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Energy poverty assessment: Indicators and implications for developing and developed countries

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ABSTRACT

Energy poverty represents a considerable challenge that is difficult to quantify, monitor, and effectively address through policy measures. Efforts to tackle this problem have proven unsatisfactory for many reasons, including insufficient data on who is experiencing energy poverty to a poor definition of what this concept entails. This study examines methods for measuring energy poverty considering spatial, household preferences, home standards, and cultural differences among countries. The focus is on two commonly used indicators to communicate energy poverty issues at the local, national, and global levels: single indicators and multidimensional indices. The advantages and disadvantages of these indicators will be thoroughly examined. A dedicated study is provided to investigate the mechanism through which energy poverty affects the quality of life. The analysis reveals the limitations of single indicators in capturing the nuances of energy poverty across diverse contexts. Multidimensional indices offer a more comprehensive approach but require careful design and data availability. A framework is proposed for selecting appropriate indicators considering local needs and cultural specificities. By integrating insights from quality-of-life studies, the recommendations guide policymakers in designing effective interventions and targeting resources to maximize the impact on populations experiencing energy poverty.

1. Introduction

The United Nations (UN) Sustainable Development Goal 7 (SDG7) was formed in 2015 to eradicate poverty and ensure universal access to sustainable, reliable, affordable, and available energy by 2030 [1]. The three key pillars required to alleviate energy poverty are reliable access to electricity and energy, resilient and cleaner cooking fuels, efficient electricity use, and increased renewable energy [2]. The International Energy Agency (IEA) estimates that by 2030, 2.4 billion people will lack clean cooking facilities, with around 1.5 billion in Asia relying on solid fuels. This surpasses the 280 million yearly adoption target for clean cooking technologies, exceeding the lack of electricity access by an eleven-fold margin [3]. An IEA report estimates a global increase of 20 million people without electricity, totalling nearly 775 million by 2030, mainly in sub-Saharan Africa [4]. Sub-Saharan Africa and South Asia are home to about five out of six poor people [5].

The energy transition is facing a pivotal moment, driven by a series of shocks that are having cumulative impacts [6]. Globally, several barriers to poverty alleviation exist, including widespread inequality, political instability and violence, climate change, COVID-19 pandemic recovery, and cost of living issues. Recent geopolitical conflicts, such as the Russia-Ukraine conflict, have led to a ten-year high in oil and gas prices, causing disruptions in energy markets worldwide. This crisis exacerbated by Russia's status as the largest gas exporter, prompted emergency measures in countries with advanced energy infrastructure [7]. The gas market's volatility extended into electricity markets, necessitating the contemplation of reforms.

Among these turbulent developments, the unveiling of landmark policies such as the unveiling of the European Union (EU) Climate Target Plan, the US Inflation Reduction Act, the EU Net-Zero Industry Act, the EU Fit-for-55 package, and Japan's Green Transformation Programme mark notable milestones, the World Economic Forum suggests certain overlooked prospects [6]. These include favoring temporary behavioral adjustments over enduring structural changes to maintain emissions reduction, insufficient incentives for private sector investment in clean energy, continued subsidization of coal, oil, and natural gas, and a lack of decisive measures to phase out fossil fuels in power generation and promote energy expansion.

The energy crisis underscored inclusivity challenges in the energy transition. Soaring energy prices disproportionately affect low-income

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households, driven primarily by surging natural gas prices [8]. This contributes to high energy prices, escalating inflation, and declining real household incomes, likely increasing the number of low-income households and compromising their living standards. Developing countries may see 100 million people reverting to traditional biomass cooking and around 75 million lose recently acquired electricity access [8]. These challenges will have implications for future UN Climate Change conferences (COPs), undermining efforts for universal access to safe, affordable energy.

The financial challenges of energy transitions complicate global economies, as countries with greater financial resources are positioned to transition to clean energy sooner [9]. This exacerbates difficulties for low-income countries due to unique socio-economic circumstances and potential consequences of delayed transition. In developing countries, the clean energy transition involves balancing low-carbon energy for economic advancement and achieving widespread energy access for human development [10]. These dual objectives, create challenges in balancing the need for affordable energy with the imperative for low-carbon solutions.

Vulnerability to energy poverty extends beyond developing countries to developed countries like Europe, facing significant energy cost increases impacting household budgets and ecological transition. Unevenly distribution across EU countries such as Italy, Spain, Poland, France, and the United Kingdom (UK) [11]. This surge places more households at risk of disconnection from gas and electricity networks because of the inability to pay bills, highlighting spatial energy injustice influenced by existing infrastructure, fuel sources, and housing characteristics [12]. Decision-makers in many countries are obliged to reconsider energy supplies and strategies to alleviate repercussions on issues like the energy and food affordability crisis and global climate change efforts [13], as energy prices and economic disruption exacerbate energy poverty and pre-existing inequalities.

Energy poverty is becoming prominent in EU policy within a framework of energy efficiency and economic decarbonization. Particularly initiatives like Fit-for-55 aim to legislate a 55 % emission reduction by 2030 and to achieve climate neutrality by 2050 [14]. The EU's green deal emphasises the importance of addressing energy poverty in broader sustainable energy transition efforts [15]. In response, various EU countries are developing national strategies, advancing definitions, measurement techniques, and solutions to combat energy poverty [16]. Proper measurement and monitoring are crucial for a comprehensive understanding of the issue, facilitating evidence-based policy planning and strategy evaluation.

Nevertheless, experts differ on appropriate metrics for measuring energy poverty, given its multidimensional causality and variability of expression over time and space [17]. Economic aspects, when used as metrics, may lead to varying identifications. For example, the 10 % indicator provides a binary assessment but is prone to fuel price fluctuations, originally developed for the context of England [17]. Currently, the new low income low energy efficiency (LILEE) indicator, is being implemented in England, updating and expanding the previous low income high cost (LIHC) [18]. Some of these indicators are also applied in specific contexts outside the UK, such as Portugal [19], Spain [20], and Greece [21].

Global discussion on energy poverty involves diverse approaches and methods. Research explores various indicators, such as expenditure based metrics [20] and considers impacts on social and health issues [22], economic aspects, education, and political factors [23]. Furthermore, Lowans et al. [24] examined the lack of equity assessments of just transition scenarios, focusing on energy and transport poverty. Although there are numerous points of view in the literature, the problem is addressed here in such a way that the most important components can be identified. This research examines energy poverty in the sense of having insufficient access to energy rather than examining the underlying causes and effects of poverty or analyzing the different technological solutions for providing that access. This study intends to address the following questions: How is energy poverty defined in the context of developing and developed countries? How is it identified, and how does it affect society? To approach these questions, this study contributes to the energy poverty literature by examining:

1. Analyze the various single and multidimensional indicators used to track the progression of energy poverty.
2. Examine the impact of energy poverty on social life, including health, education, and climate change.
3. Provide insight into the current state of energy poverty mitigation measures, as well as short and long terms policy recommendations.

This paper is organized into seven sections. Section 2 defines energy poverty and its main drivers, while Section 3 examines international methods for measuring it. Section 4 critiques the differences between single and multidimensional indicators in developing and developed countries. The impact of energy poverty on health, gender gap, education and climate change are discussed in Section 5. Section 6 provides insight into energy poverty mitigation with policy recommendations, and Section 7 concludes the work.

