

Review

Exploring Energy Poverty: Toward a Comprehensive Predictive Framework

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Abstract: Energy poverty focuses on energy affordability in developed nations but is most often used in the developing world in the context of a lack of access to electricity, clean cooking fuels, or technologies. About 1.2 billion people still lack access to electricity and nearly 40 per cent of the world's population lacks access to clean cooking fuels. In addition, climate change mitigation strategies must be applied to a complex and diverse socio-technical landscape that varies across and within countries. Energy poverty is among the most pressing issues to be addressed within these strategies; however, due to the complexity of its causes, there is no commonly agreed upon evaluation approach or holistic set of indicators for its quantitative evaluation. In this study, a comprehensive literature review is undertaken on energy poverty measurement methods and definitions, and factors that cause energy poverty. Through this, exogenous and endogenous factors that are often overlooked in the assessment and prediction of energy poverty are identified. The need for an energy poverty prediction framework is identified, incorporating missing perspectives and elements needed to implement future energy poverty projections to enable proactive policy development. Missing perspectives included an increase in energy demand associated with the development of innovative technologies including artificial intelligence and automation, increasing fuel prices, and exogenous factors such as rising temperatures and increased acute disasters and endemic structural failures associated with climate change leading to employment impacts, all of which may be critical to the accurate prediction of energy poverty.

Keywords: energy poverty; fuel poverty; energy affordability; energy access; climate change; prediction; multicriteria index; framework; energy transition



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1. Introduction

Energy poverty, typically defined as the absence of sufficient access to adequate, reliable, affordable, safe, and environmentally suitable energy services [1], has been recognized as both a social and political issue globally that impacts individual outcomes in developed and developing nations alike. It has been heavily studied in recent years, focusing on the issues of evaluation methodologies, and the alignment of sustainable, low carbon development ideals with energy poverty alleviation [1–4]. Energy poverty is often considered alongside economic poverty; however, there is significant non-overlap between the energy poverty and the poverty group, and the two are considered dissimilar [5].

In the context of global warming, it is no exaggeration that energy poverty has become, in some cases, a matter of life or death. The year 2023 was the hottest on record since 1850 [6],

and ‘heat domes’ (a situation in which high pressure in the earth’s atmosphere prevents hot air from escaping and the pressure above the mass of air makes it get hotter [7,8]) are occurring more frequently, and for longer periods of time—generally in large cities, but in some cases in the United States they have expanded to cover the entire country. In 2024, tragedies such as the deaths of workers in developing countries who lack access to air conditioning and many pilgrims in Mecca occurred due to the heat dome phenomenon [9]. A report estimates that heat dome outbreaks will cause \$500 billion in annual economic losses and nearly 60,000 deaths per year by 2050 in the US alone [10]. It has further been indicated that such weather events are likely to exacerbate disparity, suggesting that energy poverty aggravates problems such as liver disease, heart disease, and depression due to increased stress [11].

It should also be noted that although energy poverty is linked to poverty, energy poverty and income poverty do not always occur simultaneously [12]. In Scotland, around half of all fuel poor households are not income poor [13] and in the EU, 30% of energy poverty households experience income poverty simultaneously [12]. According to the World Bank, in order to address the larger issue of poverty itself, energy poverty must also be resolved [14]. Energy access (defined as not having access to electricity or clean cooking fuels and technologies; [15]) is the most pressing issue, with 1.1 billion people around the globe lacking sufficient access to electricity, and almost 3 billion relying on polluting fuels—most prominently in Africa. These disadvantaged people and nations also suffer from higher energy costs compared to developed nations, making energy, even if available, unaffordable. Further exacerbating this issue, policy incentives which prioritize fossil fuel subsidies have meant that as energy access is improved over time, it is not occurring in a sustainable manner, and development and energy system reform are not necessarily occurring optimally. Political will toward energy poverty-alleviating solutions such as renewable energy deployment and the provision of sufficient storage remain critical to progress a sustainable energy transition and to address energy poverty, particularly in regions where renewable energy and storage are the only electricity available for households, due to the aligned policy goals of renewable energy deployment and energy poverty alleviation [14,16].

Further, there is some evidence that the identification and alleviation of energy poverty may lead to a more inclusive low-carbon energy transition in developed nations, as when energy poor householders’ energy needs are met, their attitudes toward engaging in the energy transition improve overall, as was detailed in [17], where a clear gap between energy poor and low income households was clarified, with regard to interest in and preference toward participation in renewable energy deployment, for example. It is estimated that some form of energy poverty affects about 50 million people in the European Union (EU) [18], while a study in France showed that energy poverty exacerbates depression, anxiety, and social health, and that addressing energy poverty has a positive cascading effect on improving mental health [19]. In Spain, energy poverty is considered a human rights issue, and an analysis of comfort and health in dilapidated neighborhoods with high energy poverty rates was considered essential to identify the shortcomings and potential improvements, especially in terms of energy education [20].

Energy poverty cannot be discussed solely in terms of exogenous factors and defined indicators but requires input and opinions from householders themselves. The factors that contribute to energy poverty vary by region, culture, and household characteristics, and due to its complexity, there is as yet no established energy poverty indicator or evaluation methodology that is widely agreed to be comprehensive across developed and developing nations. Although many studies have been conducted considering the factors and mechanisms that lead to or aid in the avoidance of energy poverty in general, a comprehensive

suite of indicators has not been elucidated. Clarifying the critical endogenous and exogenous factors may make it possible to predict the future occurrence of energy poverty and implement policies to reduce its occurrence, which is expected to become more severe in the future as climate change progresses. From the perspective of an energy transition rooted in energy justice, energy poverty is an issue that cannot be overlooked.

The aim of this research is to survey existing energy poverty research and examine how energy poverty is measured and what factors are considered to impact its occurrence and evaluation. Further, we seek to identify factors that are lacking in light of global warming, technological innovation, and other important exogenous factors, to reexamine the definition of energy poverty, and consider what factors may be needed to evaluate and predict it comprehensively in the future.

The remainder of this paper is organized as follows: Section 2 outlines the materials and methods used in the literature review. Section 3 details the results of the literature review focusing on evaluation methodologies and drivers of energy poverty. Section 4 details the results and discussion, proposing additional indicators to be considered in a holistic evaluation and prediction method. Section 5 gives the conclusions, limitations, and future prospects.

2. Materials and Methods

This study utilizes a literature review approach in order to identify current research foci and to elucidate the differences in methods for energy poverty research in both developed and developing nations, and to highlight gaps in current research streams, such that a new, comprehensive evaluation and prediction method can be proposed. Although various methods exist for literature review, such as the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) guidelines and the Context Investigation Mechanisms Outcomes (CIMO) scheme, this study adopts the systematic literature review (SLR) method as proposed by [21].

The literature review in this study utilized the Scopus, Google Scholar, and Web of Science academic article databases with the parameters shown in Figure 1, in February 2025.

