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Multicriteria Decisions in Urban Energy System Planning: A Review

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Urban energy system planning (UESP) is a topic of growing concern for cities in deregulated energy markets, which plan to decrease energy demand, reduce their dependency on fossil fuels, and increase the share of renewable energy sources. UESP being a highly multisectoral and multi-actor task, multicriteria decision analysis (MCDA) methods are frequently used in the decision processes. These methods may provide support in organizing and identifying solutions to problems with conflicting objectives. However, knowing which method to use is generally not straightforward, as the appropriateness of a method or combination of methods depends on the decision problem's context. Therefore, this article reviewed scientific papers to characterize and analyze MCDA problems and methods in the context of UESP. The review systematically explores issues such as the scope of the problems, the alternatives and criteria considered, the expected decision outcomes, the decision analysis methods and the rationales for selecting and combining them, and the role of values in driving the decision problems. The final outcome is a synthesis of the data and insights obtained, which may help potential users identify appropriate decision analysis methods based on given problem characteristics.

Keywords: multicriteria decision analysis, decision support, optimization, urban planning, energy planning, urban energy system

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INTRODUCTION

In the past decades, the energy sector has undergone profound changes and is currently facing new challenges. Concerns for climate change, linked to GHG emissions and fossil fuel consumption, have led many countries to actively decrease their energy demand, reduce dependency on fossil fuels, and increase the share of decentralized and renewable energy (IEA, 2008). While the deregulation of the energy market in many countries has offered new opportunities in achieving this transition, it also increased the complexity and scope of energy planning (Makkonen, 2005). In this context, cities play an important role, by reshaping the urban form and their energy infrastructure. Since the rise of environmental and social concerns in the end of the previous century (Rittel and Webber, 1973; UNCED, 1992), the field of urban planning has opened up to include these issues. Thus, urban planners play a considerable role, as they must mediate and account for the many interests at stake when making decisions (Teriman et al., 2010). While it has been demonstrated that the lack of analytical support may lead to the use of simplified and contradictory decision rules (Keeney, 1992; Pedrycz et al., 2011), monocriterion approaches are most likely suboptimal when considering a wider range of objectives and attributes and thus support long-term sustainable development only partially (Mirakyan and De Guio, 2013a). Several methods focusing essentially on monetary aspects, such as cost–benefit analysis, cost-effectiveness analysis, or financial analysis, have been qualified as "reductionist" techniques for failing to capture the multiple facets of a problem (Dodgson et al., 2009; Browne et al., 2010). For these reasons, multicriteria decision analysis (MCDA) methods have become increasingly popular in the field of energy planning (Pohekar and Ramachandran, 2004; Zhou et al., 2006; Løken, 2007; Wang et al., 2009), enabling users to better understand the decision problem they face, negotiate, quantify and communicate preferences, and make decisions more explicitly and rationally (Pohekar and Ramachandran, 2004; Ghafghazi et al., 2010).

Several reviews of MCDA methods have been realized, some with more specific focus on energy-related problems. The initial review of MCDA applications in energy and environmental studies by Huang et al. (1995) was later updated by Zhou et al. (2006), who underlined the important increase in applications. Pohekar and Ramachandran (2004) classified and reviewed more than 90 papers on MCDA applications to sustainable energy planning, aiming to highlight the suitability of methods to different application areas, namely "renewable energy planning, energy resource allocation, building energy management, transportation energy management, planning for energy projects, electric utility planning and other miscellaneous areas." Polatidis et al. (2006) proposed a framework to help select suited MCDA methods for decisions related to renewable energy sources (RES). Løken (2007) discusses and classifies energy planning studies, which adopted various MCDA methods including value measurement models, goal, aspiration and reference models, and outranking models. Wang et al. (2009) reviewed the most frequent criteria used in MCDA for energy system sustainability, as well as corresponding methods for criteria weighting, evaluation, and aggregation. Dodgson et al. (2009) provide an overview of MCDA techniques, as well as practical guidelines for their application in various areas of government decision-making, including energy issues. Strantzali and Aravossis (2016) reviewed papers that applied various decision support methods (MCDA, cost–benefit analysis, and life cycle analysis) to renewable energy investment studies, classifying them by year, application area, and geographic distribution. Greco et al. (2016) present a historical context for MCDA, as well as in-depth descriptions of outranking methods, multiattribute utility and value theory methods, non-classical methods to cope with uncertainties and fuzzy measures, and multiobjective optimization methods.

Given the current needs for urban areas and their energy systems to help solve the climate and energy challenges discussed above, the present review examines more specifically the studies making use of MCDA in this area. Several lacks identified in the literature have in particular motivated this article and its focus on the urban scale. First, it has been noted how MCDA studies so far have rather focused on the macro scale (national and regional) or the micro scale (single building or user) and avoided the intermediate urban and neighborhood scales (Makkonen, 2005; Løken, 2007). In addition, the importance of these local scales for energy planning has become a central topic of research, as will be elaborated in Section "Urban Energy System Planning." Løken (2007) also observed a lack of studies covering simultaneously multiple sectors and energy carriers, advocating more integrated approaches. More generally, he and Hobbs and Horn (1997) also advocated the combination of multiple MCDA methods, as the choice of a method strongly influences the decision outcome. Stemming from these lacks, as well as other open issues impacting decision outcomes (Section "Review Questions"), this review investigated the literature on UESP involving MCDA, with the aim of achieving the two following objectives:

1. To characterize and classify the nature and types of MCDA problems related specifically to UESP, investigating aspects such as the problem's scope (localization, spatial scales, temporal scales, topics, and planning focus), alternative generation methods, criteria used, decision problematic, and planning driver.
2. To survey the MCDA methods (and supporting methods) used to solve these problems, the reasons for selecting them, and when applicable, the rationales for combining them.

After addressing these objectives by analyzing the reviewed papers, a synthesis is performed by combining the data into a multicriteria decision support framework to facilitate the choice of appropriate MCDA methods in the area of UESP. As a simple and intuitive way to explore multivariate data, parallel coordinates are adopted to visualize and interactively select relevant methods. In fact, several authors previously noted that choosing an appropriate MCDA method was a MCDA problem in itself (Al-Shemmeri et al., 1997; Løken, 2007; Ghafghazi et al., 2010). However, Guitouni and Martel (1998) recommend avoiding the "vicious circle" of using an MCDA method to choose an MCDA method, advocating instead the definition of methodological principles and decision-making situation typologies to help choose appropriate methods. A review-based approach as proposed here, which characterizes the decision problems and corresponding decision support methods, therefore offers a framework to help choose methods according to various problem characteristics.

The present review can be useful for both researchers in the fields of urban planning and decision science and to practitioners. To the latter, it offers an overview of existing methods and a means to identify those most suited to their problems and decision contexts. To the former, several research priorities and topics, based on the findings, are addressed and proposed in the concluding section.

The article is structured as follows. First, core concepts and definitions used throughout the article are presented, as well as the review methodology, and describing in particular the review questions (Section "Definitions and Methodology"). Next, the results gathered from the review of all articles are analyzed, and a synthesis is performed by combining the data into a decision support framework (Section "Results"). Main insights and findings are discussed (Section "Discussion"), before concluding the article with some general outlooks and critics of the work (Section "Conclusion").

DEFINITIONS AND METHODOLOGY

Definitions

This article links the fields of MCDA and urban and energy planning. Basic definitions from these fields, which will be used throughout the article, are clarified in this section.

Multicriteria Decision Analysis

Multicriteria decision analysis allows to organize and structure complex decision problems characterized by multiple, often conflicting objectives. Several scholars in the field of MCDA have stressed that MCDA should not be mistaken for decision-making techniques, but rather techniques for analysis and aid (Keeney, 1982; Roy, 1996; Belton and Stewart, 2002). Keeney (1982) for example wrote that "decision analysis will not solve a decision problem, nor is it intended to." Belton and Stewart (2002) stated that the main goal of MCDA should be "to facilitate decision-makers' (DM) learning about and understanding of the problem faced, about their own, other parties' and organizational priorities, values and objectives and through exploring these in the context of the problem to guide them in identifying a preferred course of action." As discussed in the studies by Dodgson et al. (2009) and Wang et al. (2009), from the definition of the problem to the desired decision analysis outcome, four mains steps should be followed (**Figure 1**). This process is not necessarily sequential and may have iterations (Guitouni and Martel, 1998).

A multicriteria decision problem thus essentially consists of a set of alternatives that are evaluated on the basis of conflicting and incommensurate criteria, according to the DM's preferences (Malczewski and Rinner, 2015). Therefore, the main elements of any multicriteria decision problem include values, alternatives, criteria and their weighting, and DMs.

Values can be defined as principles or beliefs, held by individuals or groups, which reflect their conception of what are good or desirable states or behaviors (Connelly and Richardson, 2005; Balint et al., 2011). In this sense, they rationalize actions and guide the selection or evaluation of behaviors and events. According to the study by Keeney (1992), values are typically indicated in seven different forms (ethics, traits, characteristics, guidelines, priorities, value tradeoffs, and attitude toward risk). To be of use in decision-making, they are made explicit through associated statements, criteria, objectives, and weights. Values are rather ends in given time horizon and should not be confused with means. As proposed in the study by Keeney et al. (1987), a "value tree" can be established to elicit the values of stakeholders and derive an organized hierarchy of corresponding criteria that achieve or describe the given values.

An alternative is a means toward the satisfaction of the values and criteria. In some cases, it is the aim of MCDA to short list a wide range of existing alternatives and, in others, the identification of alternatives is itself a necessary and active process (Dodgson et al., 2009). As suggested by Keeney (1992), alternatives are only important in the way that they satisfy the values (and the criteria involved), and their identification should therefore be driven by these values. Alternatives can be generated either automatically (as often the case in multiobjective optimization) or manually (Pedrycz et al., 2011).

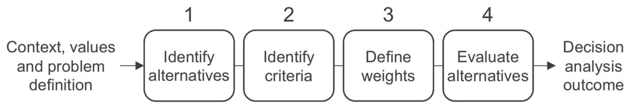


FIGURE 1 | **Main steps involved in multicriteria decision analysis**.

Although there is no standard definition of the expression "criteria" (Nijkamp et al., 1990), generally speaking, a criterion represents a standard of judgment to test the acceptability of an alternative (Pedrycz et al., 2011). In multicriteria literature, it is used to describe two distinct concepts: objectives and attributes. Objectives indicate the desired direction toward which a DM wishes to move (for example, minimum cost or maximum energy efficiency) (Pedrycz et al., 2011). We can distinguish objectives from goals, which represent a threshold or target level to reach, in terms of a specific state in space and time, while the objective gives the desired direction (Hwang and Masud, 1979). Attributes are a set of characteristics chosen by DMs that measure the performance of an alternative (e.g., how it impacts employment, quality of life, environmental parameters) (Hwang and Masud, 1979; Pedrycz et al., 2011). Weights are determined to indicate the relative importance or preference of criteria (Wang et al., 2009).

The DM is but one among several types of actors in a decision process. Roy (1996) describes three main types of actors: stakeholders, third parties, and analysts. The former are those who have an important interest in the decision and directly intervene in the decision process. They consist either of individuals, a clearly defined group of individuals (an elected body, a panel of experts, etc.), or a group with less well-defined boundaries (a lobby, public opinion, etc.). Usually, the objectives and values of the different stakeholders are diverse and conflicting. Because the decision aid cannot simultaneously benefit all stakeholders comprehensively, one stakeholder is generally identified as the DM. The second type of actors are referred to as third parties, as they do not actively take part in the decision process, but are affected by its consequences, and thus whose preferences must be taken into account (typically the citizens, end-users, consumers, etc.). A third type of actor is the analyst, who plays a role in supporting the DM. In some cases, the DMs may develop the decision aid themselves, but generally this task is performed by an analyst different from the DM. This is in particular the case when the DM does not possess the technical or methodological background, or when an external party is desired to ensure a neutral and more objective approach. In summary, stakeholders are the actors who actively take part in the decision process and include the DM. These can be assisted by an analyst whose role is to provide methodological support to help answer questions posed by a stakeholder in a decision process. This support must take into account the interests of not only the stakeholders, but also third parties who are affected by the decision.

