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Accomplishments and challenges of metrics for sustainable energy, population, and economics as illustrated through three countries

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The global Sustainable Development Goals require meeting multiple objectives on energy, population, economics, and ecosystems. Development and economic growth as defined by current metrics requires energy inputs, yet energy growth can also increase negative impacts on natural systems. To achieve sustainable development goals, policymakers and technologists will need energy system solutions that consider not only cost and efficiency but also population, quality of life, natural ecosystems, and culture that accommodates different starting points and transition timelines of various countries. To explore possible approaches, this perspectives paper summarizes energy in the context of economic growth and population, illustrating concepts through the diverse status and direction of three countries—Japan, the United States, and Bangladesh—as potential views into a post-growth sustainable future. Four fundamental questions on long-term energy development are identified, related to optimal energy use per capita, sustainable global energy demand, managing an energy transition with stable population, and the need for generalizable approaches across countries.

KEYWORDS

sustainable energy, sustainable development goals (SDG), metrics, Japan, Bangladesh, United States

1. Introduction

Access to energy is a fundamental requirement for life, from sunlight for plants to heat for human homes. Energy for human civilization has been under continuous transition, especially over the past 200 years, as societies expand beyond plant and animal power to include electricity, fuels, and advanced materials (Smil, 2004; Bashmakov, 2007). Energy demand growth and expansion of energy types has often been at the expense of the environment and human health (Smith et al., 2013). Thus, in recent decades, the emphasis has been to "ensure access to affordable, reliable, sustainable and modern energy for all," as stated in Sustainable Development Goal (SDG) 7 (United Nations, 2015).

Most energy technology researchers and developers are technologists thus their emphasis has been on developing new modern energy sources and advancing their reliability across delivery systems. Similarly, energy business and policy experts have focused on affordability (cost) and access for all. Energy cost, reliability, and access are quantitative and measurable objectives trackable at the system, country, and global scale (International Energy Agency, 2022; REN21, 2022; BP, 2023). As such, energy decisions have been largely economic and resource based with varying levels of cultural and political influence. Additionally, the provision of energy has been viewed as essential for absolute economic growth [measured by gross domestic product (GDP)] with variable strengths of this relationship emerging as countries develop and grow their industrial processes and their populations (Georgescu-Roegen, 1975; Stern, 2011). Even though they are measurable, it has been observed that current metrics to assess energy access and energy use, such as energy use per capita (which is lowest in low-income households), have proven inadequate to ensure the energy transition progresses or is measured in a just and equitable way (O'Sullivan et al., 2020; von Platten et al., 2020; Sovacool et al., 2021).

The remaining SDG 7 metric is sustainability, which has been variably defined vis-à-vis energy as clean, renewable, advanced, net-zero, and other versions of these terms (United Nations, 2015; Engel-Cox and Geocaris, 2023). Without an agreed upon qualitative definition, the energy community has not reached consensus on quantitative metrics defining sustainable energy, especially across global resources, supply chains, and cultures. Technoeconomic and life cycle assessment tools provide insights into the cost and to a lesser extent environmental impacts of energy technologies. However, quantitative metrics of the relationship between society and energy that can be measured, reported, and generalized for decision making on energy technologies do not seem to exist (Engel-Cox et al., 2022). One approach may be to evaluate energy technologies relative to the other SDGs (such as food, water, work, innovation etc.); yet, while the SDGs can complement each other, they can also conflict and may not be comprehensive across all possible sustainability measures of energy (Fader et al., 2018; Wiedmann et al., 2020).

The challenge of measuring sustainable energy is also tied to challenges of the concept of green growth and the ability to grow an economy while reducing environmental impacts. This requires a decoupling of a country's GDP from its energy and other resource use, which economic analysis has found to be persistently elusive (Parrique et al., 2019; Hickel and Kallis, 2020; O'Neill, 2020). While energy efficiency and a change from fossil to renewable energy reduces greenhouse gas emissions and other types of pollution per unit of energy generated, an overall increase in energy consumption has resulted in continued growth of the use of fossil fuels as well as other energy minerals for the transition (REN21, 2022). This is consistent with the finding that the primary accelerator of global environmental impacts is per capita consumption (Wiedmann et al., 2020).