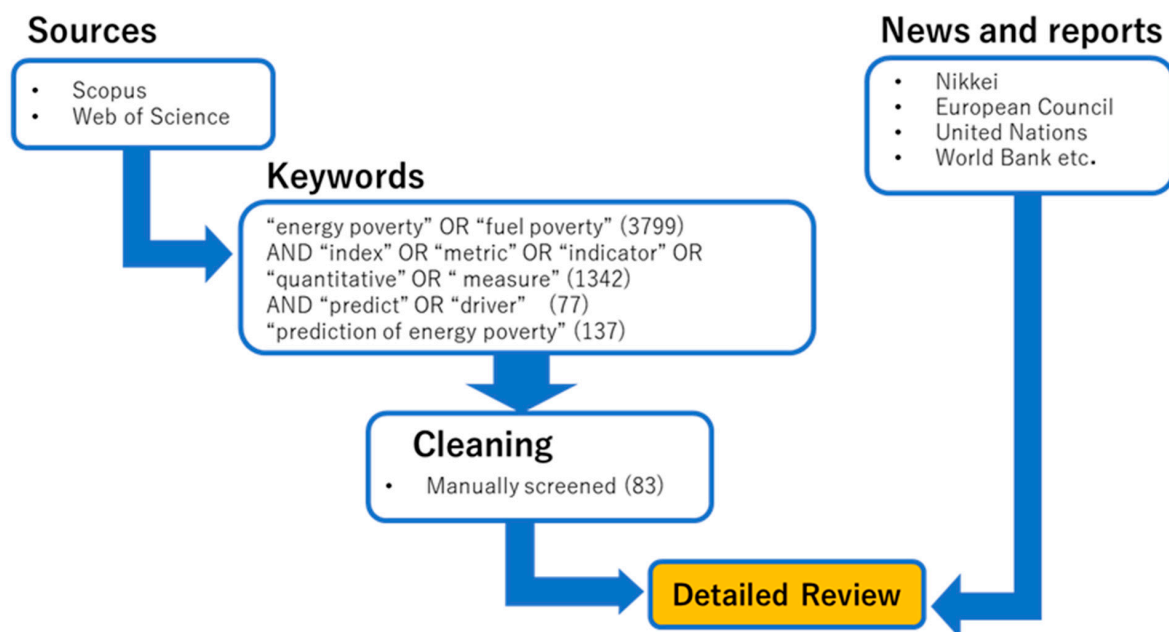


Figure 1. Literature review scheme (numbers in brackets indicate number of papers).

First, a keyword search was undertaken, using the keywords of energy poverty and fuel poverty in combination with index, metric, indicator, quantitative, or measure to identify current and proposed evaluation methodologies. In addition, the keywords of predict and driver and prediction of energy poverty were also incorporated to elucidate the existence of any prediction frameworks. Next, through a cleaning process, articles that were highly relevant to this study were selected via manual screening. From these, duplicate references were removed, and relevant documents were identified. In addition, because research on energy poverty is often conducted by government and business entities, we did not limit article type, and also utilized recent institutional reports and news articles in addition to the academic literature, where appropriate. We also did not specify a time period in order to take a comprehensive view of energy poverty research across its complete history. As a result, it was identified that many studies on energy poverty and fuel poverty have been conducted and discussed in developed countries, mainly in Europe, focusing on energy affordability, while in developing countries, the focus tended to be on energy access with research often using fieldwork or practical approaches. Very limited work which considers developed and developing nations' energy poverty was identified. The literature review outcomes are detailed categorically in Section 3.

3. Literature Review

The literature review, as detailed below, investigated the definition of energy poverty, evaluation frameworks, and its drivers, and summarizes common methodologies used to evaluate energy poverty to date. The aim of the review is to identify any gaps in existing research approaches, focusing on research that has been undertaken on the methods and mechanisms used to evaluate energy poverty in developing as well as developed nations, and whether these methodologies are being used for future projections, for example, in anticipation of global warming and other exogenous impacts.

3.1. Definition and Measurement Regimes for Energy Poverty

Energy poverty is often spoken of synonymously with monetary poverty, fuel poverty [22,23], energy hardship [24], and energy security [25]. Likewise, this study treats these synonymous concepts as linked, relevant to energy poverty, yet not identical. There is no agreed, comprehensive definition of energy poverty due to the complexity and qualitative nature of the phenomenon. Definitions and criteria can vary according to the country or region in which energy poverty is being studied, as they are influenced by cultural aspects, degree of development, climate, and income of the area being measured. The United Nations has defined energy poverty as either (1) a lack of access to electricity networks or (2) a dependence on burning solid biomass, such as wood, straw, and dung, requiring the use of inefficient and polluting stoves to meet household energy needs [26]. In the EU, energy poverty has been defined as the inability to cover energy costs or to maintain comfortable temperatures and health, or the need to reduce energy consumption to a degree that adversely affects the health and wellbeing of inhabitants [27]. Bouzarovski and Petrova qualitatively defined energy poverty as “the inability to secure the material and socially necessary energy services for household heating and appliance use” [28].

In terms of the evaluation of energy poverty, different nations do so in different ways. For example, in Great Britain and other nations, a singular, 10% rule is used, due to its ease of deployment. The 10% rule is an indicator which was developed by Boardman in the United Kingdom in 1988, based on household income [29], whereby a household that spends more than 10% of their income on energy consumption is considered to be energy poor. It is still used today because of its versatility and simplicity. However, this indicator may also be considered arbitrary as there is no significant difference between “energy

poor households” who use 10.1% of their income, and “non-energy poor households” who use 9.9%, for example [30]. Single indicators such as the 10% indicator are simple and practical; however, they narrow the problem of energy poverty to a limited number of dimensions, overlooking broader, often interrelated issues [31]. In Hungary, the 2M indicator is used (an indicator that measures the economic cost per household of meeting energy demand), with energy poor households defined as those spending over 25% of their disposable income on energy, roughly twice the median energy expenditure [32]. In France, the ministry of energy transition defined energy poor households as those within the first three equivalized income deciles whose energy bill amounts to 8% or more of their income [33]. In Australia, householders whose income falls below 50% of the median income poverty risk threshold are considered energy poor (i.e., an income below half of that of the median or middle income, established as the ‘poverty line’ for the evaluation of energy poverty) [31,34]. In the United States, a more complex approach using the ‘energy equity gap’ index which is defined as the difference in the inflection temperatures for engaging air conditioners between low and high-income groups was used to visualize relative energy limiting behavior, taking into account the effect of ambient temperature on energy consumption, and to identify households with energy insecurity [35].

Moving away from national level indicators, researchers have also attempted to define energy poverty considering multiple dimensions. This is often undertaken quantitatively, and the use of multiple indicators instead of a single indicator is strongly supported in the literature [27]. The Multidimensional Poverty Index (MPI) [25,26] which is not specific to energy poverty but focuses on poverty itself is an index that measures the percentage of households in a country deprived along three dimensions of monetary poverty, education, and basic infrastructure services, utilizing national surveys—to capture a more complete picture of poverty, including aspects of energy poverty [36]. Another prominent example is the Multidimensional Energy Poverty Index (MEPI) [37], often deployed in developing nations, utilizing a number of weighted measures including for example telecommunications, cooking, energy access, and air quality, weighted according to the aims of the study. These studies rely on data sets including demographic and health surveys (DHS), World Development Indicators (WDI) and statistics on income and living conditions, for example; however, as degree of development varies from country to country and region to region, there is some question as to whether the actual energy poverty situation can be ascertained and contrasted when this index is applied in both developed and developing countries [31,38]. The dual measure, Low Income High Cost (LIHC) regime considers households to be energy poor if their household income is below the monetary poverty threshold and their energy consumption expenditures are higher than the national threshold. Another multidimensional indicator known as the Low-Income Low Energy Efficiency (LILEE) [39], was implemented by the UK government in 2010 taking into account two indicators; Fuel Poverty Energy Efficiency Rate (FPEER) and low income (households whose residual income is below the official poverty line using modeled energy costs). These approaches are all multidimensional in nature; however, the dimensions used vary among approaches.