2. Energy poverty definition and main drivers

This section explores the concept of energy poverty and its definition, followed by an in-depth discussion of the main drivers of energy poverty in both developed and developing countries.

2.1. Energy poverty definition

The consensus definition of energy poverty is the inability to secure materially and socially necessitated energy services, such as heating a home or using appliances [25]. Defining energy poverty is simpler than measuring its occurrence and characteristics [26], which is challenging due to its dynamic nature, confinement to households, and cultural influences on subjective expectations of energy services.

The implications and challenges of energy poverty vary greatly depending on the country's level of development. In developing countries, energy poverty is mostly about the lack of access to basic clean energy, particularly prevalent in low-income nations in South and Southeast Asia and Africa [27]. In developed countries, the focus is primarily on affordability [28]. The UN provides a comprehensive definition of energy poverty, emphasizing its multidimensionality, including the inability to access reliable, high-quality, affordable, secure, and environmentally safe energy [29]. Understanding the contextual nuances of energy poverty is critical for developing effective strategies to address this issue.

In developed countries, there is no universally accepted measure of energy poverty. However, commonly used measures include household expenditures or subjective assessments of energy affordability [19]. Some developed countries (i.e., Cyprus, France, Ireland, Scotland, Slovakia, and the UK) officially define energy poverty as an issue of affordability, as shown in Table 1, while others (i.e., Austria, Italy, and Malta) have unofficial definitions.

2.2. Main drivers of energy poverty

Knowing the extent of energy poverty is important for improving residents' mental and physical health in low energy efficient housing, and enhancing environmental quality [39]. The energy poverty triangle, as illustrated in Fig. 1, highlights low income, inadequate energy efficiency in buildings, and high energy prices as primary drivers globally [40]. Improving energy efficiency, increasing incomes, and reducing energy costs benefit households facing energy poverty. The impact of energy costs on service provision, household tenure, property size, and supportive services is significantly, influenced by policy changes. Household energy efficiency directly affects energy usage, making

Table 1
Various global definitions of energy poverty.

Country	Indicator	Definition	Source
Italy	10 %	A household falls in poverty if monthly expenses exceed the absolute poverty line due to spending over 10 % of income on energy bills	[30]
UK – England	LILEE	A household falls in poverty if its energy efficiency rating is band D or below and its residual income is below the official poverty line	[18]
UK-Scotland, Wales, and Northern Ireland	10 %	Households must spend over 10 % of their income on fuel to qualify as fuel poor	[18]
Hungary	2 M	The National Energy and Climate Plan defines energy poor households as those spending over 25 % of their disposable income on energy, roughly twice the median energy expenditure (2 M)	[31]
Macedonia	–	The poverty line is set at 70 % of the median equivalized consumption	[32]
Slovakia	–	Energy poverty occurs when a household's monthly expenses for electricity, gas, heating, and hot water constitute a significant portion of its income, as defined by Law No. 250/2012 Coll	[33]
Ireland	10 %	Fuel poverty is when households spend over 10 % of their disposable income on energy services (electricity, heating oil, gas, or solid fuels)	[34]
France	8 %	Households spending over 8 % of income, struggling to meet basic energy needs due to resource or living condition constraints	[35]
Australia	–	Households whose incomes fall below 50 % of median income poverty risk threshold	[36]
Cyprus	–	A difficult financial situation prevents a household from meeting essential electricity needs	[37]
Belgium	–	The problem is multidimensional as households struggle to meet basic energy needs	[38]

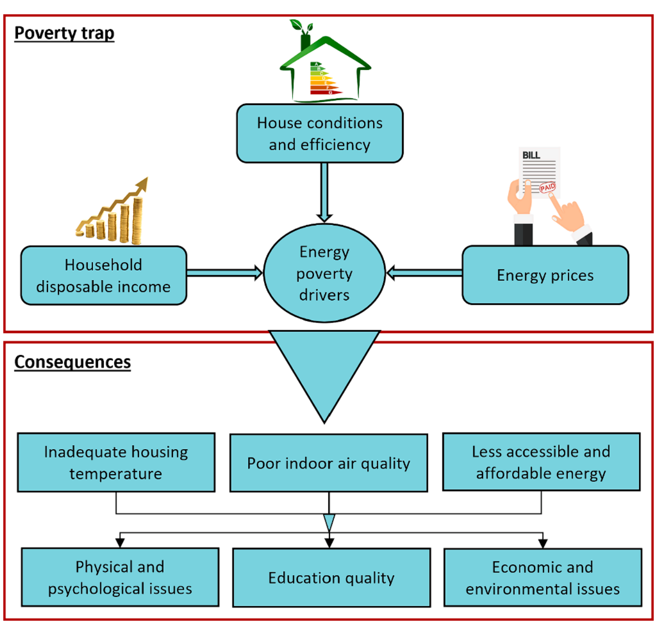

Fig. 1. Main drivers and consequences of energy poverty, source (authors).

enhancements a direct means of alleviating energy poverty. Innovative, energy-efficient technologies can also indirectly contribute to mitigating energy poverty.

Other socioeconomic climate factors, including policy frameworks, housing tenure systems, and volatile energy market prices, play a role [41]. International policy goals may not adequately capture regional challenges [42]. Furthermore, the socio-political system significantly shapes a country's political and economic structures, affecting consumers' energy access and affordability. When the energy market is highly centralized and monopolized, policy interventions may instead focus on expanding the grid system or investing in large-scale energy projects to improve access. Contrary to this, an energy market with high degrees of liberalization and competition will benefit from policies designed to increase energy supplies' efficiency and affordability. Last, climate change affecting heating and cooling demands, is a major influence, directly impacting spending on heating systems and building fabric efficiency, influencing energy service tariffs and affordability interventions [43].

In summary, energy poverty is a complex issue with different understandings in developed and developing countries. It negatively impacts health, education, and the environment, emphasizing the need for holistic approaches to address it.

3. Energy poverty measurement methods

Measurements of energy poverty can generally be classified into three methods consensual-based, expenditure-based and direct measurements. These methods, focusing on technological, physical, or financial thresholds for energy access, are complementary. A detailed comparison is shown in Table 2.

3.1. Consensual based method

This method relies on the occupants' self-reported experiences and evaluations of thermal comfort and household characteristics within their homes (i.e., a damp-free, warm home, and the ability to pay for and guarantee essential energy services) [45]. It uses a technological threshold based on the concept that energy poverty originates from an inability to access modern energy services, referring to sources of energy other than biomass for home heating and cooking. The population without access to these services determines the number of people living in energy poverty. EU statistics on income and living conditions (EU-SILC) indicators are well-known examples of this energy poverty indicator. The Energy Poverty Advisory Hub (EPAH) classifies households into two categories [46]: (i) Primary indicators of energy poverty include the percentage of the population unable to adequately heat their homes and having unpaid utility bills; (ii) Secondary indicators do not directly measure the issue but provide information on various facets of energy poverty (i.e., the percentage of the population with leaks, dampness, or rot in their residence). While the consensual method is often used for cross-country comparisons, it is important to note that the indicators used in this approach are subjective, and their accuracy may depend on how questions are interpreted by respondents. Therefore, while the consensual method can provide useful insights into the prevalence of energy poverty, estimations based on subjective questions should be interpreted with caution and may not always be entirely accurate.