A relationship between economics and sustainability in development has also been proposed using the Environmental Kuznets Curve (EKC), which suggests that a nation's level of development will also affect environmental quality, ultimately turning positive as per capita income increases. By utilizing an aggregated ecological footprint, researchers confirmed the EKC hypothesis, but found that GDP growth is not consequential for all aspects of the ecological footprint, suggesting some decoupling here (Kostakis and Arauzo-Carod, 2023). Further, it has been identified that while the EKC hypothesis is generally confirmed in 276 metropolitan areas around the globe for the residential and industry sectors, this was not the case for the energy sector (Fujii et al., 2018). Both EKC studies mentioned here suggest that support flowing from developed toward developing nations alongside additional renewable energy deployment will be critical to enable developing nations to proceed past their EKC tipping points.

Ultimately, some economists and scientists have proposed that meeting global climate objectives and other sustainability goals may require de-growth of consumption, higher resource efficiency, circular economy, and/or reduced population levels (Van Vuuren et al., 2018; Hickel and Kallis, 2020; UN Department of Economic, 2021). For some nations the linkage between labor per capita and economic growth has not been shown to be significantly related, in contrast to accepted classical growth models, and the stimulation of improving labor force participation, particularly for women, and encouraging better education and training opportunities may lead to economic growth in these cases (Taha et al., 2023).

To achieve objectives around sustainable energy, policymakers and technologists need to seek multiple energy system solutions that consider not only cost and efficiency but also population, quality of life, meaningful work, natural ecosystems, and a respect for culture. Global objectives for sustainability require a generalizable approach that also accommodates different starting points and transition levels of various countries. Using three countries as illustrations of different types and stages of sustainable development, this paper identifies challenges for future sustainable energy in the context of economics and population. Through these examples, the paper provides perspectives on measuring and addressing challenges for post-growth countries, growing countries, and the range of options in between. The overall objective is to advance the conversation of sustainable energy beyond technology and economics toward more holistic future-focused solutions.

2. Illustrative examples: Japan, USA, Bangladesh

Three countries with different baselines of energy consumption, population, and economic growth were chosen to illustrate similar and differing approaches. Specifically, these include:

- Japan: declining energy consumption and high energy access with declining population and low economic growth rate.
- United States: flat energy consumption and high energy access with a slightly increasing population and moderate economic growth rate.
- Bangladesh: increasing energy consumption and low energy access with a growing population and high economic growth rate.

Relevant facts about each country are described in this section with insights and comparisons presented in Section 3.

2.1. Japan

Due to a post-World War II baby boom, Japan's population increased year on year up until around the year 2010, since which the population has been in decline causing an aging, shrinking population with a median age of 48.4 in the year 2020 (United Nations, 2023). It is estimated that the median age in Japan will continue to increase as the population decreases in the foreseeable future. Although a population decrease may logically lead to an overall lower carbon footprint for the nation, it has been identified that as households with fewer and more elderly members increase, energy related household emissions also increase (Huang et al., 2019; Shigetomi et al., 2019). The overall peak for greenhouse gas emissions in Japan was predicted to have occurred in 2020, and as demographics shift in response to aging and shrinking, the contribution of lower income, older households is becoming more pronounced (Shigetomi et al., 2020).

The Japanese government recognizes this challenge and aims to usher in a new approach which they call Society 5.0 (Cabinet Office of Japan, 2023). Under the auspices of Society 5.0, the Japanese Government hopes to balance economic advancement with the resolution of social problems, with a special focus on the needs of the elderly and disparities caused due to the depopulation of rural areas. On the energy side, energy diversification and local production will be employed to ensure a stable energy supply with reduced emissions, and social innovations including robotics and automation are expected to support agriculture, manufacturing, and the elderly, specifically regarding aged care.

Japan is a relatively homogeneous society with very limited immigration when compared to other developed nations, while also highly dependent on imports of fossil fuels. This is also likely to be the case in terms of imported energy moving forward, particularly if a hydrogen economy is realized, perhaps meaning that emissions are avoided (or created) in other nations (Chapman et al., 2020). If Japan is to become a successful post-growth economy, will Society 5.0 ideals be sufficient to engender the transition such that energy goals and quality of life can be maintained long term?

