). Additionally, in Appendix 1, we offer the data, as originally compiled from the different databases.

Analysis of Results

The metrics were implemented by calculating the CEPI for each of the selected countries and subsequently analyzing the results in detail for each of the cases studied.

Validation of the Results

As a way to validate the results obtained with the implementation of the CEPI, an analysis of energy poverty at the domestic level was carried out for the case of the country with the lowest performance according to CEPI.

RESULTS

CEPI Results

In **Figure 2**, we observe the results of the CEPI (W_1, W_2, and W_3) for the four countries under analysis. The results provide many insightful details that can be described as follows:

- Analyzing energy poverty from a unidimensional perspective, and only considering the energy access indicator (CEPI-W_1), we observe that Argentina and Uruguay have had positive and consistent results during all the periods of analysis (2000–2016). Brazil, at the beginning of the period of analysis (2000), showed greater gaps in terms of energy access, but important improvement in the following periods of analysis can be observed, reducing energy poverty by almost 75% in the same period of analysis. Then, Paraguay has shown the worst performance, with energy poverty levels almost 11 times greater than Uruguay in the year 2000. During the period 2000–2016, Paraguay reduced energy poverty by ∼46%, but the gaps in comparison with its neighbors remains, showing an energy poverty level 21 times greater than Argentina in the last period of analysis (2016). This approach could underestimate energy poverty levels, as it only considers one aspect of the problem.
- From the multidimensional perspective of energy poverty, assuming equal weights for the four indicators of the analyzed dimensions of energy poverty, accessibility, availability, and affordability (CEPI-W_2), we again find Paraguay as the most energy-poor country in the analysis, showing the worst performance during the period 2000–2016, and has only reduced energy poverty by 11% in the same period of time. Argentina presents again one of the best performances in the region, but the improvements are more modest in comparison with the previous scenario. Then, Brazil and Uruguay show remarkably similar results during the period of analysis, with

TABLE 4 | Energy indicators data – EEUU (2000, 2006, 2012, 2016).

			EEUU			
N°	**Indicator**	**Unit**	**2000**	**2006**	**2012**	**2016**
1	Access to electricity, urban population	%	100	100	100	100
2	Access to electricity, rural population	%	100	100	100	100
3	Total population with access to electricity	%	100	100	100	100
4	Access to clean fuels and technologies for cooking	%	100	100	100	100
5	Total primary energy supply per capita (TPESpc)	toe/capita	8.1	7.7	6.8	6.7
6	Total final energy consumption per capita (TFECpc)	(kg of oil equivalent)	5,480	5,224	4,608	4,697
7	Energy intensity	MJ/$2011 PPP GDP	7.34	6.37	5.69	5.41
8	Electric power consumption per capita (Kwh)	KWh	13,671.05	13,583.27	12,964.33	12,993.96
9	Fossil fuel energy consumption	%	85.88	85.63	83.44	82.43
10	Energy use	(kg of oil equivalent) per $1000 GDP (constant 2011 PPP)	176.45	152.62	135.73	127.92

Source: Compiled from https://datos.bancomundial.org/; https://www.iea.org/data-and-statistics.

very small reductions of energy poverty in the same period of time, with Uruguay being more consistent and Brazil showing a stagnation in the improvement since 2012. In this scenario, closer gaps between countries and greater levels of energy poverty in the region can be observed.

- In the last scenario (CEPI-W_3), the same trend as in the previous scenarios remains, with Paraguay having the worst performance and a greater level of energy poverty in the region, while Argentina consolidates its position as the least energy-poor country.
- Despite the limited analysis of the three proposed scenarios, we observed from the results that energy accessibility is not the main problem in the region, as shown in the results for scenario W_1 (excepting Paraguay). Nevertheless, when including energy affordability and energy availability, energy poverty gaps tend to increase, worsening the results of the CEPI for scenarios W_2 and W_3. Additionally, we note scenario W_2 as a baseline for the analysis of multidimensional energy poverty, from which we could start a sensitivity analysis including different weight sets according to the context of each country.
- Considering these results, we decided to analyze the case of Paraguay at the city level, in order to improve our understanding of the causes of its performances in the different indicators used to measure energy poverty gaps in this study (see section Energy Poverty at the city level: Paraguay).

CEPI Results—Country Analysis

Argentina

Access to Electricity and Other Modern Energy Sources

Argentina shows an optimal result in electricity access, having access to electricity rates nearly 100% at the national level. Nevertheless, there are still gaps to be filled in terms of access to modern and clean energy for cooking (see **Figure 3**).

Consumption of Modern Energy Sources

A high level of consumption of fossil fuels, aligned with the position of the country as a producer of oil and gas, and its recent role as one of the biggest players on the production of shale gas through the exploitation of the Neuquén basin, known as Vaca Muerta, can be observed. Additionally, the energy consumption per 1000 US$ GDP represents ∼84% in comparison to the reference country (EEUU) for the last period of analysis (2016) (see **Figure 3**).

Energy Supply

The total primary energy supply per capita is much lower than the reference country. Nonetheless, it must be underlined that the country has a very diversified supply of energy, including nuclear energy (1.107 MW)[8], an interesting mix of renewable energy sources (stimulated through the RenovAR program[9]), hydraulic energy [representing 33% (11.170 MW) of the installed capacity of the country for electricity generation][10], other thermal energy sources, and fossil fuels (see **Figure 3**).

Overall Situation

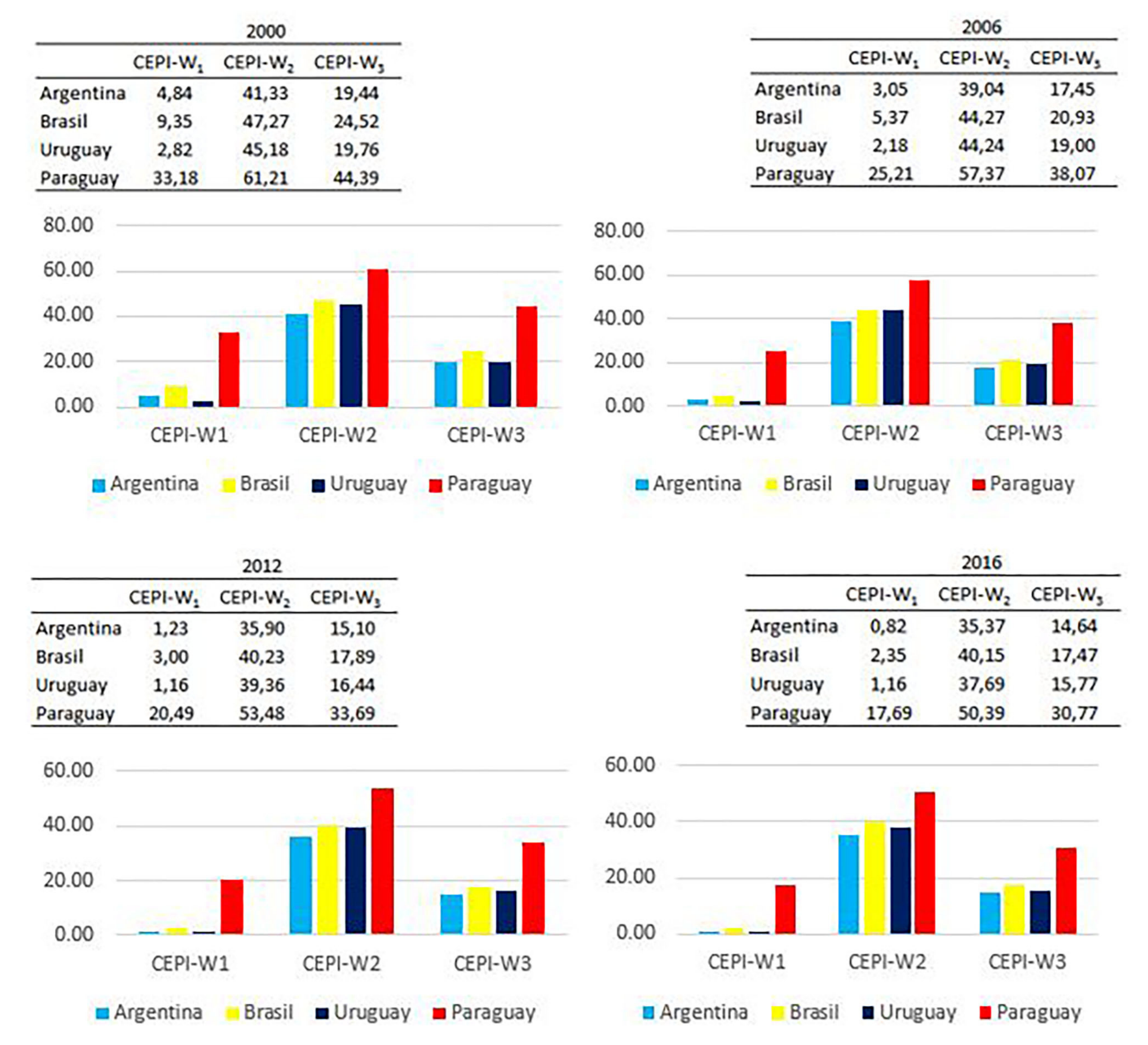
Argentina is the country with the best performance in almost every scenario (W_1, W_2, and W_3) of multidimensional energy poverty evaluated in this study, considering the three indicators (energy access, energy availability, and energy affordability) guiding this holistic approach.

Moreover, Argentina has shown sustained and positive results throughout the period of analysis (2000–2016), especially in the electricity access rates that had a notorious growth in rural areas in the last decades (see **Figure 4**).

[8]Argentina's Ministry of Energy: https://www.argentina.gob.ar/produccion/energia/electrica/nuclear/centrales

[9]RenovAR Program: https://www.argentina.gob.ar/energia/energia-electrica/renovables/renovar

[10]Argentina's Ministry of Energy: https://www.argentina.gob.ar/energia/energia-electrica/hidroelectrica/hidroelectricidad-en-argentina-y-en-el-mundo



2000	CEPI-W_1	CEPI-W_2	CEPI-W_3
Argentina	4,84	41,33	19,44
Brasil	9,35	47,27	24,52
Uruguay	2,82	45,18	19,76
Paraguay	33,18	61,21	44,39

2006	CEPI-W_1	CEPI-W_2	CEPI-W_3
Argentina	3,05	39,04	17,45
Brasil	5,37	44,27	20,93
Uruguay	2,18	44,24	19,00
Paraguay	25,21	57,37	38,07

2012	CEPI-W_1	CEPI-W_2	CEPI-W_3
Argentina	1,23	35,90	15,10
Brasil	3,00	40,23	17,89
Uruguay	1,16	39,36	16,44
Paraguay	20,49	53,48	33,69

2016	CEPI-W_1	CEPI-W_2	CEPI-W_3
Argentina	0,82	35,37	14,64
Brasil	2,35	40,15	17,47
Uruguay	1,16	37,69	15,77
Paraguay	17,69	50,39	30,77

FIGURE 2 | CEPI (2000, 2006, 2012, 2016)—Scenarios W1, W2 and W3.

Brazil

Access to Electricity and Other Modern Energy Sources

Brazil shows high levels of electricity access rates, both in rural and in urban areas, achieving almost 100% electricity access rates at the national level. Nevertheless, there still exists a small gap to be closed in terms of energy access in rural areas (including isolated and indigenous communities), where access to modern and clean energy sources for cooking and heating should also be improved (see **Figure 5**).

Consumption of Modern Energy Sources

There is a relatively high consumption of fossil fuels in comparison with the reference country. The country has important oil and gas deposits (onshore and offshore), some of which are being exploited and others are auctioned.

The energy consumption per 1000 US$ GDP is ∼76% of the consumption of the reference country. Despite being one of the greatest producers of hydroelectric energy in the world, Brazil shows a notoriously low electricity consumption per capita, as well as final energy consumption per capita, in comparison to the reference country (see **Figure 5**).

Energy Supply

The total final energy supply per capita is 21% in comparison to the baseline of the reference country. It must be underlined that with a growing population, having the seventh largest megacity

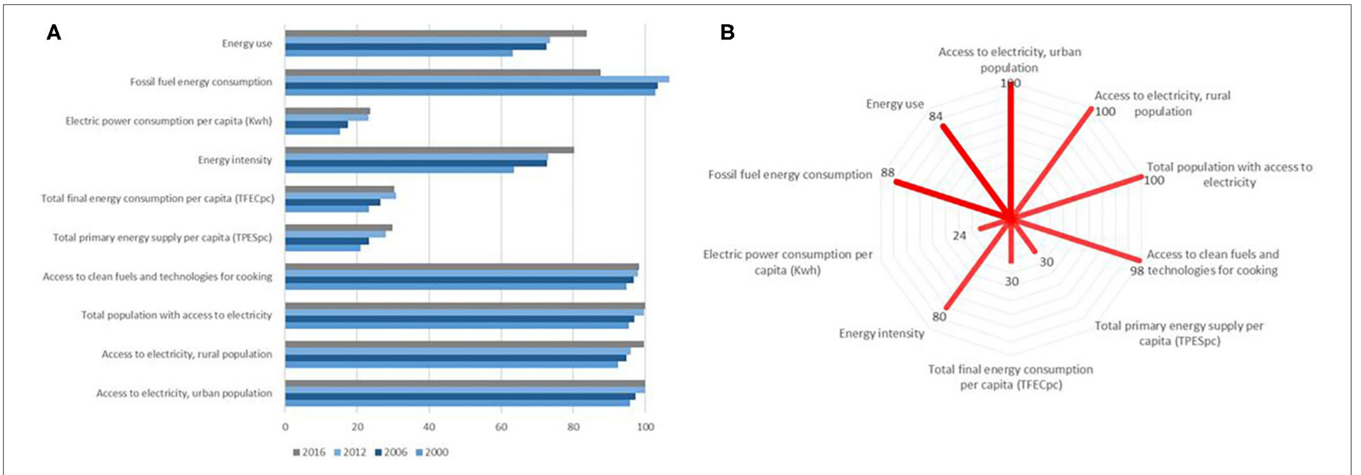


FIGURE 3 | Energy indicators (normalized)—Argentina (2000, 2006, 2012, 2016).

ARGENTINA

	CEPI-W_1	CEPI-W_2	CEPI-W_3
2000	4,84	41,33	19,44
2006	3,05	39,04	17,45
2012	1,23	35,90	15,10
2016	0,82	35,37	15,10

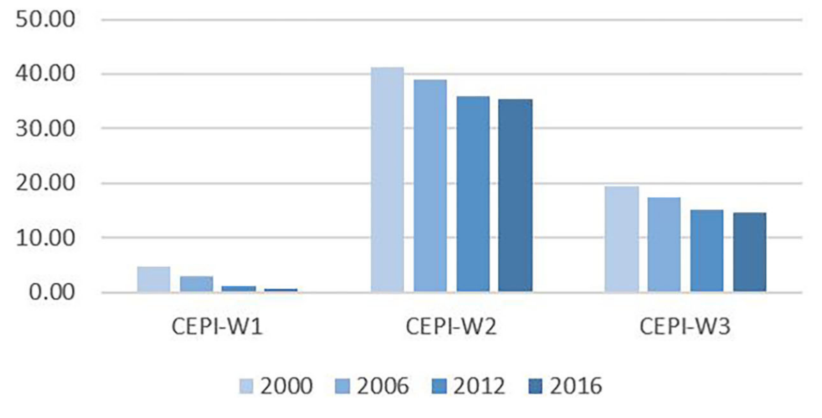


FIGURE 4 | CEPI — Argentina (2000, 2006, 2012, 2016).

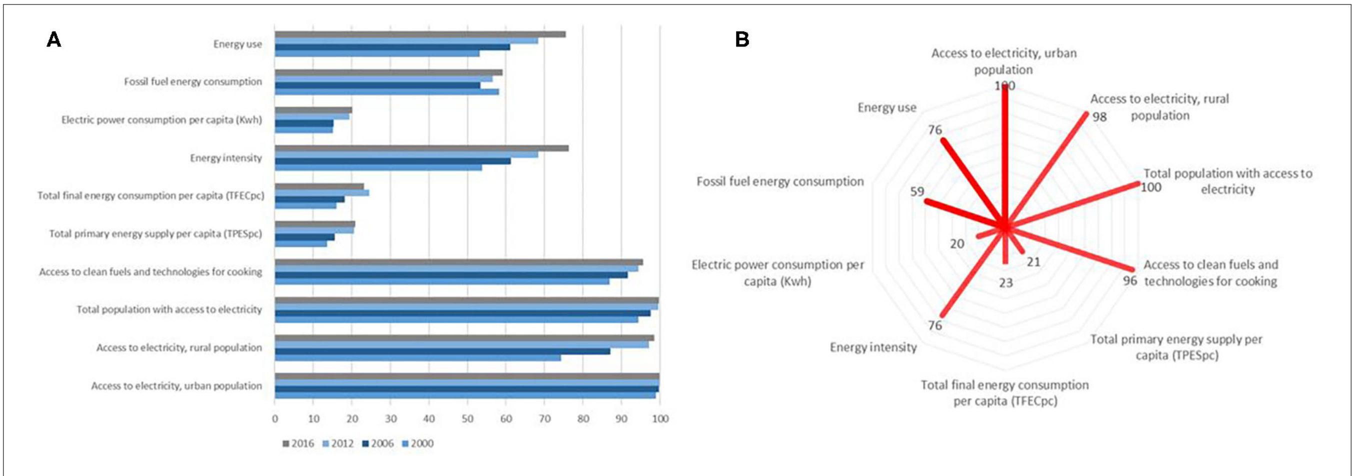


FIGURE 5 | Energy indicators (normalized) — Brazil (2000, 2006, 2012, 2016).

BRASIL			
	CEPI-W$_1$	CEPI-W$_2$	CEPI-W$_3$
2000	9,35	47,27	24,52
2006	5,37	44,27	20,93
2012	3,00	40,23	17,89
2016	2,35	40,15	17,47

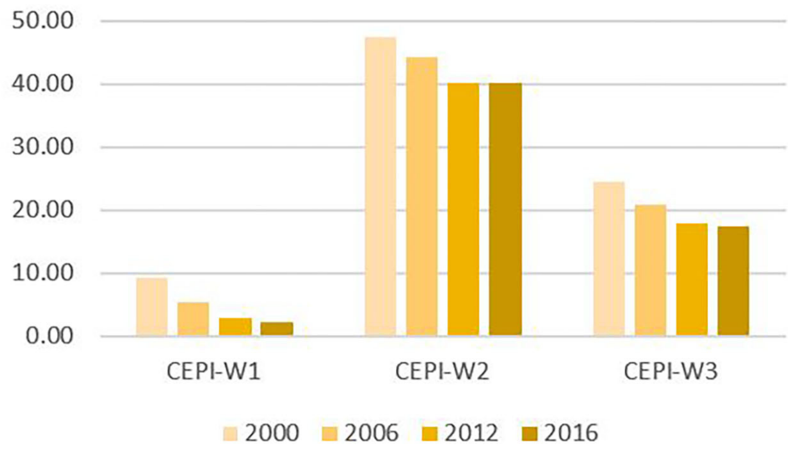


FIGURE 6 | CEPI — Brazil (2000, 2006, 2012, 2016).

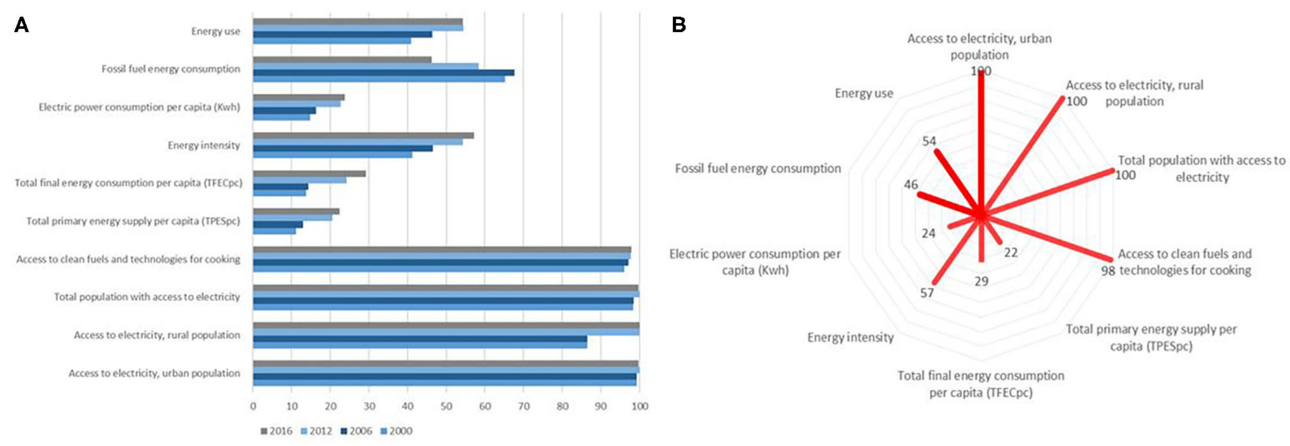


FIGURE 7 | Energy indicators (normalized) — Uruguay (2000, 2006, 2012, 2016).

URUGUAY			
	CEPI-W$_1$	CEPI-W$_2$	CEPI-W$_3$
2000	2,82	45,18	19,76
2006	2,18	44,24	19,00
2012	1,16	39,36	16,44
2016	1,16	37,69	15,77

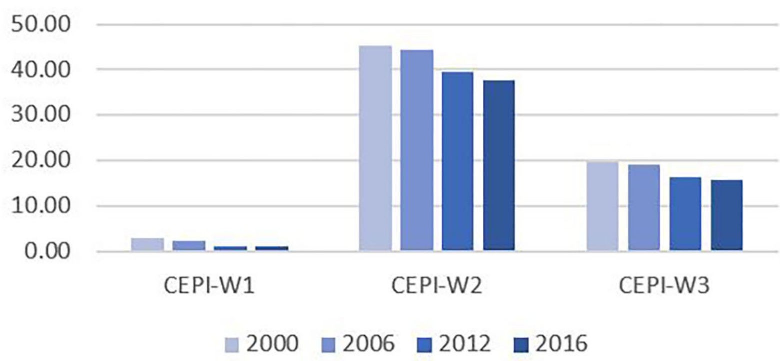


FIGURE 8 | CEPI — Uruguay (2000, 2006, 2012, 2016).

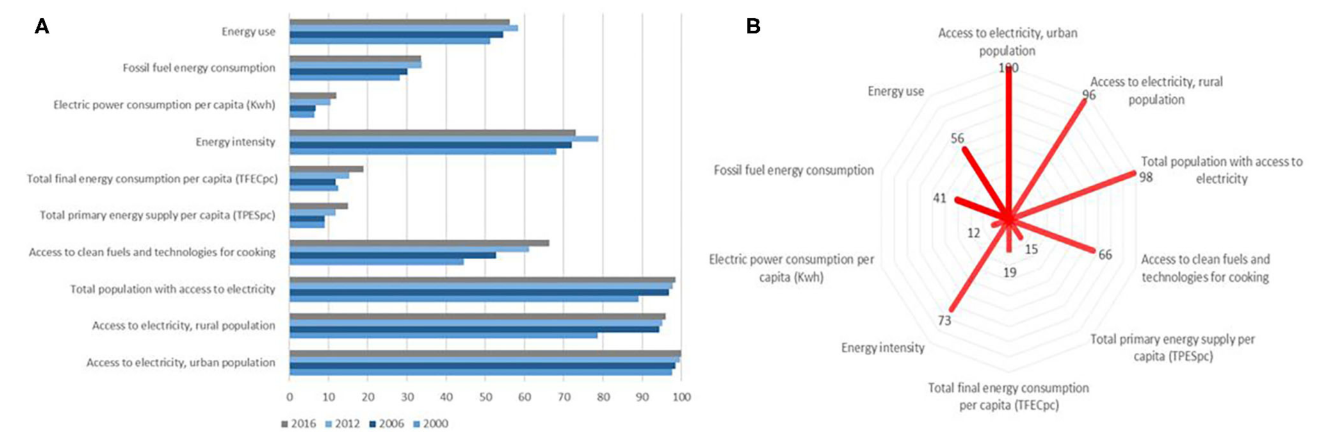


FIGURE 9 | Energy indicators (normalized) — Paraguay (2000, 2006, 2012, 2016).

PARAGUAY	CEPI-W$_1$	CEPI-W$_2$	CEPI-W$_3$
2000	33,18	61,21	44,39
2006	25,21	57,37	38,07
2012	20,49	53,48	33,69
2016	17,69	50,39	30,77

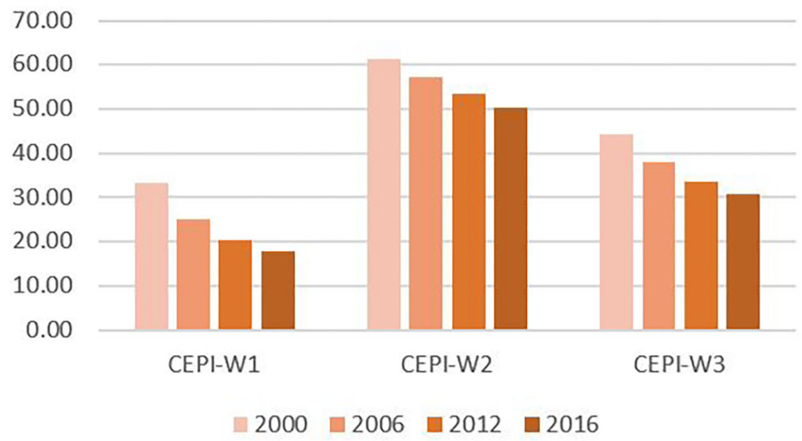


FIGURE 10 | CEPI — Paraguay (2000, 2006, 2012, 2016).

of the world (i.e., São Paulo[11]), and a high population density in slums (i.e., favelas), Brazil needs to increase its energy supply, capable of providing sufficient and reliable energy services to the people (see **Figure 5**).

Overall Situation

Brazil is a country that has achieved a remarkable improvement in electricity access rates in rural areas, with a steady and fast improvement during the period of analysis (2000–2016). These results are also reflected in the CEPI results, especially in the scenario CEPI-W$_1$.

Nevertheless, when the energy availability and energy affordability variables are included, we observe that during 2012 and 2016, there was almost no improvement in the reduction of energy poverty in the country (see **Figure 6**).

[11]Demographia World Urban Areas (2020): https://www.newgeography.com/content/006693-demographia-world-urban-areas-2020-tokyo-lead-diminishing

Uruguay

Access to Electricity and Other Modern Energy Sources

Access to electricity rates in Uruguay has grown rapidly in the last decade, especially in the rural areas, which closed the gap between urban and rural areas and helped the country in accomplishing an almost 100% electricity access rate at the national level. On the other hand, we observe some difficulties with access to modern and clean energy for cooking, as many of the South American countries under analysis (see **Figure 7**).

Consumption of Modern Energy Sources

Uruguay has shown a remarkable reduction in the consumption of fossil fuels, a situation that can be explained by the strategy of the country, focused on renewable energy. In the period 2000–2016, Uruguay has invested ∼US$ 7.800 million in electric infrastructure, and in 2018, the breakdown of its electric energy generation is as follows: 38% wind energy, 3% solar energy, 7% biomass, <3% thermal energy sources, and almost 50%

hydroelectric energy[12]. Despite the favorable context described before, there are still gaps to be filled in the access to clean energy for cooking (see **Figure 7**).

Energy Supply

Uruguay has remarkably improved its energy supply in the last decade, diversifying its sources of energy generation since 2013, increasing investments on renewable energies and specially in wind energy, which at the present is the second largest contributor in the generation of electric energy at the national level[13] Furthermore, the country continues to invest in several projects and programs to improve energy efficiency (Project Movés—Sustainable and Efficient Urban Mobility), circular economy for energy generation (Circular Opportunities Program and BioValor Program), and many others (see **Figure 7**).

Overall Situation

Uruguay shows one of the best and more consistent performances throughout the period of analysis, having accomplished important improvements in energy affordability and energy availability indicators. The country had successfully leveraged investments in the energy sector to accelerate the penetration of renewable energies, reducing their dependence in fossil fuels and mitigating the impact of multidimensional energy poverty (see **Figure 8**).

Paraguay

Access to Electricity and Other Modern Energy Sources

Paraguay has high electrification rates at the national level, but they are lower than those of its regional neighbors, showing important gaps in electricity access in rural areas and isolated communities. Moreover, only 2/3 of the population has access to modern and clean energy for cooking, with moderate improvements in the last 20 years (see **Figure 9**).

Consumption of Modern Energy Sources

Paraguay imports all the oil and gas consumed nationally for energy uses, which should be regarded as an energy security issue.

Despite being one of the largest producers of hydroelectric energy through binational projects with Brazil (Itaipú Binacional) and Argentina (Entidad Binacional Yacyreta), high rates of non-certified biomass consumption can be observed.

Furthermore, the electric power consumption per capita is lower than that observed in the region and the country has low industrialization rates, enabling it to export its hydroelectric surplus to its neighbors at lower prices than the market price (see **Figure 9**)[14].

Energy Supply

The total primary energy supply per capita is the lowest among the countries under study in comparison with the baseline of the reference country. Even so, Paraguay is one of the largest producers of hydroelectric energy per capita in the world and one of the largest exporters of electricity in the region (43.564.247 MWh in 2017)[15].

Nevertheless, the country still has problems to achieve the full use of its available energy, having low levels of industrialization rates, lack of sufficient investments in transmission and distribution infrastructure for electric energy, and low quality and reliability of the energy services (BID, 2020).

Moreover, the country shows a relatively important dependence on fossil fuels (representing 40% of total final energy consumption), which are fully imported in the international market. Additionally, an important role of biomass on the energy mix of the country can be observed, representing 36% of the country's energy supply and 43% of the total final energy consumption [Vice-Ministerio de Minas y Energía (VMME), 2020].

Nevertheless, the extremely high rates of deforestation in the Gran Chaco and particularly in Paraguay must be underlined, where the forest lost nearly 44,000 km^2 in the 1987–2012 period (see **Figure 9**)[16].

Overall Situation

Paraguay has accomplished an important improvement in electricity access rate at the national level, but the gap in rural areas and isolated communities remains, a situation that should be addressed to effectively reduce energy poverty.

Additionally, the country has two main challenges: increasing access to clean and modern energy for cooking rates (especially in rural areas) and reducing its dependence on imported fossil fuels, improving the use of its own and available hydroelectricity in the final energy consumption.

Finally, Paraguay shows the highest levels of energy poverty, in all the scenarios (CEPI-W_1, CEPI-W_2 y CEPI-W_3), among the evaluated countries (see **Figure 10**).

Energy Poverty at the City Level: Paraguay

From previous results, we found that Paraguay has the highest level of energy poverty, facing important challenges in the near future. Taking a closer look at the case of Paraguay, in the analysis of cities and departments, we observe that energy poverty is not a problem of energy availability (electricity and biomass) or electricity access, but an issue of energy affordability and access to technologies and cleaner sources of energy for cooking, which should be considered a priority, in order to reduce multidimensional energy poverty at the national level.

In **Table 5**, we observe high rates of electricity access in Asunción (capital of the country) and the main departments of Paraguay, but analyzing the energy used for cooking, only Asunción has <10% of its population using biomass or coal for

[12]Promoción de Inversión, Exportación e Imagen País (Uruguay): https://www.uruguayxxi.gub.uy/es/noticias/articulo/uruguay-lider-en-energias-renovables/#:$\sim$:text=URUGUAY%2C%20L%C3%8DDER%20EN%20ENERG%C3%8DAS%20RENOVABLES&text=En%202018%20el%2038%25%20de,%2Dcasi%20la%20mitad%2D%20hidroel%C3%A9ctrica

[13]Uruguay's Ministry of Industry, Energy and Mining: https://ben.miem.gub.uy/oferta3.html

[14]The Itaipu's and Yacyreta's treaties oblige Paraguay to sell (cede) its energy surplus to each country from the binational companies at a preferential price

[15]Vice-Ministerio de Minas y Energía: https://www.ssme.gov.py/vmme/index.php?option=com_content&view=article&id=1218&Itemid=605

[16]Earth Observatory (NASA): https://earthobservatory.nasa.gov/images/92078/deforestation-in-paraguay

TABLE 5 | Electricity access (%) & fuel for cooking (%) - Asunción and Paraguay's main departments (2019).