3.2. Expenditure based method

This method examines the affordability ratio, correlating household income and expenses for energy, and access. The income is an economic threshold determining the highest percentage legitimately set aside for energy expenditures. However, expenditure is a physical threshold defining minimal energy consumption for basic needs. The energy burden, the percentage of total household expenses or income allocated

Table 2
Strengths and weaknesses of various energy poverty measurement methods.

Measurement method	Strengths	Weaknesses	Source
Consensual based	The main basis for assessment to date	It may not accurately quantify energy poverty	[17]
	It can be utilized as a complementary indicator in conjunction with others	The income dimension might not be included in the survey	
	Survey infrastructure is in place, just needs improvement	Critics highlight that subjective indicators in this approach may lead to exclusion errors, as households may not recognize themselves in energy poverty despite meeting criteria in other measures	
	Data collection is more straightforward, making it a useful temporary indicator of energy poverty in countries lacking a thorough housing survey	Composite indices, aggregating various dimensions of energy poverty for cross-country benchmarking, are widely favored for their ability to capture the multifaceted nature of energy poverty	
	This approach has the potential to encompass broader dimensions of fuel poverty, including social exclusion and material deprivation	There is concern about the extent of overlap between consensual measures and expenditure measures	
Expenditure based	The identification of the main aspects of energy poverty is facilitated by the objectivity and quantifiable nature of the approach	If based on households' energy, implementation becomes challenging across all countries as it requires extensive modelling	[41]
	Many EU countries have already implemented and tested	Sensitive to changes in energy expenditure	
	Use various thresholds to record the severity	Energy prices, unlike income, fluctuate dynamically, complicating the evaluation of energy poverty	
Direct measurement	Actual outcome measurement	It might be challenging to access utilities, determine adequate standards, and ethical issues going into houses	[44]
	Brings in utilities as an essential stakeholder to help with solutions	Limited to measuring specific indicators, such as energy consumption and access to energy services, rather than broader poverty indicators	
		Along with energy poverty, a variety of other factors also have an impact on health outcomes, but this depends on what is measured	

to energy use, is a fundamental component of this approach. A household is in energy poverty if spending exceeds a predetermined threshold, similar to how the World Bank calculates extreme monetary poverty at $2.15 a day[1] [47]. However, the expenditure-based method is not fully comparable to World Bank absolute poverty, using relative share in the former and absolute income in the latter.

To measure hidden energy poverty based on absolute expenditure, an absolute threshold limit is specified using a predetermined percentage of income allocated to energy costs. This approach is more related to absolute poverty. Note that the thresholds change with energy price fluctuations, making analysis challenging. A relative threshold is based on a median or average energy burden and depicts energy poverty more accurately but comparing across countries with various economic conditions is difficult [17]. Finally, this method includes indicators (i.e., 10 %, 2 M, M/2, and LIHC indicators), with the UK pioneering such studies.

3.3. Direct measurement method

This method assesses the energy services in a household, including heating, lighting, refrigeration, and cooling, by taking precise measurements and comparing them with a predefined standard. Two controversial aspects in measuring poverty are noteworthy. First, "needing to spend on energy services" does not refer to actual expenses but to a theoretical level tied to thermal energy efficiency. Second, "acceptable level" means the home is heated according to World Health Organization (WHO) standards (i.e., 18 °C for bedrooms and 20–21 °C for living rooms), especially for vulnerable groups like the elderly, infirm, or children [48]. This range is in the energy poverty models of England, Wales, and Northern Ireland, based on WHO criteria. In contrast, Scotland uses a slightly elevated threshold of 23 °C for living rooms of disabled, infirm, and elderly households, acknowledging potentially higher heating needs [49]. Measuring domestic energy deprivation faces practical challenges because, with some exceptions, datasets on other energy services, including indoor temperature surveys, are essentially non-existent. Therefore, choosing a suitable standard is challenging as thermal comfort is subjective and depends on cultural, climatic, geographical, and psychological factors [46].

4. Energy poverty indicators

Cross-country comparisons yield different results based on the energy poverty indicator employed. The chosen definition significantly impacts the sociodemographic makeup of energy poverty within a polity. Determining the target population for policies combating energy poverty requires critical consideration of the definition and measurement. This section provides an overview of the significance of various indicators in different global policies.

4.1. Single indicators in developing countries

Various methodologies are used to assess energy poverty in developing countries. One approach involves using individual indicators that focus on specific aspects (i.e., assessing access to electricity, clean fuels and technologies for cooking) [50]. These indicators provide a comprehensive understanding of the specific issues faced by communities, with variables weighted based on the proportion of the population with access to both electricity and sustainable energy sources.

For example, the global poverty indicator creates a deprivation profile for each person, indicating specific indicators where they experience deprivation among the 9 specified dimensions shown in Table 3. These SDGs dimensions include poverty alleviation, healthcare, education, and gender parity, collectively represent the essence of human progress. Individuals are categorized as either deprived or non-deprived for each indicator, based on a specified deprivation threshold. For instance, if data indicates any member of a household is in energy poverty, every individual in that household is classified as deprived in terms of nutrition. As Table 3 indicates, the UN defined targets for each dimension in 2030, detailing the number of vulnerable individuals affected [51]. While there have been certain advancements observed across various targets, a study in [52] indicated that these advancements fall short of fulfilling all the 2030 and 2050 targets. Specifically concerning environmental goals, progress often diverges from the intended direction, moving away from the set targets. It was concluded that a substantial improvement in the implementation of sustainability policies is imperative across both socio-economic and environmental

[1] The World Bank periodically updates the global poverty line to account for changes in price disparities around the world. The international poverty line was increased from $1.90 to $2.15 per person per day in September 2022.

Table 3
Worldwide poverty dimensions, indicators, and 2030 targets.

SDG area	Poverty dimension	Poverty indicator	Current state	Target 2030
1	Income, Access to Resources	Proportion living below international poverty lines	575 million were still in extreme poverty	Eradicate extreme poverty for all
		Proportion living below national poverty lines		Reduce poverty by at least 50 %
		Proportion covered by social protection systems	4 billion remained entirely unprotected	Implement social protection systems
2	Food Security, Nutrition	Prevalence of undernourishment	735 million people faced chronic hunger	Zero hunger and access to food security for all
3	Health	Mortality rate under-5	Global rate was 38 deaths per 1,000 live births	12 per 1,000 live births
4	Quality Education	Completion rate of primary education and secondary education	In 2021, primary school completion reached 87 %, lower secondary 77 %, and upper secondary 58 % globally	Education financing must become a national priority, with 84 million still out of school by 2030
5	Gender Equality	Gap in economic participation and leadership between men and women	In 2023, women held 26.5 % of seats in national parliaments and 35.5 % in local governments worldwide	End all forms of discrimination against women everywhere, with a yearly increase of 0.5 points
6	Water and Sanitation	Proportion of population with access to safe drinking water and safe sanitation	In 2022, 2.2 billion lacked safe drinking water, 3.5 billion lacked proper sanitation, and 2 billion lacked basic handwashing facilities	To achieve universal coverage, the current rates of progress would need to increase by three to six times
7	Affordable clean energy	Proportion of population with access to electricity	Global electricity access: 91 % in 2021, leaving 675 million without, with 2.3 billion still using polluting cooking	To ensure universal energy access, invest in renewables, enhance efficiency, establish supportive policies
10	Social Inequality	Gini coefficient of income inequality	The poorest 40 % experienced faster income growth in many countries, while one in six people globally faced discrimination	Global inequality reduction: fair resource distribution, education and skills investment, social protections
11	Sustainability	Proportion of urban population living in slums	In 2022, 50 % of global urban people accessed public transport; urban issues: pollution, limited public spaces	Ensure access for all to safe, inclusive, accessible, green and public spaces

spheres to achieve the SDGs.