Table 1 summarizes a range of single and multidimensional indicators which are currently utilized to define and measure the occurrence of energy poverty.

As shown in Table 1, most indicators refer to income, which indicates economic poverty. In developed nations, the 10% indicator appears most popular with some variation in thresholds to account for economic norms [31].

Table 1. Commonly engaged single and multiple dimension energy poverty evaluation approaches and definitions.

10% Rule (TPR)	Ref.	Definition
Ireland, England, Scotland, Wales, Italy, and other nations have adopted the 10% Rule (TPR), whereby households who spend more than 10% of their income on energy are considered energy poor.	[40].	Households are energy-poor if they spend more than 10% of their income on energy services.
“High share of energy expenditure in income” indicator (2M indicator)		
In Hungary, the 2M indicator (An indicator that measures the economic cost per household of meeting energy demand) was adopted in the national energy and climate plan, and defines energy poor households as those spending over 25% of their disposable income on energy, roughly twice the median energy expenditure.	[32]	Households whose energy expenditure share of their income is more than twice the national median.
“Low absolute energy expenditure” indicator (M/2 indicator)		
The M/2 indicator represents the share of households whose absolute energy expenditure is below half the national median, or in other words, low. This could be due for instance to high energy efficiency standards but may also be indicative of households abnormally under-consuming energy (i.e., hidden energy poverty).	[41]	Households that spend less than half the national median share of their income on energy.
Multidimensional Energy Poverty Index (MEPI)		
In the commonly used Multidimensional Energy Poverty Index (MEPI), energy poverty measurement indicators are weighted among aspects such as TV and radio ownership and access to energy, clean cooking and telecommunications.	[37]	Defines energy poverty as the lack of access to modern energy services, such as electricity for lighting and cooking, and modern fuels for cooking, heating, and ownership of household appliances
Low Income High Cost (LIHC)		
The Low-Income High Cost (LIHC) measurement method considers households to be energy poor if their household income is below the monetary poverty threshold and their energy consumption expenditures are higher than the national threshold.	[42,43]	A household energy-poor if their energy costs are above the national median level and, after paying those costs, their residual income falls below the official poverty line
Multidimensional Poverty Index (MPI)		
The MPI is an indicator that focuses on poverty itself, rather than on energy poverty specifically.	[36]	A household’s inability to access essential energy services like electricity, clean cooking fuel, and heating, which are necessary for basic living standards and well-being
Low Income Low Energy Efficiency (LILEE)		
The Low-Income Low Energy Efficiency (LILEE) measure considers two indicators: the Fuel Poverty Energy Efficiency Rate (FPEER) and low income.	[39,44]	A household is considered to be in fuel poverty if they live in a property with an energy efficiency rating of D or below, and if their remaining income after paying for heating is below the official poverty line
Qualitative Definitions		
United Nations Development Programme: inability to cook with modern cooking fuels and the lack of a bare minimum of electric lighting to read or for other household and productive activities after sunset. In Europe: a household’s lack of access to essential energy services that provide basic levels and decent standards of living and health, including adequate heating, hot water, cooling, lighting, and energy to power appliances, in the relevant national context, existing social policy and other relevant policies, caused by a combination of factors, including but not limited to non-affordability, insufficient disposable income, high energy expenditure and poor energy efficiency of homes. In the Literature: Energy poverty is a lack of access to modern energy services in the home. The inability to secure the energy services that are materially and socially necessary for household heating and appliance use.	[28,45,46]	

For multidimensional indicators, there are a number of issues regarding consistency of application across regions and nations, and the application of weighting regimes. For the often-used MEPI, weights are applied according to the region or nation of study and vary widely, making it debatable whether the weights can capture the nuances in a qualified manner, consistently across all countries and regions. For example, with regard to telecommunications, as personal computers and tablets can be purchased at a lower

cost than televisions, and due to the wide availability of services such as video streaming, there is likely to be a certain segment of the population that will prefer not to own a television, perhaps inaccurately exaggerating their perceived level of energy poverty. This is particularly important in evaluating energy poverty in developed nations. Another example may be that some people in developed countries intentionally use wood stoves and fireplaces as a personal preference, and are almost certainly unlikely to cook with biomass, making a consistent weighting and evaluation regime using the MEPI across development levels impractical. For the LILEE, a dual indicator-based evaluation regime, some studies have raised concerns about its validity as it excludes households based on their Energy Performance Certificate (EPC) rating. A survey conducted in London found that 28.2% of respondents were experiencing energy poverty, over 1.5 times higher than the LILEE estimate, and there was a discrepancy between poverty and the expected incidence of fuel poverty [47]. Finally, even though energy poverty and economic poverty tend to be synonymous, indicators such as the Multidimensional Poverty Index [48] are not energy poverty-specific, rather seeking comprehensiveness in the overall measurement of poverty. Given that it is not exclusively the poor who suffer from energy poverty, it also may not be suitable for the accurate demarcation of energy poverty.

3.2. Potential Drivers of Energy Poverty

This subsection discusses the factors that are thought to contribute to energy poverty. The five main causes of energy poverty have been said to be: energy-inefficient homes including a lack of energy access, high energy homes, high energy prices, poverty, and household characteristics (e.g., age, ethnicity, location, tenure, single, and parenthood) [49]. These factor's severity is estimated using national statistics, taxation data, and the analysis of lived experience through surveys, observation, and longitudinal studies. Other factors such as health issues, ethnicity, gender, or educational achievement are also important factors influencing energy poverty, with data for these sourced from sources such as national DHS [50,51]. With regard to gender, it is interesting to note that the impacts of energy poverty on each gender varies by country and region [28,47]. Also, household characteristics impact differently from country to country, for example in India, relying on data from the National Family Health Survey and DHS, the energy poverty rate was found to be lower for smaller households [52–54], whereas in Japan, using data from the Family Income and Expenditure Survey and Residential Energy Statistics, single households have been shown to be particularly vulnerable to energy poverty [55]. Energy poverty and monetary poverty have been shown to be strongly correlated and are used in almost all energy poverty evaluation approaches [56]. In England, for example, the most significant influences on energy expenditures at all income levels were shown to include residential energy efficiency rating and floor space, relying on data from the Fuel Poverty Dataset, containing 11,974 observations [57]. In terms of income inequality, government spending, and unemployment were influential and some studies suggested that capital flight (a rapid outflow of money or assets from a country due to economic or political events) also had an impact on energy poverty [58]. In Bangladesh, an application of the MEPI revealed a negative correlation between energy poverty and household health and educational status, considering 68,396 households' data from the Household Income and Expenditure Survey [59]. Further, in Indonesia, remittances from overseas migrant workers were shown to help alleviate multidimensional energy poverty, considering approximately 28,000 household samples from the Indonesian Family Life Survey [60]. In Poland and Norway, an investigation on the impacts of aging on energy poverty across 52 interviews, found that socioeconomic conditions predominate over age, with marital status and welfare robustness also found to be influential, while the key factor driving energy poverty was

identified as the heating technology used in the household, i.e., the energy efficiency of the house, which, coupled with economic vulnerability, was shown to lead to energy poverty [61]. It was also found through the analysis of 22 semi-structured interviews in Norway that policies intended to encourage household investment in energy efficient solutions often amplified the experience of social inequality among low-income households and it is also clear that the lack of linkages between energy efficiency policies and social housing policies fails to address housing inequality [62].