Department	Electricity access	Fuel used for cooking					
		Liquefied petroleum gas (LPG)	Biomass/coal	Electricity	Kerosene, alcohol	Other[a]	None/Doesn't cook
Asunción	99.93	66.76	6.34	23.37	0.00	0.05	3.47
Concepción	99.07	41.59	43.56	12.78	0.00	2.07	0.00
San Pedro	99.27	25.05	57.82	14.75	0.00	0.00	2.37
Cordillera	99.53	42.04	43.70	11.74	0.00	0.00	2.51
Guairá	99.45	30.70	52.66	14.38	0.00	0.12	2.14
Caaguazú	99.59	35.03	46.33	16.09	0.00	0.00	2.54
Caazapá	99.31	31.08	54.23	13.47	0.00	0.00	1.22
Itapúa	99.81	50.31	31.45	16.58	0.00	0.00	1.67
Misiones	99.58	51.75	32.04	14.44	0.00	0.00	1.77
Paraguarí	98.20	27.87	60.63	9.50	0.00	0.00	2.00
Alto Paraná	99.88	77.12	11.45	9.59	0.00	0.00	1.83
Central	99.91	66.30	12.58	19.71	0.00	0.00	1.41
Ñeembucú	98.34	56.81	33.24	7.34	0.00	0.00	2.61
Amambay	97.98	80.37	15.04	2.32	0.00	0.00	2.27
Canindeyú	99.58	54.12	35.19	7.81	0.00	0.00	2.88
Presidente Hayes	97.98	48.82	25.83	22.82	0.00	0.00	2.53

Source: DGEEC Encuesta Permanente de Hogares Continua 2019. Promedio annual.
[a]*Includes: Sawdust.*
Red > 30%; 10% < Orange < 30%; Green < 10%.

cooking. On the other hand, we find that in other departments, the percentage of the population using biomass or coal is higher than 10%, and in some cases, even higher than 60%.

Paradoxically, despite being one of the largest producers and exporters of clean hydroelectric energy in the region, Paraguay still has low levels of electricity as source of final energy consumption (17%), while biomass and fossil fuels account for 83% of the total final energy consumption [Vice-Ministerio de Minas y Energía (VMME), 2020]. As observed in **Table 5**, the main challenge concerning the transition from biomass/coal to cleaner energy sources for cooking is located outside the capital (Asunción), and especially in non-urban zones or departments where the main economic activities are agriculture and/or cattle raising.

Additionally, we observe that the population of Asunción also has higher levels of access to home appliances and electrical devices in general (refrigerators, air conditioners, TVs, electric water heater, etc.), as well as cleaner technologies for cooking (electric kitchens, microwaves, LPG kitchens, electric oven, etc.), providing better conditions for well-being and development of the cities and people (Dirección General de Estadísticas, Encuestas y Censos, 2020).

Then, if we analyze the technologies used for transport, we find that in the city of Asunción, most of the population have a car (51.2%) or a motorcycle (22.5%), while at the department level, we have the opposite results (in average), with more people having access to motorcycles (67.6%) rather than cars (30.2%) (Dirección General de Estadísticas, Encuestas y Censos, 2020). In both cases, fossil fuels are needed, and as we mentioned before, the country imports 100% of its demand of oil and LPG.

In Organización Latinoamericana de Energía (OLADE) (2020), we observe that energy prices in Paraguay have been stable in recent years. During the period 2015–2019, the price of electricity for the residential sector has been around 58.30–61.00 US$/MWh, that for the commercial sector is in the range 62.70–70.00 US$/MWh, and that for the industrial sector is between 38.50 and 45.50 US$/MWh. On the other hand, during the period 2014–2018, LPG prices have been around 1.25–0.73 US$/kg, while gasoline prices for the transport sector have been between 1.16 and 0.88 US$/L. Although energy prices in Paraguay are very competitive at the regional level, energy affordability should not be underestimated as an important variable in multidimensional energy poverty, especially at the city level and when considering the affordability of clean fuels and technologies for cooking, where more data are needed to follow-up the improvements or setbacks in this indicator.

Then, when analyzing multidimensional energy poverty in Paraguay, we find a mixed set of conditions in the different cities and departments, where access to electricity is not a major issue. Nevertheless, energy affordability and the access to clean fuels and technologies for cooking still represent big challenges for the country, especially in isolated regions (i.e., Chaco Paraguayo) and with the most vulnerable population (people in extreme poverty).

LIMITATIONS

The methodology implemented in this study had some implications in the obtained results, which are explicated by its limitations. The main limitations include the following aspects:

- The choice of EEUU as the reference country (benchmark). It is a decision that could overestimate energy poverty situation in the analyzed region, considering the current gaps, in terms of energy indicators, between EEUU and South American countries.
- The results are very sensitive to the selection of different weights (W_1-W_2-W_3) for the different approaches proposed for the analysis of energy poverty. The results must be interpreted cautiously.

Despite the limitations, the study offers a wide range of results that provide a good diagnosis of energy poverty in the region, considering the challenges each country will have to face to mitigate the consequences and to reduce the gaps (nationally and regionally), considering energy access, affordability, and availability.

CONCLUSIONS AND POLICY IMPLICATIONS

Through the measure of the CEPI and its multidimensional approach, we have been able to evaluate the multidimensional energy poverty in a group of South American countries. Then, independently of the weights assigned to each variable (W_1-W_2-W_3), we observe a predominant trend, where Paraguay presents greater difficulties concerning energy poverty in the region, as well as existing important gaps with Brazil, even greater compared to Argentina and Uruguay, which, from a general perspective, present the best performances.

Despite limiting our analysis to three scenarios, we identified that energy accessibility is not the main problem in the region; however, when including energy affordability and energy availability, energy poverty gaps tend to increase, worsening the CEPI for scenarios W_2 and W_3 in the countries under study.

Overall, as expected, each country presented different characteristics in the supply and demand of energy. Regionally, the energy accessibility rates observed, at the country level, are high; however, further studies are needed to evaluate the lack of access in rural (or isolated) areas within the countries, and the impact of the deprivation of energy services on the well-being of the population. Nevertheless, there are different initiatives regionally, from multilateral institutions (BID, FONPLATA, CAF, PNUD, etc.) and public–private partnerships, financing projects to close the energy infrastructure gaps and to reduce energy vulnerability.

Additionally, results show that countries with national projects to accelerate the integration of renewables in the energy mix reduced the multidimensional energy poverty in the period of analysis, as shown in the cases of RenovAr in Argentina, and the numerous wind energy projects in Uruguay. On the other hand, countries like Paraguay, which has not diversified its energy mix in the last decades, introduced new renewable energy sources, or improved its final energy consumption of electricity, have higher levels of multidimensional energy poverty, depending heavily on fossil fuels and non-certified biomass.

The results obtained for the countries studied reflect the current situation from a macro perspective, and having a critical review of the implemented methodology, when we analyze the case of Paraguay, with local data, the results clearly show, at the level of the capital and main departments, high electricity availability and also high rates of electricity access; however, energy affordability is a problem that is reflected in aspects such as cooking with biomass or coal, which has negative well-known effects in well-being and health. We decided to study Paraguay at the local level because it became the most representative case of multidimensional energy poverty in the region and has been a country that is not usually studied or mentioned in the global literature of this topic. We are convinced that the results of our study can serve as a starting point for discussions on multidimensional energy poverty in the country. Moreover, this case study allowed the validation of the general results obtained through the implementation of the multidimensional energy poverty metrics proposed for the countries under analysis, showing an evidence of the current situation of the country and the need to deepen the study of energy poverty.

Furthermore, the results show that during the period of analysis (2000–2016), Argentina and Uruguay have had a consistent performance in many energy indicators, considerably reducing energy poverty. These cases require an in-depth analysis to better understand the causes behind those good performances. A common strategy in both countries has been their investments in renewable energy through different programs.

We observed that an analysis of energy poverty, exclusively done through the lens of the energy access (CEPI-W_1), can underestimate the problem in the countries under study. In this context, we consider the use of multidimensional approaches to study energy poverty in the region necessary, in order to have a holistic vision, closer to the real situation of the region. Then, from a multidimensional approach, evaluated through the scenarios CEPI-W_2 and CEPI-W_3, we conclude that further studies are needed to evaluate the quality of the selected indicators used to measure the multidimensional energy poverty in the region, and if it is necessary to add new variables to improve the quality of the proposed index and to reflect a closer reality of energy poverty in the countries under analysis. In this regard, we can already observe the efforts of the OLADE[17], to guide the regional discussion to standardize the measuring and reporting of energy indicators, in order to facilitate the measure and comparability of energy poverty in the future.

Policy Implications

From a public policy perspective, efforts should focus on improving access to modern and clean energy for cooking, especially in rural and isolated areas. Additionally, we observe high levels of fossil fuel consumption, which is a situation that needs further study to understand if that is aligned

[17]In 2020, OLADE conducted a series of workshops with the Energy Statistics Departments of the country members, in order to discuss the methodological harmonization of energy statistics in the region.

with the national strategies and energy policies of the countries we have analyzed, and how, under this context, energy poverty of the most vulnerable population can be reduced. We have not identified any official document from the analyzed countries evaluating transnational actions or policies to reduce energy poverty in the region. Instead, we observe geopolitical situations and barriers to regional energy integration[18]. We are convinced that a regional commitment and policies to the reduction of multidimensional energy poverty are needed. Considering the wide range of potential variables affecting the multidimensional energy poverty, the scope of actions from the countries should include regional energy integration policies, regional incentives on energy efficiency, tougher sanctions and regulations on the use of non-certified biomass, incentives on technology transfers oriented to the improvement of technologies for cooking, and many others. In this regard, some of the regional commercial incentive policies and technology transfers could be discussed through the MERCOSUR platform, while other policies concerning more wider aspects could be analyzed through sectorial round tables established with representatives of each country.

Moreover, decision-makers and policymakers must understand that energy poverty is a multidimensional issue that requires actions on many fronts. Nowadays, we observe that most of the strategies against energy poverty in the region are focused on tariff subsidies (energy affordability) for the household's electricity consumption.

Solutions to the multidimensional energy poverty at the regional level must necessarily involve a wider discussion, which should consider the challenges and energy gaps identified in each country, focusing efforts on the design and implementation of a regional agenda of development, oriented to the creation of synergies and achievement of shared objectives. On the other hand, at the domestic level, we consider that energy poverty should be part of the academic debate and decision-making in different countries, for the construction of the different public policies on energy and development. We suggest strengthening the role of local administrations (municipalities, states, or other respective administration established at the domestic level in each country) in the development of different projects to reduce multidimensional energy poverty, especially in vulnerable cities and isolated communities within the countries.

Furthermore, it is important to underline that these countries, as members of the UN, have adopted the 2030 Agenda and the commitment with the SDGs, including the SDG 7, focused on granting universal access to energy, at affordable prices, from modern and clean sources and technologies.

We must underline that within the dimension of "energy access," the indicators of "*proportion of population with access to electricity*" and "*proportion of population with primary reliance on clean fuels and technology*" are the same indicators used by the SDG 7 included in the 2030 Agenda. These indicators refer to the SDG indicators 7.1.1 and 7.1.2, respectively, and considering the evolution of the results and improvements achieved by the selected countries in these indicators, they seem to be in the path to partially achieve SDG 7 (at least in 7.1.1, but in 7.1.2, the gaps are greater and more complex to improve). Finally, regional energy policies should be analyzed to create synergies and to improve energy services (quality and reliability), funding projects for energy system integration, cross-border cooperation, and programs targeting the improvement of the access to clean and affordable energy for the most vulnerable communities in these countries.

Future Research Work

Future research work should be oriented to the implementation of regional and standardized multidimensional energy poverty indicators, as those proposed by Dehays and Schuschny (2019) from the OLADE. However, energy poverty measures at the domestic level (cities, departments, etc.) should not be neglected, considering that it is at this level where this issue takes place, and its effects could be distributed with high levels of heterogeneity within the countries.

Additionally, a wider study of multidimensional energy poverty, including all the countries in South America, could provide a more realistic vision of this issue in the region. The metrics used in the proposed methodology addresses multidimensional energy poverty in a simple and reliable way, taking into account the difficulties and restrictions that arise with regard to data availability. Then, these complementary analyses could also lead to the consideration of a closer country as benchmark for the analysis and the use of additional parameters for the study of multidimensional energy poverty. Moreover, a sensitivity analysis that assigns different weights to the indicators in order to have a wider vision of possible results (according to the different weights sets) is also recommended.

We also recommend the use of a regional benchmark that is not a single country in the region, but the general average of all the indicators of the countries under study, in a certain period of time (i.e., the average performance of a decade), in order to avoid underestimating or overestimating energy poverty and provide a comparable result to that obtained through a traditional benchmark such as that of the United States used in this case.

Finally, we must underline the importance of a regional academic network for the study of multidimensional energy poverty from different perspectives, in a collaborative approach. Some successful experiences in the region, such as Red de Pobreza Energética (RedPE in Chile)[19], influenced many academic works in addition to public policies that could be emulated in different countries. Other emerging regional collaboration networks, such as the Red de Inclusión Energética Latinoamericana (RedIEL in Latin America)[20], the Observatorio de Pobreza Energética en Mexico[21], and the Red Energías Solidarias, should strengthen regional academic

[18]This is especially the case of Paraguay with Brazil and Argentina, through the binational projects (Itaipú and Yacyreta).

[19]RedPE: http://redesvid.uchile.cl/pobreza-energetica/

[20]RedIEL: https://www.rediel.org/

[21]Observatorio de Pobreza Energética en Mexico: https://pobrezaenergetica.mx/

collaboration in order to influence public policies (nationally and regionally).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

GP: conceptualization, methodology, validation, formal analysis, investigation, literature review, data curation, writing original draft, visualization, and supervision. AG: conceptualization, validation, methodology, literature review, and project administration. RR: conceptualization, methodology, and validation. All authors contributed to the article and approved the submitted version.

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frontiers in Sustainable Cities

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Territorial Energy Vulnerability Assessment to Enhance Just Energy Transition of Cities

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Energy poverty is a crucial concept in current global energy policy, both for the importance of securing equitable access to high-quality energy services to all human populations and to advance toward a just energy transition to a decarbonized economy. Nonetheless, one of the limitations of this concept due to its focus at the household scale, it has tended to omit relevant energy conditions at a territorial scale, which can also be a dimension of significant deprivation (e.g., transportation, schools, hospitals, public services, industrial uses among others.). On the other hand, energy services are highly dependent on context: on the geographic, ecological, technical, economic, and sociocultural conditions. This context-dependency determines the range of energy and technological alternatives available in a territory. Hence, a conceptual framework is required to better understand the starting point to a just energy transition, capable of integrating the complexity of socio-techno-ecological systems. To fill this gap, we present a framework based on the concept of Territorial Energy Vulnerability (TEV), defined as the propensity of a territory to not guarantee equitable access—in quantity and quality—to resilient energy services that allow the sustainable human and economic development of its population. That is a greater probability of inequity in access to energy services or a significant impacts derived from socio-natural risks that make it incapable of guaranteeing a sustainable and resilient provision of these services. Built on state-of-the-art conceptualizations of risk, we develop an indicator-based framework on vulnerability understood as the combination of sensitivity and resilience characteristics of socio-techno-ecological systems. Sensitivity relates to economic, demographic, infrastructure, technology, culture, and knowledge characteristics of socio-techno-ecological components. Meanwhile, resilience is presented in a three-dimensional framework based on flexibility, register, and self-transformation capacity of socio-techno-ecological systems. An application of this framework is developed using three case studies: Arica, Los Andes and Coyhaique, all Chilean cities with diverse ecological, technical, economic, and sociocultural conditions that shape territorial vulnerability. Using this framework as a diagnostic tool, the development of a just energy transition could adapt existing concepts of energy poverty and decarbonization pathways into context-specific guidelines and policies.

Keywords: energy poverty, cities, vulnerability, territorial, resilience, just energy transition

INTRODUCTION

Ensuring access to affordable, reliable, and sustainable energy for all is a crucial pillar of sustainable development (United Nations, 2015), supporting as much economic development as the satisfaction of a large variety of human needs (Bhatia and Angelou, 2015; Thomson et al., 2017; Nadimi and Tokimatsu, 2018; Robić and Ančić, 2018). At the same time, however, generation, distribution, and consumption of energy account for more than 70% of global GHG emissions (Climate Watch, 2019), a result of approximately 81% of global energy demand being met by fossil fuels including oil, coal, and gas (International Energy Agency, 2019). Urgent efforts toward the decarbonization of energy systems are needed to maintain global warming below 1.5°C. over pre-industrial levels (Falk et al., 2019; IPCC, 2019a).

The need to simultaneously ensure a secure energy provision, advance toward a more environmentally benign energy matrix, and reduce energy poverty, is known as the energy trilemma, a key challenge for advancing toward sustainable energy development (International Energy Agency, 2018; World Energy Council, 2019). Facing this trilemma requires devising strategies for a just energy transition (McCauley and Heffron, 2018), which complies with climate goals while ensuring energy justice.

Cities play a key role in tackling this trilemma: they are hotspots in the global carbon cycle, accounting for the majority of the CO_2 emissions from global final energy use (Nangini et al., 2019), while they also influence and mediate the effects of climate change on society (McCarthy et al., 2010). Conversely, cities can act as frontrunners and sites of innovative climate action and governance (van der Heijden, 2019). This fact urges the development of an integrated approach to design climate-sensitive urban governance, i.e., able to enact mitigative, adaptive, and transformative efforts in the face of a changing planet (Brondizio et al., 2016; Bai, 2018), while also fostering justice and equality. However, up to this point, urban governance remains a strongly fragmented field targeted by a variety of epistemic communities encompassing urban planning, disaster management, and climate vulnerability, to quote just a few (Wolfram et al., 2017).

At the same time, a significant interlinkage exists between urban and energy planning and priorities, so that a stronger understanding is needed of the spatial, political, and ethical dimensions of urban energy transitions, including how these may either transform or reproduce existing forms of injustice and segregation (Rutherford and Coutard, 2014; Debizet et al., 2016; Huang and Broto, 2018). Along these lines, an emerging literature on Positive Energy Districts (PEDs) and Energy Positive Neighborhoods (EPN) has been arguing for a form of urban planning seeking to synergically reduce GHG emissions and alleviate energy inequalities by means of a higher energy efficiency and renewable energy generation (Ala-Juusela et al., 2016; Monti et al., 2016; Walker et al., 2017).

Fostering a just transition based, for example, on PEDs or EPNs, requires paying deep attention to the context in which the transition occurs: territorial characteristics and dynamics, in fact, influence not only the particular energy needs and acceptability thresholds of energy services but also the chances of success of energy transitions efforts and the emergence of potential unintended consequences of said transitions upon the inequality and vulnerability of the target communities (Bouzarovski and Tirado Herrero, 2017a; Frantál and Nováková, 2019; Urquiza et al., 2019; O'Sullivan et al., 2020). Moreover, it must be noted that while often there is a tendency on the part of scholarship and public policy to grant absolute preference to "modern" energy services (mostly based on electricity), place-based evidence discards the possibility to conceive a unique hierarchy among energy sources: not only households tend to mix different sources in their daily routine (combining different kinds of technologies), but the relative desirability of each of these tend to vary according to the specific context, including socioecological, sociotechnical conditions, and sociocultural practices (Scarpellini et al., 2015; García-Ochoa and Graizbord, 2016; Herington et al., 2017; Billi et al., 2018).

On the other hand, methodologies and indicators used to gauge energy poverty and deprivation have tended to pay limited attention to territorial contexts. Even pioneering studies struggling to incorporate these variables have mostly focused their analysis on the household domain. In contrast, little attention has been paid to: (a) non-household manifestations of EP (e.g., related to transportation, workplace, education and health institutions, public lighting, among others), or (b) extra-domestic determinants of household energy deprivation. Moreover, there is a lack of comprehensive approaches clarifying how energy deprivation may be affected by context dynamics, including technological, socio-political, and climatic trends.

To fill this gap, this paper aims to outline an analytical framework to examine what we call "territorial energy vulnerability" (TEV in the following), understood as the propensity of a territory to see its ability to ensure high-quality energy services affected by hazards or dangers such as climate change or socio-natural disasters. TEV is not meant to be a substitute, but rather as a complement, for household EP measures, struggling to provide context and depth to the analysis of energy deprivation and just energy transitions. Territorial energy vulnerability is animated by a holistic understanding of energy security, understanding the latter as the capability of a territory to ensure equitable access—in terms of both quality and quantity—to resilient and sustainable energy services furthering the human and economic development of its population, respecting both planetary and local ecosystem limits (Urquiza and Billi, 2020).

To inform such a framework, we combine notions and insights from energy poverty and sociotechnical transitions literature with those deriving from a socio-anthropological understanding of territorial dynamics, plus the latest advancement of the climate change community on the conceptualization of risk and vulnerability. Also, the integrated view of urban planning proposed in PEDs literature, where multiple energy uses are considered simultaneously (e.g., households, public luminaires, commercial, etc.), and the importance of context-specific trajectories to PEDs is at the core of our territorial framework (Ala-Juusela et al., 2016; Lindholm et al., 2021; Moreno et al., 2021). An analysis based on TEV framework can facilitate the implementation of a just energy transition based on context-specific guidelines and policies coherent with existing concepts of energy poverty and decarbonization pathways (such as PEDs).

To illustrate our framework, we analyze three case studies of major cities in Chile: Arica, Los Andes, and Coyhaique. Chile is a perfect testbed for our approach both because of its strongly varying climatic, economic, and sociocultural characteristics. Because of its condition of a "middle-development" country, it represents a category that has traditionally been under-attended by energy poverty literature (Urquiza et al., 2019). Noticeably, while in this paper we develop the framework with an explicit focus on urban spaces, in the future it could be extended to rural or peri-urban contexts.

The rest of the paper is structured as follows: section Literature review provides a literature review on existing attempts to include a territorial perspective in energy poverty research, discussing the lack of complex and multiscalar understandings of territorial dynamics. Section Theoretical framework illustrates our analytical framework. section Description of case studies introduces our case studies. Section Results presents the data and methods used in the cases studied. Section Results and section Discussion respectively present and discuss our results to broaden our understanding of energy poverty and just energy transition in cities. Finally, the article is closed in section Conclusion with the main conclusions.

LITERATURE REVIEW

Energy poverty has been traditionally measured through either of two pathways: on the one hand, economic indicators, such as the well-known "Ten Percent Rule" (Boardman, 1991), the "Low Income-High Cost" (Hills, 2012), the "Minimum Income Standard" (Moore, 2012) among others, that had mainly focused on the affordability of energy expenditure in high-development countries (Urquiza et al., 2019). On the other hand, energy access indicators such as the Multidimensional Energy Poverty Index (Nussbaumer et al., 2012) have concentrated on geographical or technological barriers to energy, observed in access to technology. This aspect has tended to be especially relevant in low-development countries (Urquiza et al., 2019).

However, both affordability and access-oriented energy poverty indicators must assume quality standards as evaluation criteria (Urquiza et al., 2019). Quality can thus be visualized as a third "hidden" dimension of energy poverty, in two relevant senses: as underlying the need to adopt quality standards suitable to different particular socioeconomic, cultural, climate, and geographical conditions as a precondition to evaluate both energy affordability and access; and as an object of evaluation in its own sake—e.g., in terms of reliability or safeness of energy provision—. As argued in Urquiza et al. (2019), this hidden dimension is significant when observing energy poverty in territorially heterogenous, middle-development countries like Chile.

The quality dimension, in turn, drive us to think about patterns and determinants of energy availability—or lack thereof—in a territory and how this impacts household energy poverty. In this context, the link between the energy trilemma (International Energy Agency, 2018; World Energy Council, 2019) is fundamental: to tackle energy poverty, we need to improve reliable and high-quality energy provision, that is to say, adequate, reliable, safe, and non-polluting energy, to reach an environmentally benign energy matrix. However, energy provision depends on territorial structural conditions (such as infrastructure, politics, markets, among others) that contribute to reproduce spatial inequalities related to energy. Bouzarovski et al. (2015) have emphasized the importance of understanding the sociotechnical legacies of countries' development trajectories to understand the political and economic landscape that frame energy poverty expressions; these conditions can be understood as driving forces of energy poverty.

The effect of household characteristics on the probabilities of becoming energy poor is well known (Imbert et al., 2016; Belaïd, 2018; Primc et al., 2019), but recent literature has expressed the importance of a geographical analysis where energy poverty conditions can relate to phenomena occurring at a larger scale (Bouzarovski and Simcock, 2017; Robinson et al., 2019). Scientific literature offers at least two different ways to understand the spatial dimension of energy poverty.

First, some authors have emphasized the importance of spatializing energy poverty, e.g., understanding it through a spatial lens as an energy injustice problem (Bouzarovski and Simcock, 2017; Bouzarovski et al., 2017; Robinson et al., 2019). They have identified how spatial variables can explain energy poverty expressions more precisely than other variables like household socioeconomic conditions (Jimenez, 2017; Besagni and Borgarello, 2019; Mattioli et al., 2019). This has been studied especially in the case of Central and Eastern European countries (Bouzarovski et al., 2015; Bouzarovski and Tirado Herrero, 2017a; Sokołowski et al., 2020) but increasingly in other European countries (Besagni and Borgarello, 2019; Mattioli et al., 2019; O'Sullivan et al., 2020), highlighting geographical disparities and central-periphery relations in the EU community (Bouzarovski and Tirado Herrero, 2017b; Golubchikov and O'Sullivan, 2020). In the same context, energy poverty incidence has also been related to neighborhoods' urban and architectural conditions, emphasizing the importance of understanding the historical context and development of housing complexes in urban and rural areas (Besagni and Borgarello, 2019).

The second perspective of territorial effects on energy poverty has paid attention to climatic and geographical conditions that generate differentiated energy poverty expressions, such as in the case of islands (Wolf et al., 2016; Surroop et al., 2018; Ioannidis et al., 2019; Lozano et al., 2019). An emphasis has been made regarding how altitude (Katsoulakos and Kaliampakos, 2016; Papada and Kaliampakos, 2016), temperature (Puzzolo et al., 2016; Kerimray et al., 2018; Besagni and Borgarello, 2019), and climatic variability (Ioannidis et al., 2019) relate to different energy needs that households can have. Similarly, literature has stressed the importance of daily (Puzzolo et al., 2016) and seasonal variability (Puzzolo et al., 2016; Pollard et al., 2018) of these conditions. This group of the energy poverty literature usually emphasizes how remote (Dugoua et al., 2017; Pollard et al., 2018), mountainous (Katsoulakos and Kaliampakos, 2016; Papada and Kaliampakos, 2016), or isolated areas face specific conditions that create barriers for improved access to cleaner, more efficient fuels, posing a challenge to energy transitions.

Both perspectives, the spatial expression of energy poverty and geophysical conditions as a cause of energy poverty, have been observed across different scales, for example, climate macrozones that can produce a different heat demand (Besagni and Borgarello, 2019); geographical conditions like isolation (Dugoua et al., 2017) that can condition energy access; the spatial distribution within a city (Mattioli et al., 2019) or between different regions (Bouzarovski and Tirado Herrero, 2017a); among others. Other studies have focused on how economic conditions at a regional scale can increase the risk and prevalence of energy poverty conditions creating an regional risk measure or structural energy poverty vulnerability, such as energy prices, income, unemployment rate, labor market conditions, energy market characteristics, among others (Dodson and Sipe, 2006, 2008; Velte et al., 2013; Recalde et al., 2019).

Furthermore, some authors (Bouzarovski and Thomson, 2018) identify differences within urban contexts, producing different landscapes and typologies of energy vulnerability, forming particular socio-spatial forms of inequity. This literature also concludes that expenditure indicators are insufficient to describe the complex ways in which socio-spatial vulnerabilities interplay toward an intensification of energy poverty conditions, related to equally complex geographical and demographic contexts (Robinson et al., 2018).

The relationship between these two perspectives—that is, between the literature on the spatial expressions of energy poverty and the literature on climate and geography as drivers of energy poverty—is complex, sometimes overlapping (Bouzarovski and Simcock, 2017). Despite these considerations, this literature still fails to integrate both perspectives better and describe territorial determinants of energy poverty.

Regarding this issue, there have been some notable contributions in this sense from Robinson et al. (2019) and Mattioli et al. (2019). These authors have made efforts to assess the occurrence of energy poverty at a smaller, neighborhood-like scale. Similarly, Besagni and Borgarello (2019) and Pollard et al. (2018) have made efforts to produce a detailed sub-national disparities outlook. All these proposals, however, support what Bouzarovski and Simcock (2017) have noted, namely that "aggregating and averaging figures over units of political and material space both reveals and hides differences; justice (...) defined at one scale does not necessarily mean justice is achieved elsewhere" (p. 642). The recognition of the complex spatial embeddedness (Bouzarovski and Tirado Herrero, 2017a) of energy poverty is, however, still tied to the availability of sufficiently detailed, spatially disaggregated data.

Another aspect not commonly covered by energy poverty literature is that energy poverty conditions, i.e., unequal access to high-quality energy services, can also occur outside the household, especially in crucial social services such as education and health institutions, but also in diverse workplaces like offices, outdoor work, commerce, among others. Some articles have done this by focusing on relevant energy uses that are often not considered in the broader context of energy poverty, such as transport (Mattioli et al., 2019). The recognition of the relevance of educational, health-related and other social and productive uses of energy has been present mostly in the energy transition literature (Wolf et al., 2016; Surroop et al., 2018; Lozano et al., 2019).

Finally, and most important for this paper, there remains a limited understanding of how spatial and territorial determinants could mediate the vulnerability of the energy system to potential climatic, economic, or socio-political threats, thus potentially generating or increasing future energy deprivation. Hence, recent literature suggests the importance of developing a dynamic perspective of energy poverty that may address this aspect, where not only the analysis of the current energy access gaps is necessary, but also a reference to short and long-term impacts on high-quality, equitable energy access, that is, the risk of the energy system (Urquiza and Billi, 2020).

Several studies (Dugoua et al., 2017; Baptista, 2018; Besagni and Borgarello, 2019; Munro and Bartlett, 2019) emphasize the importance of considering the historical context of specific technical and sociocultural trajectories, and how energy poverty changes not only through space but also through time. However, usually, there is a lack of attention to the "risk" component of energy security, especially considering the impacts of the new globally changing scenarios. Relevant scholarship on energy vulnerabilities (Middlemiss and Gillard, 2015; Petrova, 2018; Ioannidis et al., 2019; Mattioli et al., 2019; Robinson et al., 2019) has focused on household sensitivity toward energy poverty while neglecting a broader systemic perspective that integrates environmental hazards (e.g., climate change) and sociotechnical complexities (e.g., energy transitions as a source of uncertainty to some energy system actors). Some authors have emphasized that energy transitions can increase social vulnerability—rather than decreasing it—highlighting the need to consider the links between energy vulnerability and energy transitions from a geographical perspective (Bouzarovski et al., 2017).

Even though there is a growing literature that considers, on the one hand, energy vulnerability (Middlemiss and Gillard, 2015; Petrova, 2018) and on the other the multiscalar nature of the problem, there is a need for a comprehensive framework able to embrace the complex territorial determinants of energy vulnerability and poverty, considering not only sociotechnical conditions but also socioecological and sociocultural domains. A narrowed approach can cause energy transition policies to rely on energy poverty and security measures that underestimate the complexities of sociotechnical processes existing in-between households and with national energy systems.

Improving the attention to the "risk" component through a TEV lens can provide a tighter link with sustainable development and energy transition literature, providing more tools to analyze temporal dynamics within energy poverty.

THEORETICAL FRAMEWORK

Vulnerability in Risk Literature

Following the conceptualization of the Intergovernmental Panel on Climate Change (IPCC) on its fifth assessment report, risk is a multidimensional concept understood as the probability that something of value to society would be in danger with an uncertain outcome, as a result of the interaction between three components: hazard, exposure, and vulnerability of the system [IPCC, 2012, 2019b; Centro de Ciencia del Clima y la Resiliencia (CR)2, 2018]. In this proposal, vulnerability is understood as a system's propensity to suffer negative impacts derived from a hazard [IPCC, 2012, 2019b; Centro de Ciencia del Clima y la Resiliencia (CR)2, 2018].

In turn, Vulnerability can be decomposed into two dimensions: sensitivity, understood as the systemic characteristics that increase the probability of the exposed components to suffer negative impacts, and response and adaptation capacity, which relates to the systemic capacity of facing and overcoming adverse conditions presented by hazards, exposure, and sensitivity.

Following previous efforts [Centro de Ciencia del Clima y la Resiliencia (CR)2, 2018], we propose to relate the concepts of response and adaptation capacity with the thriving literature on resilience, which would allow for a more systemic and holistic account on the matter. Although there are different definitions of resilience, one of the most known conceptualizations comes from the ecological systems literature and is understood as the capacity of a complex system to reduce the impact of disturbances by adapting and/or preserving its structural relationships (Folke et al., 2005; Cumming, 2011). In this conceptualization, the system maintains its identity and essential characteristics (function and organization), but multiple balance points are considered as viable, avoiding a rigid conceptualization of resilience (Gunderson and Holling, 2002; Folke, 2006; Cumming, 2011).