In developing countries, a positive development in living standards is the recent surge in the adoption of solar home systems, playing a significant role in achieving over 50 % of the improvements in access in sub-Saharan Africa in the past year [53]. The IEA notes a substantial increase of 25 million people gaining electricity access in sub-Saharan Africa through solar home systems since 2019, totalling 45 million in 2022 (4 % of households). Mini-grids cover 2 %, and main grids extend access to over 40 %. Additionally, the rise of solar lanterns and multi-light systems is promising, benefiting around 18 % of the population without access in the region as a first step towards essential electricity services.

Studies have shown that solar home systems can reduce energy poverty and significantly benefit households [54]. However, affordability and willingness to pay are key considerations for households, as the cost of solar home systems can be a barrier to adoption [55]. Government intervention and innovative pricing mechanisms are necessary to address affordability challenges and promote wider adoption. Understanding the household adoption dynamics and the impacts of solar home systems on energy expenditure and greenhouse gas emissions can inform policy decisions and support sustainable energy transitions.

Prior research has shown that socioeconomic factors, including income, wealth, age, and education are significant in the adoption of solar photovoltaic (PV) systems [56]. Additionally, factors like attitudes, expectations, and environmental knowledge also influence the adoption of solar panels [57]. Affordability challenges impact the willingness to pay for solar home systems, with market prices often exceeding what households are willing to pay [58]. Policymakers need to consider market price reductions and innovative pricing mechanisms to bridge the affordability gap and promote wider adoption of solar systems in off-grid rural areas [59]. Understanding these factors can optimize household PV products and policies, promote green development, and help achieve carbon neutrality goals.

The World Bank's proposed strategy, named "Scaling Up to Phase Down," outlines a plan to address financing obstacles and establish a comprehensive financial strategy for this energy transition [60]. Developing countries usually face higher electricity costs due to a lack of financial resources to fund both energy transition and network infrastructure [10]. This financial constraint hinders their participation in energy efficiency or renewable energy initiatives, forcing them into fossil fuel projects with elevated and unpredictable expenses [61]. Essentially, they encounter a threefold penalty in their pursuit of an energy transition, creating a cycle of poverty.

The World Bank suggests that about 89 % of the global coal-fired power generation, facing the risk of being stranded, is located in low- and middle-income countries [60]. Effectively financing a just transition to sustainable power will demand significantly increased capital inflows compared to the current mobilization levels, essential to support the necessary expansion in lower carbon electricity production. The framework "Scaling Up to Phase Down" outlines the obstacles encountered by developing countries striving to transform their power sectors, aiming to identify strategies for overcoming these challenges [60]. Three primary barriers limit the acceleration of energy transition in these countries:

1. The substantial initial capital costs associated with renewable energy projects lead many nations to commit to expensive and high-carbon energy options due to inefficient energy subsidies.
2. Developing countries have high capital costs, which skew their investment decisions away from renewables.
3. Deficiencies in energy sector fundamentals, particularly institutional capacities, impede the widespread scaling of the transition.

4.2. Single indicators in developed countries

A commonly used metric for assessing energy poverty in developed nations is the expenditure approach, examining the relationship between household income and energy spending. The count of households in energy poverty and their characteristics are influenced by the definition of the energy poverty threshold. This section explores enduring single indicators of energy poverty thresholds along with their limitations.

The 10 % indicator introduced in [62], considers a household in energy poverty if 10 % or more of its income is spent on energy expenditure. Critical decisions in this approach include selecting between absolute and relative expenditure thresholds and determining household income. Expenditure thresholds are based on various assumptions. In an absolute measure, a household is deemed in energy poverty when their expenditure exceeds a fixed percentage of income. For example, in Northern Ireland, the threshold is set at 10 %, and energy poverty rates escalate with increasing fuel prices [63]. Although this indicator is easy to deploy and establish an effective policy course, it is criticized for its limited assessment and reliance on energy prices [64]. Critics agree on two points: (i) the energy prices significantly impact the results, leading to high-price periods are high and lower values in low-price periods; (ii) the 10 % threshold is considered arbitrary.

This indicator received criticism for not excluding households with high incomes and strong preferences for energy services above socially accepted standards [27]. In another study [65], the criticism focused on using full income without excluding household expenses and overlooking potential household benefits (e.g., rent, pension, etc.). Consequently, the indicator neglects the heating and eating effects arising from the inability to afford both food and minimal energy consumption. This dilemma arises due to a lack of financial resources, forcing households to decide between paying their energy expenditure and purchasing the essential food required for survival [66]. Another weakness is the omission of dwelling characteristics. Many households inefficiently use their dwelling systems due to their characteristics, priorities, and customs. Additionally, they lack knowledge of the proper utilization of heating systems, cookers, lights, and other systems, resulting in a significant increase in energy consumption [67]. This situation could be improved by providing useful guidelines and individual advice to these households.

The minimum income standard (MIS) indicator considers a household as being within the energy poverty level if its income, after energy expenditure, is less than the minimum standard income [65]. This indicator aims to measure energy poverty based on income, providing adaptability to various socioeconomic contexts [20]. In the UK, the “minimum income calculator” platform enables a household to quantify their MIS based on several aspects of daily life [68]. However, the indicator’s ability to identify vulnerable people is limited as defining the proper MIS involves a challenging and arbitrary task, such as determining household disposable income available to cover minimum energy needs.

The high share of energy expenditure in income (2 M) indicator detects households with high energy expenditure [69]. This indicator shows the proportion of households with an income-to-expenditure ratio more than double the national median. The 2 M indicator consists of four comparable indicators: double the mean, double the median, double the mean share, and double the median share of household energy expenditure [70]. However, these variations may be redundant, as the 2 M indicator is commonly referred to as “double median.” Essentially, when a household spends more than twice the median, mean, and median share of its income on energy services, it is labelled as being in energy poverty. Notably, the fourth indicator, “double the median” in the list, is based on Boardman’s work [62], specifically identifying 5 % of the median share of household spending on energy relative to the total revenue of British households in 1988.