2.2. United States

Similar to Japan, the United States (U.S.) is an industrialized country with a high GDP and well-developed energy infrastructure. However, unlike Japan, the U.S. population continues to grow, from growth rates of nearly 2% per year in the 1950s to a lower but still growing average annual rate of about 0.75% from 2010 to 2020 (United States Census Bureau, 2021b). U.S. population growth consists of both immigration and births with significant but variable contributions from both. It is notable that 2021 was a historic low in U.S. population growth (0.1%) and that the contribution from immigration exceeded births for the first time, although both were very low, a trend accelerated by the COVID-19 pandemic (United States Census Bureau, 2021a). The history of immigration has made the U.S. a highly diverse country, with about 14% of the current population born outside of the U.S. (United States Census Bureau, 2021c).

Energy use per capita in the U.S. is high, as is CO_2 equivalent emissions per capita, although both peaked about the year 2000 [U. S. Energy Information Administration, 2023]. Total energy use has been essentially flat and total CO_2 emissions have declined since 2000 even with continued population growth, largely driven by advances in energy efficiency and conversion of a portion of the electricity sector from coal to natural gas and renewables. Since U.S. GDP and GDP per capita grew significantly over the same time period, it indicates that the U.S. may be at least partially decoupling its energy resources use from economic and population growth.

While the U.S. electricity demand is expected to grow based on policies toward electrification of buildings and transportation, it is less clear if this will result in a change in overall total energy demand or merely a shift from fuels to power, with increased systemic efficiency. At the same time, U.S. population may stabilize or even start to decline based on immigration policy and economic advancement in other countries. The question for the U.S. is can it continue to improve its sustainability, reduce its resource use, and increase its efficiency to be more in-line with the energy intensity of Europe and Japan, while maintaining economic strength?

2.3. Bangladesh

Bangladesh is a rapidly growing, developing nation with an increasing appetite for energy, with energy consumption growing by 4.5% a year, alongside 6.9% annual economic growth (Enerdata, 2023). As Bangladesh aims to improve the quality of life of its populace, access to electricity is rapidly increasing, from approximately 55% in 2010, to 96% in 2020; however, grid reliability and resilience remains an issue and access to clean fuels for cooking is still limited to just 25% of households (Rose et al., 2020; Our World in Data, 2021).

Bangladesh is a young, rapidly growing nation, experiencing what some describe as a "demographic dividend", whereby the working age population is growing rapidly. In order to benefit from this dividend before population stabilizes, rapid digitalization and increased energy intensity are anticipated to provide employment opportunities for this burgeoning sector, whose impacts on the achievement of environmental goals is uncertain (Hosan et al., 2022). Recognizing this challenge, technological innovation will be critical in Bangladesh; further, the ability to learn from other nations in terms of the stimulation of innovation through conducive policy making will also be critical. As it has been shown that research and development, environmental taxes, and a growing GDP all have a positive long run relationship toward technological innovation, Bangladesh could shorten its energy transition timeline and more rapidly achieve its sustainable development goals through those approaches (Karmaker et al., 2021).

One concern for Bangladesh in its energy transition is the strong relationship between economic activity, GDP growth, and urbanization, which are all increasing, and energy consumption—intrinsically linked to carbon emissions in a heavily fossil fuel dependent nation (Rahman et al., 2021). The shift to renewable energy is of critical importance to Bangladesh. There is strong evidence from global energy transition evaluations that the shift toward renewable based electricity will pay dividends for lower income nations such as Bangladesh in terms of employment, health, and energy access (Chapman et al., 2021). A remaining question is at what point in the sustainable development of countries like Bangladesh is it reasonable to transition to new energy technologies and to aim to decouple energy consumption from economic growth?

3. Insights on sustainable energy development

While the literature has focused primarily on economics of energy and population, better metrics are needed from the perspective of sustainable energy development. Classic sustainable development means giving equal weight in decision-making to people, ecosystems, and economy, while providing for inter-generational equity for current and future generations. The challenge for sustainable energy is providing sufficient energy for quality of life for current and future humanity when it results in environmental impacts, no matter the energy source employed.

Consider the three countries described above and their economies as measured by GDP per capita (a proxy metric for economic growth). As seen in Figure 1, Japan's GDP per person is slightly increasing, even while Japan's overall GDP and population have remained flat for some 30 years. The U.S. continues to experience GDP growth both per capita and overall, as well as an increasing population. Bangladesh's GDP is currently comparatively very low but beginning to rise. Bangladesh's population has rapidly grown over the assessed period.