The sensitivity varies depending on the specific threats the system faces. Conversely, the response and adaptation capacities—in addition to having a specific expression to a particular hazard—can also be understood from a generic perspective. This means that resilience can be visualized as emergent characteristics of the system, allowing it to maintain its functions in the face of multiple threats, in some cases unknown. For example, a response protocol can be designed for socionatural disasters, but it can later be adapted to other types of hazards and increase the system's response capacity in general. On the other hand, an adaptation strategy whose focus is on scientific research and public awareness of risks could identify new sources of risks not priorly acknowledged. This article aims to describe energy systems' vulnerability; hence, a specific point of view will be developed centered on energy sociotechnical systems.

Moreover, resilience could be analyzed from two perspectives. First, an expressive perspective focused on the effects of disturbances and how the system could reduce the impacts and maintain its services after the event occurred. Second, from a predictive perspective focused on the characteristics of structures and components of a system that could estimate a system's resilience to a future threat (Folke, 2006; Urquiza and Billi, 2018). Although both perspectives are relevant, this work's interest is to account for a predisposition toward energy vulnerability, therefore, it focuses on a predictive perspective of resilience.

As previously argued [Centro de Ciencia del Clima y la Resiliencia (CR)2, 2018], there are three attributes associated with a resilient system: flexibility, memory, and self-transformation [Biggs et al., 2012; Centro de Ciencia del Clima y la Resiliencia (CR)2, 2018; Urquiza and Billi, 2018]. A resilient system is one that can react adequately and re-establish the provision of its services after a threat (flexibility); generate information and learning about its relationship with the environment, considering the reaction of its structures to hazards (memory); and adapt and/or transform its structures and components to maintain its services over time (self-transformation) (see **Table 1**). This transformation can occur spontaneously or in a planned way, based on specific objectives. The latter is crucial when talking about complex adaptive systems with cognitive capacities—such as socioecological, sociotechnical or sociocultural systems—since they have the quality of reflexively adapting to their environment (Gunderson and Holling, 2002; Berkes et al., 2003; Luhmann, 2006).

The literature relates at least three characteristics to flexibility: diversity, connectivity, and redundancy of its components and structures (Smith and Stirling, 2010; Molyneaux et al., 2016; Binder et al., 2017). Second, memory relates to the production of information about system functioning and its relationship with the environment (distinguishing itself from it) and with the ability to produce learning from this information (Berkes et al., 2003; Folke et al., 2005; Nykvist, 2014). Finally, self-transformation implies the degree to which the coordination of the system components, the capacity for anticipation and decision-making allow a socioecological or sociotechnical system to adapt to a threat and manage the risk it faces (Desouza and Flanery, 2013; Urquiza Gómez and Cadenas, 2015; Urquiza and Billi, 2018). This quality of the system can be aimed at adapting current structures over time (adaptive governance) or transforming these structures toward new equilibrium (transformative governance) (Biggs et al., 2015; Centro de Ciencia del Clima y la Resiliencia (CR)2, 2018).

The state of this set of characteristics (flexibility, memory, and self-transformation) is historically dependent and in turn conditions the system's response and adaptation capacity. In this way, with greater flexibility, learning, and self-transformation, a

TABLE 1 | Resilience in sociotechnical systems.

Expressive resilience		Predictive resilience		
Response capacity	Flexibility	**Diversity:** qualitative diverse components.	**Redundancy:** diverse components with similar functions.	**Connectivity:** a diverse and redundant network that allows communication.
Adaptation capacity	Memory	**Records:** generation, maintenance, and publication of data about system functions and environment relations.	**Reflexivity:** capacity to process data and create distinctions about its relationship with the environment.	**Learning:** capacity to integrate new information and alternative interpretations from the register and reflexivity.
	Self-transformation	**Coordination:** active participation of public, private, and civil society in public decisions.	**Anticipation:** capacity to implement current actions to cope with future scenarios.	**Decision:** capacity of private, public, and societal actors to make public decisions about the structure and operation of the system.

Source: adapted from Red de Pobreza Energética (2020).

socioecological, sociocultural, or sociotechnical system can better face the hazards and manage the risks it experiences (Folke et al., 2005; Desouza and Flanery, 2013; Urquiza and Billi, 2018).

Vulnerability in Energy Sociotechnical Systems

As we are changing the scale of analysis from household to territorial level, the concept of sociotechnical system is interesting to integrate the diversity of vulnerability characteristics present both inside and outside the household. Sociotechnical systems literature acknowledges the importance of considering both the technological (hard) aspects and the structures, agents, and processes (soft) that shape the development of complex systems such as energy, transport, among others (Rip and Kemp, 1988; Smith and Stirling, 2010). Elements such as artifacts, knowledge, economic capital, human resources, cultural meanings, natural resources, regulations, among others, are the central focus of sociotechnical analysis (Geels, 2002, 2004, 2011).

Hence, energy sociotechnical systems' sensitivity and resilience characteristics should be observed considering infrastructure, regulations, institutions, actors, and organizations involved in the production of energy services and technologies (Geels, 2004). At least five components of energy sociotechnical systems should be accounted for in the context of vulnerability analysis (see **Figure 1** for a graphical summary).

First, companies that produce, distribute, and commercialize energy and technologies, commonly oriented by economic criteria, even though in some contexts they can be part of the public sector, meaning the existence of mixed criteria in decision making. Their role and behavior in sociotechnical systems depend on characteristics such as economic resources, infrastructure, technologies, organizational culture, and specialized knowledge (Arnold-Cathalifaud, 2008; Rodriguez, 2008).

Second, regulators are the actors in charge of applying the normative ruleset that configure the interactions within an energy sociotechnical system as well as the design and implementation of policies that directly intervene on infrastructure, technologies, markets, and energy uses (Geels, 2004; Urquiza et al., 2018). As an organization, a government's capacities depend on its economic resources, infrastructure, technologies, organizational culture and knowledge, but its decisional logic is based on a complex relationship between political and technical criteria (Arnold-Cathalifaud, 2008; Rodriguez, 2008).

Third, technology and energy consumers who require high quality energy services related to food, hygiene, air conditioning, lighting, electrical devices, and productive uses to meet their needs (Urquiza et al., 2019). Among consumers we find households—the usual focus of energy poverty literature—but also, from a territorial perspective, companies that produce goods and services, and public services, which implies a diversity of both rationalities and energy needs. On the other hand, these consumers can be producers of energy at the same time when they have the technological capabilities or resources required. Examples of this possibility are generation based on solar energy or, in some contexts, the use of firewood from recollection in nearby forests (Schueftan et al., 2016).

These three components interact in an immediate level within the energy sociotechnical system, and they are the ones who, based on their constant interactions, shape the specific structures that Geels defines as sociotechnical regime. Two other components are relevant from a territorial perspective as they represent a specific base upon which companies, regulators, and consumers interact: the territorial memory and the common infrastructure and resources.

Territorial memory refers to a territorial system's capacity to learn about the relationship with its immediate environment, considering its structures and processes (Urquieta et al., 2017; Amigo, 2019). This is expressed in the availability of knowledge, information, decisions, and historical experiences, but also in values and perceptions, which condition the disposition to technologies and energy uses. This notion rests upon a rich field of discussion regarding the complex cultural values, perceptions, assemblages, and flows through which energy systems are shaped at territorial levels (Stephenson et al., 2010; Strauss et al., 2016; Munro and Bartlett, 2019; Kumar, 2020).

The common infrastructure corresponds to the artifacts and material components of shared use necessary for the generation,

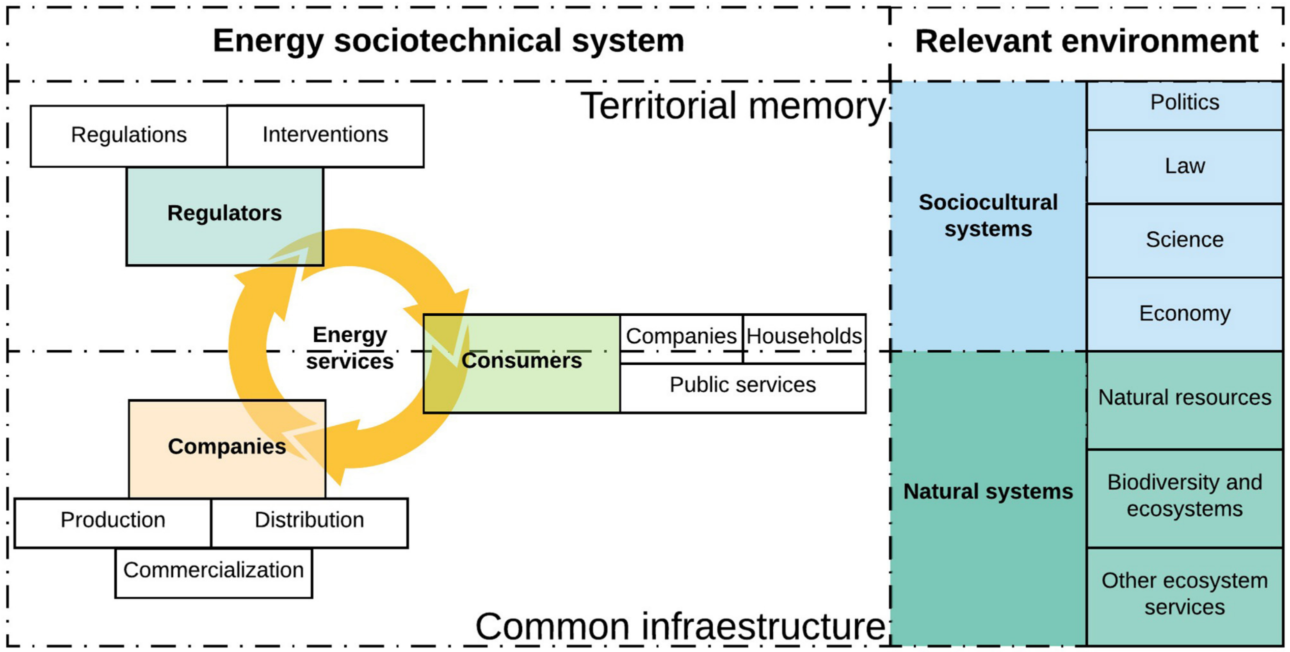

FIGURE 1 | Schematic representation of energy sociotechnical system. Source: adapted from Red de Pobreza Energética (2020).

distribution, and energy use. Given that some aspects of the sociotechnical energy system require high-cost investments (Makki and Mosly, 2020), it is common to encounter policies designed to incentivize the adoption or construction of a particular technology (Geels, 2004; Acosta et al., 2018).

This energy sociotechnical system has constant interactions with its environment, especially with some elements of the sociocultural and ecological systems that are crucial for its operation. Regarding sociocultural systems (Luhmann, 2006), the political system is relevant as its decisions impact public organizations and market characteristics; the legal system generates laws and regulations, which synthesize the formal "rules of the game" for various aspects of sociotechnical systems; the scientific system generates knowledge and applied research on relevant technologies for the production and use of energy; and the economic system conditions the demand and energy supply both at macro and microeconomic scales (Geels, 2004).

In the case of ecological systems, they provide various contributions necessary for the operation of the system, among them the natural resources used for the production, distribution and use of energy (Kadykalo et al., 2019); and the climatic conditions of the territory, which affect the energy demand but also on the energy potential of the territory. Likewise, the energy sociotechnical system impacts biodiversity and ecosystems, primarily due to pollutants' emissions at a global and local scale (Rogelj et al., 2018; IPCC, 2019a).

Territorial Energy Vulnerability

Considering the above, TEV is understood as the propensity of a territory to not guarantee equitable access—in quantity and quality—to resilient energy services that allow the sustainable human and economic development of its population. That is, a greater probability of gaps in access or inequity in quality energy services or significant impacts derived from socio-natural risks that make it incapable of guaranteeing a sustainable and resilient provision of these services.

This propensity is conditioned by the sensitivity and resilience characteristics of the energy sociotechnical system of the territory. The sensitivity characteristics refer to economic resources, sociodemographic, infrastructure, technological, cultural, and knowledge characteristics of the sociotechnical systems' main components (companies, regulators, consumers, common infrastructure, and territorial memory). On the other hand, resilience refers to the capacity for response and adaptation that emerges from the capacity for flexibility, memory, and self-transformation of the energy system structure. In this way, the emergent combination of these conditions (sensitivity and resilience) describes a specific sociotechnical configuration that affects availability, prices, demand, reliability, security, adequacy, and pollution of the sources and technologies used for energy services.

This sociotechnical configuration helps describe a global view of the context where gaps in equitable access to high-quality energy services occur for various users in a territory. Also, given a certain hazard, TEV will make it possible to understand, and in some cases project, how the energy sociotechnical system would react, visualizing the intermediate impacts and the risk that this entails on access to high-quality energy services (see **Figure 2**).

DESCRIPTION OF CASE STUDIES

To test the heuristic potential of the TEV framework proposed in this paper, we analyze three middle-sized Chilean cities located

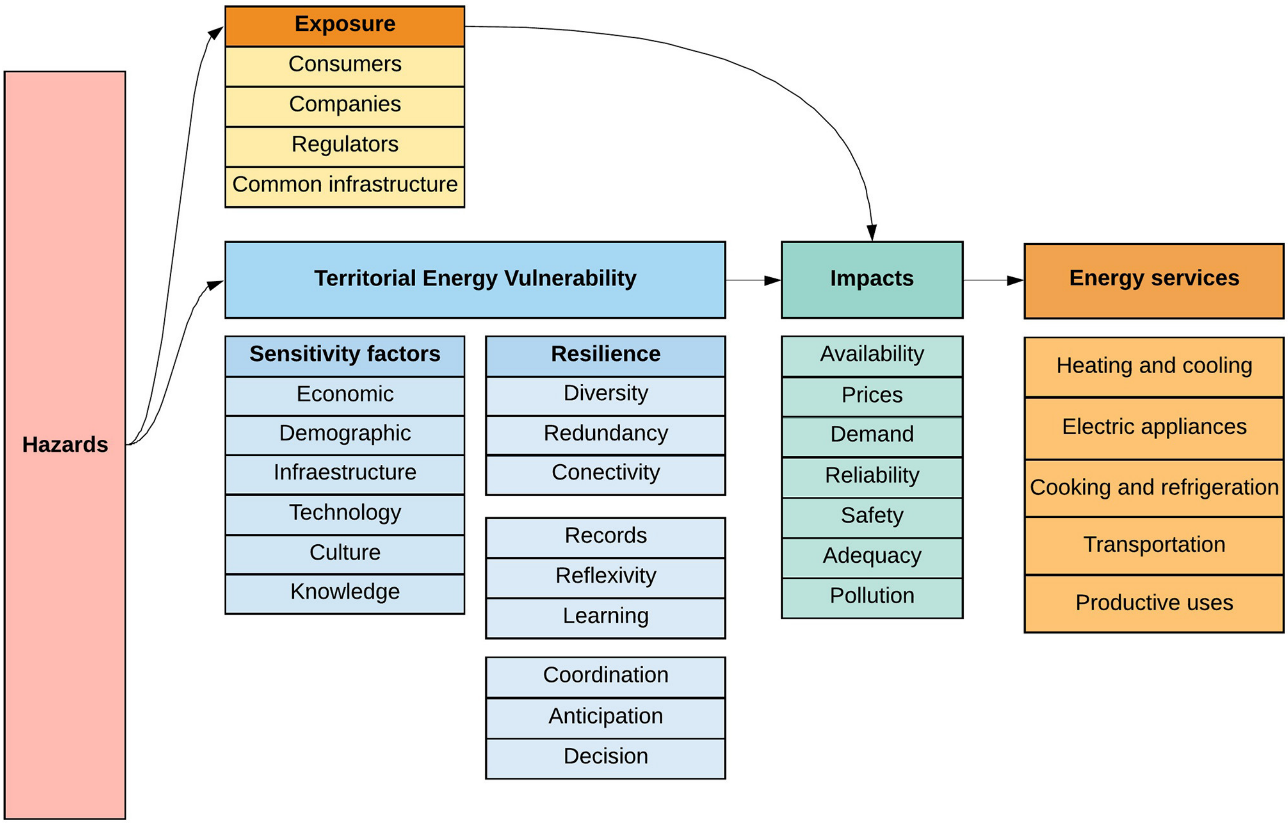

FIGURE 2 | Schematic representation of territorial energy vulnerability. Source: adapted from Red de Pobreza Energética (2020).

in different climates: Arica, a city located at the northern coast of Chile with a hot-desert climate; Los Andes, a cold semi-arid inland city located in a valley near Andes mountains; and Coyhaique, a tundra inland city located in the southern extreme of Chile, within near Patagonia (Sarricolea et al., 2017). A brief description of case studies is presented in this section, providing general geophysical, climate and demographic characteristics.

Arica, Arica and Parinacota Region

The city of Arica (18°28′S, 70°18′W) is Chile's northernmost urban settlement, and it is the capital of the Arica and Parinacota Region (see **Figure 3**). Its location is close to national borders with Perú (within 15 km) while being considerably distant (over 300 km.) from other similarly sized cities in Chile. This port city has 221,364 inhabitants, which is over 90% of the regional population, and doubles (8%) the national average (4%) proportion of the international migrant population (Instituto Nacional de Estadísticas, 2018).

According to data from the (CR)2 (Ministerio del Medio Ambiente, 2020) for the 1981–2010 time period, the annual average temperature in Arica was 17.2°C, with a thermal amplitude of 9.2°C. Likewise, The annual daily maximum temperature for the period 1981–2010 was 27.9°C, while the average daily minimum is around 12.6°C. Even when located within the Atacama Desert, its location on a coastal area explains the fact that on average onlyapproximately 83 days of the year exceed 25°C as a maximum temperature.

Los Andes, Valparaíso Region

The city of Los Andes (32°50′S 70°37′W) is a mid-sized urban settlement with 66,708 inhabitants located on the Aconcagua Valley near the Andes mountains (Instituto Nacional de Estadísticas, 2018). Its main economic activities are agricultural and cooper mining, strongly influencing its surrounding landscape.

Located in a semi-arid climate, Los Andes has an average temperature of 13.3°C, with a thermal amplitude of 14.9°C. The annual daily maximum temperature for the period 1981–2010 is 31.1°C, while the average minimum is just over 5.9°C. Unlike Arica, Los Andes has 107 days of the year reaching over 25°C as a maximum temperature, of which 20 days exceed 30°C. Another aspect to highlight is that the temperature of the coldest day reaches 6.3°C on average.

Coyhaique, Aysén Region

Coyhaique (45°34′S, 72°40′W) is one of the southernmost cities in Chile. Located in western Patagonia, it is the largest urban settlement on the Aysén Region and it's Region's capital city, with 57,818 inhabitants. Settled at the beginning of the twentieth century, it has historically relied on the surrounding livestock,

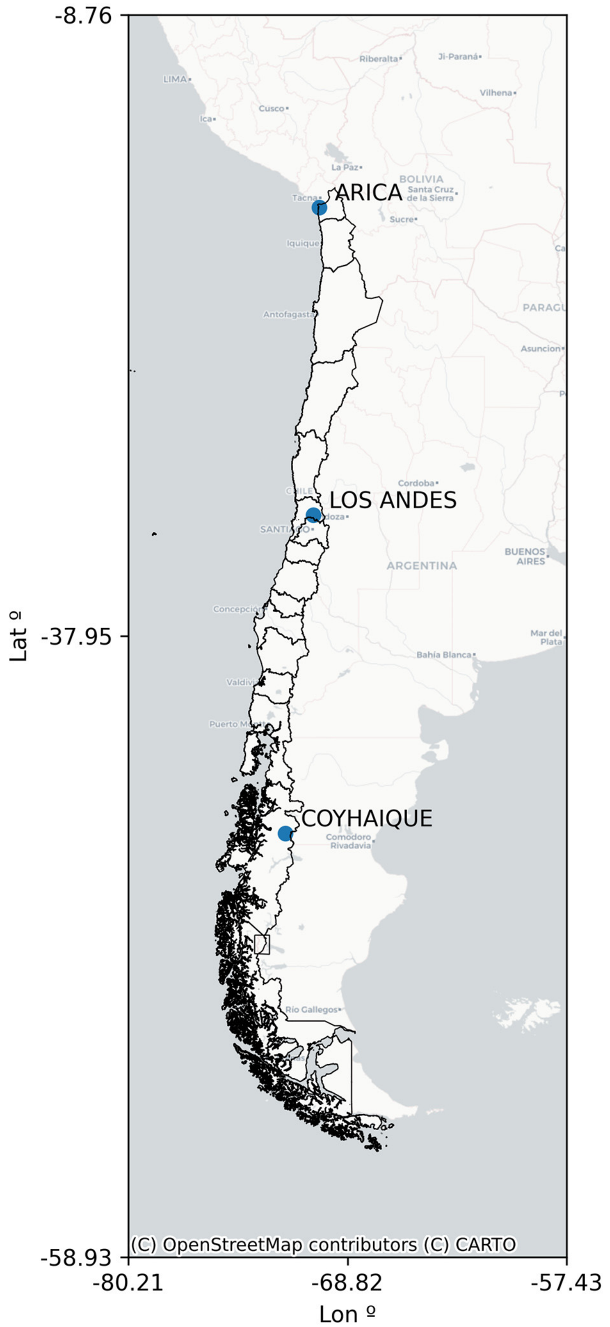

FIGURE 3 | Case studies location.

forestry resources, and natural tourist attractions as its main economic activities. Due to massive residential firewood use as a heating and cooking source, high PM2.5 concentrations are common throughoutthrough the coldest months of the year (Huneeus et al., 2020).

Coyhaique's annual average temperature for the 1981–2010 period was 7.6°C, with a thermal amplitude of 10°C. This period's daily maximum temperature corresponds to 28.2°C and has the lowest daily average minimum temperature of the three case studies, reaching 2.6°C in the 1981–2010 period. Also, this city has the fewest days that exceed 25°C, reaching only 6 days of the average year, and where the coldest night temperature goes down to −11.5°C, with 92 days of the year with a minimum temperature below 0°C.

DATA AND METHODS

As stated above, we follow an indicator-based methodological structure inspired by the work of IPCC Assessment Report 5 and the Center for Climate concept of risk, Resilience Research (CR2) Vulnerability Framework and GIZ climate change impact evaluation methodological guidelines [IPCC, 2012; GIZ, 2017, 2018; Centro de Ciencia del Clima y la Resiliencia (CR)2, 2018].

To describe the territory's sensitivity factors related to hazards and gaps in equitable access to high-quality energy services, a set of indicators were estimated for the three case studies (see **Table 2**). Although the proposed framework in section Theoretical framework comprises six dimensions (economic, demographic, infrastructure, technology, culture, and knowledge), in this article only four of them will be included due to lack of data related to culture and knowledge dimensions.

Finally, to describe the resilience of the sociotechnical system, we use analysis of the set of indicators presented in **Table 3** to understand better the flexibility, memory, and self-transformation characteristics of the system.

RESULTS

In this section, we offer a description of sensitivity characteristics of Arica, Los Andes, and Coyhaique that impact present and, probably, future conditions of energy access and could become barriers to just energy transition policies. Also, we describe some characteristics of the energy system and territory that can help to project response and adaptation capacity (resilience) of each case study.

Sensitivity Analysis

Demographic Characteristics

Regarding the sociodemographic characteristics of the populations of each case, all three cities share a relatively similar dependency ratio (ratio between economic active population and children and elderly): 48.9% for Arica, 46.89% in the case of Los Andes, and 47.5% for Coyhaique, above of the national dependency ratio (45.9%) as registered by the last National Census in 2017 (Instituto Nacional de Estadísticas, 2018). The presence of vulnerable age groups shows differences between these cities. While the proportion of the elderly population (above 65 years) in Coyhaique is 7% of its total, Arica and Los Andes proportions are 10 and 10.8%, respectively, reaching the same national average levels (10.6%). On the other hand, the presence of children (under 5 years) is relatively similar in these cities, although Arica (7.2%) and Los Andes (6.1%) exhibit a slightly greater proportion than Coyhaique (5.8%), the latter closer to the national average (5.7%).

TABLE 2 | Sensitivity indicators.

Dimension	Indicator	Description	Year	Data source
Demographic	Dependency ratio	Ratio of population with >65 or <5 years old over the population between 6 and 64 years old.	2018	Instituto Nacional de Estadísticas, 2018
	Women-led household	Proportion of women-led households with presence of person with >65 or <5 years old.	2018	Instituto Nacional de Estadísticas, 2018
	Elderly population	Proportion of population with >65 years old.	2018	Instituto Nacional de Estadísticas, 2018
	Child population	Proportion of population with <5 years old.	2018	Instituto Nacional de Estadísticas, 2018
Socioeconomic	Income poverty	Proportion of households under the Chilean poverty line.	2017	Ministerio de Desarrollo Social, 2017
	Multidimensional poverty	Proportion of households with more than three deprivation on education, health, work, social security, dwellings, or environment.	2017	Ministerio de Desarrollo Social, 2017
	Electricity prices	US$ per kW/h based on the cost of a standard electric bill of 180 kW/h.	2020	Comisión Nacional de Energía, 2020
Infrastructural	Proportion of dwellings constructed before year 2000	Proportion of dwellings constructed before year 2000.	2019	Red de Pobreza Energética, 2019
	Presence of urban vegetation	Proportion of area covered with forest or shrubland according to De Gregorio and Jansen, 2005 classification.	2014	Hernández et al., 2016; Zhao et al., 2016
Technological	Electricity consumption	Electricity regional annual average in kW/h.	2020	Comisión Nacional de Energía, 2020
	Firewood consumption	Firewood regional annual average in stereo meters.	2015	Corporación de Desarrollo Tecnológico, 2015
	Liquified Petroleum Gas consumption	LGP regional annual average in kg.	2020	Comisión Nacional de Energía, 2020
	Proportion of firewood users	Proportion of household users of firewood for heating.	2017	Ministerio de Desarrollo Social, 2017
	Proportion of electrification	Proportion of household with electricity access.	2017	Ministerio de Desarrollo Social, 2017
	Proportion of Liquified Petroleum Gas users	Proportion of households Liquified Petroleum Gas users for heating.	2017	Ministerio de Desarrollo Social, 2017
	Proportion of households without heating devices	Proportion of households without heating devices.	2017	Ministerio de Desarrollo Social, 2017
	Proportion of electrification	Proportion of electrification.	2017	Ministerio de Desarrollo Social, 2017

As for women-led households, all cities share similar proportions as well, not far from the national average of 42%: 44.8% of Arica's households were headed by women, 41.3% in the case of Los Andes, and 43.4% in Coyhaique (Instituto Nacional de Estadísticas, 2018).

These demographic conditions are useful to begin to understand the energy needs present in each city and to identify factors that increase vulnerability of the territory. For example, the higher presence of children and elderly population in Arica and Los Andes could increase negative impacts of heatwaves in present conditions. Also, the presence of women-led households could increase negative impacts of energy prices shocks given the gender income inequalities present in Chile.

Socioeconomic Characteristics

Los Andes and Arica have a 7 and 8.3%, respectively, of households under conditions of income poverty, different from Coyhaique, which stands out with only 2.7% of households living below the national poverty line. According to a multidimensional poverty index (Ministerio de Desarrollo Social, 2017), a different trend is observed as Coyhaique has 18.1% of poor households, Los Andes 11.89% of households living in poverty, and Arica with 21.1% of households. Given the greater presence of poor households in Arica, even though it is still relevant in Los Andes and Coyhaique, energy transition policies (such as PEDs guidelines) should be careful not to increase vulnerability and include equity principles in its design.

Regarding electricity prices (for an average household consuming 180 kW/h) exhibit similar magnitudes in these cities near the national average cost of US$ 0.17 per kW/h. In Los Andes and Coyhaique, prices are slightly higher (US$ 0.18 per kW/h), and Arica cost is slightly lower with US$ 0.16 per kW/h. It is worth noting that these electricity prices are regulated by the Tariff Equity Law designed to transform highly unequal energy

TABLE 3 | Resilience indicators.

Dimension	Indicator	Description	Year	Data source
Flexibility	Energy system integration	Autonomy or integration of energy system.	2020	Comisión Nacional de Energía, 2020
	System Average Interruption Duration Index (SAIDI)	Average duration of electric system interruption.	2018	Comisión Nacional de Energía, 2020
	Dependency	Proportion of domestic demand electricity meet by domestic generation.	2020	Comisión Nacional de Energía, 2020
	Diversity-balance	Shannon-Weaver index of installed electricity generation capacity.	2020	Comisión Nacional de Energía, 2020
	Diversity	Percentages of each energy sources in electricity generation.	2020	Comisión Nacional de Energía, 2020
	Photovoltaic potential	Global horizontal irradiance (KWh/m^2/day).	2017	Ministerio de Energía, 2017b
	Distributed energy	Installed capacity of photovoltaic distributed generation.	2020	Comisión Nacional de Energía, 2020
Memory	Open data portals	Existence of open data portals managed by government institutions.	2020	Comisión Nacional de Energía, 2020
	Quality of open data portals	Comprehensiveness of open data portals	2020	Comisión Nacional de Energía, 2020
	Energy-specific data sources on users	Existence of periodic energy-specific surveys or real-time data through Internet of things technology.	2020	Ministerio de Desarrollo Social, 2015; Comisión Nacional de Energía, 2020
	Quality of energy-specific data sources on users	Comprehensiveness of energy-specific data sources on users.	2020	Ministerio de Desarrollo Social, 2015; Comisión Nacional de Energía, 2020
Self-transformation	Local policies on energy system	Existence of local and participative policies about energy system.	2020	Scientific and gray literature

prices in previous decades, this law reduces prices so that no bill is 10% above the national average (calculated for a standard household with a 180 kW/h monthly bill). Official estimates point out that both Arica and Coyhaique are currently benefited by this measure, with a 16 and 52% reduction in electricity bills, respectively (Ministerio de Energía, 2017a).

Infrastructural and Technological Characteristics

Each city's technological and infrastructural characteristics have social and environmental implications that increase the propensity to energy-related deprivations. First, due to the massive use of high humidity firewood, a higher concentration of particulate material 2.5 ($PM_{2.5}$) is observed in Coyhaique (Red de Pobreza Energética, 2019), reaching an annual average of 39.5 $\mu g/m^3$ in 2019 and at least 92 days of the same year above 50 $\mu g/m^3$ daily average according to the data from the National Air Quality Information System (SINCA). On the same topic, Arica's 2019 annual average was 11.8 $\mu g/m^3$, however, the sources of these particles were related to vehicle emissions and other minor sources. Unfortunately, there are no air quality stations in Los Andes.

In terms of infrastructure, the housing stock built before 2000 was not regulated by nationally thermal enforced from the year 2000, meaning that at least 66% of these buildings suffer from thermal efficiency problems (Schueftan and González, 2015; Red de Pobreza Energética, 2019). This proportion rises to 70% in Arica and Coyhaique, in Los Andes, this proportion is comparatively lower with 50% of the dwellings, but still is a significant number of households. This condition increases the vulnerability to harsh weather conditions (such as extreme cold in Coyhaique, and heatwaves in Los Andes and Arica) as households struggle to cope with unhealthy indoor temperatures.

Coyhaique stands out with 93% of households that use firewood with a higher household consumption (see **Table 4**). The latter is also true for Liquified Petroleum Gas usage, for which Coyhaique also consumes significantly more than Los Andes and Arica. Both of these results can be attributed to the higher base heat demand in Coyhaique households due to climatic conditions (Schueftan and González, 2015; Sarricolea et al., 2017; Red de Pobreza Energética, 2019).

Finally, the proportion of forest or shrubland cover within the city is interesting because a greater presence of urban vegetation reduces heat waves and heat island impacts (Salmond et al., 2016; Zölch et al., 2016). According to the classification proposed by De Gregorio and Jansen (2005) and applied by (Hernández et al., 2016; Zhao et al., 2016), Coyhaique has the highest proportion of its area covered by forest or shrubland, reaching 52%, while Los Andes comprises 14% and Arica only 1% of its total area.

Resilience

Resilience could be observed in emergent properties of energy sociotechnical systems such as flexibility, memory, and self-transformation capacity. The Chilean National Electrical System provides on-grid connections for 14 of the 16

TABLE 4 | Case study sensitivity indicators.