The 2 M indicator is designed to detect households with high energy expenditure relative to their income. However, it fails to exclude households with high incomes and high preferences for energy services above socially accepted standards [71]. This criticism also applies to the exclusion of households from being classified as fuel poverty, a key feature of the 2 M indicator [67]. Comparing the metrics 2 M indicator, the mean is statistically more sensitive to anomalous values and changes in behavior than the median share. However, using the mean as a threshold for identifying households in fuel poverty poses a potential weakness. For example, if anomalous values result in a high percentage of income spent on energy, this could increase the mean and incorrectly classify more households as not in fuel poverty. In such cases, using the median share can be advantageous in avoiding this problem. It should be noted that the 2 M indicator considers the nation’s characteristics and income and expenditure distributions to prevent arbitrary threshold calculation.

Furthermore, the low absolute energy expenditure (M/2) indicator identifies households with abnormally low energy expenditure, less than half the national median [72]. It serves as a proxy for hidden energy poverty (HEP), indicating either highly energy efficient or because households consume less energy than usual. This indicator is considered more reliable in capturing energy poverty compared to the 2 M indicator because it focuses only on absolute energy expenditure levels, without considering income. However, it has drawbacks as the threshold level may not be suitable for all households in different locations [67].

Lastly, the after fuel cost poverty (AFCP) indicator classifies a household as being in energy poverty if it cannot afford necessary energy services after meeting basic needs such as housing [73]. This indicator aims to reduce social inequalities among low-income households by identifying the minimum income required for a person’s well-being. It differs from others (i.e., LIHC) in that it can identify energy poverty households with lower incomes and expenditures relative to the threshold, indicating a higher risk of being in fuel poverty according to the LIHC indicator.

4.3. Multidimensional indicators in developing countries

Recognizing that poverty is a multidimensional concept, a single indicator cannot fully capture its complexity. Several studies highlighted the need to consider multiple dimensions of poverty (i.e., health, education, and standard of living) [74]. Indicators commonly used to measure multidimensional energy poverty cover dimensions (i.e., energy availability, energy affordability, and energy cleanability) [75]. These dimensions may vary across countries, but common dimensions include disempowerment, physical and mental suffering, struggle and resistance, social and institutional maltreatment, lack of decent work, insufficient income, and material and social deprivation [76].

These indices have been utilized in studies across different regions. In [77] a comprehensive energy poverty index used four indicators: access to electricity, clean fuels, cooking technology, total energy supply, and total final energy consumption. This index, designed for developing countries, more closely measures energy access than energy poverty. Different approaches proposed in [78] include evaluating energy poverty by considering economic indicators, geographic or technological barriers to energy access, and quality considerations, as argued by [79], especially crucial in spatially heterogeneous, middle-developing countries.

The Multidimensional Energy Poverty Index (MEPI) developed in [80] uses four main indicators to evaluate household energy access: fuel use, affordability, safety, and reliability, reflecting various variables in South Africa. This MEPI is further adopted [81] utilizing eight dimensions categorized into cooking, lighting, and additional measures. Building on earlier research, a study in [82] investigated the impact of remittances on MEPI in Bangladesh, utilising six dimensions of energy deprivation. These dimensions include accessibility indicators (i.e., lighting and cooking) and affordability instruments (i.e., space cooling/heating, home appliances, education and entertainment, and communication). The findings suggest that increased remittance income might enable households in developing nations to meet their necessary energy needs.

While a MEPI comprises the combination of these indicators, certain factors may be more important than others depending on the situation. Some factors may not contribute to vulnerability and thus can be excluded from the assessment. To conduct a thorough assessment of energy poverty, an appropriate strategy including a combination of drivers and outcomes is necessary. However, such an analysis faces challenges due to the complexity and diversity of energy poverty in statistical data, which typically involves data compression to exclude certain information and factors [83]. Challenges also arise due to limited data availability on various dimensions of energy poverty in developing countries, attributed to resource constraints hindering comprehensive data collection for all MEPI components [84]. Several methods for combining multiple indicators, focusing on various causes, drivers, or results, have been proposed in the literature [85]. Innovative methods like remote sensing, geospatial technologies, and mobile tools offer more efficient and cost-effective data gathering, especially in remote areas where traditional surveys may be impractical [86]. It has been proved that machine learning algorithms that include remote sensing environmental and geographical variables, and socioeconomic indicators such as income, expenditure, and energy efficiency, can effectively predict energy poverty [87]. This underscores the essential role of leveraging technological advancements and innovative approaches for a comprehensive understanding of energy poverty and effective interventions.

However, the MEPI may not fully capture the complexity of energy poverty, especially in developing countries with heterogeneous and challenging energy situations. It overlooks environmental and social impacts (i.e., greenhouse gas emissions, indoor air pollution, and gender inequality) [81]. Therefore, some scholars proposed alternative indices like the Energy Poverty Severity Index (EPSI), the Energy Poverty Gap Index (EPGI), and the Energy Poverty Vulnerability Index (EPVI), to consider more dimensions and indicators, acknowledging the diversity of contexts and population needs [88]. Combining these indices allows policymakers to identify the root causes of energy insecurity and target support programs more effectively. This framework considers the interconnectedness of various factors and the historical changes in regional realities, providing a comprehensive understanding of energy insecurity. By analyzing the multidimensional nature of energy poverty and access, policymakers can tailor approaches to address the specific needs of different regions [89]. The adaptability of this framework enables a more accurate assessment of energy insecurity and facilitates the design of targeted interventions. Additionally, it aids policymakers in understanding the geographical disparities in vulnerability to energy policies, supporting the development of just and equitable energy transitions [90].

4.4. Multidimensional indicators in developed countries

In developed countries, methodologies for measuring MEPI differ significantly from those in developing countries due to unique socioeconomic and infrastructural contexts. While both settings share the overarching goal of assessing and addressing energy poverty, methodologies in developed countries often exhibit variations in terms of data sources, indicators, and analytical approaches.

For instance, research in [91] applied a quantitative approach to measure vulnerability levels for all civil parishes in Portugal, utilizing numerical indicators to identify vulnerable areas that contribute to a spatial understanding of energy poverty. Furthermore, the authors in [92] used a composite assessment involving quantitative measures, including monetary, energy consumption, thermal comfort, and health-related quality of life cost analysis, to evaluate vulnerability to energy poverty in case studies across Spain. Another study in [93] employed a quantitative model-based expenditure approach to determine energy prevalence, followed by the application of various indicators to delineate energy poverty profiles at the local level in Poland. Principal component analysis and multiple linear regression added quantitative rigor to predict energy poverty households accurately.

Alongside quantitative methodologies, several studies applied quantitative methodologies, including machine learning models and statistical analyses, enabling data-driven multivariate analysis to understand the intricate causes of energy poverty. In [94], a classification matrix was developed to assist decision-makers and support providers in better understanding the relative importance of general deprivation or energy poverty issues in various geographical regions in England. Findings indicated that the current English Index of Deprivation inadequately addresses energy poverty, an additional and distinct form of deprivation. Additionally, machine learning models surpassed traditional regression models by handling large datasets more effectively, managing non-linear dependencies and not requiring prior assumptions about variable relationships, crucial when researching complex issues resulting from energy poverty [95]. While these models are replicable, their construction and analysis techniques are complex and potentially unavailable to local governments or organizations. Nevertheless, deterministic methods supported by assumptions, are easier to use and allow for a wider range of parameter testing, albeit being less reliable and scientifically sound. In both methods, the quantitative model result (i.e., to be in energy poverty) can take on various shapes, such as a binary representation or a range of values.