A majority of these studies were conducted in colder regions, using disparate approaches and varying sample sizes, where multiple heating fuels and approaches are available. This is not the case in temperate and tropical regions where there is no alternative equipment to maintain appropriate temperatures other than air conditioning (requiring the use of electricity). With regard to fuel poverty, this was previously thought to be predominant in the Northern Hemisphere; however, recently the phenomenon has also been explored increasingly in the Southern Hemisphere due to the effects of climate change [63]. The concept of Summer Energy Poverty (SEP) has been discussed in Southern Europe [64], and in recent years, energy poverty related to summer cooling has been actively studied. However, not enough research has been done in temperate to tropical regions such as Japan, Australia, and the United States, where further temperature increases are expected due to climate change. The studies conducted in the European nations of Portugal and Spain which used a literature review of policies and energy poverty definitions show that similar regions often have similar problems, such that it is understood that energy poverty may be related to regional characteristics [65]. In addition, Portugal is one of the hottest countries in Europe, with an average summer temperature of 30 °C. In Spain, a heat wave with temperatures up to 44 °C occurred in Cordoba and Madrid in 2023, and there is not yet enough research in terms of energy poverty projections to analyze scenarios in which temperature increases become even more severe in the future. Considering aspects outside of temperature, studies relying on WDI, national energy outlooks, the Household Income and Expenditure Survey, and the Bangladesh Energy Scenario found that remittances from migrant workers alleviate energy poverty in developing regions such as South Asia and nations such as Bangladesh, finding that an increase in remittance inflows increases energy consumption in the long run [66,67]. In addition to remittances, urbanization and increased energy efficiency are also effective in minimizing energy poverty [68].

So far, many assessments have been made using endogenous factors such as income, energy prices, and building characteristics [69,70]; however, these have been limited to single country or regional studies, and among these studies and their analytical approaches, some use of machine learning (ML) has been undertaken [71–73], further discussed in the results and discussion. In addition, while a lot of research has been undertaken considering income, energy prices and energy efficiency of buildings, there is still room for research which considers emerging technologies and their impacts. Furthermore, although a large amount of data are available, it is also predominantly national or regional in nature, and no research has been conducted to provide a comprehensive global consideration of regions with different climates and cultures [74].

As global warming continues, residential areas are becoming more heavily investigated, and an energy poverty vulnerability index combining data on regional income, electricity prices, and regional climatic conditions, using observations from approximately 3000 weather stations has been proposed [75]. In France, the penetration rate of air conditioners is less than 10% due to the need for permission to install air conditioners in old apartments. This is due to the fact that the outdoor units of air conditioners are said to spoil the scenery, and the fact that the humidity is not high in Europe as a whole, and from an environmental protection perspective overall. On the other hand, in Japan, the

air conditioner penetration rate is relatively high, at 83.9% for single-person households and 91.8% for two or more person households [76]. In Japan, people used to beat the heat not by using air conditioning, but by using methods such as “uchimizu” (sprinkling water to create a gentle breeze using vaporization heat and temperature difference), “sudare” and “yoshizu” (a window covering made of reeds). However, using these environmentally benign behaviors on their own can be life-threatening, because of the high humidity as well as the temperature, with rising temperatures due to climate change. Of the heat stroke victims who die in Japan, 60% own air conditioners but do not use them appropriately, in order to keep the temperature comfortable in the home [77]. As a result, the Japan Meteorological Agency has issued heat stroke alerts to warn people of the danger, and there are many educational activities in place to prevent its occurrence [78]. Despite these efforts, the number of deaths due to heat stroke in Japan is on the rise, and in recent years, it is not unusual for the number of deaths to exceed 1000 people per year. This is partially due to the fact that people with dementia, mental illness (schizophrenia, depression), diabetes, and other illnesses may use the air conditioner inconsistently, (e.g., accidentally using the heating function instead of the cooling function) and therefore need to be monitored and educated to preserve their wellbeing [79,80]. In regional Ghana, using a household survey across 775 households, under the five scenarios of economic growth and diversification, energy transition and technological innovation, climate change impacts and vulnerability, stagnant policy interventions and social safety nets, and rising inequality, energy poverty as measured by the MEPI alongside socioeconomic predictors and sensitivity analyses of poverty variation revealed that household income, size, and food security have the greatest impact on urban energy poverty levels [81]. It was also identified that scenarios involving economic growth and technological innovation have a positive impact on reducing energy poverty, while climate change and economic stagnation increase vulnerability and intra-group disparities. In another longitudinal energy poverty study, computer analysis of remote sensing data taken from space over approximately 3000 nights at the University of Michigan produced an index of settlement level and power poverty over time. The results revealed an energy poverty rate 60% higher than the official global estimate of 733 million people without access to electricity. Furthermore, it was found that the majority of energy poverty is regional in nature, affecting those living in remote, less densely populated, and more rugged areas, rather than in energy-sufficient areas such as developed urban areas where energy poverty is less prevalent [82]. In the Visegrad Group of nations (V4; an informal regional cooperation between Poland, the Czech Republic, Slovakia, and Hungary), a study measured energy poverty using three indicators from WDI and Eurostat data (total utility arrears, utility arrears of child-supporting households, and population unable to maintain an adequate standard of living), and, based on mean group estimates, income inequality as indicated by the Gini index worsened energy poverty [4].

While there are a number of substantial studies concerning people who are already experiencing energy poverty, these studies lack aspects such as the perspectives of these people and the effects of exogenous factors (economic and environmental) and climate change, that are expected to worsen in the future. Research has also revealed a link between energy poverty and green energy consumption, as higher energy productivity is associated with lower energy poverty and higher energy poverty corresponds to a higher share of green energy [3]. In Japan, Castaño-Rosa et al., studied energy poverty, focusing on regional and seasonal characteristics of energy poverty and the novel aspect of the influence of new technologies [55].

Considering the body of work assessed above, the present study seeks to develop a theoretical framework for analyzing vulnerability to energy poverty, considering both existing and new perspectives such as economic indicators, climate change, catastrophes

in resource rich regions, exogenous factors such as the spread of artificial intelligence (AI) and the occurrence of disasters etc., for which future projections remain controversial and understudied. Figure 2 details the research activities, aims and future goals of this study.