Dimension	Indicator	Arica	Los Andes	Coyhaique	National
Demographic	Dependency ratio	48.9%	46.9%	47.5%	45.9%
	Women-led household	44.8%	41.4%	43.4%	42.0%
	Elderly population	10%	10.8%	7%	10.6%
	Child population	7.2%	6.1%	5.8%	5.7%
Socioeconomic	Income poverty	8.3%	7.0%	2.8%	7.5%
	Multidimensional poverty	21.1%	11.9%	18.1%	14.5%
	Income				
	Electricity prices US$ KW/h	0.16	0.18	0.18	0.17
Infrastructural	Proportion of dwellings constructed before year 2000	71%	49%	70%	66%
	Presence of urban vegetation	1%	14%	52%	–
Technological	Electricity consumption (KW/h)	170	157	153	–
	Firewood consumption (m^3)	1,4	3	17,5	–
	Liquified Petroleum Gas consumption (kg)	68.47	72.1	115.82	–
	Proportion of firewood users	0.6%	28.2%	85.3%	29.2%
	Proportion of electrification	99.2%	100%	99.7%	99.9%
	Proportion of Liquified Petroleum Gas users	4.2%	36.2%	4.3%	27.8%
	Proportion of households without heating devices	92%	10.2%	0.6%	13.4%

regions in the country's continental ground. Autonomous from this large system, Mid-sized Electric Systems are not connected to the National System and supply electricity to smaller and distant cities. Coyhaique is supplied by one of these Mid-size systems (Sistema Eléctrico Aysén, SEA); meanwhile, Arica and Los Andes are part of the National System.

One aspect of resilience related to flexibility is the response capacity of the system. In this regard, Coyhaique had an average System Average Interruption Duration Index (SAIDI) between 2015 and 2018 of 22.8 h; meanwhile, Los Andes and Arica had 10.7 and 15.6, respectively, in the same period. The extreme weather conditions of Coyhaique, where snowstorms are common in winter, are a source of electric interruption; nonetheless, the national average SAIDI of 15.7 suggest that quality of Chilean electric service is low compared to international standard and its vulnerability to diverse kind of hazards results in high interruption duration. The Coyhaique electric source's autonomous condition could amplify the risks if the system is not resilient to the local conditions that it faces.

A second interesting energy system feature is its dependency or autonomy of its installed capacity related to domestic demand. This measure is better understood at a regional scale rather than at a city scale, because given the centralized model of energy generation in the Chilean case, cities are dependent of generation units located outside city borders commonly associated with industrial uses. Hence, regional energy systems have a large impact on the city energy supply's resilience. In this dimension, Arica and Parinacota Region (Arica) have a dependency of −67% of its total electricity consumption, meaning that the 60 GWh produced locally are not sufficient to meet the 185 GWh required to its domestic demand. Even though this city is connected to the National Electric System, given the large distance between cities (for example, between Arica and Los Andes there are ∼2,000 km by road) the operational cost of electric grids could increase if no local generation is secured, moreover, given the greater temperatures projected under climate change scenarios the efficiency of these transmission lines could be dramatically decreased (Burillo et al., 2019).

Aysén Region (Coyhaique) has an external dependency of its electricity consumption of −59% as its 27 GWh produced locally are not capable of meeting the 67 GWh demanded, hence, being an autonomous system, currently, private off-grid self-generation technology helps to overcome this deficit. Valparaíso Region (Los Andes), on the other hand, produces approximately 3.5 times the domestic demand of 4.026 GWh.

A distributed energy system on urban settlements could improve response capacity of the system if its design is coherent with the territory's renewable potential as improve redundancy of energy supply—in addition to reduction of GHG emissions. In this regard, Arica and Los Andes cities have a high photovoltaic potential as the annual average of Global Horizontal Irradiance is 5.7 and 5.75 KWh/m^2/day, respectively. Coyhaique is far behind with 3.45 KWh/m^2/day, well below the national average of 4.96 KWh/m^2/day (Ministerio de Energía, 2017b). This geophysical condition can explain that the present distributed potential capacity of Arica is 471.4 KW, Los Andes 393 KW, while Coyhaique only sum a total of 25.5 KW (Comisión Nacional de Energía, 2020). This aspect is relevant to PEDs oriented policies in these cities given that northern regions of Chile (e.g., Los Andes, Arica) have high photovoltaic generation potential, even at a global scale.

Another aspect of flexibility relates to the diversity present in the energy matrix of each system (Molyneaux et al., 2012, 2016; Binder et al., 2017). Shannon-Weaver index (Binder et al., 2017) of these three cities describes that Aysén Region (Coyhaique) installed electricity capacity is the less diverse of the three regions compared with 0.37 index (where 0 means no balance and diversity, and 1 the opposite), followed by Arica and Parinacota Region (Arica) with 0.46 and Valparaiso (Los Andes) with a 0.57 Shannon-Weaver balance/diversity index. This is caused by the importance of Diesel generation in Aysén and Arica and Parinacota with 54 and 41% of the total installed capacity, respectively (see **Table 5**). In both cases, the second most important electricity source is mini-hydro generation with 39 and 33%, respectively. On the other hand, Valparaiso Region has a more diverse electricity generation matrix with Natural Gas, Coal, and Diesel as its main source (46, 24, and 18%, respectively).

The relative importance of renewables in the Chilean energy matrix is increasing faster than expected, hence, the observed 25% of photovoltaic solar generation in the Valparaíso Region and the 5% of wind power generation observed in Arica and Parinacota. Although it is crucial that renewables become the main energy source worldwide to reduce GHG emissions, it is also vital to ensure that its variability does not pose a vulnerability to the energy system but as a source of diversity and sustainability.

Other dimension of resilience relates to the capacity to store, publish, and learn from diverse kinds of data sources about the energy sociotechnical system's functioning. In this regard, official open data platforms such as www.energiaabierta.cl or www.energiaregion.cl display a large quantity of information at national and local scale about installed capacity, generation, energy prices, among other crucial information about electricity and LPG. Nonetheless, there is a large gap on open demand-side information such as residential, commercial, or industrial consumption.

Data surveys about residential use are applied bi-annual at commune scale, in the case of de Socioeconomic Characterization Survey (Ministerio de Desarrollo Social, 2017), but only consider information about energy sources chosen by households and not about quantity, expenses, technological characteristics, among others crucial data to estimate residential consumption and access. Other relevant household surveys include a detailed view of energy consumption, technological and dwelling characteristics, even about informal markets such as firewood consumption, nonetheless, their application occurs sporadically and led by private consultants (Corporación de Desarrollo Tecnológico, 2010, 2015, 2019). Smart meters, capable of producing real-time data, are still reduced to a small percentage of users and policies to installed this kind of technology have faced major public scrutiny (Revista Electricidad, 2019).

Data about other kind of consumers—public, commercial, or productive uses—are less accessible than residential data, even at aggregated level. In this regard is relevant to note that energy models used to evaluate energy policies in Chile, such as climate change mitigation plans, rely heavily on assumptions of energy consumption rather than empirical data (MAPS Chile, 2014; Centro de Energia, 2019).

TABLE 5 | Case study resilience indicators.

Dimension	Indicator	Arica	Los Andes	Coyhaique
Flexibility	Energy system integration	National Electric System	National Electric System	Mid-Size Autonomous
	System Average Interruption Duration Index (SAIDI) 2014-2018	15.6	10.7	22.9
	Dependency	–67.57%	27.8%	–59.70%
	Global Horizontal Irradiance (KWh/m^2/day)	5.7	5.75	3.45
	Photovoltaic distributed generation (KWh)	471.4	393	25.5
	Diversity-Balance	0.46	0.57	0.37
	Proportion of diesel electricity installed capacity	41.5%	18.5%	54.1%
	Proportion of coal electricity installed capacity	–	24.9%	–
	Proportion of solar electricity installed capacity	25.1%	3.7%	–
	Proportion of wind electricity installed capacity	–	–	5.8%
	Proportion of Natural Gas electricity installed capacity	–	46.2%	–
	Proportion of hydroelectricity installed capacity	33.2%	0.08%	39.9%
Self-transformation	Local policies on energy system	In process	Local energy strategy	Local energy strategy

The third dimension of resilience proposed in this article relates to the capacity to self-transform the energy sociotechnical system's structure and components. This dimension is closely linked to governance and political system, hence on of the aspects to analyze is the presence of policies oriented to regulate and transform the actual energy sociotechnical system. One of these policies in the Chilean context is called Local Energy Strategy, which comprises a detailed participative diagnostic on the city's energy system, consumption, access, and energy potential. This instance could enhance local governance of the energy system in the context of a highly centralized political system. Both Los Andes and Coyhaique have already defined a Local Energy Strategy which highlight some of the aspects already exposed in this article (Municipalidad de Coyhaique, 2014; Municipalidad De Los Andes, 2017).

On this topic is relevant to mention the recent failure of a massive change of electricity meters to smart ones due to public rejection of the project, mainly because public opinion refused to the idea that households would have to pay for its installation costs (Revista Electricidad, 2019). On the contrary, "Energy 2050" was a relatively successful long-range participative policy construction where private, public, and scientific actors engaged together in a forecasting exercise that built a broad image of energy system development in Chile and is still legitimated for most of stakeholders as a guideline (Urquiza et al., 2018).

DISCUSSION

The results presented above show how climatic, demographic, economic, infrastructural, technological, and institutional variables combine into very different profiles of TEV across the three case studies.

Arica is the largest city analyzed where sensitivity characteristics related to the presence of age vulnerable population (both children and elderly), higher proportion of both income and multidimensional poverty and as an older city, most housing stock was constructed without regulation. Resilience capacity in this city seems to be transforming as renewable electricity generation (solar and hydro) covers up to 74% of total installed capacity and is expected to grow over time (Ministerio de Energía, 2015). Nonetheless, its dependency on the national electric system to meet its domestic demand could be a source of risk if climate change impacts or socio-natural disasters compromise its integration. These issues should be considered in its current process to define the Local Energy Strategy to increase the city's response and adaptive capacity and enhance the energy transition process. Distributed photovoltaic potential of this city is higher compared to national average, and the inclusion of PED concept into local policies could increase its autonomy and redundancy.

Los Andes has a similar demographic profile to Arica, but the former's population size and poverty incidence (both income and multidimensional) are smaller. As only 49% of its housing stock was built before the year 2000, Los Andes could be an example of recent developed cities in Chile under new dwelling regulation. There are large and diverse electricity generators near this city. Its service interruptions index is the smaller of these three cities, and its resilience capacity looks well-suited to confront climate change and socio-natural disaster impacts. However, this condition is explained as other mid-size cities, and large metropolises (such as Valparaíso and Santiago) are located near and depend on the same generation, hence its capacity should be planned to integrate all of this growing cities. On the other hand, its dependency on fossil fuel-based electricity generation could endanger this capacity as a major transformation is required to meet NDC Chilean compromises on GHG emissions (Gobierno de Chile, 2020). In this regard, PED could become a transformative guideline to benefit from the photovoltaic potential and increase distributed energy importance.

Coyhaique is the smaller and is the one who faces the coldest weather conditions of these three cities. Although the presence of age vulnerable population (elderly and children) and income poverty is smaller, probably due to the same harsh weather condition, the multidimensional poverty incidence could be symptomatic of a different kind of sensitivity. The large thermal energy demand and low quality of buildings could explain the massive use of firewood as a heating energy source (Red de Pobreza Energética, 2019) and the high PM2.5 concentrations in this city. On the other hand, the autonomous condition of its electricity generation and high service interruption could express the energy system's difficulties in adapting to its harsh environment. This antecedent could endanger economic development and energy transition trajectories as user untrust of the electrical system causes rejection of electric-based heating technologies.

These profiles translate into significantly diverse conditions of sensitivity and resiliency of the three cities to various possible disturbances that may arise in the future and endanger the provision of energy services. Also, a territorial assessment based on TEV concept can better inform PEDs policies in multiples aspects. First, it can help identify crucial sensitivity conditions to avoid policies that may inadvertently increase inequality and causes negative impacts on population wellbeing. For example, in the case of Arica and Los Andes the presence of children and elderly population and its vulnerability to heatwaves. requires specific planning to protect these groups. Second, it may contribute in describing preexisting gaps (technical, economical, informational, etc.) necessary to face before beginning a process of PED implementation, For example, the dependence on private off-grid self-generation in Coyhaique to satisfy the local energy demand need to be addressed in early stages of PED projects. Third, it may offer a baseline assessment of response and adaptive capacity (resilience) of the energy system and possible indicators of the positive impact of PED model, for example, to increase the learning capacity of a territory implementing better data acquisition on consumers, ideally on real-time, to improve decision making and efficiency of energy system management. This territorial scale assessment, hence, could enhance the integrated view of energy system present in PEDs literature by describing the preexisting vulnerability conditions.

CONCLUSION

Adopting a territorial, system-based outlook on energy poverty and energy transition is a necessary step to advance a more integral understanding of energy security, one which recognizes the contextual conditions that influence both energy uses and the processes of sociotechnical provision, and that acknowledges the potential impacts of diverse hazards in maintaining equitable access to energy for all. A deeper attention to the territorial and spatial conditions that determine the range of energy and technological alternatives available in a territory, and their vulnerability to hazards and stresses, is necessary to advance toward a just, sustainable and resilient energy transition to a decarbonized economy. Within cities, in particular, this may support a more contextualized and spatially-aware approach to the integration between urban planning and energy development in general, and to the deployment of Positive Energy Districs and PENs policies in particular.

To contribute to this challenge, the article proposed a framework based on the concept of TEV, defined as the propensity of a territory to not guarantee equitable access—in quantity and quality—to resilient energy services that allow the sustainable human and economic development of its population. In particular, the paper proposed and illustrated by a case study of three Chilean cities crucial sensitivity and resilience indicators to assess preexisting gaps in energy access and resilience of energy services within urban spaces.

Since most of the factors observed relate to the daily provision of energy services, it can also work as a proxy of *present* capabilities to satisfy energy needs. As such, it is a very useful complement to traditional energy poverty analysis, based on indicators of energy affordability, access, or quality (Urquiza et al., 2019). While energy poverty focuses on *expressing* energy deprivation, TEV describes the underlying systemic conditions which may *explain* or *anticipate* such deprivation.

In terms of a just transition to sustainable cities based on PED guidelines, the contribution of our proposed approach is two-fold: first, in visualizing structural inequalities relating to energy deprivation, it contributes to making a stronger case for the need for a deep transformation of the energy regime: a transformation motivated not only by the need to decarbonize the energy matrix but also by the imperative of ensuring access to affordable, reliable, and sustainable energy for all, as implied in sustainable development goals (United Nations, 2015). Second, it pushes to reflect both on the possible dangers which may befall the transition effort—potentially hampering its results—*and* upon the risk that the transition itself can have on energy deprivation: as shown by previous research (Reyes et al., 2015; Bouzarovski and Tirado Herrero, 2017b; Frantál and Nováková, 2019; Urquiza et al., 2019; van der Wiel et al., 2019; O'Sullivan et al., 2020). If not properly planned, transitions may end up worsening—instead of alleviate—existing conditions of inequality, particularly among the most sensitive groups and sectors, and/or in territories showing the lower resiliency to change.

Moreover, because it takes the territory as its fundamental unit of analysis, the framework can provide an outlook of the differential distribution of energy deprivation across different territories. Therefore, it relates both to strands of literature that have attempted to identify climate and geographical drivers of energy poverty (Katsoulakos and Kaliampakos, 2016; Besagni and Borgarello, 2019; Ioannidis et al., 2019) and those striving to spatialize energy deprivation (Bouzarovski and Simcock, 2017; Bouzarovski et al., 2017; Robinson et al., 2019). Hence, it offers a strong analytical platform to deepen our understanding of different manifestations of energy deprivation that may occur outside the household boundary (Wolf et al., 2016; Mattioli et al., 2019). Along these lines, it is our contention that the TEV approach offers a powerful and flexible platform to advance toward a better understanding of forms of energy deprivation occurring outside the household (Mattioli et al., 2019). Future studies may extend the work presented in this paper by complementing the framework with indicators explicitly tackling technological, economical, or socio-cultural barriers to a full and equitable access to high-quality energy services within educational, health-related, and other social and productive uses, as suggested by Urquiza and Billi (2020). Likewise, an interesting future avenue of research may involve combining traditional energy poverty analysis and the TEV framework, exploiting the two approaches' complementarity while contrasting the descriptions of the energy deprivation they provide.

Before concluding, a warning must be raised about information requirements: the TEV approach is way more demanding in terms of data concerning traditional energy poverty indicators. We do not consider this a drawback, however. While in our case studies, we could only apply a fraction of the variables identified in our framework, the results were highly informative concerning differential patterns of sensitivity and resilience across the examined cities. On the other hand, outlining an ambitious yet operable analytical framework may signal the need to develop more data to provide a more complete picture on territorial energy processes and their impacts on energy deprivation, a requirement already pointed out by existing literature on energy poverty spatialization (Bouzarovski et al., 2017).

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: Ministerio del Medio Ambiente (2020). Proyecto Atlas Riesgos Climáticos (ARClim). https://arclim.mma.gob.cl Ministerio de Desarrollo Social (2015). Encuesta de Caracterización Socioeconómica (CASEN). http://observatorio.ministeriodesarrollosocial.gob.cl/ Ministerio de Desarrollo Social (2017). Encuesta de Caracterización Socioeconómica Nacional (CASEN). http://observatorio.ministeriodesarrollosocial.gob.cl/ Comisión Nacional de Energía (2020). Energía Abierta. http://energiaabierta.cl/ Instituto Nacional de Estadísticas (2018). Censo de Población y Vivienda 2017. https://www.ine.cl/estadisticas/sociales/censos-de-poblacion-y-vivienda.

AUTHOR CONTRIBUTIONS

RC, CA, MB, and AU: conceptualization, methodology, investigation, writing—original draft, supervision, and funding acquisition. MF: conceptualization, methodology, investigation, and writing—original draft. NA and JN: methodology, investigation, and writing—review and editing. All authors contributed to the article and approved the submitted version.

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Local Culture and Urban Retrofit: Reflections on Policy and Preferences for Wall and Roof Materials

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Retrofitting strategies aim to reduce environmental footprints promoting the development or upgrade of existing infrastructure. One crucial aspect of successful retrofitting strategies is local culture, which can harmonise or come into conflict with retrofitting initiatives. However, investigations on the influence of local practises, particularly in the global south, are limited and such influence deserves more attention. This article explores the connexion between local culture and retrofitting strategies, focusing on wall and roof material selection in the Metropolitan Valley of Oaxaca in Mexico (ZMVO). We begin with a brief review of the retrofitting initiatives at related governmental levels. Then, through a survey, we analyse the choices and reasons for selecting specific materials for walls and roofs in the ZMVO. We discuss to what extent cultural practises and preferences have been considered or left behind in the strategies and ensuing challenges. The findings confirm important premises. First, tradition and community support were not relevant factors in wall or roof material selection. Material reuse, energy efficiency, and sustainability-related reasons were also not essential to the preferences. Instead, protection (against rain, earthquakes, theft and accidents), hygiene, and aesthetics had a consistently higher priority. We also found that poverty or lack of other options intersects with the use of precarious materials, creating constrained choices. However, the most crucial finding was that choosing less environmentally or culturally compatible materials was strongly connected with deprivation, having important implications in the selection of materials and retrofitting strategies. The current retrofitting initiatives call for sustainability and efficiency, but the local practises render these efforts insufficient and incoherent. Poverty and informal housing are the main emphases of the local policy. However, the policy focuses on new infrastructure and much less on the existing housing, causing less efficient retrofits. Guidelines for more sustainable material selection have advanced, but regulation and enforcement remain weak. We conclude by discussing all these challenges and providing a set of recommended actions in new initiatives.

Keywords: retrofitting, social inclusion, low-carbon transitions, urban retrofit, local culture, building enclosure, policy, Global South

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INTRODUCTION

One key strategy for achieving ambitious carbon and energy reductions is urban retrofitting. Retrofitting refers to the development or upgrade of the existing infrastructure of a city or region to reduce energy consumption (Dixon and Eames, 2013). Retrofitting strategies cover diverse aspects of low-carbon reconfigurations on houses, buildings, and common areas (Dixon, 2014). These focus on resilience, security, and ecology (Eames et al., 2014; Hodson and Marvin, 2017). By upgrading materials and incorporating more efficient technologies, energy and carbon emissions are curtailed (Gupta and Gregg, 2016).

Urban centres have the greatest potential for retrofitting strategies because they have the highest energy consumption rates. Therefore, retrofitting literature has placed considerable interest on it, focusing on new dwellings in urban cores and the periphery of cities (Eames et al., 2013). However, there is less attention on the redevelopment of existing suburbs (Dunham-Jones and Williamson, 2008), and urban retrofitting perspectives from the global south, which are increasing but insufficient compared to higher-income nations (Silver, 2014).

The perspective from rising urban centres in developing countries requires presence because of the potential environmental stress from their growing economies and populations (Cohen, 2006). In most of these contexts, existing infrastructure in the suburbs is also more critical, given the more informal settlements. Some factors can also undermine retrofitting strategies, such as pressures associated with poverty, economic development, land use, and governance (Dixon et al., 2018). Culture could be another type of pressure, given that retrofitting initiatives can come into conflict with socio-cultural elements (Sunikka-Blank and Galvin, 2016; Khalid and Sunikka-Blank, 2017). Nevertheless, many retrofitting initiatives overlook this, and it has surprisingly received little attention in academic literature (Opoku, 2015; Rau et al., 2020).

One crucial perspective for retrofitting literature from the developing world is Latin America (LA). LA has two of the five largest megacities (Mexico City and São Paulo) and large populations living in smaller urban centres (Vargas et al., 2017). Secondary cities[1], in particular, are expected to grow rapidly, but a large percentage of households still have inadequate materials and other deficiencies that retrofitting policy should address. However, the unique peculiarities of local contexts are neglected, and the experience in larger cities are ignored (Gillich et al., 2018). Furthermore, rural traditions in smaller urban settings are usually decisive in local practises. For example, the use of fuelwood for cooking, the mixed provision of space and water heating with cooking, or the use of adobe[2] and other traditional materials are commonplace. Climate is also varied, resulting in a wide diversity of contexts where policy should be implemented (Tahsildoost and Zomorodian, 2020).

For cities in southern Mexico (Oaxaca, Guerrero, and Chiapas) further challenging conditions exist. Deficient housing intersects with informal employment (Alvarado Juárez, 2008) and poverty (CONEVAL, 2020) in contexts of indigenous presence. Thus, understanding local practises and preferences in selecting household materials and in the provision of energy services is essential for retrofitting strategies.

A growing literature has demonstrated how the behaviour of inhabitants of residential buildings affects energy use (Stephenson et al., 2010; Gram-Hanssen, 2014). Activities, expectations, aspirations, and social contexts of everyday life can significantly influence energy consumption (Stephenson et al., 2015; Rau et al., 2020), and this knowledge has significant consequences on the success of retrofitting policy (de Feijter et al., 2019; Stephenson et al., 2021). However, the study of such connexions in the global south is not as solid, particularly in mid-sized cities.

Based on the above, this article explores the role of culture and preferences in designing locally-oriented retrofitting strategies. We focus on a middle-sized ethnically diverse metropolitan area with a rising economic activity: the Metropolitan Area of Oaxaca City (ZMVO in Spanish), i.e., the city of Oaxaca de Juárez and 22 surrounding municipalities.

We start with a review of the principal retrofitting policies at different government levels. Then, we analyse preferences that could explain the reasons for using certain materials in walls and roofing in the urban core and suburbs within the ZMVO. For this, we design a questionnaire based on the national energy consumption survey (INEGI, 2018b) with additional items on the preferences for material selection (economic, environmental, safety, aesthetics, hygiene, tradition, and community support among others). Then, we survey households and finalise discussing the results in light of relevant retrofitting literature, centring on the role of the local culture in retrofitting strategies.

METHOD

Methodology

To investigate local culture in retrofitting strategies in the ZMVO, we adopt a two-stage methodology. We first review the retrofitting policy in Mexico at the three levels of government—the federal, the state, and the metropolitan levels—to identify all retrofitting initiatives. Details are provided in section Retrofitting Policy Review Process. We then survey the preferences in selecting wall and roof materials—the design of a questionnaire and the survey are detailed in section Questionnaire for Wall and Roof Material Preferences. We conclude by discussing the findings from both policy and local preferences and the implications for retrofitting policy design.

Retrofitting Policy Review Process

We review retrofitting policies through the core documents related to housing features, materials, and household energy efficiency in Mexico. We include governmental plans, guidelines and regulations related to housing, national standards directing the use of materials, and the most updated governmental policies for construction and retrofitting strategies. This information is summarised at the federal, state and municipal level, emphasising the local initiatives.

[1] Officially, UN-Habitat defines a secondary city as an urban area with a population of 100,000 to 500,000 (Bermudez et al., 2019).

[2] Adobe is a traditional clay material widely used in Mexican temperate regions.

TABLE 1 | Principal reasons hypothesised in the selection of wall and roof materials.

Factor group		Reasons for selection (factors)
1	Economic	Low cost
2	Practical	Easy/fast to build
3	Protection	Protection against natural disasters, accidents, animals
		Protection against theft
4	Hygiene, maintenance	Hygienic or cleaner
		*Waterproof (only for roofs)
5	Aesthetics	Visually beautiful
6	Tradition, local community	To follow a tradition
		To support my community
7	Constrained selections	Already there
		No other option in the community
8	Environment	Reuse of materials
		Energy efficiency

Questionnaire for Wall and Roof Material Preferences

We then surveyed the preferences for wall and roof materials in the ZMVO in October and November 2020 using Qualtrics® XM Software, which has a built-in location and time tracking to filter responses outside the target location.

The questionnaire comprised 29 items structured in four main sections:

1. Background information of respondents (sex, ethnicity, education, occupation, etc.).
2. General information about the household (income, location, size, type, rooms, electric and water supply).
3. Wall materials, reasons for the choice, and wish/motivations for change.
4. Roof materials, reasons for the choice, and wish/motivations for change.

The questions in the first and second section, as well as those inquiring about the type of walls and roof materials, were similar to the ones in the National Household Survey (ENIGH) (INEGI, 2018a) and the National Survey on Energy Consumption in Households (ENCEVI) (INEGI, 2018c). Using these official databases simplified the design of these items and helped to corroborate the obtained sample. The types of materials can be classified into five groups for walls: (1) concrete and cement, (2) bricks and stones, (3) adobe and earthy organic materials, (4) wood, and (5) sheets (metal or asbestos); and for roofs: (1) concrete and cement, (2) tiles, (3) thatching, (4) wood, and (5) sheets (metal or asbestos).

The additional questions on the selection of wall and roof materials were the focal content of the analysis. We designed these questions using twelve/thirteen factors hypothesised as principal reasons for selection, classified in eight large groups (**Table 1**). The first group encompassed economic reasons. The second, perceptions that the material is practical for use or in the construction. Third, concerns on protection against natural disasters, theft, accidents or wild animals. Fourth, concerns on hygiene and maintenance of the material. Fifth, related to aesthetics and visual beauty. Sixth, involving tradition or local community support. Seventh, related to constrained selections, such as roofs and walls already built with those materials or lack of other choices locally. Finally, eighth, related to energy efficiency, reuse of materials or any other aspect. Respondents were asked to select the five most meaningful and rank them in importance using the "Pick, Group, and Rank" question type in Qualtrics XM (Qualtrics, 2020). For a complete summary of all the questionnaire items, please refer to **Supplementary Table 1**.

To collect the data, we utilised a non-probability sampling frame and verified it with official statistics. Although we initially intended to bring an equal representation of materials in the sample, given the difficulty to obtain data with an increasing rate of COVID-19 infections in the ZMVO during collection, we opted for a chain-referral method. A group of students from the Universidad Tecnológica de los Valles Centrales de Oaxaca (UTVCO) acted as volunteers to recruit respondents through their local contacts. This sampling choice could ultimately represent respondents with similar backgrounds and consequently possible bias. However, the proportions of demographics, household types, and materials were verified after collection to guarantee the reliability of the sample. This procedure consisted of comparing the proportions with the official statistics mentioned above.

RESULTS

A Brief Review of Retrofitting Strategies in Mexico

Having reviewed the main retrofitting initiatives in Mexico, it is noticeable that institutional interest in housing has a long history. However, the strategies feature a few concerns on local culture and the environment. The concept of sustainable housing has only appeared recently in policy, but more specific and localised guidelines are still needed, as well as further considerations about local culture. This brief review will provide the basis for these findings.

Retrofitting in Federal Government Policy

The first mention of housing in Mexican laws appeared in the national constitution of 1917, in which housing was declared a mandatory benefit (Villar Calvo, 2007). However, it was not until the 1970's that it materialised institutionally with the creation of the Institute of the National Housing Fund for Workers (INFONAVIT) and the Housing Fund of the Institute of Social Security and Services for State Workers (FOVISSSTE). Today, both entities are the principal governmental institutions responsible for developing public housing (CESOP, 2006), supervising the construction by public and private companies.

Environmental and cultural reforms, on the other hand, have appeared only recently. The first amendment to the National Housing Law in 2006 made it mandatory to promote the utilisation of housing materials abiding by national standards (CESOP, 2006), including those adequate for maintaining cultural identity to retain local singularities and diversity (Article

TABLE 2 | Maximum thermal transmittance (U-values) in Mexico (CONAVI, 2017).

Element	U value [W/m^{2}K]
Roofs	0.2725
Walls	0.3633
Walls in "very dry,", "dry," and "semi-dry" climates	0.70

TABLE 3 | Maximum thermal transmittance (U-values) in selected countries (EURIMA, 2018; Ahlers et al., 2019).

Country	U-Value walls [W/m2K]	U-Value roofs [W/m2K]
Mexico	0.3633–0.7	0.2725
Sweden	0.18	0.13
UK	0.25–0.35	0.13–0.20
Germany	0.3	0.2
Austria	0.35–0.5	0.2–0.25
France	0.36–0.4	0.2–0.25
Italy	0.46–0.64	0.43–0.6
Spain	0.66–0.82	0.38–0.45
Belgium	0.6	0.4
Portugal	0.5–0.7	0.4–0.5
Greece	0.7	0.5
Macedonia	0.9	0.6–0.65

6 part VII). In June 2017, a subsequent reform explicitly emphasised "material quality" and introduced the idea of "sustainable housing" (ONNCEE, 2017). However, the concept of sustainability was not accompanied by a specific definition or notion related to in-use materials or energy efficiency. In a general sense, these reforms have incorporated cultural and environmental concerns, but more specific guidelines were needed to define strategies in different contexts.

In 2017, the federal government, together with the IFC (International Finance Corporation), developed the National Edification Code (CEV for its Spanish acronym) (CONAVI, 2017), established as the primary guideline for housing projects. CEV is the latest attempt to bring together domestic normative and locally adapted international standards for construction and retrofitting. The latest edition states that the selection of the housing construction's materials should be in accordance with bioclimatic zones—a significant step forward due to its recognition of the climatic diversity affecting household materials (Herrera, 2018). According to the CEV, the ZMVO has a template sub-humid climate (CONAVI, 2017), and the values for optimal thermal comfort and recommended electricity savings must comply with the maximum thermal transmittance factors (U values) in **Table 2** (CONAVI, 2017). As shown in **Table 3**, these requirements are similar to international standards (Atanasiu et al., 2014). However, the code is not compulsory, and the actual thermal transmittance of diverse materials in local households has an extreme variation (**Table 4**).

Other joint programs related to retrofitting strategies between the federal government and foreign institutions exist. The EcoCasa program has promoted sustainable housing

TABLE 4 | Thermal transmittance of diverse materials in Mexican households.

Material	U-value [W/m^{2}K]	Reference
Concrete/cement	0.53	Guillén Guillén and Vélez, 2020
Red Brick	0.814	Guillén Guillén and Vélez, 2020
Adobe	0.46 – 0.81	Moscoso-Cordero, 2016
Wood	0.13	Guillén Guillén and Vélez, 2020
Thatching	0.137	Guilln Guilln et al., 2018

construction through a series of guidelines since 2010 (Infante et al., 2018). The Green Mortgage has incorporated clean technologies in low-income houses since 2011 (Infante et al., 2018). Moreover, the National Appropriate Mitigation Actions (NAMA) set greenhouse gas mitigation guidelines for existing housing in 2013 (Muñoz Torres, 2016).

Despite all these efforts, substantial challenges persist. The Mexican housing sector accounts for 32% of Mexico's GHG emissions, 16.2% of the total energy and 26% of the total electricity consumption. The government estimates that 33% of the units would require partial to total retrofitting by 2030 (SEDATU, 2014). Meanwhile, the enforcement of the housing laws is difficult, particularly among new and existing private housing for which retrofits usually occur without even knowing the norms. Overall, retrofitting laws and norms seem very well-structured at a document level, but the application of regulations is problematic.