Rationales for using MCDA in energy planning have been discussed and compared to other decision support methods (cost–benefit approach, cost-effectiveness approach, energy ecological footprint, etc.) or simply to informal judgment unsupported by such methods (Dodgson et al., 2009; Wang et al., 2011). The main arguments in favor of MCDA from the studies by Pohekar and Ramachandran (2004), Dodgson et al. (2009), Browne et al. (2010), Coelho et al. (2010), Ghafghazi et al. (2010), and Wang et al. (2011) can be summarized as follows:

- Useful to resolve conflicting interests and reach compromises
- Transparent, explicit, and flexible

– Promotes public participation in decision-making processes
– Can be process—rather than results—oriented to favor understanding of the problem
– Synthesizes multiple aspects in a single decision output
– Facilitates multidisciplinarity
– Can represent the preferences of multiple stakeholders by varying weights
– Can analyze incommensurable or uncertain criteria
– Can handle and aggregate qualitative and quantitative information
– Can complement a reductionist approach by providing a more holistic approach

Browne et al. (2010) nevertheless point out two key drawbacks of MCDA in energy planning, namely the dependency on subjective judgment in qualitative approaches and the difficulty to quantify environmental or social impacts. MCDA has also been criticized for providing inconsistent results, being highly dependent on method choice and subjective stakeholder preferences (Guitouni and Martel, 1998).

Urban Energy System Planning

Energy planning is a complex issue for involving not only multiple criteria but also for spanning across multiple scales, from the building scale up to national or international scales (Wierzbicki et al., 2000; Thery and Zarate, 2009; Prasad et al., 2014). However, the urban scale has received particular attention in the past years regarding energy issues, as cities are acknowledged to play an important role in mitigating climate change. The International Energy Agency estimates that cities represent two-thirds of the world's energy consumption and GHG emitters and could therefore notably curtail climate change impacts through local authority engagement (IEA, 2008). The Intergovernmental Panel on Climate Change has recently noted urban planning and other city scale interventions among the key measures for climate change mitigation (IPCC, 2014). The United Nations similarly advocates municipal-led energy conservation and carbon emission reduction plans (Habitat-Iclei, 2009). Cities themselves have recognized their strengths, as noticeable through the Aalborg charter signatories (Aalborg Charter, 1994), who declared "that the city or town is both the largest unit capable of initially addressing the many urban (…) natural resource and environmental imbalances (…) and the smallest scale at which problems can be meaningfully resolved in an integrated, holistic and sustainable fashion." The "Covenant of Mayors" (Covenant of Mayors, 2016) is a city-based European initiative, which aims to help cities achieve the EU's climate targets (EC, 2007, 2014), by fostering exchange of experience. The network of megacities C40 also acknowledges, through various studies, the important role cities play in addressing climate change (C40, Arup, 2014; C40, Arup, UCL, 2015).

This trend for planning energy at the urban scale is further supported by research in various fields. The urban level is believed to offer a more direct and concrete space to act regarding energy consumption and supply, allowing for effective adaptation of policy measures to local specificities (Chapuis et al., 2010; Keirstead and Schulz, 2010; Caputo and Pasetti, 2015). St. Denis and Parker (2009) identified that given recent technological advancement and better access to local knowledge, communities have become more active in planning their own energy systems. They identified several advantages at this local scale, including increased social input and participation of locals, more agile responses to opportunities and threats, more personal investment and interest of actors, and a clearer link between local consumption and generation. On the other hand, the more localized scale of the individual building scale is found less effective than wider district or urban scales, neglecting possible benefits of considering multiple buildings on the demand side (e.g., by taking shading into account when planning the building stock) and on the supply side (e.g., enabling economies of scale or energy-efficient centralized systems) (Ratti et al., 2005; Koch, 2009; Zanon and Verones, 2013; Immendoerfer et al., 2014; Petersen, 2016). As a means to effectively perform this "upscaling" (UN-Habitat, 2009; Gossop, 2011; Zanon and Verones, 2013; Cajot et al., 2015; Strasser, 2015) have argued that energy issues should integrate existing urban planning processes. A survey from UP-RES (2011) made clear the interest and need from building scale specialists to access training regarding the energy solutions on the urban scale.

The planning of energy infrastructure is not essentially new to the wide range of urban activities; however, its handling by means of integrated, cross-sector, and multiactor approaches is relatively recent. Many cities are struggling to develop new methods to successfully bring together energy issues in the framework of urban planning procedures (Zanon and Verones, 2013; Immendoerfer et al., 2014; Strasser, 2015). Because of the novelty of such approaches, the term of *urban energy system planning* itself can be subject to debate and is worth clarifying. Based on a compilation of fragmented definitions of its subterms from literature, we put forward a synthetic definition of UESP, in an attempt to facilitate and improve the discussion on this emerging field.

- UES is defined by Keirstead et al. (2012) as "the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area."
- Hopkins (2001) refers to urban planning as "intentional interventions in the urban development process, usually by local government," and where "the term 'planning' (…) subsumes a variety of mechanisms that are in fact quite distinct: regulation, collective choice, organizational design, market correction, citizen participation, and public sector action." The concept of urban planning, previously confined to the task of designing a physical and spatial framework, has grown to serve also a more strategic function, defining and influencing the development of society (Albers, 1986). As such, urban planning is as much concerned with the spatial organization and interrelations between urban components and activities, as it is with the strategic, intersectoral, and more abstract planning of a city's development, translating visions into goals, actions, and investment priorities (Healey, 2004; UN-Habitat, 2009).

- Model-based energy planning in cities or territories is defined by Mirakyan and De Guio (2013a) as "an approach to find environmentally friendly, institutionally sound, social acceptable and cost-effective solutions of the best mix of energy supply and demand options for a defined area to support long-term regional sustainable development. It is a transparent and participatory planning process, an opportunity for planners to present complex, uncertain issues in a structured, holistic and transparent way, for interested parties to review, understand and support the planning decisions."

On the basis of the above, we define UESP as the inclusion of energy issues (related to the acquisition and use of energy) in the processes of urban planning (which strategically and spatially organize the development of a city) to find environmentally friendly, institutionally sound, socially acceptable, and cost-effective solutions to satisfy the demands of an urban area.

Review Methodology and Scope

The review presented hereafter analyzed papers obtained by searching the Scopus database. The search included papers ranging back as far as the database allowed (the oldest paper surveyed going back to 1990), to the date of writing of the present article (the most recent paper being from 2016). The query performed aimed at identifying all papers dealing with MCDA in urban and energy planning by searching titles, abstracts, and keywords. Search terms were selected according to the following aspects. Literature on MCDA frequently replaces the latter term with "making" or "aid." To avoid missing any entries, only the key words "multi criteria" were employed. The keywords "energy," "planning," and "decision" were included to narrow the search to the topic of interest. "Urban planning" can be interchangeably referred to as "city planning" or "town planning." The latter did not influence the search results and was not included in the query. Furthermore, urban planning spans across several administrative scales and therefore the keywords "district" and "neighborhood" were included to reflect this.

After testing the sensitivity of the different key words and of logical operators AND/OR, the final query included all studies published in both journals and conference proceedings, leading to 127 papers. Papers were only kept for the review if they explicitly discussed or applied MCDA in urban or urban-related contexts. From the 127 papers identified, 23 were thus discarded as being off-topic and 17 were unavailable, leaving 87 reviewable papers. Two of the papers included 2 distinct MCDA studies. The identified sample of 89 MCDA studies is deemed sufficient to address the present review's objectives (Section "Introduction").

The relevant studies applying MCDA for UESP were found in a total of 58 different journals and conference proceedings and are well dispersed across the various sources. The journal energy contains the majority of studies (10), followed by Applied Energy and Energy Policy (4 studies each).

Figure 2 reveals the increasing popularity in MCDA applications in UESP, which took off in the 2000s, with an average of 1.7 papers published per year until 2010 and an average of around 11 papers per year since.

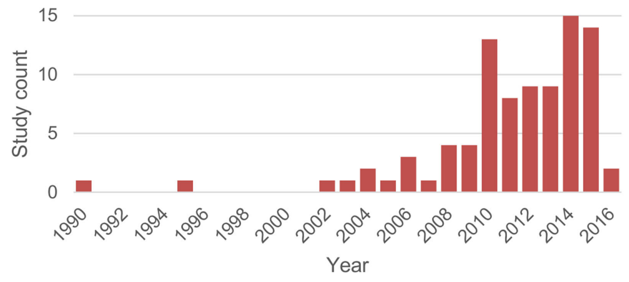


FIGURE 2 | Distribution of publication dates for the 87 papers reviewed involving multicriteria decision analysis in urban energy system planning.

Review Questions

Seven review questions were defined to address the two review objectives stated in the introduction. The first objective of characterizing UESP problems was achieved by analyzing the following five questions for each study:

(i) What was the problem's scope (including geographical location, physical scale, temporal scale, topic, and planning focus)?
(ii) How many alternatives were considered, and how were they elicited?
(iii) How many criteria were used, and how were they selected?
(iv) What was the expected decision outcome or problematic?
(v) Was the problem driven by values or by alternatives?

The second objective of characterizing the MCDA methods was done by exploring the following two questions:

(i) How many MCDA and supporting methods were adopted, which ones, and why were they chosen?
(ii) Which methods were combined, and for what purpose?

Each question is further described in the following sections.

Problem Scope

In each reviewed study, the general scope of the problem was hereby investigated, considering the geographical location in which the problem was set (classified by continent), the physical scales bounding the problem (whether the focus of the planning was set on the building, neighborhood, city, regional, state, or country scale), and the temporal scale covered by the problem (noting any temporal horizon considered by the authors in their study). The different studies were also classified according to topic and planning focus. Concerning the topics, six broad themes were found sufficient to cover the extent of the reviewed papers, as follows: (1) heating and cooling, (2) power, (3) mobility, (4) environment, (5) waste, and (6) water/wastewater. The papers were further classified according to their planning focus as follows:

a. System specific planning: when only a subpart of the UES is considered, e.g., heating system, electrical system, demand side analysis in residential sector
b. Integrated or master planning: when different energy carriers, sectors, or demand and supply systems are considered

c. Operative planning and management: when the main focus is not on long-term system design and investment, but rather on operative aspects, e.g., optimization of energy supply or energy use

Alternatives

This review question counted the number of alternatives analyzed by each study and the methods used to identify them. Keeney (1992) emphasizes the importance of alternative creation, writing that it "may be more important to create alternatives than to evaluate readily available ones." He blames decision methodologies for often neglecting this aspect or inhibiting it. If many MCDA problems in literature may lead to believe that the typical application involves a predefined set of alternatives, this is often not the case (Belton and Stewart, 2002), and the more complex problems such as those found in UESP require careful thought in the structuring of the problem and identification of alternatives. For example, Feng and Lin (1999) point out the limitations of conventional approaches for generating new urban layout plans. They argue that the urban development process should begin with a systematic generation of physical layout alternatives, but deplore that conventional processes for generating alternatives are usually considered "a 'black box' inside which planners are subjective and alternatives are few." In response, they propose an optimization model to systematically elicit alternatives maximizing public comfort and convenience, with which they were able to identify four alternatives performing better than the original plan. Typical methodologies that can be used to support alternative generation are discussed in the study by Siebert and Keeney (2015), who review existing methodological approaches for creating alternatives (structured techniques, creativity techniques, value-focused thinking, etc.). Mirakyan and De Guio (2014) reviewed the main methods that can support alternative identification, including brainstorming, soft systems methodology; strengths, weaknesses, opportunities, and threats (SWOT) approach; Delphi; means-ends objective network; and network of problems. They further proposed a methodology for finding innovative alternatives in planning, where common solutions may not be satisfactory, but where satisfying solutions are not obvious. Belton and Stewart (2002) present various methods for idea generation, some of which can help think about and identify alternatives. These include checklists to stimulate idea generation, alternative-based thinking methods, where users analyze and compare alternatives to stimulate the generation of new ones, and value-focused thinking using means-ends objective network, introduced by Keeney (1992), where value elicitation is performed prior to alternative identification. Despite the advancement of research in this field, the reviewed studies usually remained implicit or fairly superficial in describing how the alternatives were generated. In this context, the review distinguished the following cases for alternative generation: by the authors themselves, based on literature; by external experts or actors; by relying on heuristic approaches such as mathematical multiobjective optimization, systematic combinations, and enumeration; or simply externally defined (e.g., the evaluation of grant request submitted). When specified, any supporting method used by experts or actors was noted [including Geographic Information System (GIS) software, SWOT analysis, communities of practice (CoP), or interactive user selection].