If GDP continues as a key economic measure, an emphasis on GDP per capita could be a better measure of benefit to individuals with less dependency on population growth and its environmental impact. However, increasing individual consumption at levels well beyond meeting quality of life indicators may raise GDP per capita without a corresponding environment benefit or worse. Multiple alternative economic metrics to replace GDP have been proposed and used in limited circumstances (Fleurbaey, 2009; Giannetti et al., 2015), although a full review beyond the scope of this paper. However, none have been accepted on a global scale. GDP per capita with all its flaws is a small step to a more nuanced metric but far from adequate, with new economic measures that encourage sustainability needed.

Energy represents a specific type of material consumption that can be generated from multiple sources with varying impacts and conserved through means of efficiency yet nevertheless results in similar utility outcomes. Considering consumption in terms of energy, Figure 2 explores power use over time for the three nations. Japan's moderate and flat electricity use per capita represents a middle path between the high but flat to declining power use of the U.S. and the low power use of Bangladesh, yet to reach an adequate level for its growing population. Japan residents have a high quality of life, so countries such as Bangladesh aspiring to energy use per capita at the U.S. scale may not be necessary yet the question remains, is the electricity consumption by Japan sufficient or also excessive? There is no consensus to what is the "right" amount of electricity per capita nor may there even be a single universal answer given the widely varying cultural, geographic, and infrastructure differences in each country.

Additionally, the decline in U.S. electricity demand per person represents a success in the advancement of energy efficiency in buildings, industry, and equipment. Yet, as electrification increases, the decline may be reversed although it may also be compensated for by a commiserate decline in direct fuel use. Similarly, Bangladesh may increase its use of electric cooking and other domestic activities, decrease fuel use, and potential grow its transportation options to include both electricity and fuels. Thus, while electricity access and use per capita is a key metric, its variability may depend on multiple end use factors in each country.

The ultimate challenge of these and similar metrics is defining measures of sustainability and the role of energy in achieving sustainable nations and energy transitions across a range of demographics and economics. The fundamental questions which need further research and insight include:

1. **What is the optimal level of energy use per capita for each country for a decent quality of life?** Energy use per capita should be a key metric, yet inter-country comparisons may need to be normalized or avoided. While this issue has been studied recently (Smil, 2004; Jackson et al., 2022), each country will have a different optimal energy use based on the country's size, natural resources, industrialization, culture, and climate. Energy use will need to include electricity, fuels, and direct heat, for transportation, buildings, industry, and other applications. Trade of materials and fuels may result in indirect transfer of energy use between countries, distorting use per capita. While imports and exports could be calculated in terms of energy use, a simpler approach would be to measure countries according to their own baseline. Significant multi-disciplinary analysis is needed to model energy use in consideration of human society and ecological impact, as well as the policies to achieve consensus objectives.
2. **What is the absolute global energy demand that is sustainable for the planet?** Another measure would be a total energy use metric for the planet, thus taking into consideration both demand and population. However, every type of energy engenders different environmental impacts, but they are often challenging to compare across energy types. A simplified metric of greenhouse gas emissions related to climate change has been used to represent a "cap" on energy and other emission sources, yet this misses a variety of other effects, including material extraction, air and water pollution, land use, etc. Additional inter-comparable measures of environmental impact beyond GHG emissions are needed to identify concepts around sustainable global energy capacity, which may include water demand and land use per energy unit, life-cycle efficiency, and recoverability or circularity.
3. **How can societies manage an energy transition with a stable or declining population?** As countries develop, the trend has been toward stable and then declining populations. When combined with more systemic energy efficiency, this could result in dramatic decreases in energy production. A reduced population could also provide unique opportunities for adaptation to the effects of climate change, including rewilding for natural buffer zones along coasts, increasing land conservation to address drought, and rebuilding communities at risk. Energy planning and larger economic measures rely on growth, yet quality of life should ideally remain high even if absolute growth declines. While economists are working on new metrics to replace GDP, an understanding and vision of an energy transition that reduces consumption overall and enables adaptation that benefits communities are essential. Policies and incentives that reward countries,