Retrofitting Strategies at the State Level (Oaxaca)

State-level governments adopt the federal housing initiatives, but the marginalised socio-economic conditions might explain an insufficient regulatory control. Furthermore, the state-level review here demonstrates that few policies are created following the local context.

Oaxaca is one example of a culturally diverse state with contrasting conditions. Divided into 570 municipalities, Oaxaca is the entity with the largest number in Mexico. Around 34% of the population can speak an indigenous language, and roughly half of its population lives in cities (INEGI, 2021). However, 94.2% of the municipalities (537) concentrate more than 50% of the population living below the poverty line (Miguel-Velasco et al., 2017), and only 33.2% of the houses have access to basic services, namely electricity, water and sewage (Miguel-Velasco et al., 2017).

The state government sets the housing objectives and strategies in the Strategic Housing and Basic Services Plan (Oaxaca, 2016), which adopts federal housing strategies. It states that "the promotion of new housing or improvements should guarantee access to legal, decent and quality housing with infrastructure and basic services, particularly for regions lagging behind." More specific strategies mandate that housing improvement and new housing incorporate "adequate and safe" materials. Nevertheless, precise guidelines about the type of materials are not available. Moreover, the guiding principle of the plan seems to concentrate on reducing the large percentage of housing shortages (Oaxaca, 2016). For example, there are specific targets to reduce 1.9% of "poor" housing at the state level, and retrofitting targets are between 0.5 and 1%. Other strategies are inexistent, especially related to the cultural diversity in the state.

Concerning the regulation, there is a Housing Law in Oaxaca from 2009, but it makes no remarks about materials or sustainable housing (Oaxaca, 2009). In principle, the CEV is the guiding document for household expansion, and potentially, local retrofitting policy.

On the other hand, migration in Oaxaca plays a critical if indirect role in retrofitting practises. Migrants send remittances to relatives for house maintenance and acquisition. From the 570 municipalities in Oaxaca State, 92.8% reported having people working abroad (United States of America) sending money to their families (Cervantes, 2018). It is plausible that these funds are greater than the local budget of initiatives. As a result, government strategies do not have the same reach as the help from migrant relatives to lower-income households.

As noted above, state-level strategies adopt the cultural and environmental concerns found at federal level, but the ethnic and climatic diversity calls for differentiating policies at this level. However, specific policies customised to the varied contexts within Oaxaca are not available.

Retrofitting Strategies in the ZMVO

At a more local level, state laws and regulations are followed, but local strategies related to retrofitting in the ZMVO could not be found.

The ZMVO is composed of 23 municipalities once separated and now merged (see **Table 5**). In the latest census (2015), the total population was 676,400, having grown 4-fold from 1980 to 2015. Land use in the ZMVO has also dramatically increased 15 times (from 836 to 13,000 Ha) during the same years (SEDATU, 2014). This rapid expansion has drastically raised land and housing prices to the extent that it is now the second-highest in Mexico (Miguel-Velasco et al., 2017). Consequently, large informal settlements exist in the outskirts, which are lower-value areas. Given this, housing plans in the ZMVO focus on land use planning and urbanisation over other concerns, including local culture or the environment. For that purpose, the above-mentioned "Strategic Housing and Basic Services Plan" (Oaxaca, 2016) is adopted as the master plan. ZMVO municipalities also have to follow the State Housing Law and the CEV (Mexico, 2006). Meanwhile, one study estimates that housing and retrofitting activities produce 320,000 tonnes of CO_2 per year in the ZMVO (Miguel-Velasco et al., 2017), suggesting substantial environmental impacts.

On the other hand, a unique vernacular architecture was once characteristic of the ZMVO (Torres Zárate, 1999). According to the International Council on Monuments and Sites, it was "the traditional and natural housing way in which communities continuously adapt to social and environmental constraints" (ICOMOS, 1999). This traditional architecture used stone foundations with adobe walls; during colonial times, it also incorporated other materials such as tile roofing and wood to improve resistance. During the latter half of the twentieth century, and particularly in the last decades, scarcity of local materials, e.g., wood and adobe, and the incorporation of more commercial ones, namely concrete blocks, have influenced the gradual loss of these traditions. Moreover, the considerable rate of migration in Oaxaca also influences the selection of materials for housing. It is common for migrants to provide the funds to retrofit houses and suggest using some materials that are not easy to find locally. Such modifications have created hybrid constructions with reduced climatic compatibility (Zafra Pinacho, 2009).

TABLE 5 | ZMVO composition and population in 2015 (INEGI, 2016).

	Municipality	Population
1	Ánimas Trujano	3,917
2	Cuilápam de Guerrero	21,597
3	Oaxaca de Juárez	264,251
4	San Agustín de las Juntas	9,342
5	San Agustín Yatareni	4,334
6	San Andrés Huayápam	5,336
7	San Antonio de la Cal	23,038
8	San Bartolo Coyotepec	9,105
9	San Jacinto Amilpas	15,720
10	San Lorenzo Cacaotepec	15,735
11	San Pablo Etla	15,993
12	San Pedro Ixtlahuaca	8,561
13	San Raymundo Jalpan	3,336
14	San Sebastián Tutla	18,195
15	Santa Cruz Amilpas	12,814
16	Santa Cruz Xoxocotlán	93,188
17	Santa Lucía del Camino	49,459
18	Santa María Atzompa	34,115
19	Santa María Coyotepec	2,971
20	Santa María del Tule	8,918
21	Santo Domingo Tomaltepec	2,988
22	Tlalixtac de Cabrera	10,208
23	Villa de Zaachila	43,279
	Total	676,400

In sum, the strategies summarised above demonstrate that few concerns have been raised about local culture or the environment at a more local level. More specific and localised guidelines are also needed. **Table 6** summarises the main strategies at different government levels.

Cultural Preferences for Housing Materials in the ZMVO

Having outlined the main retrofitting strategies applicable to the ZMVO, the evaluation of preferences in selecting walls and roof materials demonstrated that tradition, community support, and even environmental concerns are not among the main reasons for selecting wall and roof materials in the ZMVO. Instead,

TABLE 6 | Summary of retrofitting strategies in Mexico.

Normative/Policy	Latest revision	Application/type	General description
Ley de Vivienda National Housing Law	2019	Federal level/mandatory	Establishes and regulates national housing policies, instruments and programs related to housing development
CEV National Edification Code	2017	Federal to municipal level/optional	Provides the guidelines for designing safe, efficient and sustainable housing in the urban context, considering all existing normative (NMX and NOM)
NMX-AA-164-SCFI-2013 Sustainable buildings—criteria and minimal environmental requirements	2013	Federal to municipal level/optional	Establishes the environmental criteria and requirements in order to promote the mitigation of environmental impacts
NOM-020-ENER-2011 Energy efficiency in buildings: housing building enclosure	2011	Federal to municipal level/optional	Establishes the limits of heat gain in the building envelope to ration energy consumption in cooling systems
NOM-018-ENER-2011 Thermal insulators for buildings: characteristics and testing methods	2011	Federal to municipal level/optional	Establishes the characteristics and testing methods that materials must comply with for utilisation on roofs and walls for buildings
NMX-U-125-SCFI-2016 Building-Construction Industry. Roofing Coverings for High Solar Reflectance Specifications and Test Methods	2016	Federal to municipal level/optional	Establishes the characteristics and testing methods that materials must comply with to have "High Reflectance Solar Roof Covering"
Ley de Vivienda para el Estado de Oaxaca Oaxaca State Housing Law	2009	State level/mandatory	Establishes the mechanisms for urban and rural social housing development. Regulates private and public housing construction.
Ley de Desarrollo Urbano para el Estado de Oaxaca Oaxaca State Urban Development Law	2013	Federal and Municipal/mandatory	Regulates land and population settlements at state and municipal levels

protection and constrained choices due to poverty or lack of options had a more prominent place in the local preferences.

The survey conducted in the ZMVO gathered a total sample of 451 questionnaires with 77.3% valid samples (365). Responses from Oaxaca City were the largest share (25%) followed by Villa de Zaachila (14%), Santa Cruz Xoxocotlán (8%), and Santa Lucía del Camino (7%). The least represented municipalities were San Andrés Huayápam, San Agustin Yatareni, and Animas Trujano (all below 1%).

The sample was primarily composed of young adults (mean age 30) with low to mid-income levels and mid to high levels of education. The proportions between males (43%) and females (57%) were balanced, and most respondents had a high school education or above (85%). More than half (66%) were working professionals. Half of the reported incomes were between 85 and 367 USD per month (1,667 to 6,666 pesos), corresponding to a typical lower to mid-income level in the ZMVO. Finally, 46% identified as ethnically indigenous and 35% as mixed-race.

The sample also reflected typical households in the ZMVO. For the most part, respondents lived in individual houses (85%). Only a few reported living in an apartment (6%). Most had access to electricity (98%) and a piped water supply (65%), and some used firewood for heating or cooking (23%). Lastly, 20% ran a commercial business inside the house. **Supplementary Tables 2, 3** summarise all the information above.

In terms of wall and roof materials, the proportions were also typical of the ZMVO. First of all, roughly 80% of households had homogeneous materials in the walls, and it was similar for roofs (84%). The shares were equal in Oaxaca City and the suburbs. Houses with homogenous walls and roofs mostly used concrete, cement, or brick. However, houses with heterogeneous walls and roofs reported higher use of other materials, such as metal/asbestos panels or adobe.

The results on roof and wall materials indicate a low presence of traditional materials and the use of multiple materials for walls or the roof in the house associated with a more vulnerable condition. For houses with a homogeneous wall, the most represented material was concrete/cement (80.1%), followed by red brick (12%), prefabricated panels (metal, asbestos, cardboard) (3.6%), and adobe (2.9%). For houses with diverse walls, there was an increase of in the share of prefabricated panels (22.5%), adobe (12.6%), brick (12.6%), wood (6.6%), and the proportion of concrete/cement reduced to 40.4% (**Figure 1**). In turn, the predominant material for houses with a homogeneous roof was concrete/cement (80.9%), followed by prefabricated panels (metal, asbestos) (15.6%), and tiles (3.2%). Houses with diverse materials in roofs also reported a higher percentage of prefabricated panels (44.2%), tiles (9.7%), and wood (5.3%), and less use of concrete/cement (40.7%) (**Figure 2**).

The willingness to change to another type of material was notably higher among households with the least favourable types. **Figure 1** demonstrate how fewer respondents with cement/concrete and brick materials in walls wanted a change (21–36%), compared to those using adobe (47–50%), or metal/asbestos panels (76–90%). As for roof materials, there was a similar tendency. Those using traditional and, in particular, economic roof options reported higher willingness to change (**Figure 2**). Among those wishing for a change, people living in houses with homogenous cement/concrete walls chose wood and Cantera stone in the first place (28 and 23%), associating

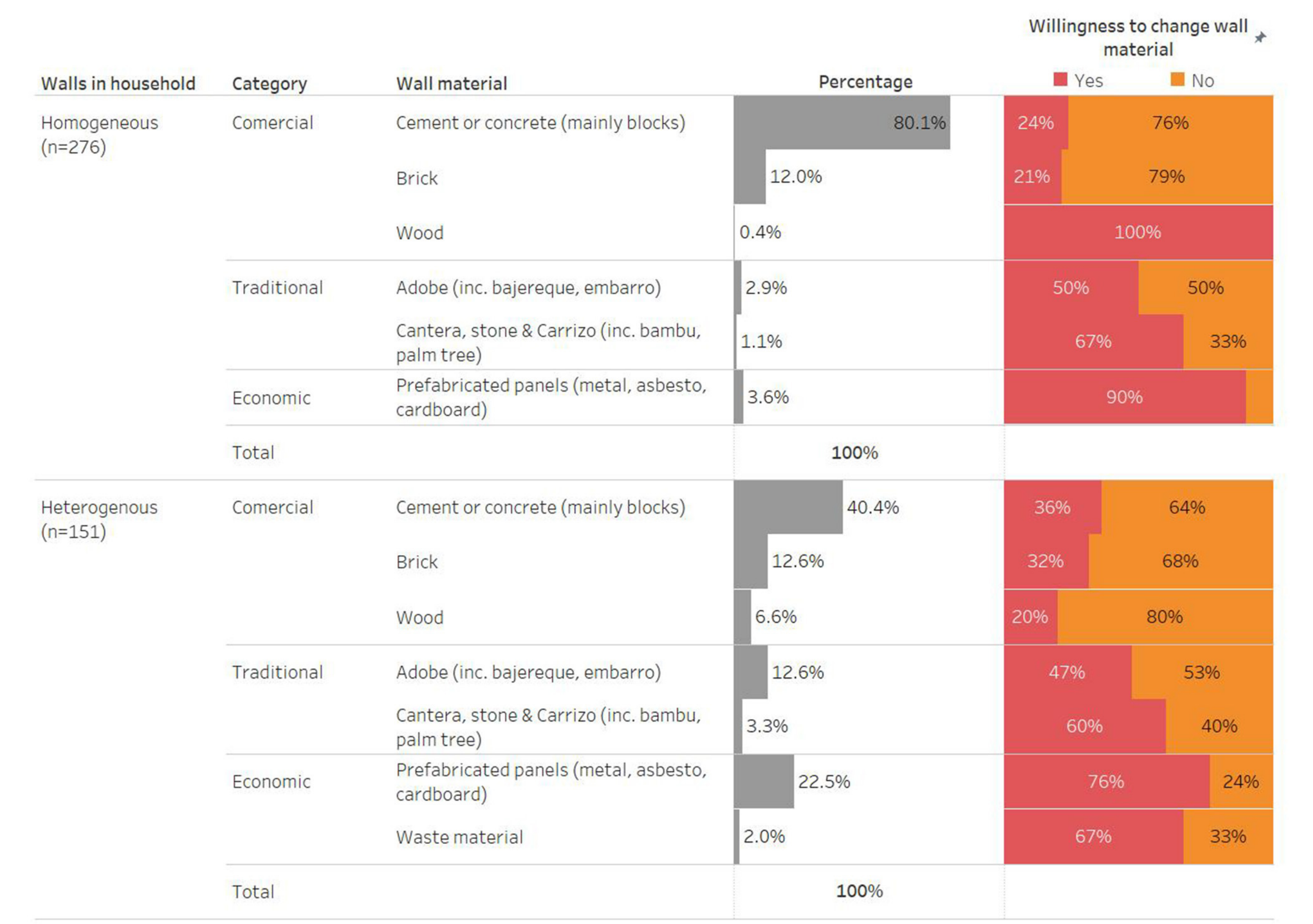

FIGURE 1 | Wall materials and willingness to change in ZMVO households.

it with more beauty (**Table 7**). Those using brick desired cement/concrete (43%) because of increased protection and, surprisingly, more beauty. As for those using adobe, the better choice was brick (75%) due to the increased hygiene. Finally, the ones using metal or asbestos panels wished for cement/concrete (89%), again for increased protection and beauty. The choices for people with multiple walls in the house were equivalent to those for homogenous walls, as well as the preferences for roof materials (**Table 8**). Households having prefabricated panels and wood predominantly desired cement/concrete (68% and 72% for homogenous and heterogeneous roofs, respectively), and the percentage of households desiring tiles or wood were higher among households using cement roofs (39 and 13% for homogenous roofs, respectively).

The analysis of the reasons behind the selection of materials demonstrates that local traditions and the environment are not essential concerns. Instead, protection, aesthetics, and other aspects, including constrained preferences, had higher importance. We observed a strong correlation between concrete/cement and both protection (against earthquakes and theft) and hygiene. Bricks had a strong correlation with protection, but also with other factors: ease of use, beauty, and preservation of traditions. Adobe, a fundamentally more traditional material, correlated with ease of use, beauty, and lower cost. Finally, metal/asbestos panels were entirely associated with lower costs, ease of building and the lack of other options (**Figure 3**).

For roofs, the results were similar. Cement/concrete was associated with waterproofing, protection (theft and earthquakes), and hygiene. Wood was associated with beauty in homogeneous roofs, and in heterogeneous roofs, it was associated with a lack of options, low cost, and ease of building. Tiles were associated with beauty, ease of building, and low cost. Lastly, metal or asbestos panels were associated with low cost, ease of building, and lack of options (**Figure 4**). For both walls and roofs, the option "already there" appeared among the five most selected choices for all materials, supporting the idea that constrained selection was another primary reason for the preference.

In sum, we confirmed that tradition, community support, and material reuse and concerns related to the environment represent a less important reason for selecting wall and roof materials. Households with concrete walls that owners wished to change to wood or Cantera stone were the closest to energy

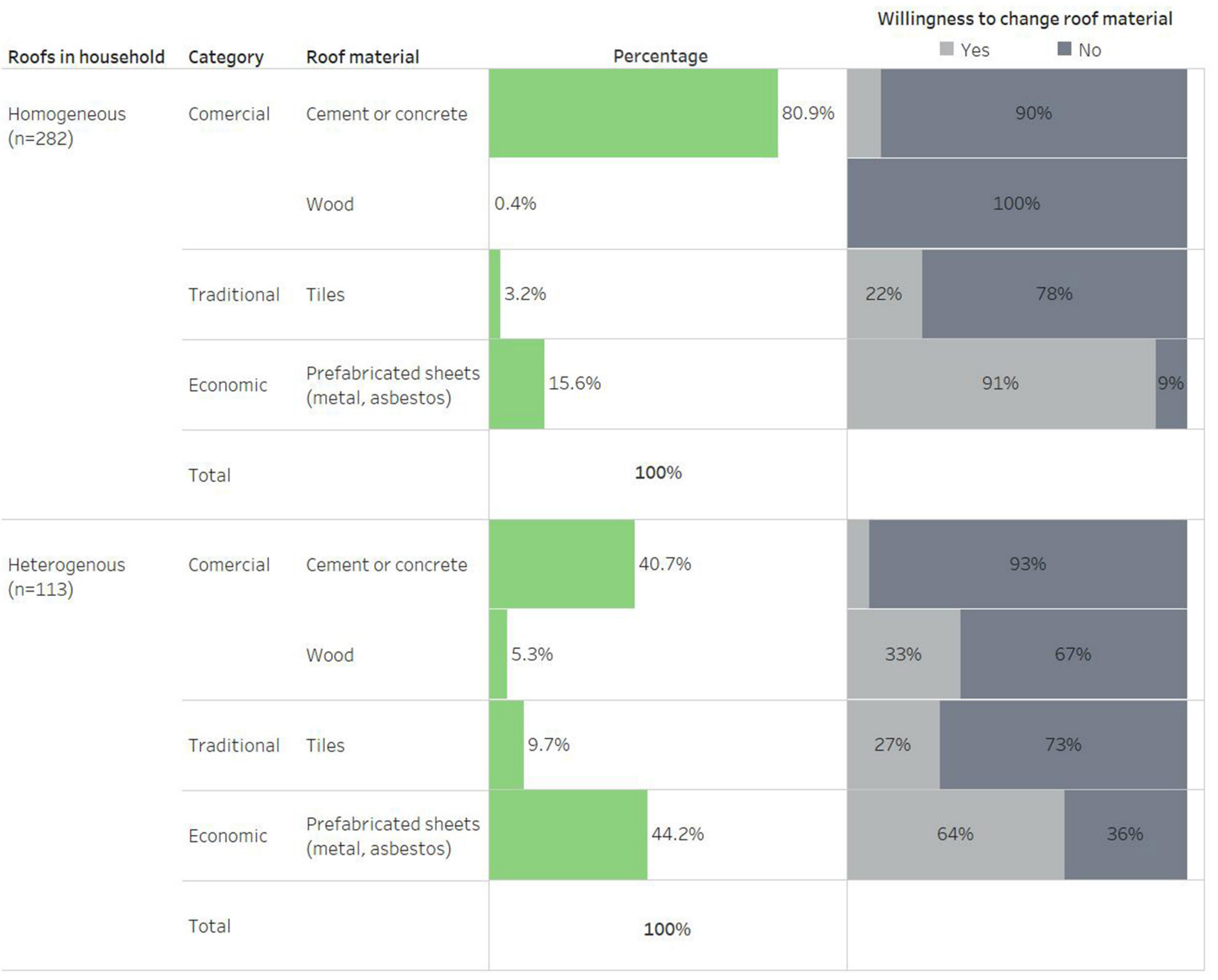

FIGURE 2 | Roof materials and willingness to change in ZMVO households.

efficiency concerns, as the second most crucial reported reason for the change was to "reuse another material." On the other hand, the closest group with concerns about local culture were householders with brick walls. The preference for adobe walls or tile roofs reflected more concerns regarding aesthetics. Overall, the most critical concern in material selection was protection against disasters (earthquakes, storms, accidents) or theft, particularly for households in a more vulnerable situation. Our results also indicate that material selection is constrained by economic status. These facts have crucial implications in the design of retrofitting strategies to increase energy efficiency in the ZMVO. In the following section, we will further discuss this perspective.

DISCUSSION

This section discusses the main findings and their implications in retrofitting policy. First, the effect of local culture on urban retrofit in the context of the ZMVO is examined, followed by recommended actions and concluding with limitations identified in the current analysis.

Local Culture and Implications on Retrofitting Strategies

The ZMVO is an excellent example of the several challenges for retrofitting policy to incorporate the local culture in the global south. From the policy perspective, we noted that the enforcement and compliance with available normative are insufficient, and localised strategies are non-existent. Sustainable initiatives, such as rules on the local origin of materials, have been recently incorporated in the main construction guidelines. However, these have not sufficiently materialised in more operational programs. Moreover, in general, existing households receive less attention, despite their more prominent role and potential impact in retrofitting initiatives.

TABLE 7 | Wall materials and ideal types in ZMVO households.

Category	Wall material	Walls in household	Desired material	Percentage
Comercial	Cement or concrete (mainly blocks)	Homogeneous	Wood	28%
			Cantera, stone	23%
			Brick	17%
			Adobe	15%
			Others	17%
		Heterogenous	Cantera, stone	18%
			Wood	18%
			Adobe	14%
			Brick	14%
			Others	36%
	Brick	Homogeneous	Cement	43%
			Cantera, stone	14%
			Wood	14%
			Others	29%
		Heterogenous	Adobe	33%
			Cantera, stone	17%
			Others	50%
	Wood	Homogeneous	Cement	100%
		Heterogenous	Brick	100%
Traditional	Adobe (inc. bajereque, embarro)	Homogeneous	Brick	75%
			Cement	25%
		Heterogenous	Brick	44%
			Cement	33%
			Cantera, stone	11%
			Others	11%
	Cantera, stone & Carrizo (inc. bambu, palm tree)	Homogeneous	Wood	50%
			Others	50%
		Heterogenous	Cement	67%
			Brick	33%
Economic	Prefabricated panels (metal, asbesto, cardboard)	Homogeneous	Cement	89%
			Wood	11%
		Heterogenous	Brick	58%
			Cement	8%
			Adobe	4%
			Cantera, stone	4%
			Wood	4%
			Others	23%
	Waste material	Heterogenous	Wood	100%

Private owners place more concern on protection than on the environment, tradition, or local identity when retrofitting occurs. The vast majority of those who currently lack resistant materials in roofs and walls desire, and require, protective options. The natural choice is to upgrade to concrete blocks. However, concrete incorporated in traditional houses diminishes thermal comfort (Torres Zárate, 1999), gradually requiring extra heating or cooling equipment. We confirmed the differences with the thermal transmittance values in Mexican households (**Table 4**), and some householders already using these materials considered adobe walls and tile roofs more thermic and aesthetic.

Nevertheless, adobe, brick, or tiles are socially associated with poverty, primitive housing, and rural regions (Contreras and Contreras, 2017). In contrast, concrete blocks suggest a higher status (Torres Zárate, 2005), particularly among households with inadequate wall and roof types. Furthermore, the use of inadequate materials can intersect with other vulnerable conditions, such as deficiencies in water supply or sewage, unstable sources of income, and poverty, exacerbating the vulnerability. This fact has been demonstrated in recent studies on energy poverty (Ochoa and Graizbord Ed, 2016; Ochoa et al., 2020) and limited access to energy services (Cravioto et al., 2014; Ochoa et al., 2021). Thus, the desire for less

TABLE 8 | Roof materials and ideal types in ZMVO households.

Category	Roof material	Roofs in household	Desired material	Percentage
Comercial	Cement or concrete	Homogeneous	Tiles	39%
			Wood	13%
			Others	48%
		Heterogenous	Cantera	67%
			Wood	33%
	Wood	Heterogenous	Cement	100%
Traditional	Tiles	Homogeneous	Cement	50%
			Panels	50%
		Heterogenous	Cement	67%
			Wood	33%
Economic	Prefabricated sheets (metal, asbestos)	Homogeneous	Cement	68%
			Tiles	20%
			Wood	3%
			Others	10%
		Heterogenous	Cement	72%
			Tiles	13%
			Wood	6%
			Others	9%

environmentally or culturally compatible materials strongly connected with deprivation is one of the most crucial aspects of retrofitting policy.

Besides this, the ZMVO also reflected other unique characteristics worth discussing. For example, apartments are scarce, and houses are the norm. Almost half of the households identify themselves in existing indigenous groups (Zapoteco, Mixteco, and others). Houses have a traditional nature of more open space, and 25% have firewood kitchens, which often also provide thermal comfort in winter. Cooling and heating of spaces are required only on a limited number of days, so almost no households use air conditioning or heaters. Thus, retrofitting strategies should target this local energy culture, distinct to typical urban settings in the global north, denser and mainly relying on gas and electricity to provide energy services (Silver, 2014; Gillich et al., 2018; nZEB-RETROFIT, 2021).

Finally, not all households are in similar conditions to receive benefits from state programmes. Silver (2014) suggests that housing initiatives cannot support many low-income households because they usually do not have title deeds required to obtain retrofit credits. This could explain why remittances are essential contributions to improve housing among lower-income households (Cervantes, 2018). In these cases, it is not rare that retrofits use materials similar to those used where migrants live, which turn out to be less effective for the local climate, again affecting environmental performance. The incorporation of all social groups is a crucial matter.

In sum, the priorities for urban retrofit in the ZMVO are distinct from other dense urban contexts in Mexico and most of the global north, where efficient technologies to reduce electricity consumption for heating and cooling spaces are the main targets of action (Goggins et al., 2016).

Recommended Actions

On the one hand, adopting more general master plans might not be easily adjustable to local retrofitting activities. Thus, we detect that governments need to create more specific guidelines tailored to the region, where locally compatible energy-efficient retrofits are easier to identify. There should be strategies to retrofit walls and roofs with a culturally and environmentally sound vision, currently unavailable. Considering the existing norms, manuals, guidelines, and construction codes at different government levels, it is clear that the enforcement of regulations is still challenging for housing development within the ZMVO. However, the adoption of master plans alone will not be easily adjustable to the actual retrofitting activities in the ZMVO.

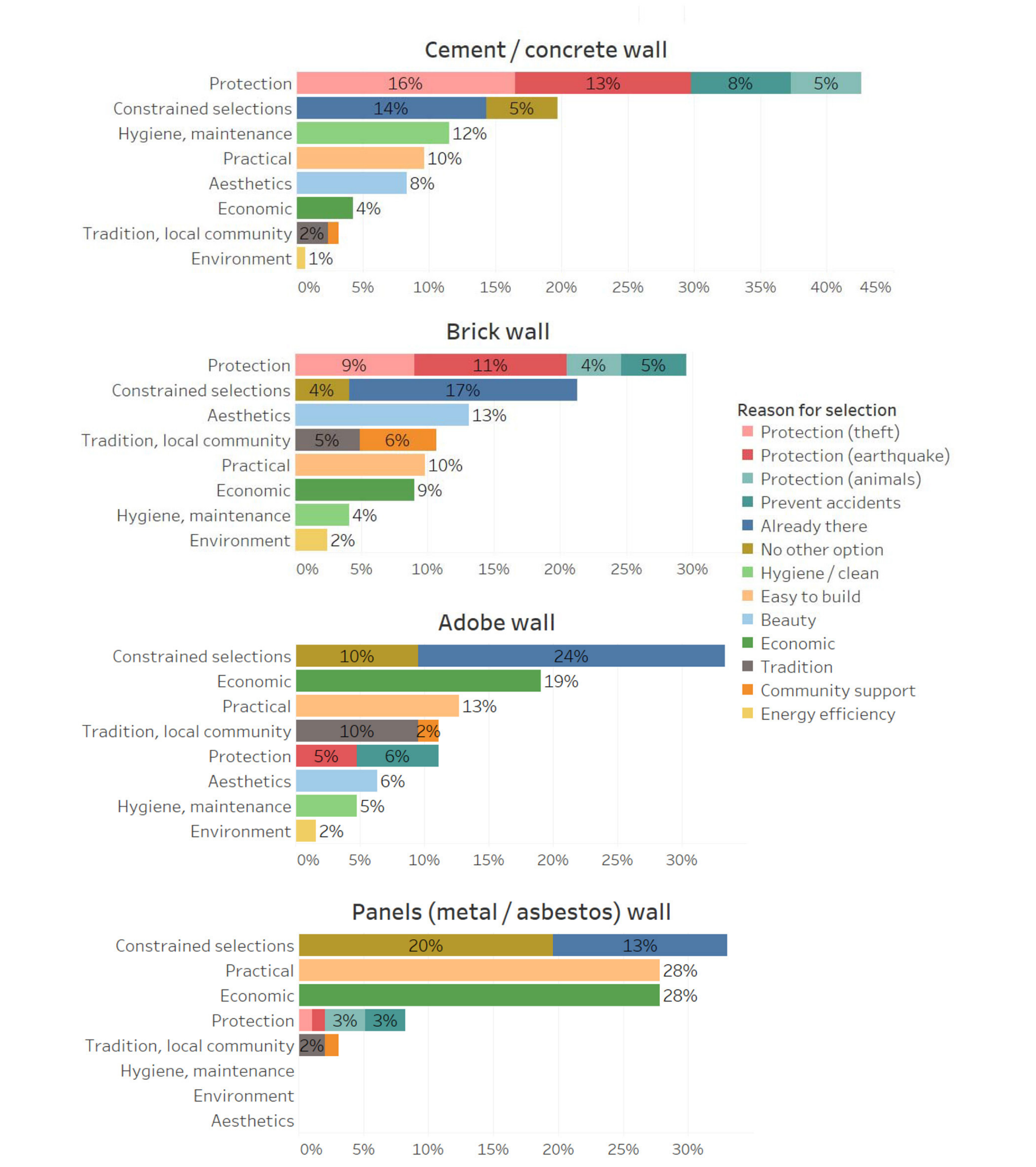

FIGURE 3 | Main reasons for wall material selection (percentage of total frequency).