Criteria

This question considered the number of criteria used in the analysis and any explicit references to their selection process. These approaches included author's judgment, literature or predefined sets of indicators, experts' recommendations, and, when specified, other supporting methods (Delphi, CoP), or any combination of these approaches.

Decision Problematic

The problem type, as posed in the study, was surveyed. This question is of particular interest in the field of MCDA and can even be considered as the first and most important step in MCDA (Chen, 2006): when addressing complex decision problems, analysts must initially consider what type of result or outcome is expected. Roy (1996) first used the term "problematic" to describe the main types of outcomes MCDA can provide. In this review, we investigated which problematics were adopted, based on the most relevant problematics proposed by Roy (1996) and Belton and Stewart (2002). According to their typologies (**Figure 3**), a MCDA approach can be applied to

- select or choose a "best" alternative, by reducing the set of alternatives to a smallest subset (choice problematic)
- help sort alternatives according to predefined categories, which shall help the DM know which treatment to give to the grouped alternatives (sorting problematic)
- rank the alternatives by order of preference, enabling the DM to think about the problem and discuss with all stakeholders (ranking problematic)
- choose a subset of alternatives, which can be combined and account for interactions and positive or negative synergies between them (portfolio problematic)
- search for, identify, or create new alternatives based on the insights gained from the MCDA process (design problematic)
- gain a greater understanding of the problem, in particular what may or may not be achievable (description problematic).

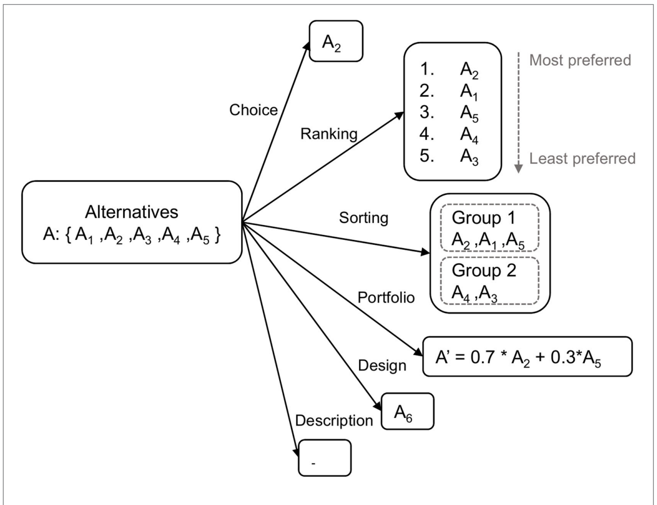


FIGURE 3 | Schematic overview of the multicriteria decision analysis problematics investigated in the review. Adapted from the studies by Belton and Stewart (2002) and Chen (2006).

It should be noted that the delimitation between problematics is not always absolute and that a certain hierarchy can exist among them. For example, a first expected outcome may be ranking, followed by the choice of a single alternative. Similarly, portfolio can be considered a type of design problematic, in which alternatives are created by combining various subcomponents. In turn, the newly created portfolios can further be ranked, sorted, described, or chosen from. In the reviewed studies where multiple problematics concurred, the predominant one was retained, relying when possible on explicit statements from the authors.

Analysts must be aware of the type of results they aim to provide (a best single solution, a ranking of all solutions, the identification of original alternatives, etc.). Often, however, this appeared to be only implicitly considered or not considered at all. As the method used may constrain the type of result, this reinforces the argument of carefully identifying the expected decision outcome early in the decision process, to avoid the generation of undesired information and associated waste of time, effort, and cost.

Planning Driver

This question investigated the extent to which the planning problems were driven by values, rather than means or resources readily available. In the reviewed papers, values most often took the form of "characteristics of consequences that matter" stated in the introductory sections of the papers or as "priorities" and "value tradeoffs" when establishing criteria and weights.

This question is particularly relevant in the light of the recent changes in urban planning, which shifted from physical, expert-led approaches, to a wider, strategic, and collaborative form (Albers, 1986; Wachs, 2001; Scherrer, 2008). A wider scope, including in particular energy issues as well as public participation, implies that planners must cope with a wider range of values than previously, which poses a series of challenges such as their systematic incorporation in decision-making or gathering information about the values (O'Brien, 2003; Balint et al., 2011). Connelly and Richardson (2005) and O'Brien (2003) point out the general lack of explicit acknowledgment of—and distinction between—the different values that should influence and drive planning. According to them, omitting them, assuming values are known, or underestimating their diversity may lead to unacceptable outcomes. Keeney (1992) originally advocated "value-focused" thinking, as opposed to what can be called "alternative-focused" or "resource-focused" thinking. According to him, failing to elicit values before defining alternatives leads to a constrained vision of the problem, which "anchors the though process, stifling creativity and innovation." In addition, how alternatives are identified also directly influences how well the values shall be satisfied. Often, DMs do not spend enough effort on alternative creation, missing many alternatives, including important ones, hindering the achievement of the objectives (Siebert and Keeney, 2015). Exploring how values were involved in the reviewed studies, these were classified as either value driven or alternative driven, following loosely the framework from the study by Keeney (1992). This classification is not meant to be an absolute one, but rather to foster thinking about values in MCDA and how these could improve the final outcomes. Based solely on the reported elements in the final publication, and without the full knowledge of how the decision problem was actually addressed, the problem cannot easily be declared either purely value driven, or purely alternative driven. Instead, it lies within a continuum between both ends (**Figure 4**), depending on the reported information regarding values, and alternatives.

Several characteristics of value-driven approaches were used to evaluate the reviewed studies (**Figure 4**). As such, the studies that were more explicit in their elicitation of values, whose values in turn appeared to influence the identification of criteria and alternatives, and which considered a broader range of alternatives, or motivated the narrow set evaluated, were marked as value driven. Those who only moderately exposed the guiding values, or which values did not appear to influence the decision analysis, or which did not motivate the choice of alternatives were marked as alternative driven. To help in the classification, three types of alternative sets were used to describe the studies:

- Type 1: The study includes and compares different categories of alternatives (e.g., renewable energy technologies, refurbishment, funding options, spatial alternatives, information, and incentives)

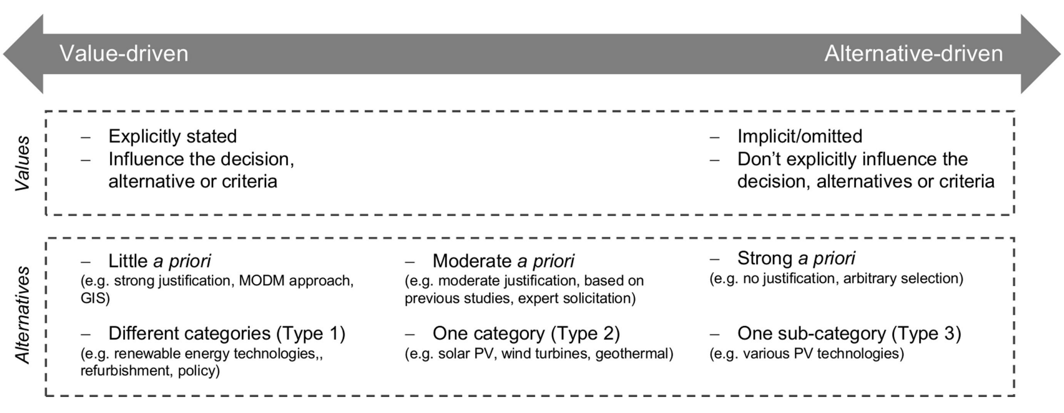


FIGURE 4 | **Considered characteristics for classifying the studies as value or alternative driven**.

- Type 2: The study includes and compares alternatives from one category (e.g., different renewable technological alternatives, such as solar PV and wind, or different locations for a waste disposal)
- Type 3: The study includes and compares alternatives belonging to a single subcategory (e.g,. different solar PV cell types)

Three specific approaches for alternative generation (previously mentioned in Section "Alternatives") were also found to be particularly in line with value-driven thinking, as they enable a transparent and comprehensive way to identify alternatives, with little *a priori* in their construction. The first approach was multiobjective decision-making (MODM)-based heuristics, in which a wider range of alternatives are automatically generated by combining decision variables to best achieve predefined objectives, allowing more informed and more rational decisions (Cohon, 1978). Similarly, some GIS approaches also assumed a broad, continuous range of locations as possible solutions, as opposed to a comparison of a limited subset of preselected sites. Other systematic combinatorial approaches were found, in which theoretically all possible alternatives of a category were considered *a priori*. This was for example the case when enumerating all possible priority sequences for restoration of district heating pipe segments (Rochas et al., 2015). Finally, to complete the assessment of planning drivers, the stated rationales for selecting the set of alternatives, if available, were also used to classify the studies (e.g., authors who provided strong justifications for the choice of alternatives were more likely to be classified as value driven as if the alternatives were not justified or appeared to be selected arbitrarily).

It should be noted that the value- or alternative-driven nature of a problem should not necessarily be regarded as "good" or "bad." Indeed, the problem context may be simply conditioning an alternative-driven approach, as for example in the study by Hsueh and Yan (2011), where a method for comparing urban development projects that had applied for governmental grants is proposed. Similarly, some studies might not claim to find the best possible alternative to achieve a valued goal, but rather purposely aim to answer a more specific question about a given technology. This is for example the case of De Feo et al. (2008), who compares various coagulants for urban wastewater treatment.

MCDA Methods

This section aimed at identifying the MCDA methods, as well as the supporting methods, employed to address the different problems and the rationales behind their choice. There are many ways to categorize MCDA methods. In this study, they have been divided into five main groups, loosely based on classifications proposed by Belton and Stewart (2002), Zhou et al. (2006), Løken (2007), and Mardani et al. (2015): (1) value measurement models; (2) goal, aspiration, and reference level models; and (3) outranking models; (4) MODM; and (5) other methods. Value measurement models assign numerical scores to each alternative, by aggregating criteria and weights. Among the most common approaches include the weighted sum approach or analytical hierarchy process. The second group is often gathered under the expression goal programming, and a typical example is the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS). The third group of outranking models distinguishes alternatives in a pairwise fashion for each criterion. This group is also referred to as the French school of MCDA methods, namely because of the pioneering work on the ELECTRE methods from Roy (1996). The fourth group included MODM methods, which relied either on linear programming techniques or multiobjective optimization heuristics such as evolutionary algorithms. This group also contained methods that were referred to as single-objective decision-making (SODM). Although in most cases, SODM considers just a single objective, providing a somewhat limited interpretation of a problem, their name can be in some cases misleading. SODM can indeed handle multicriteria aspects of a problem by resorting to various techniques (Savic, 2002). This can be achieved for example by aggregating various objectives in a single-objective function through a weighted sum (Yokoyama and Ito, 1995; Ma, 2012; Karmellos et al., 2015), by setting different constraints on criteria to evaluate trade offs with the objective, as in the ε-constraint method (Pérez-Fortes et al., 2012), or simply by varying the criteria being optimized and comparing outcomes (Ayoub et al., 2009). The fifth group included methods relying on fuzzy set theory (FST) and other methods developed more recently and referred to as decision-making aggregation methods in Mardani et al. (2015). FST can be either used to extend existing MCDA methods (Wang et al., 2009; Mardani et al., 2015) or used independently for criteria aggregation (Greco et al., 2016).