Transitioning to qualitative approaches, authors in [91] proposed the energy poverty vulnerability index, incorporating sub-indices focused on the socioeconomic behaviors of people and the energy performance of houses. Despite using a more comprehensive method of calculation, it lacked an environmental component, highlighting the qualitative aspect of environmental considerations. In [96], societal factors were examined utilizing qualitative conceptual thinking to explore the relationship between social relations and energy poverty. Positive relationships were found to both facilitate access to energy services and result from that access. Moreover, analyses in [97] explored the geographic distribution of double energy vulnerability in England, emphasizing qualitative insights into the lack of access to transportation and domestic energy. The study revealed spatial concentration in isolated rural areas due to different institutional structures and broader systems of infrastructure provision.

The EU-SILC indicators are an example of MEPI, encompassing a range of variables related to income, poverty, social exclusion, and living conditions. These offer comprehensive data for analyzing various aspects of individuals' and households' well-being. They provide source data for social exclusion and income statistics to conduct a comparative analysis across Europe [30]. These indicators operate to a coordinated standard as data on household conditions, poverty, and social exclusion are collected annually at the national and European levels. The daily life aspects analyzed for energy poverty include the inability to keep homes adequately warm during the winter, the delay in paying energy bills, and the presence of deficits in the homes, such as poor insulation, damaged walls or foundations, and conditions like mould and rot [67]. However, the EU-SILC indicators face criticism for being arbitrary, dependent on culture, and not being applicable globally due to variations in climatic conditions [67].

Turning now to LIHC indicator which is a dual threshold indicator identifies households in energy poverty if their disposal income is below the official poverty line and their energy costs exceed the national median cost [98]. The chosen threshold limits are (i) 60 % of the median equalized disposable income following social transfers and the modeled equalized energy expenditure, and (ii) the median equalized energy consumption expense based on all households in the analyzed area. To measure the severity of fuel poverty, the LIHC definition also includes a "fuel poverty gap," quantifying how far below the energy cost threshold a household is and indicating the drop in fuel costs needed to pull the household out of fuel poverty.

Prior to 2011, the fuel poverty statistics in England were computed using the 10 % indicator. In 2012, an independent review by John Hills proposed a new approach for assessing fuel poverty, introducing distinct indicators under the LIHC method to gauge its extent and depth [98]. This method was used from 2013 to 2021 but faced criticism thereafter for its complexity in calculating and inconsistent national-level application [99]. Notably, the LIHC tends to overlook the most vulnerable individuals (i.e., the elderly, people with chronic illnesses, people with disabilities, and children). Furthermore, it hinders the tracking of political interventions as it ignores rising energy prices [85].

Furthermore, the LILEE indicator is currently an official measure for fuel poverty in England [18], determining its condition based on two criteria: (i) a fuel poverty energy efficiency rating (FPEER) of band D (55–68 %) or lower, an absolute energy efficiency threshold where FPEER rating of C (69–80 %) or higher exempts a household from the fuel poverty band; and (ii) a disposable income below the national poverty line after deducting estimated energy costs, a relative income measure. The LILEE definition is an absolute measure of energy efficiency but a relative indicator of income. Regardless of income or energy prices, a household cannot be in fuel poverty if its energy efficiency rating is C or higher. The FPEER measures domestic energy efficiency, accounting for policy changes' direct impact on residential energy costs via the official standard assessment process [100]. The LILEE indicator provides information about the proportion of homes with inefficient energy use and low incomes, indicating the severity of fuel poverty. Similar to the LIHC indicator, it utilizes the fuel poverty gap to measure the discrepancy between necessary fuel costs for each household and the closest fuel poverty threshold.

In 2020, using the LILEE metrics, 13.2 % (3.16 million) of English households were in fuel poverty, a decrease from 13.4 % (3.18 million) in 2019 [101]. Of these, 52.2 % had low energy efficiency, and 27.6 % had low income. The total fuel poverty gap in 2020 is down 2.8 % from 2019′s £726 million. However, the 2019 estimates indicated that 24 % of households in Northern Ireland faced energy poverty, up from 18 % in 2018 [102]. Concerns arise due to the pandemic and increasing energy costs, potentially pushing a greater number of households into poverty. A recent study by the University of York estimated that 71.7 % of households in fuel poverty by January 2023, as shown in Fig. 2, attributed to the cost of living crisis and the Ukraine-Russia war [103]. Conversely, around 47.5 % of households in London and the South East of England are estimated to be in fuel poverty.

Finally, Table 4 illustrates the main benefits and drawbacks of the energy poverty indicators adopted from [104], which have been updated for clarity and comprehensiveness. Notably, some indicators, such as LIHC, were previously regarded as single metrics, but are now classified as MEPI because they encompass various dimensions of energy poverty. Additionally, the latest UK LILEE poverty indicator has been included as a contribution to this research endeavor. Furthermore, the table has undergone significant expansion and updates compared to previously published works, focusing on factors like simplicity of calculation and communication, while also acknowledging the importance of complexity, particularly in the case of MEPI. The key reported benefits include the objective nature of these indicators and their adaptability to national standards, while the prevalent drawback is their limited comprehensiveness.

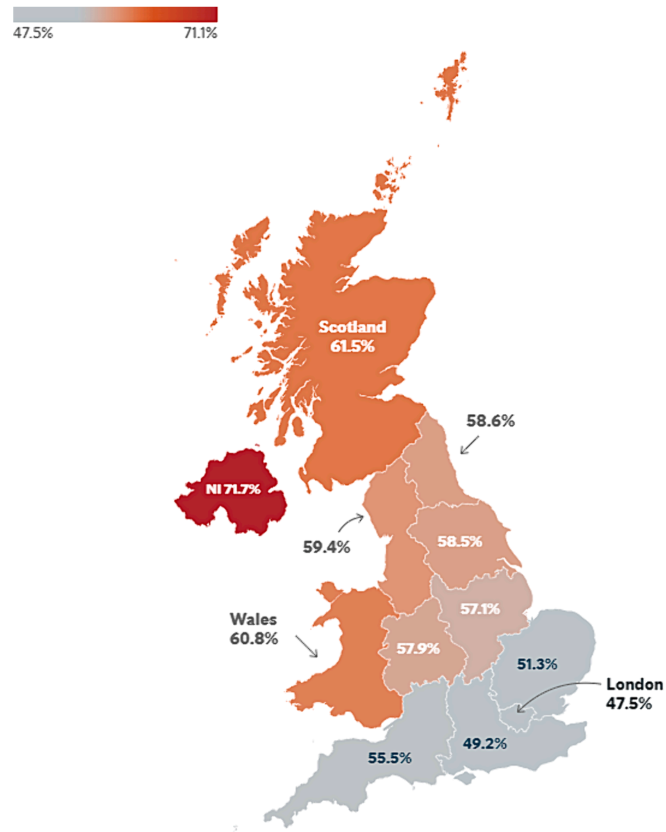

Fig. 2. Proportion of households in fuel poverty across the UK by region [103].