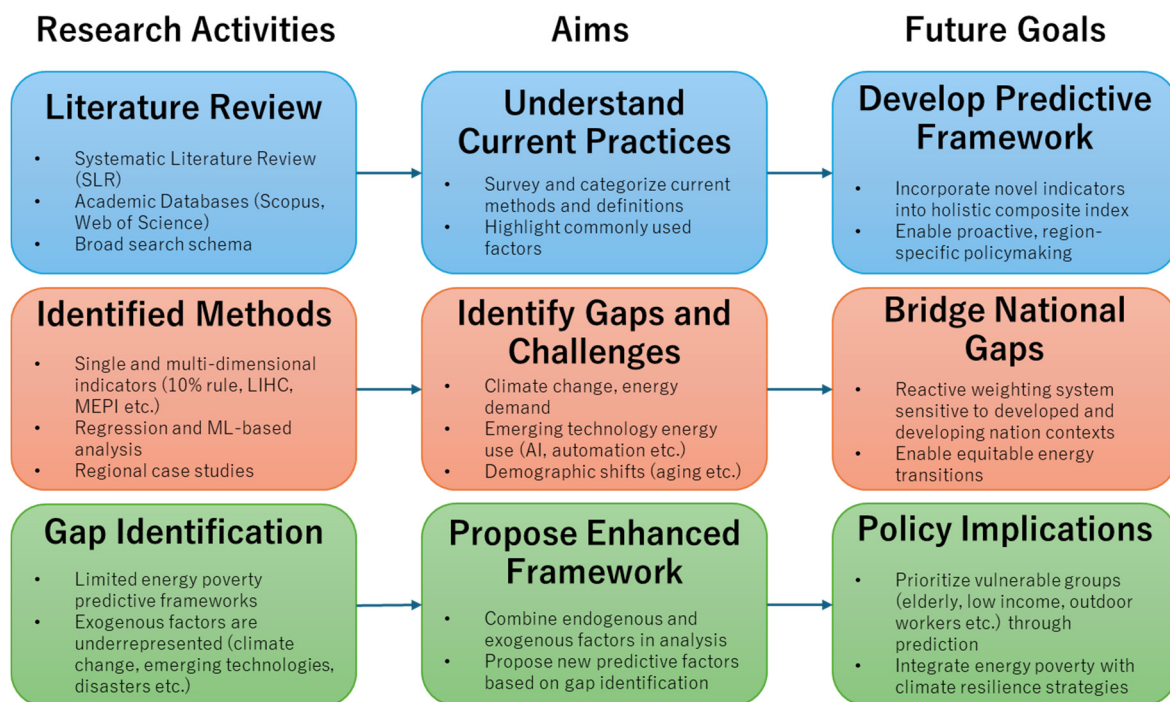


Figure 2. Research activities, aims, and future goals of this research.

4. Results and Discussion

The literature review indicates that energy poverty itself has been defined and measured both qualitatively and quantitatively and applied over a wide range of issues using various data sources and approaches. However, these evaluations do not fully recognize the impact of exogenous factors and the emergence of future challenges, including climate change. Studies that attempt to predict the occurrence of energy poverty have been based on short-term energy supply forecasts, sometimes employing ML. To overcome this shortcoming, this study proposes that a framework is needed to clarify the mechanisms of energy poverty, considering both endogenous and exogenous factors, expanding on those considered to date and from a methodological point of view.

Building on the literature reviewed in Section 3, a Sankey diagram is detailed in Figure 3, outlining the methodological approaches, key applications, and the factors most commonly considered in energy poverty related research to date. This literature-based assessment is critical both in identifying factors employed to date, and those which may play a role in future predictive approaches.

This figure is based on a survey of 89 references, extracting methodologies, applications and the most common factors employed in evaluations. The number of studies and methodologies used are shown quantitatively, noting some duplication where a study may address both energy poverty and fuel poverty, or multiple methodologies. The common factors shown to the right of the Sankey diagram express the occurrence as a ratio within each methodology.

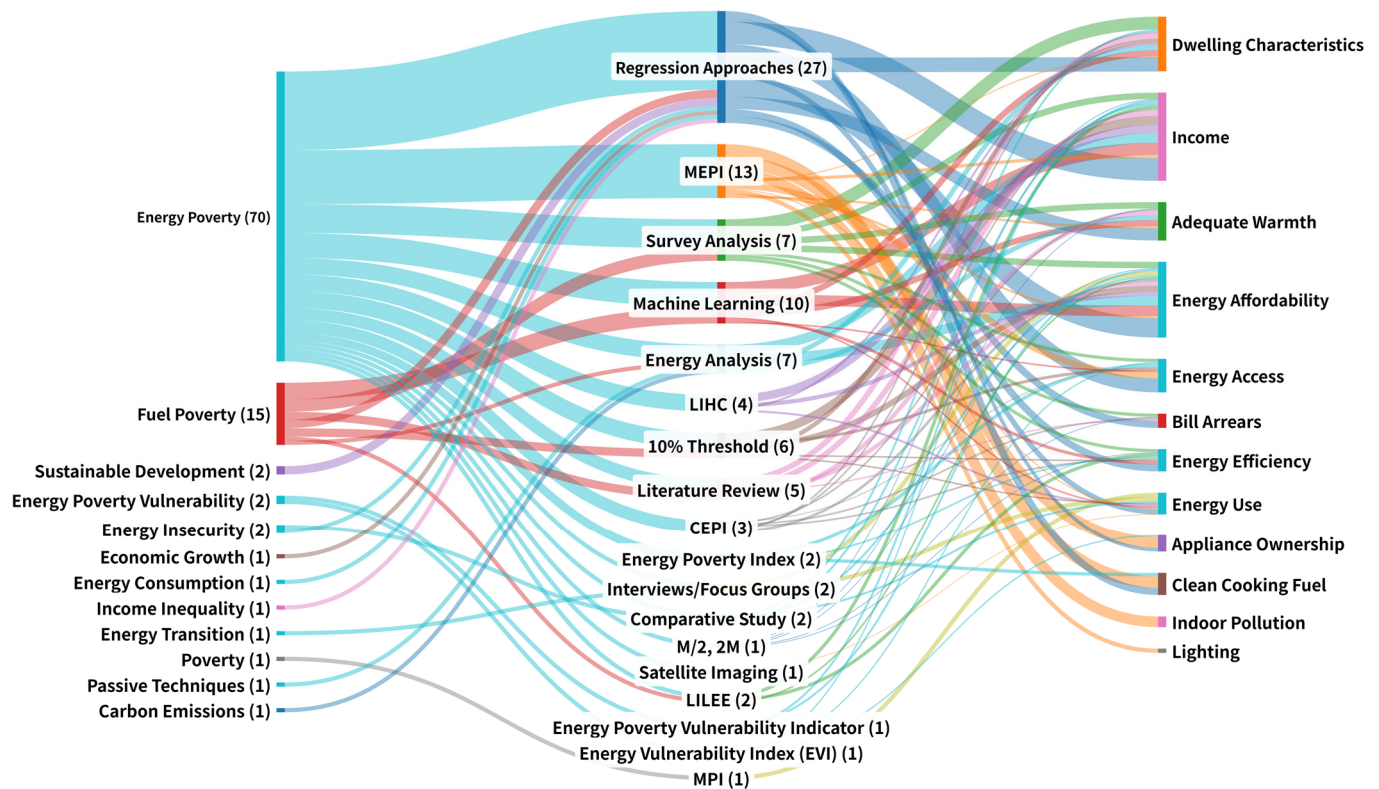


Figure 3. Sankey diagram outlining the existing applications (left), methodological approaches (center), and key factors (right). Sankey bar size for applications and methods are reflective of study numbers, and factors are shown according to their occurrence rate within methodologies.