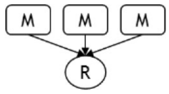
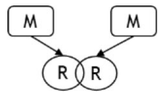
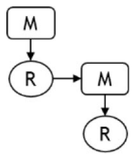
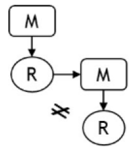
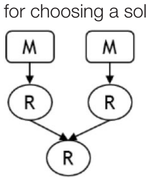
Several auxiliary methods are frequently found supporting the MCDA process. Referred to in this article as "supporting methods," these include for example the abovementioned FST, the Delphi method, SWOT analysis, GIS tools, and others.

Furthermore, the stated arguments for choosing a MCDA or their supporting methods were collected during the review. These arguments can be compared to the requirements and "quality factors" discussed in the study by Mirakyan and De Guio (2015) for choosing decision methods.

Combination of MCDA Methods

Also of interest regarding the MCDA methods was the combined use of methods and, most importantly, the rationale behind their selection and combination. Strantzali and Aravossis (2016) have recently pointed out the growing trend in combination and comparison of different methods' results. As mentioned in the section "Introduction," Løken (2007) and Hobbs and Horn (1997) have advocated using multiple MCDA methods to tackle a similar problem, as its solution may strongly depend on the method choice. Greene et al., 1989; Crump and Logan, 2008; and Mirakyan and De Guio, 2015 have discussed the various purposes and motivations for combining methods. Greene et al. (1989) initially noted five key purposes for mixing methods, which include triangulation, complementarity, development, initiation, and expansion (**Table 1**). The reviewed studies indeed often involved multiple methods, and the stated or inferred purposes were systematically monitored. As already encountered by Greene et al. (1989), the purpose stated by the authors may differ from the definitions proposed, in which case, for better coherence, the inferred purpose matching the definitions was noted. In several occurrences, several purposes were identified

TABLE 1 | Purposes for combining multiple methods.

Purpose	Reasons	Example and depiction (M = method, R = result)
Triangulation	Seek convergence and corroboration of results across different methods	E.g., Ribau et al. (2015), where 3 methods were applied for the same purpose and results compared 
Complementarity	Different methods used to measure overlapping but distinct facets, to enhance, illustrate, or clarify results from one another	E.g., Nowak et al. (2015), where a navigation tool is proposed to interpret first results 
Development	Different methods used sequentially to use results from one to develop or inform another	E.g., Koo and Ariaratnam (2008), where AHP is used to aggregate first qualitative criteria, to be used in a WSM, or Zheng et al. (2015) where ER is used to select a solution from multiobjective decision-making results 
Initiation	Also uses methods sequentially, with the aim to identify contradictions or new perspectives and learn why these exist (rarely intentional)	E.g., where an obvious optimal solution from multiobjective decision-making/SODM would not be satisfactory 
Expansion	Applies different methods for different inquiry components, increasing the breadth and quality of the results by applying the most suitable method for each task	E.g., where strengths, weaknesses, opportunities, and threats analysis is used to analyze the situation, value tree approach to identify values and criteria, and multicriteria decision analysis for choosing a solution 

and noted as primary, secondary, and tertiary purpose, by order of importance in the study.

RESULTS

Problem Scope

This section presents the general results concerning the scope of the studies, as described above. A majority of papers were published by European (44 studies), Asian (23), and North American (15) institutions.

Regarding the scale at which the studies took place, a spread from country to building level was observed. Forty-eight studies covered the city scale, 14 the neighborhood, 10 the regional scale, 7 the building, 6 the country, and 2 the state. It should be noted that this spread appeared despite narrowing the search to the urban and neighborhood scales, illustrating the tendency of urban planning to also impinge upon broader and smaller scales.

Papers were grouped according to the typologies in Section "Problem Scope." The subtopics were tackled as follows: heating and cooling (43 studies), power (41 studies), and mobility or water/wastewater projects (20 studies each). This reflects the importance of the stakes associated with heating and cooling in buildings, the leading sector regarding GHG emissions, and primary energy use (IEA, 2008; Odyssee-Mure, 2015).

Regarding the planning focus of the studies, 63 were dealing with system specific aspects, whereas 18 handled the issues in an integrated way, considering multiple subtopics, energy carriers, or types of infrastructure, and 8 focused on operative planning aspects. The temporal horizons covered by each study are plotted in **Figure 5**, classified by planning focus. The sampled studies showed that planning projects that focused on specific aspects of the system coped on average with longer time horizons than projects considering the system as a whole (24 and 21 years, respectively). The operative planning and management studies considered time horizons of days to several years, on average considering the year as time perspective. These temporal horizons are closely in line with those of the planning tasks and decision-making levels discussed by Makkonen (2005) and Mirakyan and De Guio (2015), which distinguish strategic decisions (spanning over more than 10 years), tactical decisions (between 1 and 10 years), and operational (less than a year).

Alternatives

The review showed that a majority of studies (44) considered 5 or less alternatives (**Figure 6A**). Nine studies handled over 30 alternatives, and 5 studied a continuous range of possible alternatives in GIS-based approaches. In practice, the types of alternatives considered in the UESP problems were widely diverse, ranging from the evaluation of *geographic locations* [e.g., siting of hazardous waste landfills (Feo and De Gisi, 2014) or PV recycling plants (Goe et al., 2015)], *development scenarios* [e.g., comparing environmental-, technology-, and economic-driven energy use scenarios of urban areas (Wang et al., 2011) or policy scenarios (Phdungsilp, 2010)], *actions or measures* to be implemented by urban actors [e.g., building renovation measures (Medineckiene and Björk, 2011)], or *technologies and infrastructure* [e.g., community scale RES and technologies, such as solar PV or thermal, wind turbines, geothermal, micro-hydro (Nigim et al., 2004), or residential heating systems (Kontu et al., 2015)]. Alternatives were most often generated or selected by the authors of the studies themselves, followed by alternatives generated by means of optimization methods, expert solicitation, GIS, and literature (**Figure 6B**). In the context of planning community-scale renewable energy projects, Nigim et al. (2004)

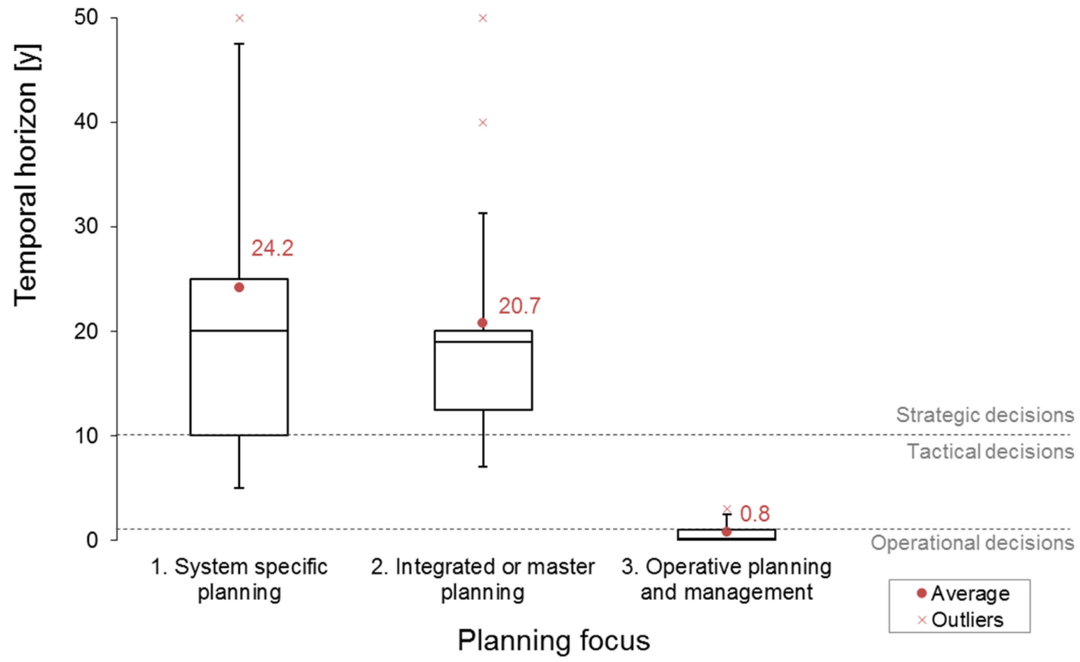


FIGURE 5 | **Boxplots of the temporal planning horizons covered by the studies in each planning focus category**. The average values for each category are based, respectively, from left to right on 63, 18 and 8 studies. Tukey style whiskers extend to points within 1.5 times the interquartile range.

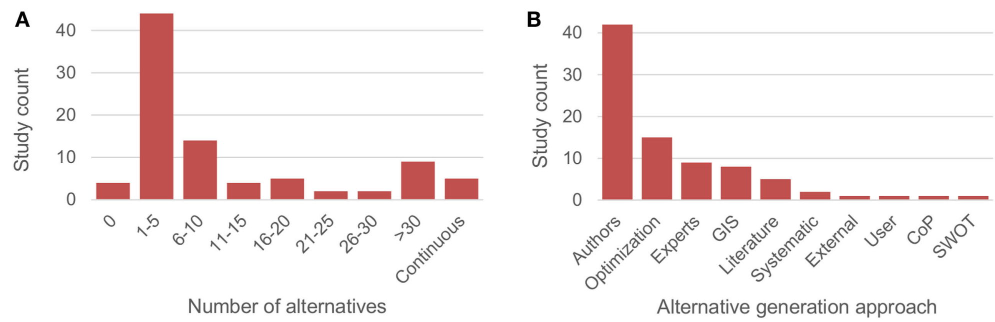


FIGURE 6 | **Alternative results from the review**. **(A)** Number of alternatives analyzed by the reviewed studies. The bin ">30" includes numbers of alternatives between 30 and 7000, whereas "Continuous" includes studies that relied on Geographic Information System methods. **(B)** Distribution of alternative generation approaches adopted by the reviewed studies.

write that "an ideal decision environment would include all possible information (…) and every possible alternative." Due to limited time and resources, they note that one must generally deal with limited alternatives. As expressed in other studies, however, this constraint should not prevent the consideration of as many alternatives as possible in the definition of the problem context. When selecting sustainable energy resources, Kaya and Kahraman (2010) and Kontu et al. (2015) underline, for example, the importance of initially considering a broader set of alternative energy resources, including possibly less-popular or less-sustainable options such as fossil or nuclear fuels. Ghafghazi et al. (2010) also consider extended energy sources for a district heating project, explicitly motivating—based on values or problem boundaries—why they keep or reject them in the study.

Criteria

The typical number of criteria used in the MCDA studies reviewed is between 6 and 10 criteria (**Figure 7A**). Only two studies used more than 40 criteria. When these were not proposed or developed by the authors themselves, which was found to be the leading approach for criteria elicitation (51), criteria were taken from literature (32), including readily available criteria sets, identified and selected by external experts (17), and occasionally adopting more formalized methods such as Delphi (3) or CoP (1) (**Figure 7B**). In a study evaluating the appropriateness of technologies for reducing heating costs of impoverished communities (Bauer and Brown, 2014), 49 criteria were ranked according to their prevalence in literature, considering this prevalence as "a proxy for importance." The most cited criteria included,

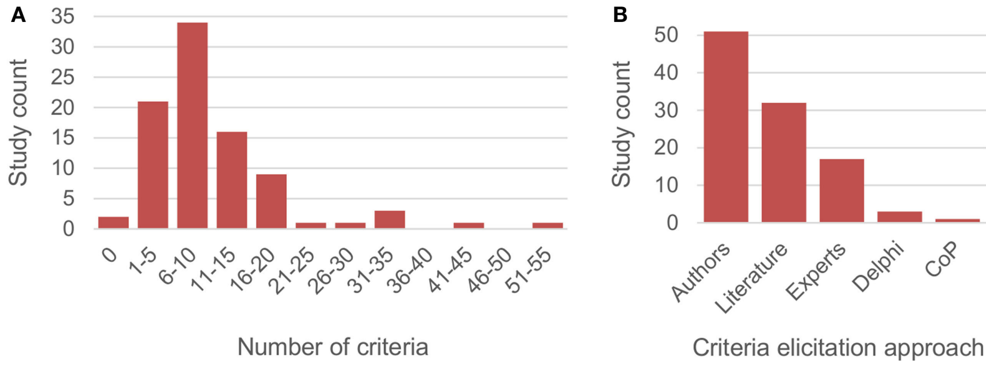


FIGURE 7 | **Criteria results from the review**. **(A)** Distribution of criteria number used in the reviewed studies. **(B)** Distribution of criteria elicitation approaches adopted in the reviewed studies.

e.g., community input, affordability, autonomy, or adaptability of the technology. In a second step, the study also ranked these criteria according to local stakeholders, whose ranking differed from the literature-based ranking. Among the top 8 selected criteria were, for example, efficiency of resource use, job creation, simplicity, and autonomy of the technology. This indicates that a literature-based listing of common criteria could be useful as a first step to identify prevalent and possibly important criteria [such a list is for example provided by Wang et al. (2009) for energy supply systems analysis]. However, its practical usability would require further classification and analysis of the criteria by topic and scale. For example, it has been noted that the relevance and perceived importance of criteria such as noise or dust emissions may be higher for small problem boundaries and scales than more global criteria such as CO_2 emissions or energy efficiency (Macoun, 2005; Koo and Ariaratnam, 2008). Eventually, some adaptation and extension of the list to meet local specificities is anyway advised (Bauer and Brown, 2014).