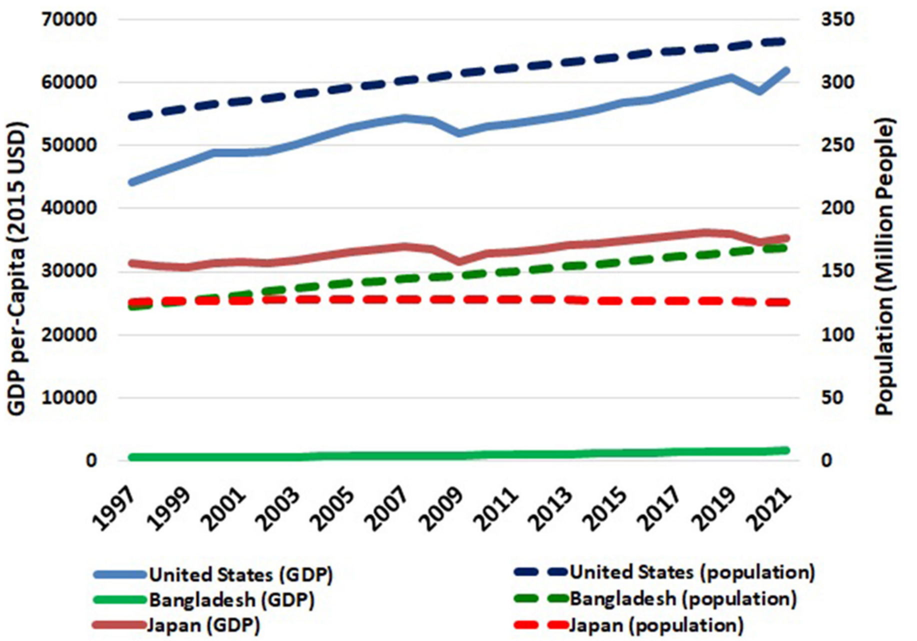

FIGURE 1
GPD per-capita (left-axis), and population (right axis) for the United States, Bangladesh, and Japan from 1997 to 2021.

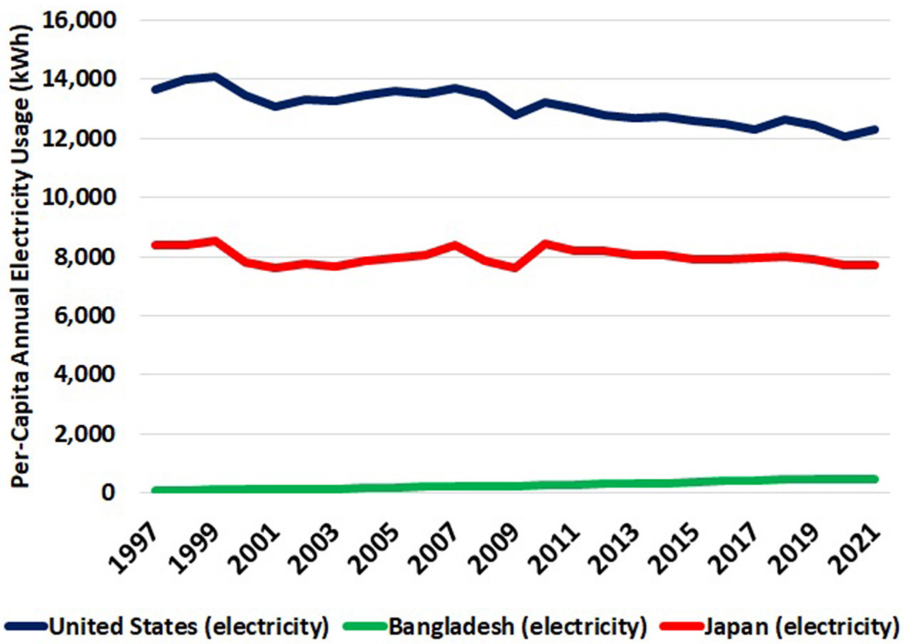

FIGURE 2
Electricity use per capita for the United States, Bangladesh, and Japan, 1997 to 2021.

industries, utilities, and individuals for reduced energy consumption, lower emissions, and increase efficiency in sourcing energy could incentivize investment and innovation even as demand declines.

4. **What generalizable approaches for sustainable energy could be used across cultures?** Every country is at a different stage of growth, with some still striving for energy access and others transforming and shrinking their energy footprints. A convergence of energy per capita between countries is overly simplistic and the narrative that energy development must go from coal to natural gas to renewables overlooks opportunities to speed up technological development and

deployment. New approaches are needed for countries to develop and maintain a high quality of life without economic and ecological disruption, no matter their starting point. Metrics that include more than just averages but also measure range of access to and quality of available energy would be important, since they focus more on the impact of energy on society rather than the sources of energy, which may vary significantly based on cultural and geographic resources.