Energy poverty evaluations use a broad range of methodologies, while fuel poverty evaluations predominantly used ML and survey analysis approaches focusing on dwelling characteristics. Except for the use of a range of regression-based and econometric analysis approaches, the MEPI was the most commonly employed evaluation framework, notably in developing nations. The MEPI employs a variety of household characteristics, including ownership of appliances, energy efficiency, access to clean energy, indoor pollution, type of fuel used for cooking, and lighting, etc. MEPI is followed by the LIHC and the 10% threshold, indicating that income-based indicators are often used in evaluations, further borne out by the fact that income is the most commonly used factor identified in our analysis. Further, among energy-based concepts, energy affordability is the most common and is strongly linked with income. Dwelling characteristics are also considered to be important, and, for example in Greece, the main causes of energy poverty were identified as, the type of dwelling, type of residence, place of residence and education level of the household head [83]. In addition, various studies have been conducted on housing characteristics, including [84–87], which all stated that the energy efficiency of dwellings was an important factor toward energy poverty, also highlighted as a critical factor in Figure 3. Other factors in household characteristics include residents with mental health problems, single parent households and unemployment, all of which increase the likelihood of falling into fuel poverty, as studies have shown that a high proportion of people who have low family involvement or have moved house are unable to escape from this situation [88].

Outside of the factors identified through the literature review and analysis detailed in the Sankey diagram, there is a need to combine household characteristics with environmental aspects. For example, climate change has led to the need to extend energy poverty research to the availability of summer cooling in cities with warmer climates [89]. Approximately 71% of the Italian population are experiencing severe energy poverty, with

insufficient air conditioning in the summer exacerbating this issue [90]. The number of cooling degree days (CDD) in the summer is considered a critical factor in the context of global warming, weather forecasting, El Niño and La Niña patterns, and the occurrence of heat domes as global warming becomes more severe [90]. On the social and environmental side, and related to predictive approaches, in India, a combination of socio-economic survey data and satellite remote-sensing data was able to determine districts with high energy poverty with 90.91% accuracy, with precipitation and fine particulate matter (PM_{2.5}) making the largest contributions [71]. In the Netherlands, ML was used to predict energy poverty risk with 80% accuracy, but the inclusion of socio-economic characteristics was deemed essential to achieve a higher level of predictive reliability. The most important factors other than income were population density and home ownership [72]. In the European Union and United Kingdom, an ML framework was devised to predict and fairly target energy poor households, finding that indicators beyond income including dwelling conditions, energy efficiency, welfare payments and energy provider switching were important household and national level indicators of energy poverty [91]. Further, an investigation of ML combined with the MEPI identified income levels, education and nutritional status as critical to prediction accuracy, sensitive to the MEPI framework employed [92]. In Bangladesh, ML was used to predict energy poverty by region, highlighting that improvements in education and financial including reduced energy poverty, and are also critical as factors to improving its prediction accuracy, alongside location and residence characteristics [93]. Considering poverty, predictive models were developed, showing that climate change on its own does not immediately effect poverty; however, rising food prices as a result of climate change do, suggesting the importance of evaluating the multifaceted impacts of climate change [94]. Neural networks were employed to assess the impact of social factors on energy poverty, suggesting that electricity and heat consumption are most influential on its occurrence [95]. A case study in Spain utilized AI and data mining using only the factors of energy prices, consumption (relative to warmer zones) and income, finding that AI can reduce workload for practitioners and predict energy poverty according to thresholds [96]. A Chilean case study using simulated data suggested that multilayer perceptron, M5P, and support vector regression delivered the best accuracy for predicting the risk of low-income households falling into energy poverty; however, testing with real data was not undertaken [97]. In the United Kingdom, ML was found to aid in mapping energy poverty at a reduced effort cost, and that income and efficiency were important predictive factors. Further, the combination of satellite imagery and ML led to a predictive accuracy of 83% [73]. Unemployment rates were found to be correlated with energy poverty in Bulgaria, Hungary Romania and Slovakia, and an ARIMA-ARNN model was used to generate prediction for future occurrence showing that they are likely to remain correlated in the future without policy intervention [98].

Macroeconomic perspectives are also considered important, and some studies have elucidated the incidence of energy poverty from the perspective of the combination of low GDP nations and varying climatic conditions in Europe [99]. It has also been shown that human capital, income and income inequality, among other factors, are all transmission channels for alleviating energy poverty [100]. Kirpinska and Smiech also calculated the likelihood of households in each country of falling into and out of energy poverty using discrete-time Markov processes. In their study, demographic, technological and socio-economic factors were identified as drivers of escaping energy poverty [101]. Further, according to Bouzarovski, a geographical conceptualization of the widespread impact of energy poverty occurring at the household level was considered important [102].

Although the prevalence of energy poverty is expected to increase over time as temperatures rise, and energy consumption is expected to increase due to future technological

developments and an aging society worldwide, there is insufficient research surrounding the energy supply-demand ratio that is expected to be strained as a result. Many of the energy poverty assessment tools currently available focus on heating, but the effects of climate change, especially in the southern hemisphere and tropical and temperate regions, needs to be considered.

Furthermore, since many energy poverty-vulnerable households include single elderly people, the demographics of the elderly need to be considered in forecasting the future of energy poverty. As the aforementioned factors exacerbate energy poverty around the world, both an effective framework and clarity on the mechanisms of energy poverty occurrence are needed to avoid a future in which energy poverty has extreme consequences, including mortality. In a large study in the EU (with a sample size of 6268), the main drivers of EP were identified as income, floor space, and household size. However, this research also identified that increased household data collection efforts are needed to improve ML prediction power and research insights [103]; however, it is not always practicable to obtain such large household data samples on a regular basis.

Understanding the general nature of energy poverty evaluations to date, as was detailed in Figure 3 and based on the evidence unearthed in the literature review of academic and grey literature, Table 2 details a range of proposed factors that may be useful for the future projection of energy poverty occurrence. Factors that have already been employed in studies as a result of the literature review are noted as “existing” and appended with appropriate references, while unique factors considered for the future prediction of energy poverty are indicated as “proposed”.

Table 2. Potential factors which may aid in future prediction and comprehensive evaluation of energy poverty.

Factor	Rationale for Inclusion	References	Evidence of Relationship with Energy Poverty	Existing or Proposed for Future Prediction
Long Term Factors				
Climate Change (e.g., El Niño, La Niña, Heat dome, torrential rainfall)	Investigation of the increase in energy consumption due to climate change and severe disasters caused by global warming	Data published by the National Centers for environmental information (NCEI) [104]	[105–107]	Proposed
Environmental factors (Precipitation, PM_{2.5} density)	Weather and regional outcomes will change due to climate change	Remote-sensing, statistical and survey data	[71]	Existing
Access to air conditioning, increased energy use	Climate change has resulted in longer hot periods and higher temperatures than in the past, which requires more energy to alleviate.	Data published by responsible ministries in each region	[90,108,109]	Proposed
GDP	Macroeconomic perspectives	Official statistics of countries surveyed	[110–112]	Proposed
Effect of a shrinking population	Disruption of electricity supply due to a lack of workers in the immediate term, and a reduction of demand in the long term	United Nations Global Issues [113]		Proposed
Technological progress, innovation and technologically based energy consumption (AI, cryptocurrency etc.)	AI and related technology energy consumption is expected to increase over time.	Global Artificial Intelligence Report, International Trade Administration [114] etc.		Proposed