The local design of retrofitting strategies will face social challenges glimpsed through the analysis presented. The most crucial aspect is probably the connexion between deprivation and the less efficient use of resources. This needs a more inclusive perspective. Around 20% of houses had inadequate materials. A large percentage may also intersect with other vulnerable

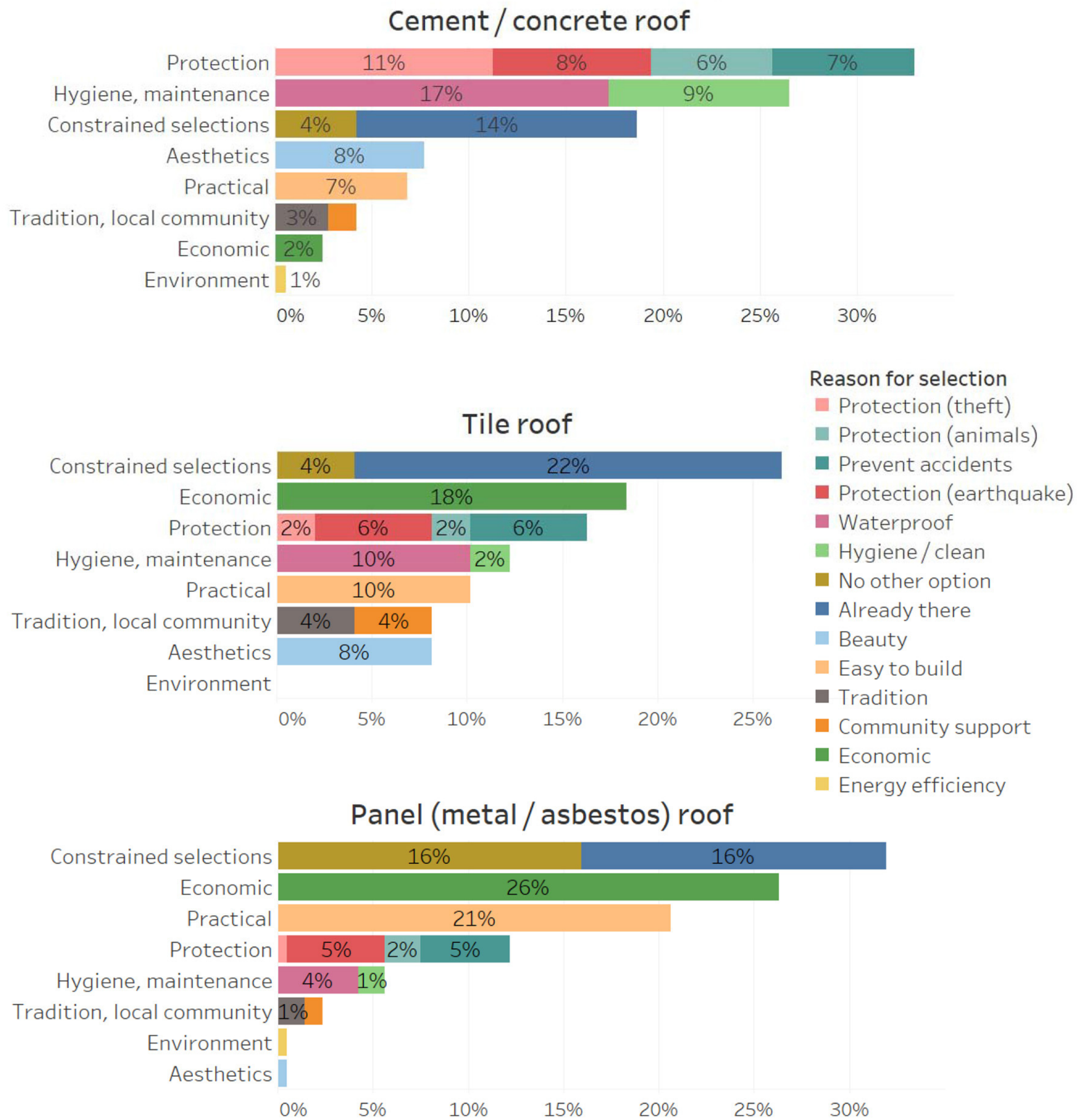

FIGURE 4 | Main reasons for roof material selection (percentage of total frequency).

conditions, such as deficiencies in water supply or sewage, unstable sources of income, and poverty. For these groups, it is essential to facilitate retrofits that reduce vulnerability while understanding local practises in the provision of energy services. Strategies should target simple but effective low-cost retrofits.

Wall and roof materials seem to have crucial roles in more efficient energy use for thermal comfort. The advantages and disadvantages of modern and traditional materials need to be incorporated in policy for new or existing infrastructure. There are already materials on the market that help the passive use of energy for thermal comfort. An example is waterproofing on roofs that can reflect heat, keeping the rooms cooler in summer, and allowing better thermal insulation in winter. This is just one example of a simple strategy that, despite being relatively accessible, has not been considered enough. In this sense, there is a substantial opportunity for policy to identify and promote traditional practises that develop highly efficient and protective materials at lower costs. Also, it is essential to identify newer versions of traditional materials, which could overcome recognised weaknesses.

Additionally, financial mechanisms for retrofits should be more accessible and explicitly target sustainable housing. On the one hand, social housing credits should be obtained based on the degree of sustainable and energy materials used on the projects. More transparent mechanisms of incentives for housing constructors and individuals are also needed. On the other hand, credits should be available for informal and independent workers. Considering the limitations in the ZMVO, new governmental institutes established exclusively for sustainable building concerns seem difficult. However, we advocate for simple but effective programs inside the local agencies in charge of urban development programs.

Not only the government, but other agents involved, can contribute to retrofitting strategies. Independent institutes such as the Cadaster Institute (ICEO is its Spanish acronym), currently in charge of assessing technical consultancy and valuation of local properties (Lucero-Álvarez et al., 2016), could be one example. This institution or others with similar faculties could assess and validate the proper utilisation of energy-efficient materials for the ZMVO housing. They could issue a certificate that can reduce, for example, the yearly housing tax.

These recommendations should be reviewed in detail in future studies, and are fertile areas to discuss new policies for the utilisation of energy-efficient materials in the ZMVO.

Future Visions in Retrofitting Policy

It is conceivable that economic conditions in the ZMVO may improve given the numerous economic stimuli in the region. According to the National Development Plan (PND) 2019–2024 (Government, 2019), the budget to support and encourage investment in the southeast part of the country amounts to 41.3 billion pesos (SCT, 2018), the highest percentage of the current federal administration. If this is successful, modern rail infrastructure and greater economic diversification from 139 strategic works will materialise (Rosales, 2019), among them highways and rural roads, the commercial port of Salina Cruz, and the trade corridor of the Isthmus of Tehuantepec.

This development will significantly impact the creation of housing in larger cities and the retrofits to existing houses. The selection of materials will affect the outcomes and equipment for heating, cooling, and hot water supply. In other words, the energy demand could increase in the ZMVO and other similar cities in the southeast. Thus, locally oriented retrofitting strategies will be essential.

In the global north, retrofitting literature is focusing on how new technology in buildings can create Positive Energy Blocks (ZEB) and Districts (PED) (Bisello, 2020; Verhaeghe et al., 2020; Lindholm et al., 2021). However, these notions are very distant from the needs in the ZMVO and probably other similar mid-size cities in developing countries. Authorities can direct the creation of infrastructure for easier transitions into efficient housing, using modern solar and hybrid power technologies. However, socio-economic conditions, the nature of local buildings and practises, and the marginal installed capacity of domestic solar technologies suggest a different strategy in these contexts. Many cities in Mexico have a great potential for more extensive use of solar technologies in homes (Grande et al., 2015) because climate conditions are favourable (Pérez-Denicia et al., 2017), and the regulation for domestic generation is prepared (Grande et al., 2015). However, the high percentage of homes in economic vulnerability and the local practises discussed above remind us of other realities to consider.

Limitations

This study utilised a questionnaire to shed light on the residents' perspectives in the ZMVO. However, there are inherent limitations in using this method to extract conclusive remarks on the local culture when selecting roof and wall materials. First, the use of questionnaires to evaluate experiences can evoke judgements articulated on heuristic answers, meaning that respondents may substitute the reason for selecting the wall and roof materials with a quicker, easier, and more accessible answer, as noted in behavioural sciences (Kahneman, 2011). We have carefully followed recommended guidelines in designing our survey structure and questions (Robinson and Leonard, 2018) to avoid usual cognitive problems on the questions regarding the householders' experience. However, we acknowledge that perfectly reasoned answers are challenging to obtain, given the ordinary tendency to substitute these questions.

This limitation suggests the necessity for complementing the observed preferences with ethnographic methods or other qualitative modes of inquiry, which could possibly validate the observed preferences and compliment the information on the reasons for the selection stated among householders who have recently engaged in retrofitting activities. Another helpful technique could be direct participant observation, which could assist in extracting more symbolic notions behind the answers (Shove, 2003). The current limitations accessing the ZMVO due to the COVID-19 pandemic makes it difficult to conduct these methods, but is another fertile ground for further research.

In addition, a large part of the literature suggests that retrofitting encompasses other stakeholders, such as developers and financiers (Dixon and Eames, 2013; Dixon et al., 2018). Although currently out of the scope of this article, targeting these would complement the current findings. The role of private agents and construction companies is equally important in the design of retrofitting policies.

Finally, further research should also address local preferences connected with other retrofitting aspects not considered in this article. Among these, we have sanitation, solid waste, public spaces, and workplaces. The concept of retrofitting encompasses a broader notion, including measures creating substantive change in city infrastructure (Eames et al., 2014; Hodson and Marvin, 2017).

CONCLUSION

This article analysed cultural preferences in selecting wall and roof materials in the Metropolitan Valley of Oaxaca and the implications in Mexican retrofitting strategies. We found that retrofitting in Mexico has advanced substantially in recent years through a review of related norms, guidelines, and policies. However, the application and enforcement of retrofitting strategies have also faced challenges.

Overall, retrofitting policy focuses primarily on poverty. At the state level, the primary objective remains on resolving informal housing and inadequate materials. Culturally compatible and environmentally friendly housing is not visible in local initiatives. Energy efficiency, passive design, efficient equipment, and local materials for more sustainable building need to be tailored to local needs.

Local governments in the ZMVO are active in implementing programs following federal or state-level directives, but retrofitting policy at that level is limited. Consequently, retrofitting strategies do not consider climate variations, the priority of specific energy services, or transformations in the use of equipment. In addition, the emphasis of policy is entirely on new infrastructure. For existing infrastructure, the programs and guidelines are marginal.

It should be noted again that houses in the ZMVO have a traditional nature of more open space as well as firewood kitchens that are used for cooking and often also for providing thermal comfort. Therefore, effective retrofits should consider these practises, different to other urban settings. Wall and roof materials have relevant roles in the retrofits compatible with these local preferences. The advantages and disadvantages of modern and traditional materials for new or existing infrastructure need a place in future policy.

From the householders' perspective, we found, the selection of materials for roofs and walls do not relate to energy efficiency or concerns about traditions and local culture. Instead, importance is placed on protection against environmental disasters or crime, particularly among households with precarious materials. The natural choice, therefore, is to upgrade to concrete blocks. However, concrete incorporated in traditional houses diminishes thermal comfort, and adobe walls and tile roofs represented a more thermic and aesthetic option for some householders.

The local design of retrofitting strategies will also face social challenges glimpsed through the analysis presented. Inadequate materials intersect with other vulnerable conditions, such as deficiencies in water supply or sewage, unstable sources of income, and poverty. For these groups, it is essential to facilitate retrofits that reduce vulnerability while understanding local practises in the provision of energy services. The most crucial aspect is probably the connexion between deprivation and less efficient use of resources, which needs a more inclusive vision.

In sum, we argue for local policy incorporating the local context, regionalising federal and state-level initiatives, but with a culturally and environmentally sound vision, something that currently is not practised. Future retrofitting strategies should also consider additional domains (water and solid waste management), diverse regimes (housing, non-domestic buildings, urban infrastructure) and multiple stakeholders (government, developers, financiers, and the public). These are also topics for further research related to urban retrofitting in the ZMVO and probably other similar midsize contexts in the developing world.

AUTHOR CONTRIBUTIONS

AM: conceptualisation, policy analysis, survey conduction, validation, and writing. JC: conceptualisation, methodology, survey design, data curation, analysis, writing, review, proof, software, and funding. All authors approved the manuscript for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2021.638966/full#supplementary-material

Supplementary Table 1 | Detailed questionnaire structure and description.

Supplementary Table 2 | Respondents' descriptive statistics.

Supplementary Table 3 | Households' general information (descriptive statistics).

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Under-Consumption Penalties in the Low Carbon Market: Reflections From a Spanish Social Housing Provider

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This proposal focuses on the analysis of three case studies of a Spanish social landlord—Basque Alokabide, submitted to the Carbon Fund for a Sustainable Economy. The calculation of CO_2 emissions follows the methodology recommended by the Spanish government. The economic viability of the cases analyzed is calculated, first without taking into account the money obtained from the carbon market, and then taking advantage of the sale of the emissions. The interest value of this work is the examination of how low incomes tend to be overrepresented in social housing, resulting in lower energy consumption and colder dwellings. Since low income tenants under-consume energy, before renovation CO_2 emissions are lower, and therefore Alokabide is taking less advantage of the carbon market. Additionally, photovoltaic systems, while easier to implement even at district level, are not eligible in the Spanish program, and this is also disadvantageous. In the policy recommendations, the ex-ante accounting of emissions should be justified on the basis of theoretical energy consumption with average consumers, rather than verifying ex-post actual emissions by low income household that under consume: energy efficiency measures lead to improved thermal comfort, and this added benefit should be taken into account in the economic viability. Toward the goal of reducing emissions after retrofitting, decarbonization is more feasible than the reduction of the energy consumption through the substitution of fossil fuels by renewables to satisfy primary energy needs.

Keywords: low carbon, social housing, energy poverty, under-consumption, positive energy districts

INTRODUCTION

The issue of environmental sustainability and low carbon regulations are becoming increasingly relevant on the European agenda. The European Commission (2020) has proposed to cut net greenhouse gas emissions in the EU by a minimum of 55% by 2030 compared to 1990. Through the Affordable Housing Initiative, the European Commission (2020) will give support to local social housing projects, including measures to protect social housing tenants against energy poverty (European Parliament, 2013).

For social housing, the good news is that they have more opportunities to implement energy efficiency (EE) measures (Walker, 2008), and therefore homes occupied by social renters tend to be more energy efficient than the general housing stock (Barnes and McKnight, 2014). Regarding energy districts, communities with district heating deal better with energy poverty by creating heat markets which enable fuel flexibility (Hathway, 2010).

Nevertheless, there is also less positive news; low income is overrepresented in social housing (Teli et al., 2016). In Spain, the consumption profile of tenants results in a lower usage of electricity and heating than an average household (Aranda et al., 2017). Jenkins et al. (2011) analyzed energy consumption in terms of carbon intensity in UK, resulting in lowest deciles of income consuming significantly less. When households are not spending enough to achieve a certain standard of energy services, Rademaekers et al. (2016) state that under-consumption occurs and, low-income householders often live under colder living conditions (Moore, 2012). Besides, due to the large deposit required in Positive Energy Districts, this represents a greater negative effect on those in social housing (Hearn et al., 2021).

In the literature of energy performance gap (Wilde, 2014), there is also space for these two situations frequently observed in social housing; the implementation of EE measures and low-income energy consumers. For such cases, Sunikka Blank and Galvin (2012) introduced the "prebound" effect; the situation before a retrofit, and indicates how much less energy is consumed than expected. However, they found that the energy intensity after retrofit of houses of low-income households is closer to one.

This also has implications for reducing CO_2 emissions from the social housing sector. Due to the "prebound" effect, Teli et al. (2016) showed the problem of achieving the anticipated carbon savings. As a result, compared to the able-to-pay, a greater EE improvement with higher costs is required in order to achieve the same carbon reduction (Rosenow et al., 2013). Moreover, Boardman (2013) emphasizes that low-carbon policies increase the energy bills when emissions are internalized, and the effect is disproportionately higher for marginalized groups.

This paper builds on earlier work for the social housing provider Alokabide. Hernández et al. (2019) performed an energy audit for the building stock of Alokabide stating its good energy performance and a lower-than-expected energy consumption by the tenants. Using a different methodology, Antepara et al. (2020) confirmed the observed energy under-consumption. Both studies draw a scenario similar to that described by Teli et al. (2016), the fuel poverty-induced "prebound effect."

Taking a step forward, the focus will be put on the accounting and selling of the carbon emissions of three different case studies of Alokabide. The methodology for the calculation of CO_2 emissions is taken from the Carbon Fund for a Sustainable Economy (FES-CO_2), managed by the Spanish Government. The article also includes a discussion of the results and some implications for policymakers, highlighting the key findings that show the negative outcomes of the carbon market when low-income households are involved.

RESEARCH METHOD

Spanish social housing is considered to be a targeted model, which means that social landlords aim to satisfy only the excess of housing demand not satisfied by the market. Allocation is made according to a set of vulnerability indicators (European Parliament, 2013), particularly income, i.e., targeted and residual model. As a consequence, low income is overrepresented. While the contract with the tenants sets out the rent to be paid for the dwelling, other energy-related payments cannot be included.

In order to study the viability of improvements that seek decarbonization, the case of Alokabide—the Basque public company for public rental—is herein analyzed. After the energy audit performed for the building stock of Alokabide, Hernández et al. (2019) concluded that the tenants are under-consuming heating, i.e., the pre-bound effect described by Sunikka Blank and Galvin (2012), but not domestic hot water (DHW).

The estimation of emission reductions is based on data taken from the information submitted to the FES-CO_2 as a "Proyecto Clima" (Ministerio para la Transición Ecológica y el Reto Demográfico, 2019). Created by Law 2/2011 of Sustainable Economy, provides financial support to projects that reduce emissions in Spain by purchasing CO_2 emissions reductions. Alokabide can only afford 1–2 investments per year, i.e., an insufficient annual renovation rate of around 1%, and this is an opportunity to scale up these interventions. Two types of EE measures were taken into consideration: the production of DHW with solar heating, and the retrofitting of a whole building. Photovoltaic (PV) systems are not eligible in this program. The project was approved in January 2021. FES-CO_2 will complete the corresponding payment once the emission reductions are verified.

First, the situation ex-ante will be described, i.e., the information and calculations included in the "Proyecto Clima," and then, based on the energy profile of the tenants at Alokabide, the expected ex-post situation—used to claim the money corresponding to the verified emissions to FES-CO_2–will be anticipated.

Fossil Fuels Substitution by Solar Thermal Energy

The two solar installations for the production of DHW submitted to the FES-CO_2 are described:

1) ZABALGANA 92. The first case analyzed is the replacement of the solar thermal panels in a building whose construction was prior to the Spanish Technical Code of Buildings (Código técnico de edificación, CTE) of 2006, and therefore does not have to comply with the minimum solar contribution of 30% of the DHW that is mandatory for projects after 2006. The multi-occupancy building comprises 92 dwellings in Vitoria-Gasteiz (Spain). Being one of the first solar thermal installations in the area, the installer failed to fix the systems correctly. Consequently, up to the time of replacement, the heating and DHW needs were covered only by the natural gas (NG) boiler. The solar panels were replaced by vacuum tubes.
2) ARRASATE 140. The second case analyzed is the replacement of the solar thermal panels in a building constructed after the CTE of 2006, which therefore had to comply with a minimum solar contribution of the 30% of the DHW. Consequently, only the computation of emissions reduction of the DHW produced exceeding this percentage is allowed.

TABLE 1 | Data for NG used in the methodology.

	Density	Low calorific value (LCV) (GJ/t)	Total CO_2 emission factor (kg/GJ)
Natural gas	0, 79	48, 6	56

The multi-occupancy building comprises 140 dwellings in Arrasate-Mondragon (Spain). Although the solar installation was relatively new, it never worked as projected due to lack of maintenance.

Within the methodologies proposed by FES-CO_2 for the residential, commercial and institutional sector, the case of the substitution of fossil fuels by solar thermal energy corresponds to the "Methodology for thermal energy projects aimed at reducing fossil fuel consumption in a new or existing installation." In general, the relationship used for the calculation of emissions is Equation 1:

$$RE_a = EEB_a - EP_a$$

where RE_a is Emission reduction in year "a," EEB_a is Emissions associated with the baseline scenario in year "a," and EP_a is Project associated emissions in year "a." The "baseline scenario," or reference scenario, depicts the state which exists prior to the implementation of the project activity. The "project scenario" depicts the future state that will exist once the project is running.

In order to calculate the emissions, the following two scenarios are defined for both projects:

- Baseline scenario; the average amount of NG used to produce the needed DHW, in cubic meters, is accessible for the social landlord for the cases analyzed, as well as the efficiency of the system.
- Project scenario; the fraction of fossil fuels substituted by solar thermal energy is also known, as well as the new efficiency of the system, as it can be calculated from the energy study carried out before the tendering of the works.

Initially, DHW needs were produced by boilers running on fossil fuels and they are partially satisfied by renewables after substitution of the solar systems. The physical-chemical constants used to calculate the emissions reduction between the reference and the project scenarios are shown in **Table 1**.

Renovation of a Building

The third project analyzed is linked to an integral building renovation (including the physical accessibility), located in San Sebastian (Spain). It is a small multi-occupancy building, of only 13 dwellings, built at the beginning of the twentieth century. The structure of the building is made of wood, with four floors and no elevator, and with a store on the first floor. In spite of not being a building of great constructive or patrimonial value, it is of interest at a conceptual and historical level. A rehabilitation was previously carried out in 1979. The initial plan of demolishing the building was abandoned, but the main part of the dwellings have been empty for a long time. Being such an old building, the renovation up to Nearly Zero-Energy Buildings was unfeasible, although the final energy demand is expected to drop to a level closer to zero emissions. The project includes the placement of insulation on the facades, the replacement of the individual boilers running on NG by a heat pump providing centralized heating, a new ventilation system with heat recovery, and the installation of renewable energies (a small PV installation). The new elevator installed is regenerative, sharing batteries with the solar panels. Since the renovation works started in 2020, it was not possible to include this integral renovation in the "Proyecto Clima" submitted in 2019.

Here, the case of the energy refurbishment of a building pertains to the "Methodology for Energy Efficiency projects aimed at reducing fossil fuel consumption in a building" proposed by FES-CO_2. The general equation to apply is the same as in the previous case, Equation 1.

The two scenarios considered to calculate the emissions are the following:

- Baseline scenario; the flow rate of NG consumed is unknown, as many of the dwellings are unoccupied. But the energy needs are taken from the energy study included in the renovation project, including both heating and DHW.
- Project scenario; the new energy needs can be calculated, and the efficiency of the heat pump is known. The new PV system is excluded.

The input data in this case is taken from the energy performance certificates, including the total living area. The physical-chemical constants used are the same—**Table 1**.

RESULTS

This section is divided into two sub-sections; the first one concerns the calculations of foreseen emissions reduction ex-ante, whereas the second one corresponds to the prospective verification by a third party.

Calculations Ex-ante

As explained above, this is the information sent to the FES-CO_2 for approval.

Fossil Fuels Substitution by Solar Thermal Energy

ZABALGANA 92. In the baseline scenario, the energy needs are fully satisfied by a boiler running on NG. The average NG flow rate from 2016 to 2018 consumed by the boiler is 113.164,60 m^3, and using the values in **Table 1**, this is 4142,75 GJ or 244,2 t CO_2e. The portion spent on DHW is unknown because there is no specific meter for this aim. However, it can be theoretically calculated according to the CTE for multi-occupancy buildings (Ministerio de Vivienda, 2017), if a quantity of 28 liters at a temperature of 60°C is considered for each tenant per day. The occupancy can be obtained from the CTE; 1,5 person in dwellings with one bedroom, 3 people with two bedrooms, and 4 with three bedrooms. In ZABALGANA 92, 2 of the dwellings have one room, 27 have two rooms, and the rest have three rooms, summing a total occupancy of 336 people. In the end, a total

TABLE 2 | NPV and IRR for the installation of the solar thermal system in ZABALGANA 92.

ZABALGANA 92	2020	2025	2030	2035	2040
Without selling the emissions					
NPV	−68376,2	−62081,3	−51209,23	−32431,8	0
IRR	−0,103531				
After selling the emissions					
NPV	−68327,45	−61772,48	−50668,92	−31860,44	0
IRR	−0,10075				

TABLE 3 | NPV and IRR for the installation of the solar thermal system in ARRASATE 140.

ARRASATE 140	2020	2025	2030	2035	2040	2045
Without selling the emissions						
NPV	−45823,33	−39124,38	−31371,73	−22399,64	−12016,31	0
IRR	−0,029335					
After selling the emissions						
NPV	−45838,72	−39205,79	−31495,23	−22531,96	−12112,46	0
IRR	−0,03021					

energy linked to DHW of 154.375 kWh. As there is no under-consumption for DHW (Astrain et al., 2019), this is an acceptable estimation of the actual DHW consumption.

In the project scenario, a total of 36 vacuum tubes are placed vertically in the roof, each of them with an equivalent area of 1,51 m^2–a total area of 54,36 m^2–. The technical characteristic of these solar collectors are; an optical performance of 0,752, a linear loss coefficient of 1,906 W/(m^2·K), and a quadratic loss coefficient of 0,004 W/(m^2·K). The average solar irradiation in Vitoria-Gasteiz in kWh/m^2 is taken from the "Atlas de radiación solar en España" (Atlas of Solar Radiation in Spain) (Ávila et al., 2012). Due to the fact that it is a multi-occupancy building, a centralization factor of 0,75 has to be included (Ministerio de Vivienda, 2017). As a result, the solar thermal collectors provide 150,4 GJ (41.350 kWh), which is the 28,4% of the calculated DHW, and the 3,63% of the NG consumed by the boiler in the baseline scenario. Hence the total emission reduction due to NG substitution is 9 t CO_2e.

The initial investment, the cost of the solar system installed, is € 57,250.00 w/o VAT. The abatement cost, the ratio between the investment and the emissions reduction, is € 57.250,00 w/ VAT/9 t CO_2e.

Additionally, every year the following expenses must be added:

- The solar installation consumes 1,000 kWh of electricity. Its price is € 0,16 per kWh, so, € 160,
- Maintenance costs are € 1,104 —€ 1 per month per person—.

The main annual savings for the return on investment are fuel savings (41.350 kWh/year), which is around € 2.067,5 per year—the price of the energy being € 0,05 per kWh—.

For this investment, it is possible to calculate the Net present value (NPV) and the Internal rate of return on investment (IRR), shown in **Table 2**. No corrections for inflation are included, it is supposed that in the EU region inflation is stable and the effects between expenses and revenues are compensated. The calculations are performed for a period of 20 years, the useful life of the solar vacuum tubes, initially without the money obtained after selling the emissions to FES- CO_2.

After submitting this "Proyecto Clima" to the FES-CO_2, the social landlord can obtain an income. The price of CO_2 emissions in 2019 was € 9.7/t CO_2e, so that 9 t CO_2e accounted for € 87. But, the emissions have to be verified, and the report adds around € 100 to the expenditures. As the report can include all the installations, only half of the cost is charged to ZABALGANA 92, i.e., € 50. In **Table 2**, the calculations are repeated with the income obtained from the FES-CO_2.

Since 2019 the price of carbon emissions rose dramatically, up to around € 50 / t CO_2e in May 2021. The IRR for that case is −0,077792. Even with these high CO_2 prices, the investment is not returned.

ARRASATE 140. Concerning the second installation, the baseline scenario is calculated taking into account the gas bills of 2018. The final flow rate of NG consumed by the boiler is 78.370,00 m^3, which equals to 2868.98 GJ (169,12 t CO_2e). The theoretical needs for DHW were calculated as in ZABALGANA 92. In ARRASATE 140, 14 of the dwellings have one room, 90 have two rooms, and 36 have three rooms. In the end, this makes a final occupancy of 435 people and a total energy linked to DHW of 145.506 kWh.

In the project scenario, a total of 42 solar collectors are placed in the roof, each of them with a total area of 2,51 m^2–the total area of all of the collectors totaling 105,42 m^2, an optical performance of 0,821, and a linear loss coefficient of 4,854 W/(m^2·K). The average solar irradiation in Arrasate in kWh/m^2 is known (Ávila et al., 2012), and the same centralization factor is used. So, the solar thermal system provides 221,2 GJ (60.819 kWh), which is the 39,4% of the calculated DHW. Only the emissions exceeding the compulsory 30% for solar heating production can be counted, as the project was approved after the new building regulation of 2006: this is 58,8 GJ (14.510 kWh), the 2,05% of the NG consumed by the boiler in the baseline scenario. Hence the total emission reduction due to NG substitution is 3,5 t CO_2e.

The initial investment of this system is € 38.884,00 w/o VAT, so that the abatement cost is € 38.884 w/ VAT / 3,5 t CO_2e. The initial investment is annually increased by the electricity consumed by the solar installation, i.e. 1,000 kWh—€ 160—, and the maintenance costs, this is € 1,700 applying the same quantity as in ZABALGANA 92.

As in the previous case, the main annual saving for the return on investment is fuel savings—the total produced by the solar system, 60.819 kWh/year—, equal to a total amount of € 3,041 per year—same NG price.

Starting with the analysis without taking into account the revenues from the FES CO_2, and assuming that the lifetime of the solar installation is 25 years, the calculations for the NPV and IRR are shown in **Table 3**.

The sale of emissions is calculated with the same price of CO_2, i.e., 3,5 t CO_2e at € 9.7 / t CO_2e, which is around € 34. The

TABLE 4 | NPV and IRR for the installation of the solar thermal system in ITURRITXO.

ITURRITXO	2020	2025	2030	2035	2040	2045
Without selling the emissions						
NPV	−480014,86	−427764,13	−359411,18	−269993,77	−153020,41	0
IRR	−0,0523084					
After selling the emissions						
NPV	−479675,46	−425835,31	−356258,62	−266345,86	−150153,17	0
IRR	−0,0499868					
After selling the emissions, taking into account the under consumption ex-ante						
NPV	−479781,23	−426434,84	−357235,85	−267473,44	−151036,92	0
IRR	−0,0507074					

remaining € 50 due to the verification of emissions report has to be included.

Considering the high CO_2 prices in 2021, the IRR is −0,02279, i.e., the investment is not returned in this case either.

Renovation of a Building

In the baseline scenario, the calculated energy demand is 279.3 kWh/m^2yr, including heating and DHW, which correspond with a label F for energy consumption—E for carbon emissions, 54.2 kg CO_2/m^2yr—. The living area of all the floors of the building is 774 m^2. Taking the same price for the NG, this results in a total amount of € 10,805. The DHW needs, calculated as in the previous cases, is 21369,5 kWh/yr. So, the heating represents the 89%, 194.735 kWh/yr. Regarding the emissions, a total amount of 42 t CO_2e; 37,3 t CO_2e for heating and 4,6 t CO_2e for DHW.

In the project scenario, the energy demand is 41,8 kWh/m^2yr, so, the energy label is B. The DHW demand is maintained, while the demand for heating is lowered down to 10,996,7 kWh (14,21 kWh/m^2yr). The emissions are further reduced thanks to a heat pump, i.e., using electricity instead of NG. The coefficient of performance (COP) of the heat pump is 4,3, which means that the needed primary energy is 7,527,02 kWh/yr. The electricity expenses are € 840—electricity price is € 0,16 per kWh—. In order to calculate the emissions for electricity, the coefficient equals to 0,399 kg CO_2/kWh (Hue CO_2 | Huella de carbono de la construcción de obras públicas, 2020). The final emissions account for 3 t CO_2e, so that 38,8 t CO_2e can be sold to FES-CO_2 every year.

For the economic viability study, the new elevator and the PV system are not taken into account. The cost of new facades is € 329.740,83, the cost of the heat pump is € 48.400,00 and its lifetime is 25 years, and the cost of the new ventilation is € 110.742,95. Additionally, maintenance costs are € 1,560. The IRR without taking into account the selling of the emissions is −0,0523084, as shown in **Table 4**.

When the income from the selling of emissions is taken into account, € 376 minus € 33 of the verification report, the IRR is −0,0499868.

In the previous calculations, the baseline scenario does not take into account the under-consumption. As most of the dwellings were not occupied, it is not possible to have a record of actual energy expenses for all the tenants, and the actual under-consumption cannot be calculated. So, the assumption for under-consumption of NG for heating is made based on a study performed with tenants in other buildings (Astrain et al., 2019), which gave a reduction of 30% of the heating in buildings with individual boilers compared to the theoretical energy performance of the building. As a consequence, the initial emissions would be 30,7 t CO_2e. The assumption for the results after retrofit is that the energy consumed for heating is the average of a consumer without income problems −3 t CO_2e do not change. So, the total emissions to be sold are 27,7 t CO_2e —€ 269. Obviously, the IRR in this case is worse, −0,0507074, and also at high CO_2 prices in 2021.

Expected Results of the Ex-post Verification

The emissions reductions must be verified by a third independent party, so, the accounting of emissions is only possible with actual energy consumption after the renovation works are finished.

In the verification after the substitution of fossil fuels by solar thermal energy to produce DHW, as there is no under-consumption for DHW, the emissions ex-post are expected to be average. Ex-ante results are maintained: NPV and IRR are only slightly improved thanks to the selling of the emissions.

In the renovation project of a building, the verification should confirm that energy consumption dedicated to heating in the baseline scenario is lower, and average in the project scenario (Sunikka Blank and Galvin, 2012). So, after renovation works are finished, the verified emissions reduction should be those calculated taking into account under-consumption before renovation −27,7 t CO_2e—, which would be disadvantageous for the rehabilitation of buildings where low-income tenants live. However, as it is not possible to verify the actual energy consumption before retrofit, the under-consumption cannot be confirmed in this case study.

DISCUSSION

The main contribution made to addressing gaps in existing knowledge of low carbon regulations is that, when low-income households are involved, before renovation CO_2 emissions are lower and therefore those projects are taking less advantage of the carbon market. Moreover, targets for CO_2 reduction after retrofitting may not be achieved (Teli et al., 2016).

The problem of under-consumption has no effect on the first two cases studied, as the solar systems produce only DHW, and the theoretical estimation of DHW and the actual consumptions are comparable. In none of the first two cases the initial investment is recovered, even in the case of taking into account the increasing price of carbon since 2019 (€ 25/t CO_2e in 2020, and € 50/t CO_2e in May 2021). In the third case analyzed, the under-consumption reduces the energy consumed for heating in the baseline scenario by a 30%, so that the benefit of low income from the emissions market is less. The economic viability is also not achieved, even after receiving the amounts corresponding to the emission reductions paid for the "Programa Clima." When FES-CO_2 asks for verification of emissions and these are calculated, additional issues may arise.