When considering these insights and the three countries described, Japan may represent a harbinger of a near-future condition for the United States and eventually in coming decades for countries like Bangladesh. With a declining and highly urbanized population, a post-growth economy (representing lower levels of consumption), and recent growth in its renewable and low-GHG energy portfolio, Japan may be moving toward sustainability balanced across multiple development goals. Its concept of Society 5.0 with an emphasis on automation and technology is an experiment in how human society may need to proactively address socioeconomic trends that will become global in the next 50–100 years.

The U.S. might leverage its higher levels of natural resources and cultural diversity into energy and technology innovation as it seeks to reduce its global environmental impact. Bangladesh may leverage its demographic dividend and advance energy development quickly, ideally through technology leapfrogging, seeking to achieve a high quality of life without the higher energy demand experienced in other economies. Both may watch how Japan manages its current energy, technology, and demographic transition to better measure and develop their own sustainable futures.

In terms of all three nations, there are some existing approaches which may be applied to solving complex yet interrelated issues, one of which is the concept of energy justice, and the measurement of inequalities and their amelioration through energy poverty-based approaches. Multi-dimensional energy poverty measures are of particular interest here, as they not only use a variety of factors to measure energy poverty (energy access, fuel type usage, participation, pollutant loads, housing stock, climate variation etc.), they also recognize inherent differences both between nations, and within nations (Halkos and Aslanidis, 2023). Considering the resolution of SDG 7, the assessment and alleviation of energy poverty considers metrics across the facets of energy availability (energy consumption and access), affordability (income, GDP and device ownership), and efficiency (taking into account access to clean fuels and emissions) (Che et al., 2021).

Specifically, for Japan the development of a multidimensional index which takes into account housing construction and age, income and family structure identified that energy poverty is increasing in Japan since the 2020′s and single mother and single-elderly households are at high risk of energy poverty (Okushima, 2017). Further, as households which are suffering from energy poverty are less likely to be engaged in the energy transition, dealing with this issue is likely to engender multiple benefits (Chapman and Okushima, 2019).

For the U.S., the lack of a formal definition for energy poverty at the Federal level has been found to limit the effectiveness of the national response, in spite of the recognition of the issue and resource allocation toward its amelioration (Bednar and Reames, 2020). In addition, it has been clarified that there are racial disparities in energy poverty in the US, and that while low-income African-American households are particularly vulnerable to energy poverty, White households experienced the greatest level of energy poverty growth between 1990 and 2015. These outcomes were also found to hinge upon the types of energy used, demand levels, regions, socio-economic aspects and climate (Wang et al., 2021).

Bangladesh, often compared to its peers in South Asia, has a slightly higher level and intensity of multi-dimensional energy poverty than other South Asian nations, and the determinants of this energy poverty go beyond income and include family size (i.e., larger households experience higher levels of energy poverty), the reliance on traditional cooking fuels, and the age and gender of the primary breadwinner (Abbas et al., 2020). Interestingly, moving beyond demographic and socio-economic aspects, it was identified that increased financial inclusion and economic development in South Asian nations including Bangladesh led to energy poverty alleviation (Li et al., 2022), suggesting some crossover with EKC findings detailed in the literature review portion of this paper.

4. Conclusions

The next century will continue to be a time of transformation for society and the natural world. The past 200 years of industrial and information revolutions have resulted in an astonishing change in human culture, much of it bringing increased levels of comfort and benefit to many people. However, it has also resulted in increasing inequity between regions and countries, as well as caused a global decline in natural ecosystems, from species extinction to climate change. Energy technology advancements were a driver and key enabler of these transitions. Therefore, the sustainability revolution in the next 50–100 years toward more efficient, cleaner, and fewer energy resources requires new measures of sustainability to engender a better energy future for all. Multi-disciplinary cross-cultural collaboration between technologists, economists, sociologists, and political scientists from a diverse set of countries is needed to develop clear, measurable, and effective metrics for sustainable and equitable energy as human population begins to stabilize and continues to diversify.

Data availability statement

Publicly available datasets were analyzed in this study. The datasets utilized in this study derived from the World Bank World Development Indicators, a publicly available resource at https://databank.worldbank.org/source/world-development-indicators.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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