Table 2. *Cont.*

Factor	Rationale for Inclusion	References	Evidence of Relationship with Energy Poverty	Existing or Proposed for Future Prediction
Short term/long term factors				
Economic Shock	Linkages between economic crises and energy poverty have been previously reported	Newspaper, Public reports	[111]	Existing
Impact of geopolitical risks (i.e., natural disasters and wars in resource-producing regions)	Severe energy access reduction due to the destruction of buildings and infrastructure, including homes. Relevant to the determination of future energy prices.	SIPRI databases/yearbook/Armed Conflict Location & Event Data (ACLED) Project/UCDP/PRIO Armed Conflict Dataset/ISW (Institute for the Study of War) [115] etc.	[116–119]	Proposed
Pandemic	Electricity costs for households increase due to an increase in the percentage of time spent at home due to quarantine and other factors, as well as a decrease in income due to the pandemic.		[116,120]	Proposed
Occupation characteristics (length of outdoor working hours)	Outdoor workers are less likely to have access to air conditioning and are more likely to have heat-related emergencies, putting them at risk	International Labor Organization (ILO) Data and Statistics [121]		Proposed
Population Density	Since the idea of densely populated areas, i.e., urban areas, and unpopulated areas, i.e., rural areas, is already important in the framework as a factor affecting energy poverty	Data published by responsible ministries in each region	[72,122]	Existing
Short term shocks				
Fossil Resource Prices	Indicators that directly affect energy affordability due to price changes.	Fossil Fuel Price Index [109,112,123,124]	[93,97,98]	Proposed
CPI (Consumer Price Index)	Soaring prices put pressure on household incomes and have an impact on energy consumption.	Statistics Bureau, Ministry of Internal Affairs and Communications [125]		Proposed

The linked concepts of fuel poverty, housing, dwelling characteristics, and vulnerability are all reflected in the proposed factors, specifically with regard to the percentage of energy bills used for heating and cooling as a portion of household budget.

Further, the related concepts of resources including fossil fuels such as natural gas and carbon emissions are encapsulated in the proposed factors of the impact of geopolitical risks such as natural disasters and wars in resource-producing regions and the closely linked aspect of fossil resource prices.

Alternatively, there are some potential evaluation and prediction factors which do not overlap with those previously extracted, reflective of the current situation in developed nations, largely drawn from statistical databases and the grey literature [126]. These include occupation, important with regard to the length of outdoor working hours, as temperatures increase.

The effect of shrinking populations and the increase in the Consumer Price Index which expresses the impacts of inflation which may directly affect household budgets etc. are also important. A hypothesis was also posited that hotspot areas may emerge around AI data centers, and this is likely to aggravate energy poverty, especially for people local to these facilities [127–129]. In addition, while AI has been used to predict energy poverty in previous studies [130] it is responsible for enormous energy consumption at the point of use itself.

Following the gaps identified in the literature, and as summarized in Table 2, this research proposes ten new factors to improve the identification of energy poverty occur-

rence and the accuracy of future projections. These factors are divided into three categories: long-term trends, short term shocks, and the factors which affect energy poverty in both the short and long term. Long-term trends are defined as those factors that are socially relevant and likely to continue for more than three years, while short-term shocks are those that are likely to remain in place for less than two years. Factors which have both characteristics were then categorized as those whose duration could vary according to individual willingness and choice, and those that might be both short-term and long-term, depending on the nature of the event. Long-term trends include climate change, access to air conditioning, occupational characteristics, GDP, technological progress, increased energy consumption due to technological innovation, the impact of geopolitical risks, fossil resource prices and the impact of population decline, while dual-characteristic factors include economic shocks, geopolitical risks, pandemics and, depending on individual will, varying occupational characteristics, and population density (i.e., possible changes due to displacement). Short-term shocks include fluctuations in oil and natural gas prices and changes in the CPI.

Based on the analysis provided above, Figure 4 details both the existing factors considered important for energy poverty evaluation, as well as a summary of the newly proposed factors for the prediction of the occurrence of energy poverty and how these factors interact.

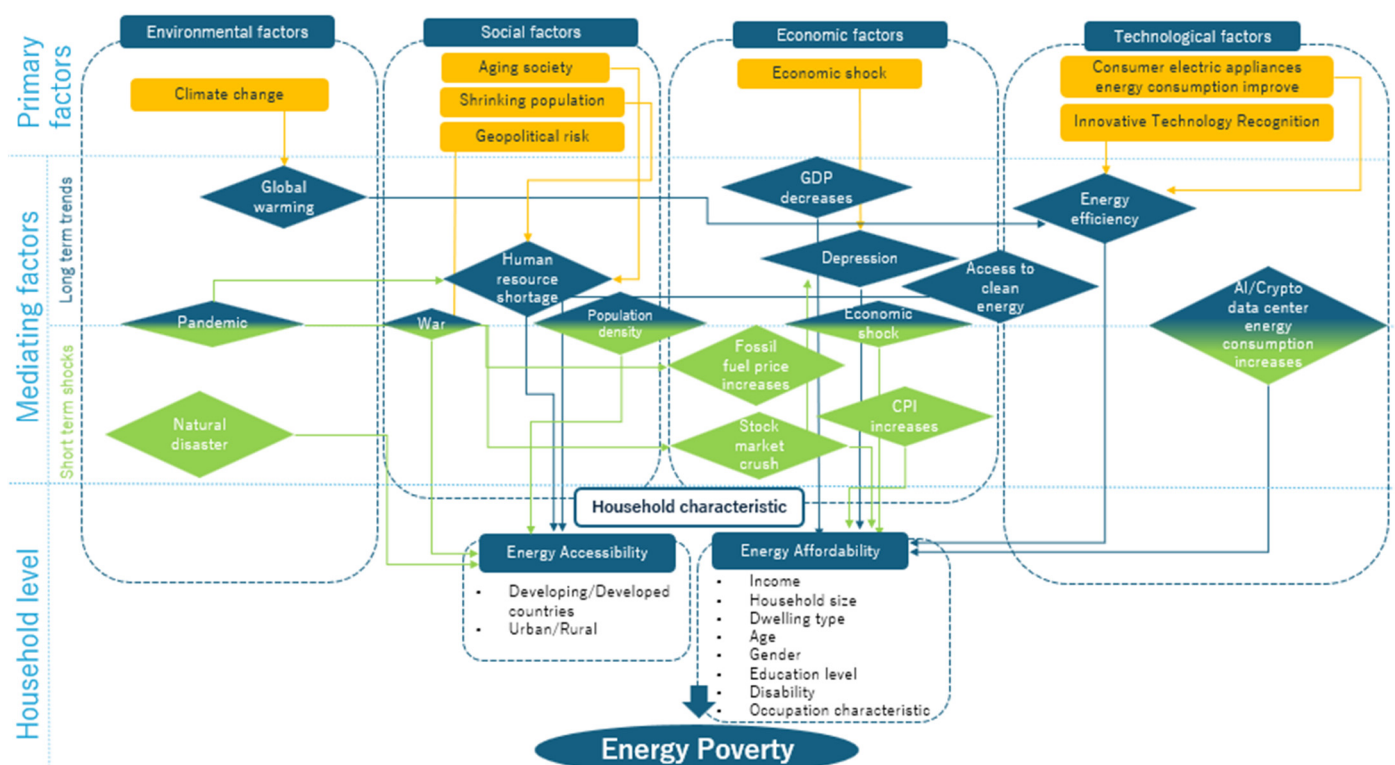


Figure 4. Flow chart of factors widely considered to influence energy poverty and those which may aid in occurrence prediction (blue diamonds represent long term trends, green represents short term shocks).