Decision Problematic

The types and number of decision problematics found in the reviewed papers are displayed in **Figure 8**. Most of the studies aimed at choosing a single best option (i.e., 32 choice problematics), followed by the goal of ranking the alternatives (22). Sixteen studies did not aim to make a decision *per se*, but rather learn about the decision problem and alternatives involved (description problematic). Bauer and Brown (2014) for example illustrate a description problematic, as the approach does not necessarily aim to choose or rank alternatives, but instead to assess even individual solutions and give them a score that could serve as general advice regarding any solution's quality or "appropriateness." Browne et al. (2010) provide another example of the description problematic, using NAIADE to assess and compare the impacts of energy policy scenarios. They write that the "purpose of NAIADE is not to produce a definitive ranking of alternatives, but to rationalize the problem and provide a framework for communication among stakeholders." Respectively, 13 and 6 studies were of the portfolio and sorting types. Notable portfolio examples consisted for example in combining energy efficiency measures in buildings, choosing from various envelope components and configurations (doors, windows, wall materials), lighting systems and other electrical appliances, and heating systems (Karatas and El-Rayes, 2014; Karmellos et al., 2015), or combining different waste recovery pathways to create municipal recycling programs (Banar et al., 2010). Li et al. (2013) propose a method to sort urban zones according to their potential of underground exploitation, distinguishing high potential zones for short-term exploitation, moderate potential zones to be reserved for long-term projects, and prohibited zones where underground exploitation would conflict with environmental or economic goals.

In **Figure 9**, the most common MCDA methods used for each decision problematic are shown. Aside from the sorting type, most problematics were addressed with a variety of methods. A few trends can nonetheless be pointed out. MODM methods were predominant in addressing the portfolio problematics. MODM indeed usually works by searching optimal combinations of decision or control variables, which combined form an optimal (or Pareto optimal) solution as regard to the objectives. As noted earlier, this problematic can typically be followed by any other decision problematic. Notable examples were the studies by Pérez-Fortes et al. (2012); Karmellos et al. (2015); Zheng et al. (2015) who followed up with choice or the studies by Karatas and El-Rayes (2013) and Yokoyama and Ito (1995) with description. MODM also proved popular in describing decision problems, as used in one-third of the description problems. A second third is handled with AHP and WSM methods. Single choices were performed predominantly with AHP, WSM, and TOPSIS, whereas ranking also was carried out in 25% of the cases by ELECTRE III, PROMETHEE, and VIKOR methods.

Regarding supporting methods, Delphi was found particularly often in description problematics, GIS in choice and sorting problematics, and FST was found in all 4 problematics, except portfolio (corresponding charts can be found in the Supplementary Material).

Several authors expressed particular comments regarding desired decision outcome and corresponding choice of methods. Zhang et al. (2014) for example pointed out that depending on the expected outcome, DMs could choose either ELECTRE I when aiming for a choice problematic or ELECTRE II for a ranking

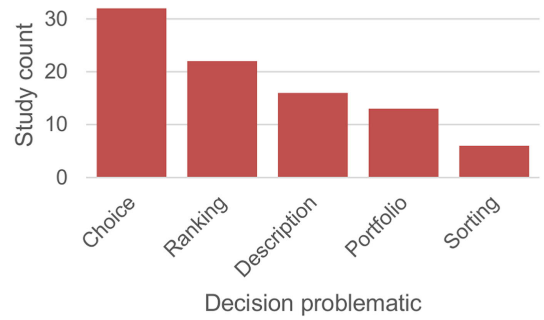


FIGURE 8 | **Distribution of problematic types in the reviewed studies**.

problematic. Medineckiene and Björk (2011) noted that DMs seeking to learn about worst performing alternatives should avoid resorting to MEW, as this method relies on multiplicative aggregation and tends to rank alternatives at 0, although these might not be the worst performing over all criteria.

Planning Driver

According to the characteristics presented above (**Figure 4**), two-thirds of the studies (60) were found to adopt rather value-driven approaches, while the remaining (29 studies) were rather alternative driven. Kontu et al. (2015) illustrates well a value-driven approach, in which values are clearly stated (e.g., sustainable development of energy system, reduced environmental impacts, safeguard economic, and social opportunities) and guide the identification of criteria and alternatives (performed in a collaboration between sustainable energy experts and practitioners). The authors also point out explicitly that alternatives were kept intentionally broad in the beginning, including also fossil fuel-based solutions, only to let the values' associated criteria assess their relevance. The alternatives were of type 2, meaning various heating and electricity components were assessed. Another value-driven example is provided by the study by González et al. (2013), in which values are clearly expressed and prioritized (sustainable urban development, promotion of positive changes in the urban context, sparing of natural resources, enhancing environmental protection, etc.) and explicitly shaped both the study's objectives, criteria, and alternatives. The alternatives in turn included comprehensive planning measures suited to achieving the values (brownfield rehabilitation, energy efficient housing construction, green space development, etc.).

MCDA Methods

Similar to previous findings (Zhou et al., 2006; Wang et al., 2009; Mardani et al., 2015; Strantzali and Aravossis, 2016), AHP is found to be the most popular method used for energy related problems (**Figure 10**). This can in part be explained by its frequent use not only as a MCDA method for criteria aggregation but also as a method to elicit preference weights. **Figure 10** further illustrates the great diversity of methods being used: nearly 30 different MCDA methods have been applied in the 89 studies considered. Besides AHP, only WSM, MODM, TOPSIS, ELECTRE methods, ASPID, VIKOR, PROMETHE methods, and MAUT/MAVT were used more than once. The methods were categorized and counted in **Table 2**. It was found that value measurements models are the most popular, representing 56% of all methods used. Second most popular are the MODM methods (15%), followed by aspiration models (11%), others (10%), and outranking methods (8%).

Similar to the main MCDA methods, **Figure 10** also shows the frequency of supporting methods used in the studies, revealing in particular the common use of FST (14), GIS (12), and Delphi (7).

Figure 11 illustrates the predominantly stated arguments for MCDA and supporting methods (the detailed information and references can be found in the Supplementary Material). It can be seen that the choice of a MCDA method was due most frequently to its perceived popularity, stated most often for AHP, WSM, and MODM. The second most frequent argument stated was that of simplicity, which was also expressed as intuitiveness, straightforwardness, transparency, or pragmatism. This argument applied most often to AHP, WSM, TOPSIS, and VIKOR. Equally frequent was the ability to handle qualitative and quantitative information, mainly for AHP and ASPID.

Regarding arguments for choosing supporting methods (**Figure 11**), the two principle reasons stated were to help in collecting and incorporating human experience and knowledge (applicable by decreasing importance to FST, CoP, Delphi, and OWA) and to cope with incomplete, uncertain, non-measurable, vague, or estimated information (stated for FST and OWA). Other reasons, essentially attributed to Delphi, were to assist in evaluating criteria and weights, as well as eliciting the criteria and alternatives. GIS tools were used mainly for their ability to quickly and simultaneously display multiple data sets, but also for efficient display of information, handling of multiple spatial and temporal scales, and flexibility in combining various tools.

Method Combinations

In **Figure 12**, we observe that a majority of studies (54) rely on a single main MCDA method, followed by 20, which combine 2 main methods and 3 combining 3 main methods. Two studies included up to four main MCDA methods. Ten studies did not include any main MCDA method, which is partly explained by those relying solely on GIS (four studies). When considering also the combination of main and supporting methods together, then a majority of studies appear to contain more than one method.

The most frequent reason for combining methods was the development rationale (26 studies), followed by complementarity (11) and triangulation (9). Secondary rationales were development (8), complementarity (8), and triangulation (1). Although it could be argued that several of the development cases also achieved the purpose of expansion, increasing the breadth of results by application of various specific methods, e.g., those involving Delphi (Haruvy and Shalhevet, 2007; Hsueh and Yan, 2011; Bauer and Brown, 2014; Jain et al., 2014; Vafaeipour et al., 2014), or SWOT (Öztürk, 2015), their sequential flow of information—characteristic of the development type—was deemed most relevant than this latter aspect. As such, no studies involved expansion nor initiation.

The most common development combination was the use of AHP to elicit the weighting of criteria, to be used in other MCDA

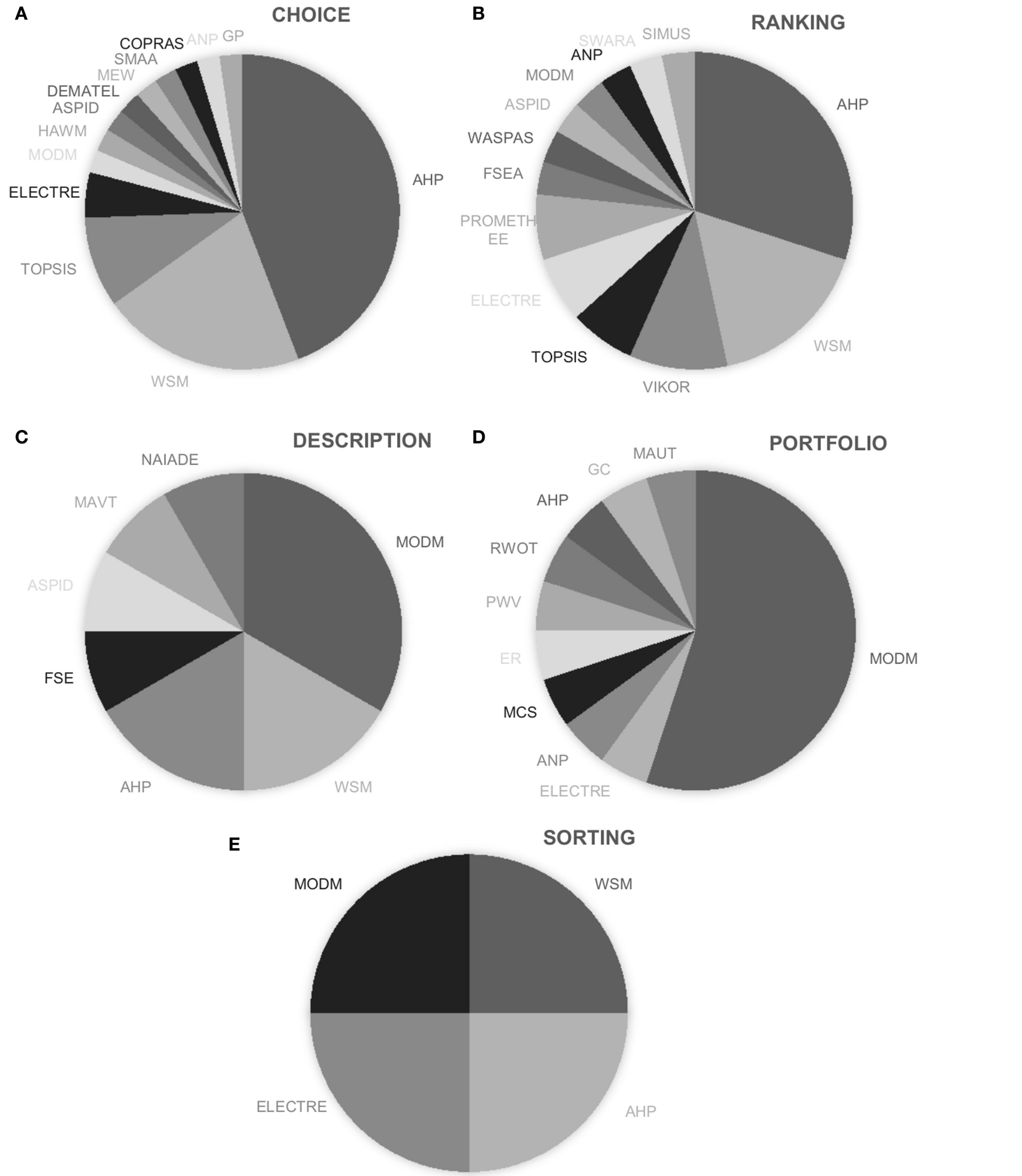


FIGURE 9 | **Distribution of multicriteria decision analysis methods used per decision problematic as follows: (A) choice, (B) ranking, (C) description, (D) portfolio, (E) and sorting**.