The subsequent policy recommendation, the ex-ante accounting of CO_2 emissions should be justified on the basis of theoretical results with average consumers, rather than verifying before retrofit emissions. In France, a specific subtype within the EE obligations is dedicated to low energy rated buildings housing low income families, regardless of the final verified carbon reductions. If low income households live in performant housing, e.g., recently renovated buildings, their energy bills will continue to be low, but they will be able to keep their homes at a comfortable temperature (Hong et al., 2009). These benefits—indoor air quality and thermal comfort, health, and also employment—should be taken into consideration (Ugarte et al., 2016).

On the key implications for positive energy districts, according to the FES-CO_2 methodology in Spain, district heating running on biomass is allowed to account for zero emissions. But it was not until very recently when the first building managed by Alokabide was renovated and connected to a new centralized heating system running on biomass at a district level. On the contrary, PV at a district level—i.e., solar energy communities, which are easier to implement, are excluded. So, this also reduces the potential for emission reductions.

Another conclusion is that, taking into account the low energy consumption of social tenants, decarbonization in the social housing sector is easier to achieve than the reduction of the energy consumed. CO_2 emissions reductions can be achieved if a part (or the whole) of the primary energy provided by fossil fuels is substituted by renewable energies. In the third case analyzed, this is achieved thanks to heat pumps (Owen et al., 2013).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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Perspectives on Energy Insecurity and Its Impacts on Urban Livelihoods: Adaptation and Resilience of Women in the Informal Sector

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Variability in temperature and precipitation due to climate change is predicted to significantly impact on Southern African countries' resources. These variations have the potential to affect the energy sector due to a heavy reliance on hydropower for electricity in the region. Energy insecurity is largely felt in cities as they are large consumers of the resource. This negatively impacts on urban livelihoods reliant on electricity like those in the informal sector. A survey of electricity dependent home-based informal businesses operated by women was conducted, to generate information on the vulnerability of urban livelihoods to energy insecurity in Harare, Zimbabwe. Households across all socio-economic backgrounds performed informal businesses to supplement household income and were heavily depended on the irregular electricity supply. Women from poor households managing informal businesses were disproportionately affected by the unstable electricity supply, as they could not afford alternative energy sources to continue business operations during power cuts. This accentuated their low adaptive capacity and vulnerability to climate change induced stresses. This paper brings to light the importance of improving the resilience and adaptive capacity of urban livelihoods to climate change related challenges like energy insecurity, whilst exploring climate-resilient energy options to sufficiently mitigate against the impacts of climate change on energy security.

Keywords: energy security, urban livelihoods, climate change, hydropower, informal sector

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INTRODUCTION

Climate change has the potential to negatively impact on water dependent power generating technologies like hydropower. This is evident in Africa as droughts have historically disrupted hydropower generation, reducing plants to half of their capacity, leading to power rationing (Chenje and Johnson, 1996; Mukheibir, 2007; Zambezi River Authority, 2016, 2019). This exposes Africa's dependency on hydropower and highlights the continent's vulnerability to energy insecurity. It puts regional economic development at risk as energy drives commerce, predominantly in cities where energy demand continues to grow [International Energy Agency (IEA), 2020]. Furthermore, energy supports the success of urban sources of livelihood like the informal sector, primarily practised by the urban poor. Their adaptive capacity is low; hence they are more vulnerable to energy insecurity.

Whilst the overall impacts of climate change on global hydropower potential appear to be slightly positive or impact minimally, IPCC (2011) and Hamududu and Killingtveit (2012), the high climate variability of Southern Africa poses a concern for hydropower potential in the region.

Africa's energy configuration with regards to access and demand is unique. Whilst energy demand on the continent is growing faster than the global average [International Hydropower Association (IHA), 2020], it accounts for a low share of the world's energy demand and high share of the global population without access to modern energy services [International Energy Agency (IEA), 2019]. The continent accounts for 17% of the world's population and only takes up 4% of the world's energy demand [International Energy Agency (IEA), 2019; International Hydropower Association (IHA), 2020]. Despite its low energy demand globally, rapid economic growth in sub-Saharan Africa since 2000 has seen an increase in energy use by 45% [International Energy Agency (IEA), 2014]. Its access to electricity grew to about 45% in 2018, according to the International Hydropower Association (IHA), (2020) and the International Energy Agency (IEA), (2020). Undeniably, increases in energy supply is necessary for the continent's prosperity. Climate change's potential impact on energy generation adds on to the complexities of energy security on the continent.

Remarkably hydropower makes a significant contribution to Southern Africa's energy mix. Within the region (except South Africa), more than 60% of the countries are dependent on hydropower mainly generated in the Zambezi River Basin (ZRB), with dependency even higher for some nations [International Energy Agency (IEA), 2010; Beilfuss, 2012]. In addition, hydropower contributes to about 40% of the regional power capacity with over 40,000 MW in generation potential (Spalding-Fecher et al., 2017). The International Energy Agency (IEA), (2020) indicates that on average, 17% of electricity generated on the African continent is from hydropower and projected to increase to about 23% by 2040. Although hydropower is capital intensive and has a longer return on investment, it is clean, has low operational costs, it is reliable, can meet peak demand, and not subject to international price fluctuations compared to fossil fuels (IPCC, 2011; Mukheibir, 2013; Cole et al., 2014; IRENA, 2020). This has made it a favourable option for electricity generation and future expansion projects for many countries. However, obsolete and aged hydropower plants result in it not generating at capacity as 60% of hydropower plants on the continent are aged 20 years. Their age, together with the effects of climate change, have affected average annual growth of hydropower capacity in Africa, dropping it to 2.4% per year [International Hydropower Association (IHA), 2020]. This situation takes away from the potential increase in energy supply, affecting economic growth of the continent, with climate change exacerbating the situation.

Zimbabwe is a relevant example to exemplify these broader issues of climate change and energy insecurity. The country's electricity demand is just over 2000 megawatts (MW), Afshar (2018), with an installed capacity of about 2000 MW [Brown et al., 2012; Kaseke, 2013; Afshar, 2018; Zimbabwe Power Company (ZPC), 2018]. However, it has failed to meet demand since the late 1990s. Makonese (2016) points out that these shortages could have been associated with increased urbanisation that shot demand together with insufficient investment in energy expansion. Zimbabwe's installed capacity mainly comprises of Kariba Hydropower Station at 1050 MW and Hwange Thermal Power Station (coal) at 920 MW [Brown et al., 2012; Kaseke, 2013; Afshar, 2018; Zimbabwe Power Company (ZPC), 2018]. Due to aged equipment, fuel shortages for diesel generators, and periodic low lake levels at Kariba, the country generates well below the installed capacity. Subsequently, it fails to meet the country's electricity demand. Massive power cuts lasting up to 16 h were experienced in Zimbabwe since the late 2000s (Makonese et al., 2011). These could be associated with the economic challenges the country was facing. Evidently so, McGregor and Chatiza (2020) report economic decline by the end of the 1990s and the period between 1998 and 2008 "Zimbabwe's Crisis Decade" both politically and economically. Hence Zimbabwe's energy obstacles emanate from a multitude of reasons largely associated with economic decline. Moreover, these are compellingly related to available installed capacity, which continues to diminish due to extreme weather events like droughts.

The dependency on climate sensitive energy generating technologies is evident in Zimbabwe. Kariba Power Station contributes about 50% of installed capacity of electricity in Zimbabwe, and is the most reliable [Zimbabwe Power Company (ZPC), 2018]. Hwange Thermal Power Station generates between 400 and 500 MW, substantially lower than installed capacity (Afshar, 2018). The contribution from the rest of the thermal power stations in Harare, Munyati and Bulawayo is insignificant or non- existent most of the time (Brown et al., 2012; Kaseke, 2013; Afshar, 2018). This suggests hydropower to be the main source of electricity for Zimbabwe. However, historic droughts have reduced the Zambezi River's inflows into Lake Kariba, resulting in the reduced power generating capacity of Kariba Hydropower Station. Regional droughts in 1992/93 droughts and more recently in 2015/2016 reduced Kariba Dam's generating capacity by 8 and 11%, respectively (Chenje and Johnson, 1996; NASA, 2016; Zambezi River Authority, 2016). In December 2019, NASA Earth Observatory images of Lake Kariba showed how much the reservoir had receded compared to the same period in 2018 (NASA, 2019). The Zambezi River Authority (ZRA) reported low dam levels at 8.50% of water usable for power generation (Zambezi River Authority, 2019) followed by massive power cuts of up to 18 h a day in Zimbabwe, threatening shut down of the dam if water levels continued to decline (Bloomberg News, 2019). These scenarios indicate the sensitivity of hydropower to climate variability and extreme weather events in Zimbabwe, together with the increased frequency of occurrence of these events. In addition, these repeated disruptions in electricity by climatic events threaten Zimbabwe's energy security and are largely felt in cities.

Establishing energy security in cities is of paramount importance. Largely so because they are energy intensive and consume about two thirds of global final energy use (REN21, 2020). However, there is limited research on how climate change might potentially impact energy availability in cities, where demand keeps increasing. It is rather focused on increase in energy demand in cities due to rapid urbanisation, especially in less developing countries (Madlener and Sunak, 2011). In addition, there has been less interest on climate change impacts on sources of livelihoods of the urban poor. Instead, many local governments have been more concentrated on poverty reduction than climate change adaptation as it was viewed as a means of reducing the vulnerability of the urban poor (Ka Lee, 2008). Most research on the vulnerability of the urban poor to the impacts of climate change focus on the direct impacts of extreme weather events on urban populations, or vulnerabilities due to lack of resilient infrastructure or services to the poor in urban areas (Carmin et al., 2012). In Zimbabwe, research on climate change impacts on livelihoods in limited and more centred on climate change impacts on rural livelihoods. This is possibly due to the agrarian based livelihoods in rural areas. Furthermore, climate change-energy research focuses on mitigation efforts rather than impacts (Haines et al., 2007; van Vliet et al., 2016). Moreover, studies that look at the climate change-water-energy nexus and urban livelihoods are scarce.

Energy plays a noteworthy role in alleviating poverty in urban areas. Brew-Hammond (2010) is of the opinion that to improve income generation in African communities, emphasis should be placed on productive uses of energy for income generation. His view implies that sectors like the informal sector could improve livelihoods of the urban poor if the energy required in these sectors is secured. This sector has grown over the years and its presence and role in providing income for urban populations acknowledged. The informal sector was well established by the 1960s, with Hart (1973) introducing the term "informal sector," referring to Ghana's towns (Potts, 2008). Nonetheless, it was internationally recognised in 1998 by the ILO in Kenya [International Labour Organization (ILO), 2003]. The International Labour Organization (ILO), (2003) defines the informal sector as all employment arrangements that do not provide individuals with legal or social protection through their work, thereby leaving them more exposed to economic risk than others, whether the economic units they work for or operate in are formal enterprises, informal enterprises, or households. In Zimbabwe, Informal Sector Operations (ISOs) include all enterprises not registered under the Companies Act or the Co-operatives' Act, together with those not assessed for taxation by central government (Paradza, 1999). The National Micro, Small, and Medium Enterprises Policy Framework of Zimbabwe acknowledges the informal sector and states that it is found in all sectors of the economy, predominantly lacks accountability, operates outside of the law and is not registered or licenced. The policy intends to formalise the informal sector which is largely constituted of micro enterprises (Government of Zimbabwe, 2015).

Literature suggests that the informal sector in poor countries grew as rapid urbanisation did not tie in with significant growth in the formal sector, hence, jobs in the formal sector were scarce (Potts, 2008). Numerous studies have linked growth of the informal sector in less developed countries with the period after Structural Adjustment Programmes (SAPs) by the IMF and World Bank had been implemented, from about the 1980s. This was the case in Zimbabwe. The sector had an insignificant role to play before this period, as the formal sector was booming immensely in urban areas (Cobbe, 2002; Chirisa, 2009; Sparks and Barnett, 2010). Government spending was greatly cut, job losses rose and economic hardships grew, forcing urban populations to develop diversified livelihood strategies as the economy shifted (Chirisa, 2009; Njaya, 2015). The above trend insinuates that as economies of countries struggle, the informal sector grows as it tends to swell during periods of adjustment when employees are laid off. This is supported in literature (Calvès and Schoumaker, 2004; Yuki, 2007; Sparks and Barnett, 2010; Benjamin and Mbaye, 2014; Njaya, 2015) and explains the continued growth of the informal sector in Zimbabwe which often goes through waves of economic challenges. Understandably, a study by the IMF found Zimbabwe to have one of the largest informal economies as a percentage of its economy in the world (Medina and Schneider, 2018). This highlights its contribution to the livelihoods of the population, creating employment and income. Energy consumption in informal sector enterprises is characterised by low to medium energy intensity compared to other high intensity formal sectors like the heavy industries (Karekezi and Majoro, 2002). It is also thought to be labour intensive rather than capital intensive as the scale of production is small, suggesting low energy use (Ihrig and Moe, 2004). However, this does not diminish the importance of availability of energy to this sector. A few studies have highlighted how the livelihoods of people in the informal sector heavily depend on availability of electricity for them to perform their trades and earn income (Karekezi and Majoro, 2002; Chen et al., 2016). Energy availability drives and grows this sector as a lot of the trades in the informal sector are energy dependent.

Activities performed in the informal sector are done either as coping strategies of individuals, or families in environments where earning opportunities are scarce. Zimbabwe began experiencing economic challenges from the 1990s when the economic structural adjustment program was implemented, with the years 1998 to 2008 identified as the crisis decade by McGregor and Chatiza (2020) both economically and politically. The dollarization of the economy from 2009 brought some sensible stability and economic recovery. Regardless, poverty is still experienced by the country's citizens. The Total Consumption Poverty Line (TCPL) for an average of five persons per household stood at $563.00 in June 2018, whilst that for one person stood at $113.00 (Zimstat, 2018). It represents the total income needed for an individual (with all their income added together) as a minimum for them not to be deemed poor (Zimstat, 2018). Thus the informal sector provides a means of alleviating poverty. It is a source of income for retrenched professionals, skilled artisans, graduates entering the job market and uneducated and unskilled persons looking to earn a living (Karekezi and Majoro, 2002; Haan and Maclean, 2006; Potts, 2008; Chirisa, 2009, 2013; Schneider et al., 2010; Benjamin and Mbaye, 2014; Njaya, 2015). About 93% of new jobs created in sub-Saharan Africa during the 1990s were in the informal sector Chen (2001, 2016), with about 80% of total employment in sub-Saharan Africa in the informal economy (Charmes, 2012). The sector continues to grow in Zimbabwe and contributes to household food security due to the commoditization of urban areas.

Women dominate the informal sector as it provides an opportunity for them to earn an income and perform their domestic roles determined by restrictive cultural barriers and lack of formal training and skills (Eapen, 2001; Chirisa, 2009; Fapohunda, 2012; Benjamin and Mbaye, 2014). The sector empowers women as they are normally self-employed or unpaid home-based workers (Chen, 2001; Charmes, 2012; Chirisa, 2013). Similarly in a study in Zimbabwe, the International Labour Organization (ILO), (2017) found 94.9% of women in the informal sector constituting own-account workers. It found women involved in various trades from cross border trading, vending, services, manufacturing, welding mining, and stone quarrying. Similar trades were observed by Chirisa (2013) and Chen and Sinha (2016). Despite the gendered landscape of some informal trades, the participation of women in some male dominated trades highlights the severity of unemployment or income sources of urban households in Zimbabwe. Whilst some literature suggesting that women in informal work are uneducated, the International Labour Organization (ILO), 2017 study found 67.7% of women in informal work in Zimbabwe had at least attained secondary education. Gindling and Newhouse (2014) add on by stating that own-account workers fall between educated and least educated. Incontrovertibly building adaptive capacity and resilience of the informal sector preserves its function as a source of livelihood for the urban population, and in particular women.

MATERIALS AND METHODS

Sampling and Data Collection

This paper is based on data which was collected between April and June 2018 in Harare, Zimbabwe. The purpose of the study was to establish the relation between changes in climatic conditions and energy insecurity and how they combine to influence sustainable urban informal livelihoods. A household survey, by use of open and close-ended questionnaires was conducted over 3 months to collect qualitative and quantitative data from women in the informal sector (**Supplementary Data Sheet 1**). The target population was women in home-based informal work who are dependent on electricity to operate their businesses. Studies have shown that women dominate the informal sector as a source of employment. However, most women in the informal sector in Harare are involved in petty commodity trade and vending in multiple locations, which do not require the use of electricity, hence these women were excluded from the survey. Rather the focus was on women in home-based trades as these are usually unaccounted for in labour force surveys. The paper focused on the informal sector referred to by the International Labour Organization (ILO), (2003). Their activities covered tailoring and grinding (mealie-meal, peanut butter), food services (catering, baking, food processing, refrigeration, etc), to hairdressing, printing, and packaging. The questionnaire was developed using the nine steps to develop questionnaires by Churchill and Iacobucci (2002). The survey gave a broad extensive profile of women in the informal sector, including their demographics and socio-economic status. The questionnaire also provided information on how availability of electricity affects their trades and livelihoods. Moreover, information on the strategies employed by women in home-based informal work when electricity is unavailable was collected.

The study was located in Harare, the capital city of Zimbabwe. The central business district (CBD) is its core, with the industrial areas to the east and south (Gamanya et al., 2009). The low density residential areas on spacious plot sizes of about 1000 m^2 or more, are mainly located in the north and northeast with some medium density residential areas measuring between 800 and 1000 m^2 found in the southern part. Conversely, the high density areas on plot sizes of about 300 m^2 are to the extreme east, south, southwest and west of the city (Gamanya et al., 2009; World Bank, 2014). Indeed, Zimbabwe's stringent and well-institutionalised urban planning bureaucracies, inherited form the Rhodesian era are lauded in literature (McGregor and Chatiza, 2020). The white colonial settlers divided the city along racial lines. They subdivided outlying private farms in the then Salisbury (now Harare) into large residential properties mainly in the north and eastern parts of the city (Zinyama, 1993). In contrast, low income native housing was developed in the south to accommodate the black working force. The settlers started with Harari (now Mbare) in 1907. Expansions continued as demand for cheap labour increased. Hence, Highfield, Mufakose, Rugare, Kambuzuma, Mabvuku, Marimba Park, Tafara, Glen View, Glen Norah, and Dzivarasekwa low income housing projects were developed. These were located in the south and west of the city within close proximity to the CBD and industrial areas for easy commute by the workforce and densely populated. Post-independence (after 1980), low income housing continued to grow in Kuwadzana, Warren Park, Hatcliffe, and Budiriro. At this point urban housing was now divided along socioeconomic lines (Zinyama, 1993; Brown, 2001; World Bank, 2014). This is still evident today. Low income high density residential areas experience poor and inadequate services and amenities when compared to high income, low density residential areas (Zinyama, 1993; Brown, 2001; World Bank, 2014).

Taking the above description of Harare's urban space into account, the participants of the study were drawn from nine different residential suburbs of Harare, differentiated by their population densities, income levels and geospatial locations. These were the high-density residential areas (HDRAs) of Warren Park, Kambuzuma, Kuwadzana; medium-density residential areas (MDRAs) of Tynwald, Parktown, Westlea, and low-density residential areas (LDRAs) of Borrowdale, Marlborough and Mount Pleasant illustrated in **Figure 1**. For the purposes of this study assumptions were made based on socioeconomic divisions of the city's residential areas that the HDRAs and MDRAs in the south and south west of Harare are where the low- and middle-income urban populations reside, and the LDRAs of the north and north east are where the high-income urban populations reside. Hence the study had three strata, allowing for a comparative study to be carried out on demographics, livelihood strategies and adaptive

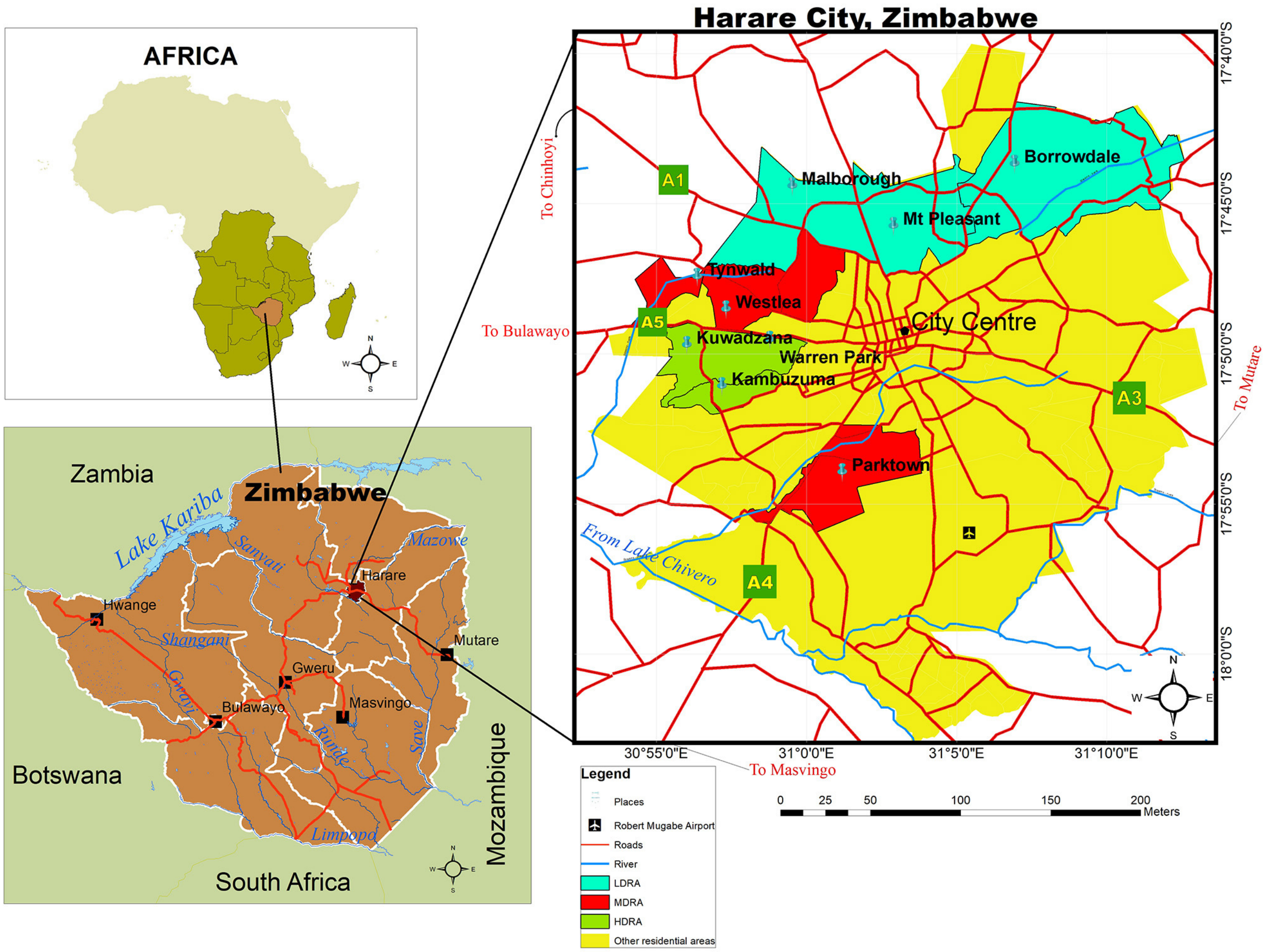

FIGURE 1 | Map of Harare and residential study sites1. Source: Memory Reid.

strategies employed by different urban populations in different residential areas.

The informal sector of Zimbabwe has 450, 816 women, with 16.7% belonging to the province of Harare (Labour Force Survey, 2014). However, there are no statistics on the women in home-based informal work, making it difficult to calculate a sample size to represent the women in home-based informal work in Harare. In addition to this, the household survey sampled respondents whose trade was based in their residential homes, making it difficult to locate them. Based on that, the study did not work with a sample size, but randomly selected the first participant in the study and used a combination of convenience sampling and the snowballing technique or referral method to get the next participant. Locating respondents from LDRAs was difficult compared to MDRAs and HDRAs as houses in LDRAs are sparsely distributed compared to MDRAs and HDRAs. The same applied to MDRAs compared to HDRAs. Based on this more participants were sampled from HDRAs, followed by MDRAs, with the least from LDRAs. We sampled 50% of respondents from HDRAs, 33% from MDRAs and 17% from LDRAs. In total, the study had 150 respondents: 75, 50, and 25 from each stratum of HDRAs, MDRAs, and LDRAs, respectively.

Analysis

Quantitative methods were used to investigate how energy insecurity impacted on urban livelihoods. IBM SPSS Statistics software, together with Excel, was used to analyse the data collected from the household survey. Questionnaire responses were first edited, and cross checked for consistency and completion. Open ended responses from the questionnaires were classified into categories thereby converting qualitative data to quantitative data. The responses were quantified by looking for common themes in the responses and placing them into categories. Each response from the questionnaire was then coded and entered into an Excel spreadsheet. Coding involved assigning a numeric identifier to each response so that it can be run through a statistical software. These responses were run through IBM SPSS statistical software using the codes created. Anonymity of the respondents was maintained by assigning a number to each questionnaire instead of respondent's name. Data collected from the household survey was primarily presented using descriptive statistics in the form of means and frequencies presented in tables and charts. These helped summarise and allowed conclusions to be drawn about the study population. Contingency tables and Chi squared tests were used to analyse the associations between categorical variables. The chi-square test for independence, also called Pearson's chi-square test, was used to investigate whether two categorical variables had a relationship. H_0 = no association/independence; H_1 = association/dependence (Field, 2013). When there was a relationship, Phi and Cramer's V were used to test the strength of the association. Phi and Cramer's V vary between 0 and 1 without any negative value. Cramer's V is an alternative to Phi in tables bigger than 2 × 2 tabulation. A value close to 0 signified weak or no association, but a strong relationship exists when the value is bigger than 0.25 (Akoglu, 2018).

RESULTS

Socioeconomic Demographics

Of the households surveyed, 52% were female headed, with an average size of five people and 47% of the women were married. These women were educated, with most being employed in the informal sector as illustrated in **Table 1**. Only 116 of the 150 households gave responses on their household monthly income, earned in United States Dollars (USD). No households in LDRAs and MDRAs had household incomes at the lower end ($101–300) as shown in **Figure 2**. Different households used various sources of income to sustain their livelihoods. The bulk of respondents' incomes were sourced from salaries and informal businesses. However, the LDRAs had more respondents that received remittances, while only 7% of HDRA respondents received pensions. A large number (76%) of MDRAs had savings as part of their source of income, as represented in **Figure 3**. In the LDRAs, 72% of the respondents had access to credit, compared to 54 and 34.7% in the MDRAs and HDRAs, respectively. Put together, only 47.3% of the entire survey had access to credit. Property ownership in the different residential areas varied, with most residents in LDRAs having purchased the properties they lived in. **Figure 4** shows that most respondents lived in homes that they had purchased. The LDRAs did not have any houses allocated to them through housing schemes that are usually provided for by government to low income groups. The ownership of other assets like cars was evident, with at least 44% of the households owning a vehicle. Only households in the LDRAs owned more than two cars.

The survey had most businesses (60%), being own-account enterprises. There was significant evidence of an association, (chi- square (2) = 19.676, $p < 0.001$), between residential area and type of business (**Table 2**). Within HDRAs, 70% of businesses were own- account enterprises, with LDRAs recording no contributing family workers. The study stems from looking at different home-based energy dependent businesses practised by women in urban areas. **Figure 5** shows the most popular business was tailoring, closely followed by catering and hairdressing. Retailing, food processing, poultry, carpentry/welding, and recording studios were also visibly common.

Income From Informal Businesses

Of the 150 questionnaires administered, only 117 responded on monthly income from informal business. A close look at **Table 3** shows most informal businesses generated a monthly income that ranged between $300–500, closely followed by $101–$300. However, residential area influenced income generated by the businesses. There was significant evidence of a strong association (chi-square (8) = 58.242, $p < 0.00$; likelihood ratio (8) = 69.351, $p < 0.00$; Cramer's V = 0.499) between residential area and income from informal business. This was reflected by higher earnings in LDRAs and MDRAs when compared to the HDRAs. In LDRAs and MDRAs 70 and 60% of the businesses made between $301 and $500 monthly respectively, whereas in HDRAs, 35.1% of businesses earned <$100 and 40.4% earned $101–300. Furthermore, high earnings of $1,001–3,000 were made by 20% of businesses in LDRAs, with the other areas making only 8 and 7 %. Therefore, the data suggests that most businesses in LDRAs and MDRAs earned incomes in the upper categories compared to those in HDRAs.

Operating businesses during power cuts, significantly contributed to monthly income. This was evident as there was a strong association, (chi-square (8) = 16.906a, $p = 0.031$; likelihood ratio (8) = 16.927, $p = 0.031$; Cramer's V = 0.269) between monthly income and business operation during power cuts as illustrated in **Table 4**. The data suggests that businesses that used manual equipment or substituted energy sources during power cuts earned more money than those that did nothing. However, the businesses that substituted for energy source made more money than those that used manual equipment. The businesses that did nothing mostly had income in the <$100,$101–$300 and $301–$500 category (14.8, 44.4, and 33.3%), whereas 25% of those that used manual equipment fetched earnings in the upper categories of between $500–1,000 per month. Furthermore,11.5% of those that substituted energy sources, fetched earnings even higher, between $1,001–3,000 respectively. This suggests that having alternative methods to continue working during power cuts was advantageous as it secured more income vs. not doing anything during power cuts. Earnings are further improved when the businesses managed to substitute energy source.

Impacts, Adaptation, and Resilience to Energy Insecurity of Informal Business

A majority of the enterprises use electricity to operate their machines and **Figure 6** illustrates how electricity was used by the various informal businesses run by women in their households. Electricity was used mainly to operate machinery with heating, refrigeration and stitching being some of the other popular uses. Businesses had to find ways to stay open during load shedding. The majority, 63%, substituted energy sources, while the rest used manual equipment or did nothing as they could not afford alternatives. There was significant evidence of a strong association, (chi-square (4) = 21.171, $p = 0.00$; likelihood ratio (4) =23.784, $p = 0.00$; Cramer's V = 0.266) as shown in **Table 5**. between business operation during load shedding and residential area. Within LDRAs and MDRAs, 76 and 80% of businesses

TABLE 1 | Marital status, level of education and employment status of women in home-based informal businesses.

Marital Status	Married	Single	Widowed	Divorced		N
	47.3%	23.3%	18.7%	10.7%		150
Education Level	Primary School	High School	Tertiary			
	3%	56%	41%			150
Employment Status	Full Time	Part Time	Informal	Unemployed	Retired/ Pensioner	
	21%	13%	60%	3%	3%	150
	2.27	2.81				

Source: Field Survey (2018).

FIGURE 2 | Monthly household income in HDRAs, MDRAs and LDRAs (in USD). Source: Field survey (2018).

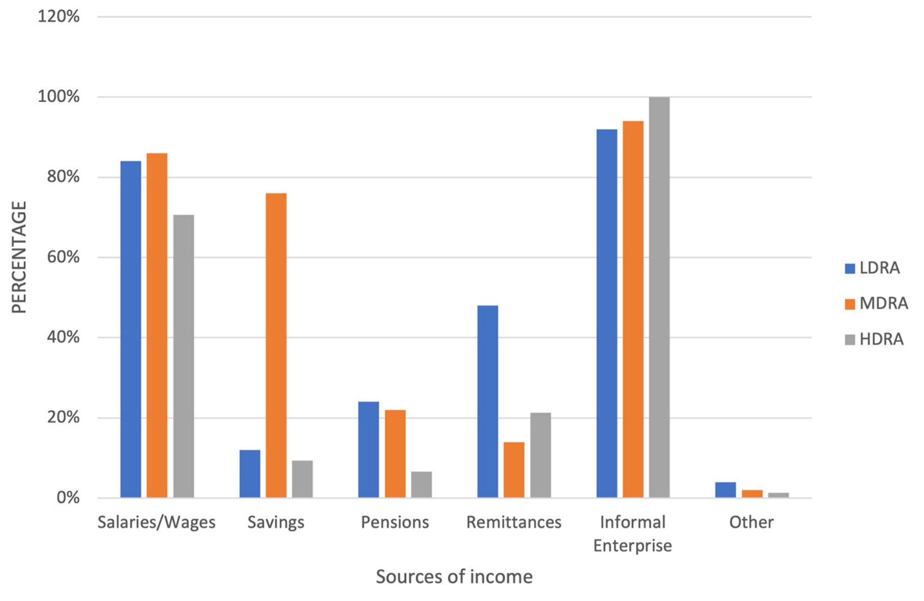

FIGURE 3 | Responses on the multiple sources of income of households in the three different residential areas. Source: Field survey (2018).