5. Effect of energy poverty on quality of life

Energy poverty comes at a terrible cost to all aspects of life, including health, happiness, social inclusion, and quality of life [105]. Energy poverty results in inadequate comfort and sanitary conditions for those affected, including inappropriate indoor temperatures, poor air quality, and exposure to hazardous chemicals and materials, which can lower productivity, cause health issues, and increase mortality. Significant psychological stress is also experienced by energy poverty due to high energy costs. According to the EPAH, adequate heating, cooling, lighting, and energy for appliances are necessary services to ensure energy-efficient homes and reasonable living standards, thermal comfort, and public health [46]. These key energy services are unavailable to households with limited energy access.

5.1. Effect on health

A substantial body of empirical studies demonstrates the link between increased energy poverty and adverse health outcomes [2]. The increasing energy costs significantly affect consumers, especially those in households struggling to afford fuel. Individuals in these fuel-deprived households often resort to limiting heating usage at specific times to manage energy expenses and express concerns about having sufficient funds to adequately heat their homes. Children, in particular, are more susceptible to respiratory conditions and other illnesses as a result of higher fuel poverty [106]. The situation escalates when the lack of access to basic energy services extends beyond affecting comfort and quality of life, posing significant health risks and well-being. This underscores the urgent need to address energy poverty and ensure universal access to clean, affordable, and sustainable energy solutions.

In developed countries, the rising cost of healthcare poses a significant challenge to preserving a comfortable standard of living. Escalating healthcare costs is a major problem for governments in wealthy nations

Table 4
Distinguishes between the pros and cons of the most widely used indicators.

Pros and cons	Characteristics	Indicators						
		10 %	LIHC	LILEE	2 M	MIS	EU-SILC	AFCP
Advantages	Simple to calculate	√				√		√
	Simple to communicate	√						√
	Adaptable to a national standard	√	√	√	√	√	√	√
	Clear distinction between income groups	√	√	√	√	√		
	A variety of householder requirements are considered		√	√		√		√
	Energy efficiency assessed		√	√	√			
	Dwelling heating comfort							√
	Vulnerability special need peoples are considered		√	√				
	Household characteristics							√
	Sensitive to expenditure	√	√		√			
	Objective indicators	√	√	√	√	√	√	√
	Provide measure for severity of poverty (gap)		√	√				√
Disadvantages	Overly sensitive to fuel costs	√			√			
	Cannot capture level of poverty completely	√	√	√	√	√	√	√
	Challenge of determining the minimum income threshold	√				√	√	√
	Inconsistency in measuring poverty across the country		√				√	
	High percentage of energy poverty for the highest income groups		√			√	√	
	Complex deployment		√	√				√
	Subjective indicators						√	

when managing fiscal budgets. However, addressing fuel poverty by providing more affordable energy in colder climate zones is projected to reduce public healthcare spending [107]. Fuel poverty in colder countries with relatively high incomes and less income inequality (i.e., Sweden and Slovenia), is often triggered by poor household conditions [108]. For instance, France, with colder winters, faces challenges related to energy affordability, cold-related discomfort, and insufficient heating [107]. Similarly, developed nations with warmer climates (i.e., Australia) face health issues related to energy poverty, including severe bushfires, summer heatwaves, and cold winters [109].

In developing countries, the negative health effects of indoor air pollution are mainly severe in rural areas with poor living conditions and limited access to electricity [110]. Poverty is concentrated in rural areas, where approximately 84 % of low income people globally reside. South Asia, in particular, exhibits stark rural–urban disparities, with nearly 87.5 % (340 million) of low income people living in rural areas compared to 12.5 % (49 million) in urban areas [111]. These rural challenges include a lower rate of electrification, reduced educational quality, and inadequate healthcare services. Women and children bear a disproportionate burden, given their responsibilities in community level fuel and water collecting [112]. Insufficient access to clean cooking results in 3.7 million premature deaths yearly, with women and children accounting for 60 % of early deaths in Africa due to smoke inhalation and indoor air pollution [113].

It is worth noting that the issue of maintaining the higher cost of clean fuel extends beyond rural households. In urban areas like China, poor quality indoor heating systems, fuel choices, and higher building material costs affect residents, resulting in inadequate insulation and ventilation [114]. In many developing nations, wood and other biomass sources (i.e., coal, dung, and crop waste products) serve as the primary source of energy for heating and cooking. These fuels are typically burned in open fires or simple stoves, emitting smoke and toxic chemicals into the room [115]. According to WHO, 2.4 billion people worldwide still rely on solid traditional fuels for cooking [116].

Candles and, to some extent, kerosene lamps are also used extensively to provide lighting, exposing households, particularly women and children, to pollution levels surpassing those found in even the most polluted global cities [116]. The primary cause of most air pollution-related mortality is particulate matter, particularly when levels exceed permissible limits of suspended particles, aromatic compounds, and carbon monoxide. Particles less than 10 mm in diameter (PM10) can easily enter the respiratory system, posing health risks, especially if composed of toxic substances like heavy metals. Additionally, PM2.5 particles, smaller than 2.5 mm in diameter, can lodge in the deepest respiratory regions, causing more severe health impacts such as cardiovascular and cancer diseases.

For example, in the UK, urban background sites have decreased in annual average PM10 concentrations from 36.1 μg/m^3 in 1992 to 12.9 μg/m^3 in 2021, while PM2.5 reduced from 12.4 μg/m^3 in 2009 to 7.9 μg/m^3 in 2021 [117]. However, the latest WHO guidelines advise an annual average PM2.5 concentration not exceed 5 μg/m^3 and PM10 should remain below 15 μg/m^3 [118]. The WHO estimates that 3.2 million people die annually from indoor air pollution, with over 237,000 deaths among children under 5 years old [116], surpassing the Institution of Health Metrics and Evaluation (IHME) estimate of 2.3 million. To contextualize, there are about 680,000 HIV/AIDS related deaths and about 1.3 million global road traffic crashes each year [119].

Despite the severity, progress has been made globally in reducing indoor air pollution, a largely solvable issue. Since 1990, the global death toll from indoor air pollution has decreased by 40 % [120], showcasing promise for poverty reduction, with most advancements happening before the onset of the COVID-19 pandemic. Clean cooking fuels, access to clean water, improved television and radio coverage of health services, reduction in respiratory and cardiovascular diseases, and prevention of early deaths from indoor air pollution are indirect health benefits resulting from improved energy consumption [121].

5.2. Effect on education

Health and education outcomes are interconnected, mutually impacting each other, as a healthier society provides a favourable environment for higher educational achievement and on-the-job training [122]. Individuals with higher education are predicted to be happier, healthier, and live longer compared to their less educated counterparts.

At the micro level, empirical data demonstrates the correlation between lower energy poverty and better educational outcomes. Research using a MEPI for India highlights education as a key factor in preventing the spread of energy poverty [123]. Access to electricity is associated with increased study time for children, especially benefiting girls in rural areas in India[124]. Another study, used academic performance in Chinese and mathematics subjects, to identify how energy poverty affects the subjective health of Chinese children [125].