methods, such as TOPSIS (Tzeng et al., 2005; Ekmekçioğlu et al., 2010; Khoshsolat et al., 2012; Ziemele et al., 2014), WSM (Medineckiene and Björk, 2011; Rochas et al., 2015), and others (Beccali et al., 2002; Kaya and Kahraman, 2010; Duan et al., 2011; Hsu and Lin, 2011; Medineckiene and Björk, 2011; Karatas and El-Rayes, 2013; Fetanat and Khorasaninejad, 2015). The Delphi approach was used in five instances to analyze the decision context while using AHP (Hsueh and Yan, 2011; Jain et al., 2014), WSM (Haruvy and Shalhevet, 2007; Bauer and Brown, 2014), and WASPAS (Vafaeipour et al., 2014) for alternative comparison. Development was also found between MODM/SODM and other MCDA methods in four studies, where WSM (Aydin et al., 2014; Ribau et al., 2015; Fonseca et al., 2016), ER (Zheng et al., 2015), and PWV and GC (Ribau et al., 2015) helped select

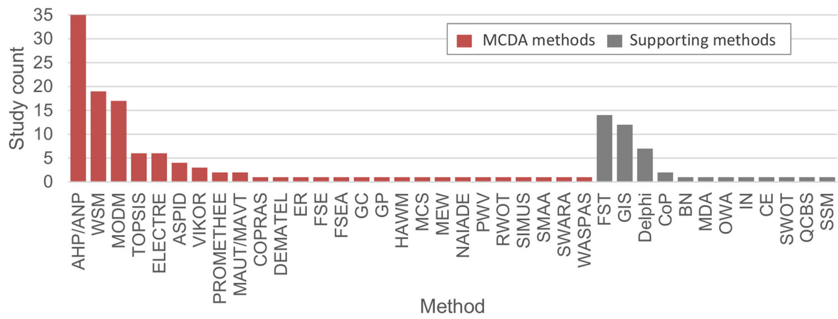


FIGURE 10 | **Multicriteria decision analysis (MCDA) and supporting methods used in the reviewed studies**. Note: ELECTRE encompasses also ELECTRE III and TRI; PROMETHEE encompasses also PROMETHEE-GAIA.

solutions resulting from optimization calculations. This was also stated as a reason for choosing these methods. One study inverted this pattern, instead making first use of a GIS-based analysis to short-list nine potential locations, which were than incorporated in an MINLP model as decision variables for the optimization calculation (Goe et al., 2015). With nine instances, WSM was the most frequently used as a follow-up method to AHP (Koo and Ariaratnam, 2008; Medineckiene and Björk, 2011; Rochas et al., 2015), optimization (Aydin et al., 2014; Fonseca et al., 2016), Delphi (Haruvy and Shalhevet, 2007; Bauer and Brown, 2014), choice experiment (Dombi et al., 2014), and GIS (Feo and De Gisi, 2014). AHP was also used in a second step in seven studies, benefiting from prior applications of methods such as GIS (Idris and Abd Latif, 2012; Feo and De Gisi, 2014), Delphi as noted above (Hsueh and Yan, 2011; Jain et al., 2014), CoP (Chrysoulakis et al., 2013; González et al., 2013), and FSEA (Wang et al., 2011).

In 12 papers, complementarity was related to the adoption of FST (Ekmekçioĝlu et al., 2010; Kaya and Kahraman, 2010; Duan et al., 2011; Hsu and Lin, 2011; Hsueh and Yan, 2011; Wang et al., 2011; Al-Yahyai et al., 2012; Khoshsolat et al., 2012; Al-Yahyai and Charabi, 2015; Fetanat and Khorasaninejad, 2015; Guo and Zhao, 2015; Colantoni et al., 2016), combining FST with existing methods such as AHP (Ekmekçioĝlu et al., 2010; Kaya and Kahraman, 2010; Duan et al., 2011; Hsu and Lin, 2011; Hsueh and Yan, 2011; Wang et al., 2011; Al-Yahyai et al., 2012; Khoshsolat et al., 2012), ANP, DEMATEL, ELECTRE (Fetanat and Khorasaninejad, 2015), TOPSIS (Ekmekçioĝlu et al., 2010; Khoshsolat et al., 2012; Guo and Zhao, 2015), GIS (Hsu and Lin, 2011; Al-Yahyai et al., 2012; Al-Yahyai and Charabi, 2015; Colantoni et al., 2016), and VIKOR (Kaya and Kahraman, 2010). In three papers, GIS was used, mutually enhancing WSM (Arampatzis et al., 2004), AHP (Al-Yahyai et al., 2012; González et al., 2013), and OWA (Al-Yahyai et al., 2012). MODM was enhanced by MAUT for the aggregation of the objective function (Karatas and El-Rayes, 2013), and by use of an interactive result exploration tool (Nowak et al., 2015). In one case, Bayesian network and WSM were combined (Awad-Núñez et al., 2015).

It is well understood that the choice of MCDA method can influence the final results. Several of the reviewed studies triangulated various methods to compare outcomes either between two common methods, e.g., between ELECTRE III and WSM (Carriço et al., 2014; Frijns et al., 2015) or ANP (Banar et al., 2010), AHP, and WSM (Feo and De Gisi, 2014), or to assess the results of less common or self-designed methods with more common ones (e.g., between TOPSIS and VIKOR (Tzeng et al., 2005), WSM and QCBS (Vadiati et al., 2012), AHP and a variant of WSM (De Feo et al., 2008), AHP and SIMUS, comparing more specifically differences in subjectivity accounting (Nigim et al., 2004), or WSM with MEW and COPRAS (Medineckiene and Björk, 2011)).

Carriço et al. (2014), Frijns et al. (2015) observed nearly similar results and pointed out that in general, MCDA literature does not discuss which method is most suited for which case nor why results would differ using different methods with same input data. They underline the fact that selecting appropriate methods for different problem types is still an open research question. Feo and De Gisi (2014) compared AHP and WSM variants and were able to obtain similar ranking of the solutions, observing however differences between the relative position of the ranked solutions. Vafaeipour et al. (2014) did not compare the results of WSM and WPM, but relied on a combination of both, arguing it to be more robust. He explicitly recommends in his conclusion to compare results with other well-known MCDA methods.

Synthesis of the Review

While the previous sections were concerned with the *analysis* of the reviewed studies, namely examining in detail the various constituents of the multicriteria problem, the present section proposes a *synthesis* of the present work. A synthesis can be defined as "the combination of components or elements to form a coherent whole" (Oxford Dictionary of English, 2005), and indeed, we hereby bring together the elements of information collected in the review, whose relationships are made coherent by use of parallel coordinates (**Figure 13**). Parallel coordinates are a convenient and powerful way to handle multivariate data and provide interactive decision support (Packham et al., 2005; Heinrich and Weiskopf, 2013; Johansson and Forsell, 2016). Their use can help identify which methods have been applied in various contexts, providing a guide to select a suitable method. Parallel coordinates consist of vertical axes representing the criteria and of polylines flowing across each axis. Six main criteria have been selected here to represent the characteristics of the

TABLE 2 | Classifications of multicriteria decision analysis MCDA and supporting methods and share of each class in the 89 studies reviewed.

Type	MCDA methods					Supporting methods
Group	1. Value measurement models	2. Goal, aspiration, and reference level models	3. Outranking models	4. Multiobjective decision-making	5. Other (fuzzy sets, other aggregation methods)	–
	AHO (Beccali et al., 2002; Yedla and Shrestha, 2003; Nigim et al., 2004, 2009; Tzeng et al., 2005; Dytczak and Ginda, 2006; De Feo et al., 2008; Koo and Ariaratnam, 2008; Ekmekçioğlu et al., 2010; Kaya and Kahraman, 2010; Massara and Udaeta, 2010; Duan et al., 2011; Hsu and Lin, 2011; Hsueh and Yan, 2011; Medineckiene and Björk, 2011; Reza et al., 2011; Wang et al., 2011; Al-Yahyai et al., 2012; Idris and Abd Latif, 2012; Khoshsolat et al., 2012; Chrysoulakis et al., 2013; Daim et al., 2013; González et al., 2013; Karatas and El-Rayes, 2013; Madadian et al., 2013; Feo and De Gisi, 2014; Jain et al., 2014; Ziemele et al., 2014; Meney and Pantelic, 2015; Rochas et al., 2015)	Technique for Order Preference by Similarity to Ideal Solutions (Tzeng et al., 2005; Ekmekçioğlu et al., 2010; Khoshsolat et al., 2012; Ziemele et al., 2014; Guo and Zhao, 2015)	ELECTRE III (Karagiannidis and Perkoulidis, 2009; Banar et al., 2010; Carriço et al., 2014; Frijns et al., 2015)	MIN(L)P, EA (Videla et al., 1990; Yokoyama and Ito, 1995; Ayoub et al., 2009; Ma, 2012; Pérez-Fortes et al., 2012; Wu et al., 2012; Al-Ani and Habibi, 2013; Karatas and El-Rayes, 2013, 2014; Rager et al., 2013; Aydin et al., 2014; Ma et al., 2014; Goe et al., 2015; Karmellos et al., 2015; Nowak et al., 2015; Ribau et al., 2015; Zheng et al., 2015; Fonseca et al., 2016)	WASPAS (Vafaeipour et al., 2014)	Geographic information system (Arampatzis et al., 2004; Hsu and Lin, 2011; Van Haaren and Fthenakis, 2011; Al-Yahyai et al., 2012; Idris and Abd Latif, 2012; González et al., 2013; Feo and De Gisi, 2014; Grubert et al., 2014; Al-Yahyai and Charabi, 2015; Awad-Núñez et al., 2015; Goe et al., 2015; Colantoni et al., 2016)
	WSM (Beccali et al., 2002; Arampatzis et al., 2004; Haruvy and Shalhevet, 2007; De Feo et al., 2008; Koo and Ariaratnam, 2008; Jovanović et al., 2009; Afify, 2010; Medineckiene and Björk, 2011; Vadiati et al., 2012; Aydin et al., 2014; Bauer and Brown, 2014; Carriço et al., 2014; Dombi et al., 2014; Feo and De Gisi, 2014; Awad-Núñez et al., 2015; Frijns et al., 2015; Rochas et al., 2015; Fonseca et al., 2016)	VIKOR (Tzeng et al., 2005; Kaya and Kahraman, 2010)	PROMETHEE II/GAIA (Ghafghazi et al., 2010; Zhang et al., 2014)		SWARA (Vafaeipour et al., 2014)	Fuzzy set theory (Ekmekçioğlu et al., 2010; Kaya and Kahraman, 2010; Duan et al., 2011; Hsu and Lin, 2011; Hsueh and Yan, 2011; Wang et al., 2011; Al-Yahyai et al., 2012; Khoshsolat et al., 2012; Al-Yahyai and Charabi, 2015; Fetanat and Khorasaninejad, 2015; Guo and Zhao, 2015; Colantoni et al., 2016)
	ASPID (Lipošćak et al., 2006; Jovanovic et al., 2010, 2011; Vučićević et al., 2014)	SIMUS (Nigim et al., 2004)	ELECTRE (Fetanat and Khorasaninejad, 2015)		COPRAS (Medineckiene and Björk, 2011)	Delphi (Tzeng et al., 2005; Haruvy and Shalhevet, 2007; Hsueh and Yan, 2011; Bauer and Brown, 2014; Jain et al., 2014; Vafaeipour et al., 2014; Awad-Núñez et al., 2015)
	ANP (Bottero and Mondini, 2008; Banar et al., 2010; Fetanat and Khorasaninejad, 2015)	GP (Nixon et al., 2014)	ELECTRE TRI (Coelho et al., 2010)		FSE (Duan et al., 2011)	CoP (Chrysoulakis et al., 2013; González et al., 2013)