In developing and proposing these potential indicators, several aspects were considered. To begin with, climate change is expected to increase society's energy consumption in summer and winter from the perspective of maintaining comfortable temperatures using air conditioning. Further, the number of people who will have to spend time in temporary housing will increase due to the increase in the occurrence of severe disasters (for example, after the Great East Japan Earthquake, people had to spend up to 10 years in temporary housing [131]). The thermal efficiency of temporary housing in many cases is poor, as air

conditioners and other equipment are often second-hand and not thermally efficient [132]. If the housing provisioning system after a disaster does not operate optimally, the disaster victims also may experience a lack of access to clean energy itself.

In addition, people who work outdoors for long hours may not be comfortable in their workplace, where they spend the majority of their day, providing essential services [133]. Although no studies which determined occupation as a factor in energy poverty were identified in this research, it is possible that, as climate change progresses, the issue of energy poverty in the workplace could be added as a new criterion.

Additionally, geopolitical risk, as an exogenous factor, will cause energy prices to rise, driving up the price of oil and various other forms of energy. In addition, in an aging society, the number of elderly people, who are considered especially vulnerable to energy poverty will increase, commensurately exacerbating energy poverty occurrence [134]. The elderly tend to spend more time at home and their overall energy consumption increases in order to maintain a comfortable temperature in their homes during summer and winter [135]. According to the 2024 UN population projection, the global population will peak in the mid-2080's, much earlier than was expected compared to estimates from just 10 years ago [136]. In Japan, an advanced aging society among its developed nation peers [137], the lack of young labor in the construction and infrastructure sector related industries, notably the electrical industry, especially in suburban areas, is already a serious problem [126]. If the population dwindles, energy consumption will also decrease. However, progress in medical care will prolong people's lifespans, and a 'super aging society' will occur in advance of the effects of a shrinking population. Hence, it is critical to discuss this issue before considering the positive effects of decreased overall consumption on energy and energy poverty outcomes from a balanced point of view. It is also expected that an increase in the CPI will lead to an increase in household expenses, including both energy and non-energy expenditures.

Further, it is expected that technological developments will contribute to the alleviation of energy poverty by reducing energy consumption through improvements in the efficiency of heating and cooling and the thermal efficiency of homes. However, if high summer temperatures are to become a permanent feature, the impact on energy poverty will need to be studied. It is also clear that not only climate change, but also advances, developments, and diffusion of energy hungry technologies including AI will inevitably increase energy use [127]. There are indications that the amount of electricity used in areas surrounding data centers will rise accordingly, and that the distribution of electricity may not be undertaken equitably, potentially creating additional pockets of energy poverty. Power consumption by data centers for AI, and the cryptocurrency sectors are expected to double by 2026, according to an IEA report [128]. Data centers are a major driver of electricity demand growth in many regions, consuming an estimated 460 terawatt-hours (TWh; 2022 global estimate), and total data center electricity consumption is expected to reach over 1000 TWh by 2026, similar to Japan's total annual national electricity consumption [128]. As these technologies show no sign of slowing, achieving efficiency improvements and the design of appropriate regulations becomes increasingly important. Furthermore, even in developed countries, energy access may well become a challenge due to power outages and other factors, caused by a shortage of personnel to perform maintenance and inspection work on energy infrastructure due to aging or shrinking populations, exacerbated by higher outdoor temperatures caused by climate change. If these workers are to be supplemented by automation technologies, energy demand may increase even further.

As we enter the era of advanced global warming, fuel poverty and energy poverty are extending to the southern hemisphere [63], it is necessary to develop a framework that can take energy poverty into account at the global level. It is also important to add

the availability of air conditioning to the definition of energy poverty, and to adjust the weighting of energy poverty relevant factors from region to region to reflect these shifts. If the diffusion of innovative technologies such as Zero Energy Buildings (ZEB) and Zero Energy Houses (ZEH), which are currently being researched, are realized and put into practical use, and actually have the effect of reducing energy consumption to net-zero, it is important to effectively prioritize the implementation of these technologies in households experiencing energy poverty. Until then, however, it is necessary to make recommendations toward policies that make full use of existing technologies that can serve as a bridge toward net-zero energy buildings.

Considering the above, energy consumption will increase due to climate change, and energy supply and demand will be strained due to increased energy usage in multiple sectors, energy prices will rise, and energy access will worsen not only in developing, but also in developed countries, due to population decline and a lack of manpower to maintain energy infrastructure due to rising outdoor temperatures [138].

Finally, to date there are no generalizable indicators of energy poverty for developed countries, nor is there an approach that can be used consistently for both developed and developing countries. If climate change continues to progress in the future, energy poverty will not only result in the inability to afford electricity and fuel bills but may also exacerbate energy access problems in developed countries. As energy poverty indicators are also likely to change over time to incorporate these developments, there is a need for a comprehensive suite of indicators that can adapt to these changes in order to facilitate global discussion. To this end, it is of urgent need to examine the mechanisms of energy poverty and to develop a methodology to predict future outcomes flexibly to be able to account for exogenous developments.

5. Conclusions

This study conducted a comprehensive literature review on energy poverty evaluation frameworks, highlighting both exogenous and endogenous factors that shape energy poverty indicators. It identified critical gaps in existing studies, particularly in their failure to account for evolving societal, environmental, and technological changes. Additionally, the study proposed key factors for improving the prediction of energy poverty and highlighted the cascading effects of emerging technologies such as AI, data centres, and automation on energy consumption and inequality.

A major finding of this study is that current energy poverty indicators have not adequately adapted to temporal changes since their initial development. Demographic shifts, global warming, and the increasing energy intensity of technological innovation have fundamentally altered energy accessibility and affordability. While energy poverty is driven by a complex interplay of factors, this study suggests that exogenous influences—including rapid technological advancements and climate change—must be considered alongside traditional socio-economic determinants. Even within ML based predictive frameworks, different studies in different regions and contexts identify a variety of factors which are critical for the prediction of energy poverty occurrence, suggesting more research is required to understand the regional challenges, but also to develop a framework which can be applied across developed and developing nations, bridging this research gap. Furthermore, the challenge of reducing carbon emissions is closely tied to energy poverty, as households with low energy efficiency often contribute disproportionately to emissions due to outdated infrastructure and inefficient energy use. Achieving Sustainable Development Goal 7—ensuring universal access to affordable, reliable, modern, and sustainable energy—remains a key pathway to mitigating energy poverty and its broader societal impacts.

From a global perspective, the development of a robust forecasting and predictive framework for energy poverty will be increasingly crucial. Such a framework should recognize both commonalities and regional distinctions in energy poverty dynamics, allowing for the design of equitable national energy policies. By integrating the influence of exogenous drivers—technological progress, climate change, and demographic transitions—alongside factors that determine entry into or escape from energy poverty, policymakers may, for the first time, develop proactive and targeted interventions.

Although this study provides a comprehensive review of the factors influencing energy poverty and its prediction, several limitations exist. Energy poverty research is rapidly evolving, with new findings emerging continuously. Future studies should build upon this foundation, incorporating the latest data and methodological advancements to ensure that evaluation frameworks remain regionally relevant and responsive to ongoing societal and technological shifts.

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