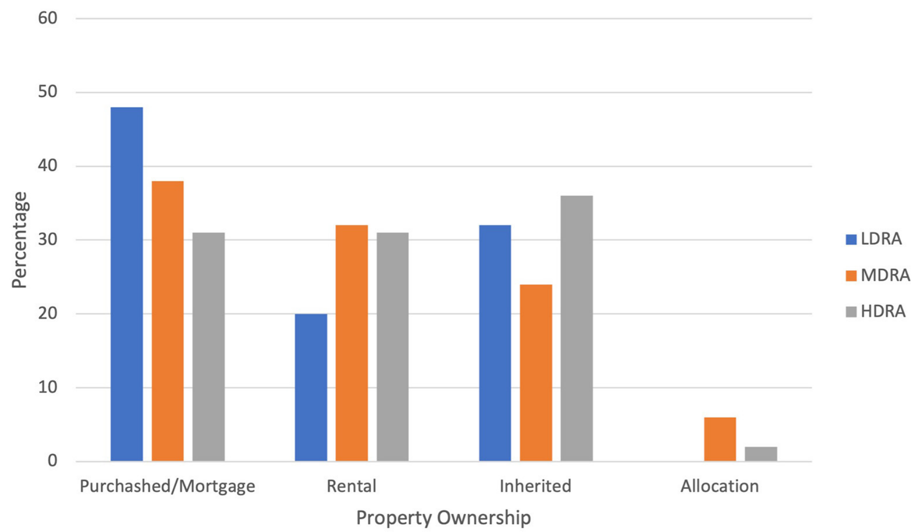

FIGURE 4 | Property ownership of households. Source: Field survey (2018).

TABLE 2 | Association between residential area and type of enterprise.

			Type of enterprise			**Total**
			Own-Account Enterprise	**Enterprise of Employers**	**Contributing Family Workers**	
Residential Area	LDRA	Count	11	14	0	25
		% within Residential Area	44.0%	56.0%	0.0%	100.0%
	MDRA	Count	26	19	5	50
		% within Residential Area	52.0%	38.0%	10.0%	100.0%
	HDRA	Count	53	11	11	75
		% within Residential Area	70.7%	14.7%	14.7%	100.0%
Total		Count	90	44	16	150
		% within Residential Area	60.0%	29.3%	10.7%	100.0%
Chi-Square Tests						
	Value	df	Asymptotic Significance (2-sided)			
Pearson Chi-Square	19.676[a]	4	0.001			
Likelihood Ratio	22.134	4	0.000			
Linear-by-Linear Association	1.032	1	0.310			
N of Valid Cases	150					
Symmetric Measures						
		Value	Approximate Significance			
Nominal by Nominal	Phi	0.362	0.001			
	Cramer's V	0.256	0.001			
	Contingency Coefficient	0.341	0.001			

[a] *1 cells (11.1%) have expected count <5. The minimum expected count is 2.67. Source: Field Survey (2018).*

used substitutes for electricity respectively. In comparison, only 48% of businesses in HDRAs could substitute for electricity, whilst a small minority either used manual equipment (26.7%) or did nothing (25.3%). Those that did nothing generated little income, as a strong association between income and operation during load shedding was indicated in **Table 4**. During load shedding, the businesses that substituted for electricity mainly opted for generators. However, the choice of substitute also had a significant association with the residential area, (chi-square (10) = 33.842, p = 0.00; likelihood ratio (10) = 36.199, p = 0.00; Cramer's V = 0.336). The businesses operating in LDRAs and MDRAs opted for generators compared to those in

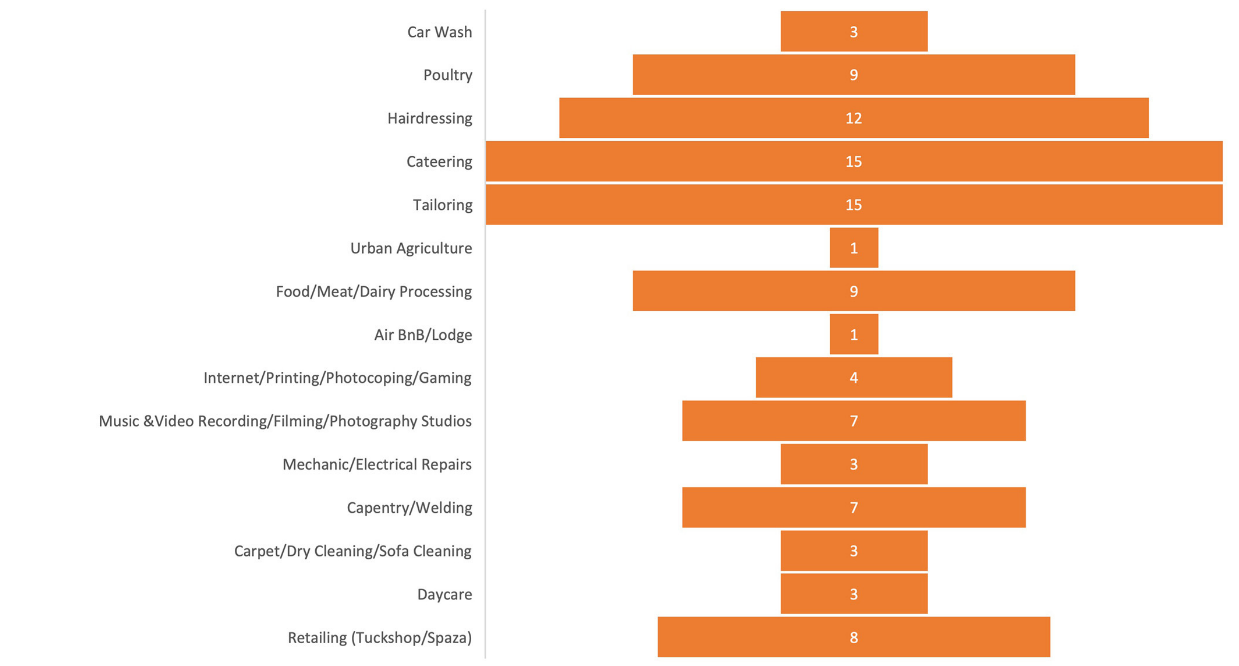

FIGURE 5 | Description of home-based electricity dependent informal businesses practised by women in percentages. Source: Field survey (2018).

TABLE 3 | Monthly income from informal businesses in the different residential areas.

			Total monthly income from informal enterprise.					Total
			<$100	**$101–300**	**$301-$500**	**$501-$1,000**	**$1,001–3,000**	
Residential Area	LDRA	% within Residential Area	0.0%	10.0%	70.0%	0.0%	20.0%	100.0%
	MDRA	% within Residential Area	0.0%	12.0%	60.0%	20.0%	8.0%	100.0%
	HDRA	% within Residential Area	35.1%	40.4%	10.5%	7.0%	7.0%	100.0%
Total		% within Residential Area	17.1%	25.6%	36.8%	12.0%	8.5%	100.0%
Chi-Square Tests								
	Value	df	Asymptotic Significance (2-sided)					
Pearson Chi-Square	58.242[a]	8	0.000					
Likelihood Ratio	69.351	8	0.000					
Linear-by-Linear Association	24.643	1	0.000					
N of Valid Cases	117							
Symmetric Measures								
		Value	Approximate Significance					
Nominal by Nominal	Phi	0.706	0.000					
	Cramer's V	0.499	0.000					
	Contingency Coefficient	0.576	0.000					
N of Valid Cases		117						

[a] *7 cells (46.7%) have expected count less than 5. The minimum expected count is.85. Source: Field Survey (2018).*

HDRAs which opted for firewood/charcoal as shown in **Figure 7**, suggesting a cheaper alternative was chosen by households with a low-income status.

Load shedding had various effects on home-based informal businesses. A closer look at **Table 6**. shows that load shedding impacted on informal businesses in several ways. The large proportion (44%) that substituted energy source found it to be costly and increased operational costs to make up for the additional cost incurred. Load shedding decreased production (78%) and declined income earned (75.2%) by home-based informal businesses. Businesses adapted differently to income losses in their business. The one item chosen by a larger

TABLE 4 | Association of income from informal business and mode of operation during power cuts.

			Total monthly income from informal enterprise.					Total
			<$100	$101–300	$301–500	$501–1,000	$1,001–3,000	
Business operation during power cuts	Manual Equipment	% within Business operation during power cuts	41.7%	8.3%	25.0%	25.0%	0.0%	100.0%
	Substitute Energy Source	% within Business operation during power cuts	14.1%	21.8%	39.7%	12.8%	11.5%	100.0%
	Nothing	% within Business operation during power cuts	14.8%	44.4%	33.3%	3.7%	3.7%	100.0%
Total		% within Business operation during power cuts	17.1%	25.6%	36.8%	12.0%	8.5%	100.0%
Chi-Square Tests								
	Value	df	Asymptotic Significance (2-sided)					
Pearson Chi-Square	16.906[a]	8	0.031					
Likelihood Ratio	16.927	8	0.031					
Linear-by-Linear Association	0.393	1	0.531					
N of Valid Cases	117							
Symmetric Measures								
		Value	Approximate Significance					
Nominal by Nominal	Phi	0.380	0.031					
	Cramer's V	0.269	0.031					
	Contingency Coefficient	0.355	0.031					
N of Valid Cases		117						

[a]8 cells (53.3%) have expected count less than 5. The minimum expected count is 1.03. Source: Field Survey (2018).

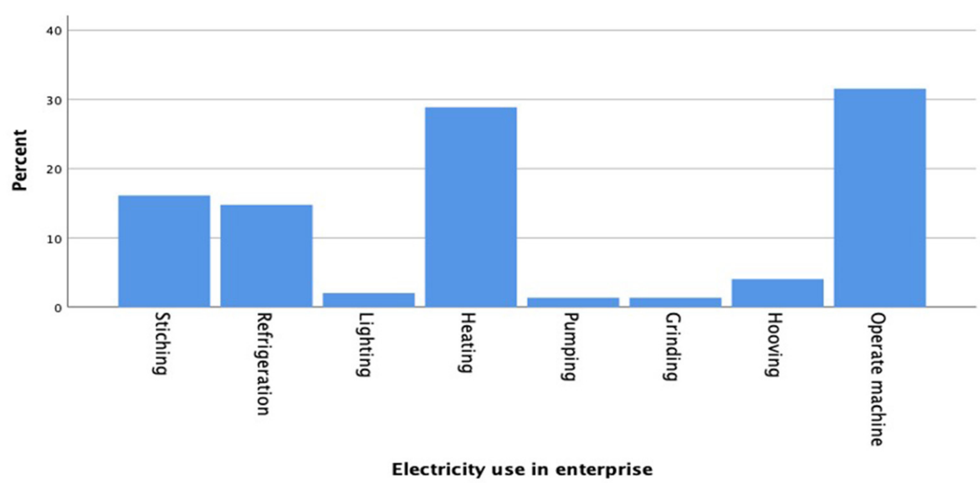

FIGURE 6 | Different electricity uses in the enterprise. Source: Field survey (2018).

proportion of businesses to represent the major activity taken to adapt to the impact on income activity due to electricity cuts was to increase the cost of their products or services (**Figure 8**). Diversifying income generating projects in the household and working overtime when power returned were some of the other measures incorporated by households that depend on informal businesses as their sources of income. Electricity cuts disturbed customer relationships resulting in a lot of disgruntled

TABLE 5 | Association between residential area and business operation during load shedding.

			Business operation during load shedding/power outages			Total
			Manual Equipment	**Substitute Energy Source**	**Nothing**	
Residential Area	LDRA	% within Residential Area	4.0%	76.0%	20.0%	100.0%
	MDRA	% within Residential Area	2.0%	80.0%	18.0%	100.0%
	HDRA	% within Residential Area	26.7%	48.0%	25.3%	100.0%
Total		% within Residential Area	14.7%	63.3%	22.0%	100.0%
Chi-Square Tests						
	Value	df	Asymptotic Significance (2-sided)			
Pearson Chi-Square	21.171[a]	4	0.000			
Likelihood Ratio	23.784	4	0.000			
Linear-by-Linear Association	2.478	1	0.115			
N of Valid Cases	150					
Symmetric Measures						
		Value	Approximate Significance			
Nominal by Nominal	Phi	0.376	0.000			
	Cramer's V	0.266	0.000			
	Contingency Coefficient	0.352	0.000			
N of Valid Cases		150				

[a] *1 cells (11.1%) have expected count less than 5. The minimum expected count is 3.67. Source: Field Survey (2018).*

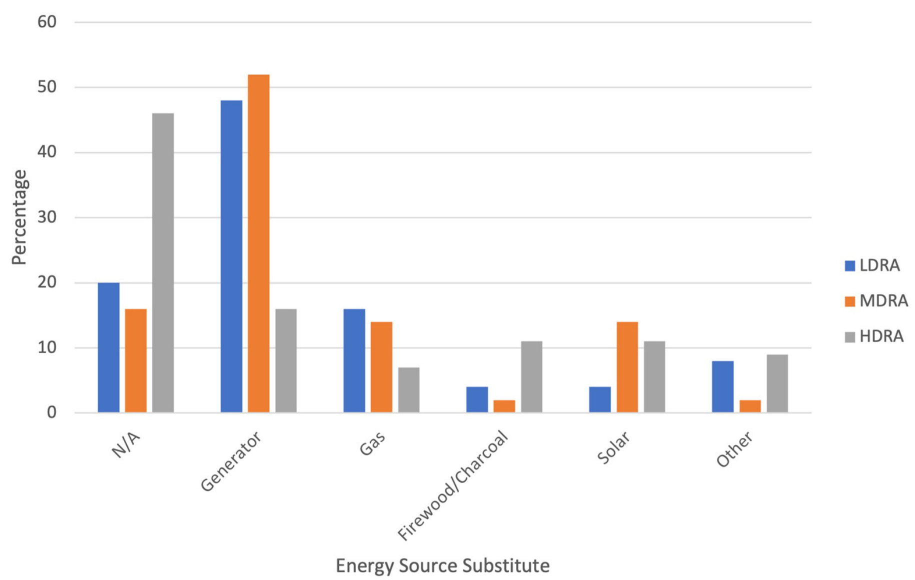

FIGURE 7 | Types of electricity substitutes in different residential areas. Source: Field survey (2018).

customers. This was mainly due to the fact that businesses could not meet set targets or produced poor products when they substituted energy sources. In addition, many products were also spoiled or damaged, especially for clients who used electricity for refrigeration. Respondents from the household survey gave various reasons that they perceived to be behind the electricity cuts highlighted in **Figure 9**. A lot of blame was placed on the economic challenges the country has been facing. Additionally, ZESA's inability to sufficiently maintain its equipment was also blamed. The respondents were also aware of the country's debt to the South African power utility (ESKOM), that exports electricity to Zimbabwe. However not a single respondent associated power cuts to climate change and low lake levels at Kariba Dam.

DISCUSSION

Socio-Economic Background and Income From Informal Businesses

The survey results show that high literacy rates are evident as women in home-based informal work are educated, with the majority having attained a high school or tertiary education qualification. This possibly assists them effectively run their businesses. Similar findings were observed by the International Labour Organization (ILO), (2017) were women surveyed had at least attained secondary education. Granting the fact that studies by Chirisa (2013) found women in the informal sector to be uneducated, he surveyed women in informal trades that included vending and hawking of retail goods. Those trades possibly required fewer skills in contrast to the current study which involved businesses that required electricity for production or service. This would, in some instances, require training or education to some level. In addition, Gindling and Newhouse (2014) point out that education levels in the informal sector of own-account workers falls anywhere between highly educated and least educated, further explaining the differences in the findings of the two surveys. The informal sector creates employment largely for women and has also been collectively observed by other authors (Chen, 2001, 2016; Karekezi and Majoro, 2002; Haan and Maclean, 2006; Schneider et al., 2010; Charmes, 2012; Chirisa, 2013; Brown and McGranahan, 2016; Chen et al., 2016). This study draws attention to the flexibility of the informal sector as other participants of the survey still held full time jobs whilst operating their informal businesses. It became an extra source of income hence it allows for diversification of livelihood strategies.Similar sentiments shared by Chirisa (2009) and Njaya (2015). It highlights the role those multiple incomes play in supporting households, as cities like Harare are largely commoditised and expensive. Food security amongst other factors can only be realised with sufficient income generation in the household. Additionally, women usually venture into informal trade as a survivalist economic activity to support the household income. The resourceful of women was evident in this research as they worked hard to support their families.

A larger proportion of households in the survey earned a decent amount of between $501–1000 per month as their total household income. Furthermore a higher proportion of the informal businesses made between $301–500 per month indicating the contribution of informal home- based work in supporting household income. At the time of the survey, the Total Consumption Poverty Line (TCPL) for an average of five persons per household stood at $563.00 in June 2018, which represents the total income needed for a household (with all their income added together) as a minimum for them not to be deemed poor (Zimstat, 2018). This income earned from informal businesses substantially contributes to food security of urban populations and allows for a more comfortable life, underlining the role the informal sector plays in poverty alleviation. However, the HDRAs had the lowest tier of total household and informal businesses earnings. This supports assumptions made about low-income earnings of households in HDRAs. There are exceptions, where, high-income earners still chose to live in HDRAs where accommodation and rates are much cheaper. This is evident as household income exceeding $5,000 was recorded there. These observations collectively indicate the informal sector's contributions to income and employment of urban populations. Its role in poverty reduction and food security of urban populations is indisputable. The LDRAs households continued to match assumptions made about their income status. They are the only ones that received remittances potentially showing the differences in family success in the various residential areas. They possibly have relatives that have travelled abroad, and work elsewhere, and hence have the capacity to send money back to family. The study revealed that their asset base was the strongest as most respondents had purchased their own homes, had access to credit and could afford the luxury of having two or more cars per household compared to the other residential areas.

The home has been identified as an essential resource for home-based informal work (Chen et al., 2016). Therefore, it is not surprising that women in the study ventured into home-based informal work because of ease of doing business at home. It is convenient as workspace can easily be created and electricity is readily available in most homes. The businesses that are easy to set up in the home include poultry and tailoring amongst others. Therefore, women do not venture into the informal sector solely because they are unskilled or because social and cultural barriers dictate their role in the home as homemakers as mentioned by Eapen (2001) and Fapohunda (2012). However, working from home is advantageous as they can combine their home-based informal work with their domestic roles to enable them to earn an income. The same observations were also identified by Carr and Chen (2002). Most businesses were own-account enterprises highlighting how the informal sector empowers women as it made it possible for most women to own their own businesses entirely. This characteristic thought to be true of most of the workforce in developing countries (Charmes, 2012; Chen et al., 2016; Stuart et al., 2018). However, in the current study, in LDRAs, women chose to employ people to help run their businesses than have family members working in the businesses they ran, whilst in MRDAs and HDRAs, the contribution of family workers was present. This could be because LDRAs families are usually affluent and wealthier and would therefore

TABLE 6 | Perceptions on impact of load shedding.

	N	Yes	No	N/A
Increased expense of substitute energy source	150	44.0%	20.7%	35.3%
Increase in operational cost	150	44.7%	20.7%	34.7%
Decline in production due toload shedding/power outages	150	78.0%	22.0%	
Decline in income due to loadshedding/power outages	150	75.2%	24.8%	

Source: Field Survey (2018).

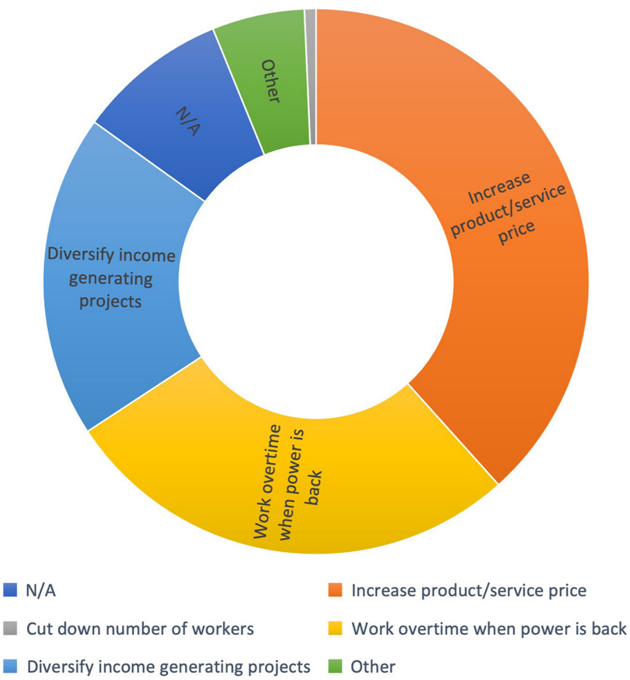

FIGURE 8 | Measures taken to adapt to income loss (n.b. respondents were asked only to select a single item that represented their most frequent activity to adapt to a loss of income). Source: Field survey (2018).

rather operate their businesses on their own or employ people to do so than involve their families for labour.

Women in home-based informal businesses performed a multitude of trades in Harare with tailoring, catering, and hairdressing being the most popular. They are generally easier to start, and common amongst women. Other trades like poultry, food processing, retailing, studios and, surprisingly, welding or carpentry were also common. In the typical male trades like welding and carpentry, it was usually men that did the work, while women were the administrators. In some instances, the women took over a family business after a spouse passed away and carried on with the previous employees or the sons managed the business. Other male dominated trades in the study where women oversaw the business but did not physically do the work included electrical repairs and car washing. The International Labour Organization (ILO), (2017) also observed women in male dominated informal work like welding and mining. However, the women also physically worked in those fields. The evidence presented in the study could be a reflection on the dire situation in the country that has forced women to venture in male dominated trades. It could also be an indication of modification of gender roles and increased women empowerment in Zimbabwe. It also indicates the survivalist nature of the informal sector where women will do whatever it takes to provide income for their households. These findings illustrate that the informal sector covers a wide range of labour markets and the conclusion that people in the informal sector practised whatever business was feasible to earn an income and sustain their livelihoods.

In addition to the ease of running from home, home-based informal businesses are operated from residential homes to reduce overhead expenses that come with operating in business centres. Transport and rental costs are eliminated, while saving time away from home (Chen and Sinha, 2016). Furthermore, location of business had an impact on income received from informal business as businesses in LDRAs and MDRAs made the most money, with less earned by businesses in HDRAs. However, in the study home-based informal businesses were practised in all residential areas regardless of income status. Households in Zimbabwe needed means to secure or supplement household income, regardless of their perceived economic status. This was also experience by Kazimbaya-Senkwe (2004), who found informal businesses in all residential areas, from the wealthy residential areas to the poor. It sheds light on the economic status of the country and how eroded income from formal jobs has become. It also highlights the survivalist nature of the informal sector and that it is indeed a livelihood strategy the aids households improve their income reducing poverty in urban areas.

Impacts, Adaption, and Resilience of Urban Livelihoods to Energy Insecurity

Electricity use in informal business drives the success of many home-based enterprises. In this study, electricity was mainly used for heating, machine operation and refrigeration, alluding to the various roles electricity plays in informal urban livelihoods. Hence access and availability of electricity is crucial for successful outcomes of home-based informal businesses. However, power cuts hinder the success of these electricity dependent businesses as energy insecurity was experienced by women in home-based informal urban work. Most households experienced electricity cuts in their homes every week and perceived to experience them more in the winter months of the year. Most national grids

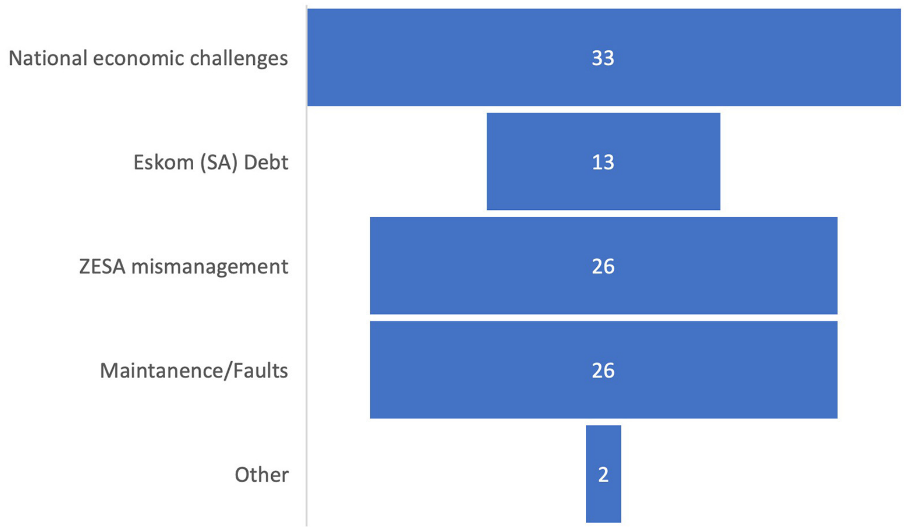

FIGURE 9 | Reasons behind load shedding in percentages. Source: Field survey (2018).

are strained in the winter months as electricity use for heating increases and likely the same experience of these businesses. The same likely occurs on long holidays. The year 2016 was revealed in the study to have the worst power cuts with 2013 to 2017 recording frequent power cuts. These years tie in with low lake levels at Kariba Dam in 2015/2016, which resulted in low generation capacity and subsequent power cuts as stated by the Zambezi River Authority (2016) and NASA (2016). The findings provide further support for the role a climate change-water-energy nexus plays in energy security for Zimbabwe and how that impacts urban livelihoods. However, it was somewhat surprising that no respondent married the two but rather alluded to other factors like economic challenges and debt were behind the power cuts. This assertion draws attention to the economic challenges Zimbabwe has been facing. Citizens could only associate power outages to the economy. Even more so because most of them have been drawn into the informal sector to try an augment their earnings to adequately support their families.

The findings of this study indicated that a business' adaptive capacity to energy insecurity stresses strongly influenced income earned and success of the home-based informal business. Businesses that did not operate during power cuts earned less than those that substituted power sources or used manual equipment. These businesses continued to be productive even though power was cut as they found alternatives. However, how informal businesses adapted to power cuts had a bearing on income earned. This was reflected in the survey as most businesses that used manual equipment earned very little compared to those that substituted energy sources, as their scale of operation was substantially reduced, even though they continued to be productive during power cuts. Manual equipment was usually tedious to use, time consuming, output was low, and quality of product was not always up to standard. Similar views were expressed by dressmakers in Asia (Chen and Sinha, 2016), who mentioned the disadvantages of manual equipment as they took longer to produce product, product quality was lost leaving disgruntled customers and loss of business. These findings highlight how energy insecurity impacted on productivity and revealed businesses' low adaptive capacity. They belong to vulnerable groups that are usually located in low-income communities.

As power cuts frequently disturbed informal business operations, businesses were energy insecure and had to adapt by finding means to continue working and earn an income when power was cut. The prevalence of generator use to substitute for electricity in LDRAs and MDRAs compared to HDRAs continues to drive the narrative that residents in HDRAs have lower household incomes. This is further reflected by how different households in the various residential areas adapted differently. Residents in HDRAs did not substitute as extensively as other residential areas and used cheaper alternatives like firewood when they did substitute. This could be associated with limited resources, which left them with no option but to wait for electricity to return, exposing their low adaptive capacity. As observed earlier, doing nothing or using manual equipment impacted on the income from informal businesses and was the likely fate of businesses in HDRAs. Businesses in HDRAs has limited capacity to adapt to disturbances and looked for alternatives that are affordable but limit their advancement in the businesses they operate. Therefore, the evidence presented here indicates that energy insecurity is largely felt by the urban poor, as they are more vulnerable to environmental shocks due to their low asset base.

The ability to adapt to shocks continued be key to the survival of informal businesses when disturbances occurred. However, it brought with it new challenges. Alternative electricity sources were expensive, increasing operational costs of the businesses. Moreover, productive hours and income were lost when electricity was unavailable, which led to businesses adapting to protect their sources of livelihood. As such, most home-based informal businesses increased prices of product or service to recover losses due to power cuts. Where possible, diversification of income generating projects or working overtime when power was back were also other coping strategies employed by women in these informal businesses. The same pattern was also common in Asian cities as home-based informal workers worked overtime when power was back, to make up for lost productive hours during power cuts (Chen and Sinha, 2016). It sheds light on the resilience and fighting spirit of women in home-based informal businesses as they did whatever it took to earn income for their households. These findings also collectively highlight the challenges and struggles low-income groups face when disturbances occur. They resort to alternatives that are cheap, which limit their ability to effectively adapt to shocks and stresses, subsequently experiencing losses in income they desperately need. Hence, energy insecurity due to climate variability impacts the groups with the lowest adaptive capacity. These are usually the urban poor.

Power cuts continued to frustrate the efforts by women to earn income to offset the economic challenges experienced by most households. They disturbed businesses' relationship with clients as they failed to meet set targets or provide a service. Loss of customers in a flooded market are likely to have worsened the situation for most businesses at it takes time to build relationships with clients. Loss of product was equally dreadful as many products got damaged or spoilt, especially those requiring refrigeration during power cuts. These disturbances could possibly result in loss of business and livelihoods. This is likely true for businesses with limited resources to recover. The economic and electricity challenges facing the country are evident. It was not surprising that most respondents were aware that ZESA relied on exports and was indebted to the South African power utility, Eskom, as it is widely publicised. Furthermore, ZESA continues to struggle to maintain and service its equipment to the dismay of Harare's population that depends on electricity. Most citizens of Zimbabwe are familiar with the Kariba Hydropower Station as it is a massive structure and a tourist attraction, and many people vacation on Lake Kariba. The failure of any respondent to link the power cuts to climatic factors could suggest information on climate change and energy security matters are not widely made public or readily available in the public domain.

CONCLUSION

In this paper, it has been argued that the current dominance of hydropower in Zimbabwe's energy production structure and the increase in extreme weather events do not seem to offer a sustainable environment for socio-economic development. The country's dependence on an energy system which is vulnerable to changes in climatic conditions, together with the deteriorations in the energy infrastructure is increasingly threatening the livelihoods of many of the urban poor and not so poor households and communities. Moreover, whole livelihood options and incomes are dependent on the stable supply of electricity. There is therefore, an urgent need for both local and national authorities in Zimbabwe to identify avenues through which to, firstly; diversify the energy sources and secondly, build the adaptive capacity and resilience of the community to these energy insecurities they encounter.

It is important to note here that the informal sector in Zimbabwean cities like elsewhere in the developing south contributes significantly to household food security and income generations, particularly in female-headed households. Governments must integrate this important sector in urban planning and development plans. It is noted that the informal sector activities in many African cities including Zimbabwe are usually considered by the urban managers to be a nuisance to the overall urban landscape and are often marginalised in policies and development strategies. However, the empirical evidence presented in this paper suggests an urgent need for urban managers to rethink how these informal sector activities are supported through many initiatives among which include the supply of reliable and stable energy. There is an urgent need to establish pro-poor institutional and policy frameworks, which would act to enable and facilitate the engagement of the urban poor, particularly vulnerable women in more productive activities. It is through the establishment of working institutions and comprehensive policies, which are responsive to the realities and needs of the urban people that the informal sector will contribute in a meaningful way and significantly to economic growth and national development.

In view of the above assertions, we argue that future energy expansion projects should consider incorporating an energy mix that does not depend solely on a technology historically affected and predicted to continue to be affected by climate change. Climate smart technologies are of paramount importance in countries like Zimbabwe, where extreme weather conditions like drought are predicted to increase. Connected to this, is the need for more research on the impacts of climate change on urban livelihoods in developing cities particularly those in sub-Saharan Africa which are compounded by a number of factors such as high poverty levels, poor infrastructure, deteriorations in both national and local economies, weak institutional and policy frameworks and the lack of political will. With energy demand set to increase as urban populations continue to grow, threats on energy security due to climate variability and climate change need to be further investigated. This is crucial for Africa as it carries the fast urbanising cities in the world. In addition, studies in more cities together with larger sample sizes would allow for a comprehensive understanding of how a climate change-water-energy nexus impacts on urban livelihoods. The findings reported in the study can only be preliminary due to a small sample size. Further research needs to examine the role institutions play in supporting urban livelihoods in a changing climate. Local institutions like municipalities shape the impacts of external shocks like climate change and energy insecurity on communities. Therefore, they are key in shaping the resilience of urban livelihoods and protection of women's income generating opportunities. Collectively, the adaptive strategies in different cities and the role institutions play provide different approaches in adapting to a climate change-water-energy nexus, creating opportunities to develop frameworks and policies which may facilitate building the adaptive capacity and resilience of urban residents as well as those of whole cities.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The University of the Witwatersrand Ethics Committee; Ethics Clearance Certificate Issued. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2021.706476/full#supplementary-material

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