(*Continued*)

TABLE 2 | Continued

Type	MCDA methods					Supporting methods
	MAUT (Karatas and El-Rayes, 2013)	GC (Ribau et al., 2015)	NAIADE (Browne et al., 2010)		FSEA (Wang et al., 2011)	OWA (Al-Yahyai et al., 2012)
	MAVT (Phdungsilp, 2010)				PWV (Ribau et al., 2015)	BN (Awad-Núñez et al., 2015)
	MEW (Medineckiene and Björk, 2011)				RWOT (Öztürk, 2015)	CE (Dombi et al., 2014)
	HAWM (Sheykhdavodi et al., 2010)				DEMATEL (Fetanat and Khorasaninejad, 2015)	SSM (Coelho et al., 2010)
					SMAA (Kontu et al., 2015)	SWOT (Öztürk, 2015)
					MCS (Ribau et al., 2015)	MDA (Wang et al., 2011)
					ER (Zheng et al., 2015)	IN (Nowak et al., 2015)
						QCBS (Vadiati et al., 2012)
% Studies	69	13	10	19	12	37

MCDA process steps (**Figure 1**), while the associated MCDA and supporting methods used are presented in the last four axes. Therefore, the correspondence of methods with problem scope, number of alternatives, and criteria is established, allowing end-users to find methods most relevant to their situation. The axes values of temporal scale, number of alternatives, and number of criteria have been clustered for better readability, e.g., temporal scales are represented by the three temporal horizons discussed in Section "Problem Scope." The charts below provide an illustration of the interactive framework. By color coding the various MCDA categories, it becomes clear which methods were predominant for different cases. The following questions can be visually answered, such as:

- Which methods were most adopted for handling many criteria or alternatives?
- Which methods depended the least on supporting methods?
- Which methods were used for which scales and planning focuses?
- Which methods supported which decision problematics?
- Which methods were combined?

Highlighting some of the insights observed in **Figure 13**, we note that value measurement methods were very eclectic, as altogether they were adopted for nearly scales and decision outcomes (**Figure 13B**). Goal, aspiration, and reference level methods were essentially used for the urban and neighborhood scales, whereas they were never used for integrated planning or description and sorting problematics (**Figure 13C**). These methods handled limited number of criteria, never exceeding 20. The outranking group was also fairly eclectic in terms of supporting all decision problematics and rarely required or relied on supporting methods (**Figure 13D**). They were combined with methods from other groups, including ANP, DEMATEL, and WSM. MODM methods handled multiple scales and planning focuses, while tackling many alternatives, but not more than 20 criteria (**Figure 13E**). The newer MCDA methods labeled "others" are also fairly broad on all criteria, avoiding however operative planning focus and temporal horizons (**Figure 13F**). Finally, the studies that did not involve any main MCDA method were also the ones handling the largest amount of alternatives and criteria, in particular because of the use of GIS approaches (**Figure 13G**).

Figure 13H presents a concrete example illustrating how the parallel coordinates can be used to filter the solutions to match a user's problem context. In the example, the context is defined by "brushing" the axes in the areas of interest, namely to support a planning problem at the urban to district scale, to tackle the system holistically, and to provide either a description of the issues at stake, or to provide support in choosing from a large quantity of alternatives. The chart reveals two methods which that similar conditions: WSM and MODM.

DISCUSSION

The review revealed several trends and insights on the ongoing applications of MCDA in UESP. The first and most notable

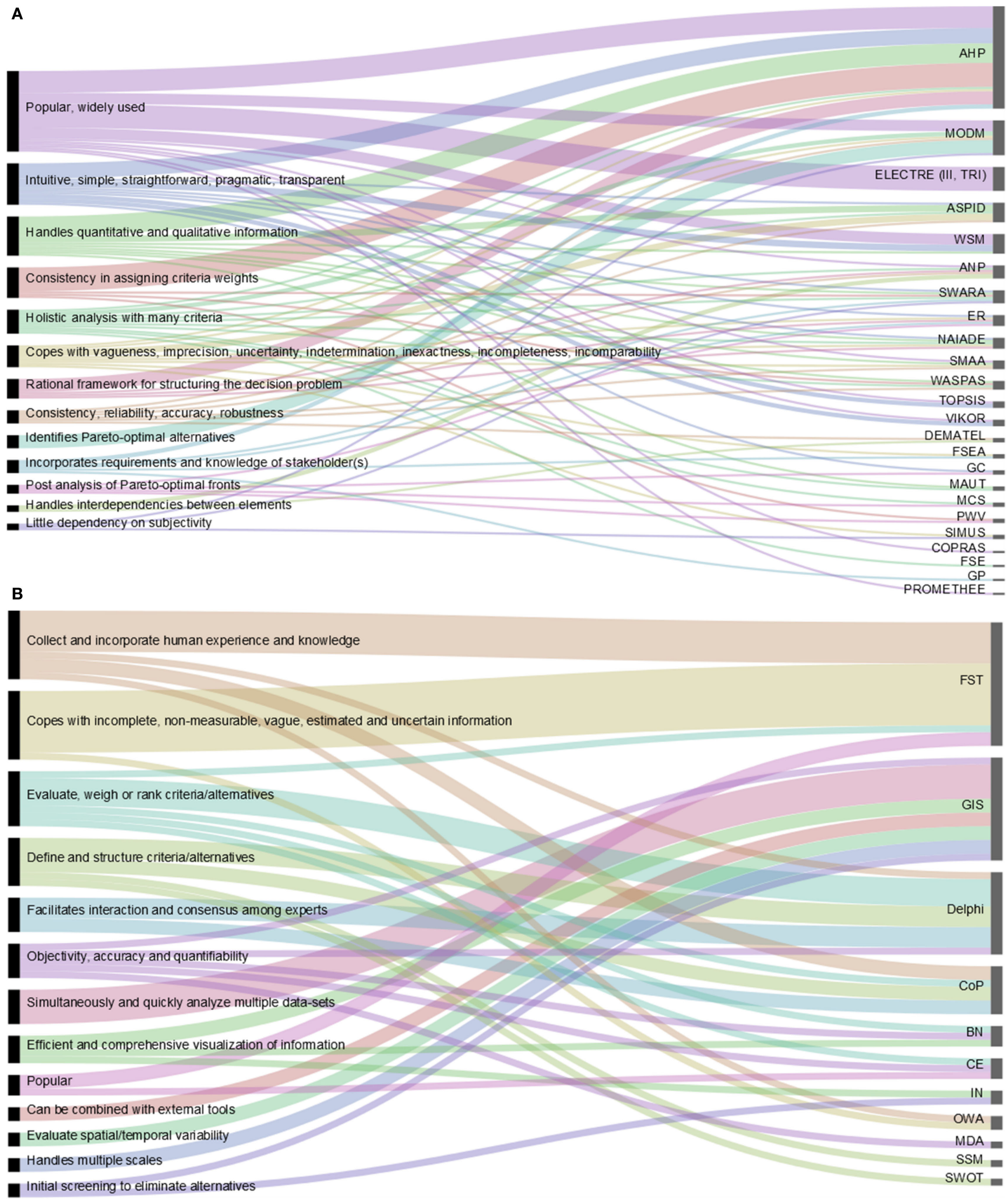


FIGURE 11 | Stated arguments for selecting the respective (A) multicriteria decision analysis methods and (B) supporting methods. Note: HAWM, MAVT, MEW, RWOT, and QCBS are not represented, as no explicit arguments were provided in the studies.

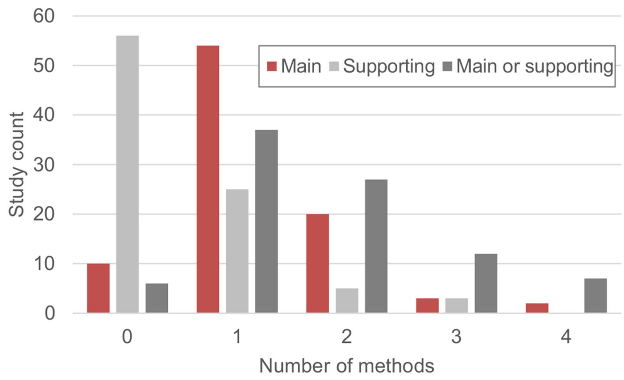


FIGURE 12 | **Number of methods used per study**.

trend is the increasing use and popularity of these methods in urban energy planning contexts, which can be interpreted in at least two ways. First, this demand for decision analysis and support may reflect the increasing complexity and intractability of issues related to urban energy planning (Cajot et al., 2017), alongside the expectation of accountability and transparency in public authorities' decision-making (Keeney, 1982). MCDA appears in these regards as an appropriate response to support the DMs involved and make their decisions more clear and justifiable. Another interpretation is the growing literature on MCDA, which reinforces its visibility, recognition, validity, and trustworthiness, thus facilitating its dissemination. As Strantzali and Aravossis (2016) also point out that DMs (DM) now tend to resort to a wider variety of methods than before, also building their own methods, when appropriate, to better face their specific issues. If the more traditional methods like AHP, WSM, MODM, and TOPSIS are still the most popular, a broad range of less common methods are tested and applied in attempts to facilitate decisions of urban actors. This was clearly demonstrated in the present selection of studies, as illustrated by the broad range of methods adopted, around 30 MCDA methods found in 89 studies.

The second key finding was the main rationale observed for choosing a method. In nearly 30 papers, one of the main arguments for choosing a method was its popularity. This seems to indicate that DMs are more likely to trust a method that has been intensively studied and applied by peers. In this regard, review papers such as the present help identify these common and popular methods.

Parallel coordinates have been presented here to synthesize the collected review information, providing a means to support analysts and DMs in selecting appropriate methods. It could be argued that the *appropriateness* of a method does not merely depend on the number of previous applications, which is why the present study strived to provide a deeper context for these applications, underlining not only the most popular methods but also the situations in which they have been applied. Even so, the selection of a method may have been the result of arbitrariness or simply misguided. However, our hypothesis is that previous applications of a method reflect at least some deliberate and motivated reason for doing so, which could in turn be of use for future users in similar contexts. This raises a first point of future work, as this approach grows in relevance by including more studies in the synthesis. As revealed in the review, the topic is currently trending, and it is expected that many more applications of MCDA in UESP will be found in the coming years. It is our hope that the present methodology could serve as a basis for an extension in the near future, investigating evolutions, new trends, and building on the existing base of knowledge.

In addition, if the present results explored in the parallel coordinates may guide end-users in selecting methods, they serve a complementary purpose for decision scientists and researchers, revealing possible research gaps. Therefore, future research may explore the lacks made visible by the parallel coordinates. It was out of the scope of this article to question why, for example, goal and aspiration level methods tended to include only limited criteria compared to other MCDA categories, or avoided the more integrated planning or operative planning problems. Similarly, it was not explored why outranking methods compared fewer alternatives than the other categories. The visual support and comprehensiveness offered by parallel coordinates facilitates this identification of trends, lacks, and subsequent questions, which could be explored in future work.

The review has also looked at the reasons for combining various methods. It became clear that MCDA can benefit from multimethod approaches, as more than half of the studies relied on a combination of MCDA and supporting methods, and about a third used a combination of two or more MCDA methods. The leading rationale for combining methods was development, with AHP frequently used for weight elicitation, Delphi for analyzing the decision context, and between various optimization and other MCDA methods. Ten studies explicitly aimed to triangulate and compare different MCDA methods, and two trends were observed here: first, triangulation that aimed at comparing common methods, and second, triangulation between a common method and a less known one. This tends to show that users of MCDA are fairly cautious in their adoption of existing or new methods and do realize the advantages of comparing several methods for an enhanced understanding of the problems.

The review focused on the context of UESP, thereby providing useful information about an emerging topic. The studies revealed that urban energy questions indeed span over decades, increasing the challenges and uncertainties in the decision process. Most planning questions concerned temporal horizons of over 20 years, meaning investments and effects will last at least that long and are worthy of analytical decision support. It was also found that although the leading topics of study were heating, cooling, and power, a wider balance with topics of mobility, water, environment, and waste also exists. However, as was already pointed out by Løken (2007), the integration of carriers and technologies is still fairly rare, as a majority of studies remain system specific. Few studies dealt with operative planning, and here as well, future work to better link the specific planning and design studies with effects at the operative stage would prove useful. Regarding the lack of studies on the urban and local scale also noted in the introduction, the number

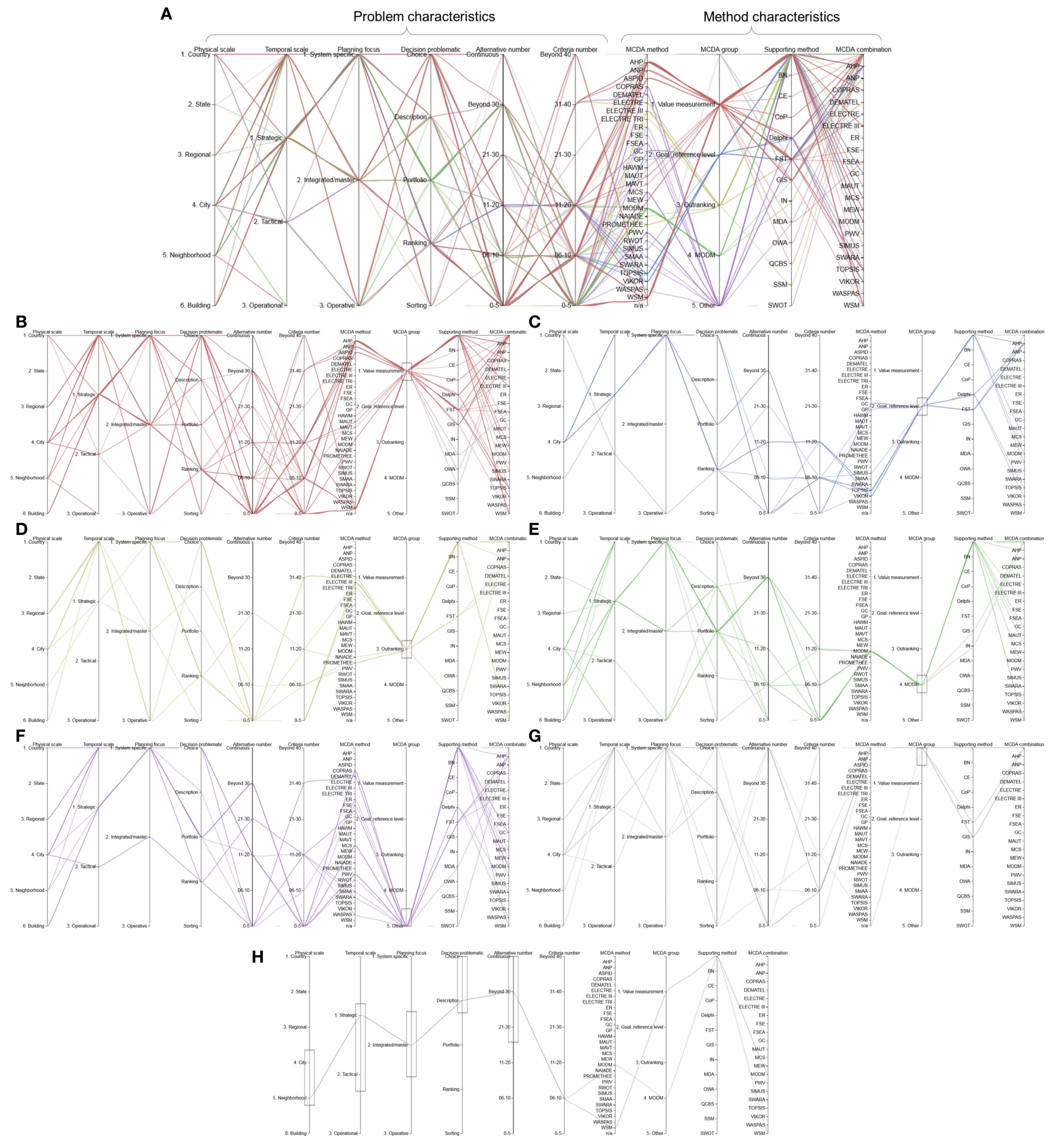


FIGURE 13 | Synthesis of data collected from the reviewed papers, depicted in parallel coordinates. See Supplementary material to access the interactive charts. **(A)** All methods displayed with their corresponding characteristics. **(B–G)** Filtering of the methods by multicriteria decision analysis group. **(H)** Identification of the methods matching a user-defined planning problem, by brushing the corresponding axes.

of studies found in the context of this review seems to indicate that the awareness of the importance of this topic has grown in the past decade and will certainly continue expanding.

Another noticeable trend was the combination of MCDA with various supporting methods like Delphi, CoP, or SWOT, which help structure the problem, identify alternatives and criteria, and prioritize them. In turn, this helped DMs better focus on values. Even without the use of supporting methods to elicit values, a majority of studies were considered driven by values, rather than alternatives. This is rather encouraging, as it reflects a healthier approach to decision analysis and problem solving, by promoting the analysis of many alternatives, leading to better decisions. Nevertheless, still one-third of the studies focused on alternatives, possibly failing to identify better, more adapted solutions.

CONCLUSION

The urban context and urban planning has a crucial role to play in shaping tomorrow's urban energy systems. The complexity of the tasks requires, however, appropriate decision analysis and support, and it appears that MCDA has a bright and necessary future in UESP. Contributing to the knowledge in these areas, this article first provided a definition of the concept of UESP and presented a systematic review and analysis of MCDA applications in this context. It investigated issues that were not tackled by previous reviews in the field, including criteria and alternative elicitation, reasons for choosing and combining methods, decision problematics, and values. Synthesizing the collected information, an interactive framework was proposed to help future users identify appropriate MCDA methods relevant to their problems.

The review allowed to respond to previous lacks identified in energy related MCDA applications, highlighted in the Section "Introduction." Indeed, the review revealed a growing body of studies focusing on the urban and neighborhood scales, previously only sparsely addressed. It also indicated that the MCDA approaches combined multiple methods more often than not, which has been advocated by Løken (2007) and (Hobbs and Horn, 1997). Finally, 18 studies were found, which tackled the energy system in an integrated way, considering various energy carriers or sectors. Although this is still a minority compared to the 61 system specific studies, there is hope that more integrated approaches will take place in the future, with the rising awareness and competences in interdisciplinary work, and increasing computational power capable of modeling large, integrated systems with greater detail and accuracy.

At the same time, new issues have emerged, and several questions have not yet been explored.

- The proliferation of MCDA methods and applications seems to indicate a flourishing research area, but at the same time decreases the accessibility to—and understanding of—the methods by novices. Future reviews should focus more specifically on organizing the new methods being developed, clarifying the practical implications of using one method rather than another. Such transparency and structure is required for the field of MCDA to successfully reach out and support those who could benefit from them.
- The role and background of DMs, their number, the inclusion of citizens, and the effect these aspects may have on the choice of MCDA method is a facet, which was not investigated in the scope of this review. Given the tendency of urban planning to involve wider groups of stakeholders [e.g., in collaborative planning approaches (Teriman et al., 2010; Cajot et al., 2017)], this research question could highlight which methods are most suitable for decisions including large groups. Certain studies reviewed here have been more explicit in describing these stakeholder interactions and could be a starting point for analysis (Yedla and Shrestha, 2003; Nigim et al., 2004; Tzeng et al., 2005; Dytczak and Ginda, 2006; Wang et al., 2011; Vafaeipour et al., 2014).
- The multiple uncertainties in the real planning processes (Mirakyan and De Guio, 2013b), as well as the many different approaches to cope with them (Mirakyan and De Guio, 2015) were not treated in this work for time and space limitations. As highlighted in the review, urban planning projects span over an average of 20–25 years, implying planners must be able to incorporate a certain flexibility in their plans, handling uncertainties related to not only the relevance of energy technologies available today, but also those which may become available in the next decades.
- Criteria were only explored here quantitatively and according to their selection process. Following the approach of Wang et al. (2009), a compilation could be done as well in the area of UESP, providing DMs with a qualitative overview of the commonly used criteria, classified by scale and topic. Wang et al. (2009) also discussed how a proliferation of criteria is not necessarily helping take better decisions, listing five principles to follow for their selection (systemic, consistency, independence, measurability, and comparability). Investigating how these rules are respected in practice, in particular whether the criteria represent well the systems studied, and whether they are truly independent, could bring insights to the validity of the results in MCDA literature.
- In addition, the recurrent methods and tools employed not only to elicit but also to evaluate the criteria could be investigated.

These open topics, as well as the approach and review questions presented in this article, could also be extended to a broader sample of studies (exploring, e.g., other databases, languages, master and doctoral dissertations, books, unpublished studies, future studies), in the topic of urban energy planning and beyond.

NOMENCLATURE

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ASPID	Analysis and Synthesis of Parameters under Information Deficiency
BN	Bayesian Network
CBA	Cost-Benefit Analysis
CE	Choice Experiment
CoP	Communities of Practice
COPRAS	COmplex PRoportional ASsessment
DEMATEL	DEcision MAking Trial and Evaluation Laboratory
DM	Decision Maker
ELECTRE	ELimination Et Choix Traduisant la REalité (from French, ELimination And Choice Transcribing Reality)

ER	Evidential Reasoning
EU	European Union
FST	Fuzzy Set Theory
FSEA	Fuzzy synthetic extent analysis
FSE	Fuzzy Synthetic Evaluation
GAIA	Geometrical Analysis for Interactive Aid
GC	Global Criterion
GHG	Greenhouse Gas
GIS	Geographic Information System
GP	Goal Programming
HAWM	Hierarchical Additive Weighting Method
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MAUT	Multi-Attribute Utility Theory
MAVT	Multiple-Attribute Value Theory
MCDA	Multi-Criteria Decision Analysis
MCDM	Multiple Criteria Decision Making
MCS	Multiple Criteria Score
MEW	Multiplicative Exponential Weighting
MI(N)LP	Mixed Integer (Non) Linear Programming
MODM	Multi-Objective Decision Making
NAIADE	Novel Approach to Imprecise Assessment and Decision Environments
NoP	Network of Problems
OWA	Ordered Weighted Averaging
PWV	Pseudo-Weight Vector
PROMETHEE	Preference Ranking Organization Method for. Enrichment Evaluations
QCBS	Quality and Cost Based Selection
RES	Renewable energy sources
SIMUS	Sequential Interactive Modeling for Urban Systems
SMAA	Stochastic Multiobjective Acceptability Analysis
SODM	Single-Objective Decision Making
SSM	Soft Systems Methodology
SWARA	Step-wise Weight Assessment Ratio Analysis
SWOT	Strengths, weaknesses, opportunities and threats
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
UES	Urban Energy System
UESP	Urban Energy System Planning
UN	United Nations
UNCED	United Nations Conference on Environment and Development
VIKOR	VIseKriterijumska Optimizacija I kompromisno Resenje (from Serbian, MUltiCriteria Optimization and compromise Solution)
WASPAS	Weighted Aggregated Sum Product ASsessment
WPM	Weighted Product Model
WSM	Weighted Sum Model

AUTHOR CONTRIBUTIONS

All authors contributed substantially to the conception of the work and to its intellectual content, and approved the final version.

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SUPPLEMENTARY MATERIAL

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