A comprehensive study across 33 African countries examined the link between energy poverty, under-5 mortality, and inequality in education, revealing a clear cointegration between energy poverty and under-5 mortalities as well as between energy poverty and education inequality [126]. Adolescent girls facing extreme poverty, residing in rural areas, with disabilities, in conflict, or from disadvantaged ethnic groups, are particularly vulnerable to educational disparities. Many girls in low- and lower-middle-income countries face challenges in accessing and completing primary and lower secondary education [127]. Globally, over 129 million girls are out of school, with 32 million girls in primary school, and conflict-affected countries exhibit twice the number of out-of-school girls compared to non-affected countries [128]. Marginalized adolescent girls are at high risk of early marriages and pregnancy, hindering their transition into work and reducing earning potential and livelihood options [129].

Policies addressing poverty and improving education outcomes must consider the unique needs of marginalized adolescent girls in the context of energy poverty, which significantly impacts education and gender equality. Single women, especially those with children, are particularly vulnerable, with around 3.8 million extremely vulnerable young women, including an estimated 127,000 under 18, facing multiple and intersecting inequalities [130]. Gender inequalities, such as the pay gap and limited work opportunities due to caregiving responsibilities, compound energy poverty. In 2020, almost 15 % of households with poor infrastructure were affected by rising energy prices, disproportionately impacting households with children led by a single adult, of which 83 % were led by women Eurostat statistics [131]. Addressing energy poverty while considering the specific needs of marginalized adolescent girls is crucial to ensure their inclusion.

While a correlation between energy poverty and education outcomes exists, it is important to note that this relationship can be influenced by other factors, such as general poverty. In some cases, energy poverty may be a symptom of broader poverty, rather than a separate issue. For example, households living in poverty may struggle to afford both energy and education expenses, creating a correlation between energy poverty and education outcomes. Therefore, understanding the underlying causes of energy poverty and its relation to broader poverty issues is vital, particularly in developed and some developing countries where general poverty is especially vivid.

5.3. Effect on climate change

The lack of access to energy often fosters the use of dirty energy sources that contribute to land use changes, deforestation, and greenhouse gas emissions.

Indoor air pollution resulting from burning wood as the primary fuel source significantly contributes to the environmental problem. Approximately half of the harvested wood globally is utilized for energy production, primarily for heating and cooking [132]. In 2021, 2.4 billion people lacked access to clean cooking, with 40 % residing in sub-Saharan Africa and 55 % in developing Asia [133]. By 2030, the IEA estimates that 1.9 billion people will still lack clean cooking, with half of them in sub-Saharan Africa [133]. In Africa, the main cause of forest degradation is the use of wood for energy, contributing to about 7 % of the world's greenhouse gas emissions [134]. The rapid deforestation in developing nations, in contrast to the growth of forests in wealthier nations, is influenced by low income people using wood as an energy source.

Another crucial relation between climate change and fuel poverty is the mutual exacerbation resulting from inefficient dwellings and inadequate housing constructions. Although climate change affects the entire globe, its negative impacts are more severe on people in low income countries. In many nations across Africa, Asia, and Latin America, climate change poses a serious threat to food security, restricts access to clean water, and adversely affects the health of low income people [135]. These are more vulnerable due to their heavy reliance on natural resources and their limited ability to prepare for climate extremes. Furthermore, the rising prices of fossil fuel, coupled with environmental pollution, further connect fuel poverty as it incentivises low income individuals to resort to traditional wood burning, posing a significant threat to poverty reduction efforts and potentially undoing years of development work.

6. Discussion and recommendations

To address energy poverty, policy options could fall under energy policy, social policy, or a combination of regulatory solutions. Generally, fuel poverty can be reduced by increasing household income and bill paying ability, lowering fuel costs, improving energy efficiency and household insulation, and providing access to affordable essential energy services and technologies. In the UK, eligible customers can benefit from payments and discounts such as the Cold Weather Payments, Warm Homes Discount, and Winter Fuel Payment, aiming to assist vulnerable customers in paying their bills [136]. The UK government has implemented an energy tariff cap to lower fuel costs, and the Energy Company Obligation promotes energy efficiency by requiring energy providers to install measures in households with limited access to fuel, vulnerability to disaster, or low incomes.

The Welsh government has proposed four policy actions to eliminate severe or persistent fuel poverty by 2035, focusing on identifying and prioritizing those at risk [101]. This also seeks to improve thermal and energy efficiency in low-income homes to reduce energy bills and harmful emissions while using standard influence to meet people's needs. Furthermore, the Scottish Government's energy strategy aims to reduce demand, develop a net zero energy system, and outline policies on domestic energy production [137]. However, Northern Ireland lacks an effective policy response to the developing energy crisis, posing a threat to households facing cold winters without immediate action.

Energy poverty is also a growing concern in many other developed countries, with several policies and programs being developed in developed. Examples include financial assistance schemes, energy efficiency programmes, incentives for renewable energy sources, or rules governing the energy market, as detailed in Table 5. The effectiveness of these policies depends on factors (i.e., the target population's needs, political will, investment levels, and the larger socioeconomic and political environment). In the EU, energy poverty reduction is a major policy concern, with the European Commission incorporating it into a just energy transition. For instance, the "Renovation Wave" policy accelerates home renovations across the EU to improve energy efficiency, reduce greenhouse gas emissions, enhance quality of life, and reduce energy poverty [71]. The strategy aims to double the rate of energy renovation in the next ten years, projecting that 35 million houses could be renovated by 2030.

In developing countries, addressing energy poverty is more challenging due to resource limitations, insufficient institutional capacity, and political instability. Policies may vary based on cultural, economic, and political differences. In countries that have begun tackling energy poverty directly, short-term measures include tax reductions and emergency financial aid, while long-term measures focus on improving housing comfort, energy efficiency, and renewable deployment, as shown in Table 6. While the utilization of renewable sources like solar PV may not directly tackle energy poverty, it can significantly contribute to enhancing access to clean electricity [147]. Access to affordable, reliable, sustainable, and modern energy services is crucial for poverty alleviation, aligning with Sustainable Development Goals, especially SDG 7 and SDG 13. Nevertheless, climate change consequences may impact poverty eradication efforts, emphasizing the need for comprehensive policies that consider both energy and climate challenges.

The issue of energy poverty is not only a matter of international justice but also has implications for future generations. With ongoing concerns about energy supply security, the Russia-Ukraine war's anticipated energy crisis, and the global move towards climate neutrality, the poverty debate remains a top priority for policymakers. Addressing these challenges necessitates a context-dependent approach, involving both local and global institutions. Multidimensional poverty is aggravated by various contextual factors, such as conflicts, environmental threats, governance issues, and economic uncertainties. This complexity

Table 5
Initiatives to tackle energy poverty in some developed countries.

Country	Initiative	Objective	Source
Canada	Clean Energy for Rural and Remote Communities (CERRC) Program	Support the deployment and demonstration of renewable solutions and strengthen local capacity to reduce diesel reliance in rural and remote communities	[138]
Austria	Support for Green Heating	Increase information and financial support for households to switch from fossil-fuel-based heating to greener options, focusing on lower income groups	[139]
Spain	DUS 5,000 and PREE 5,000 Schemes	Offer aid for small municipalities to improve energy efficiency or promote sustainable mobility in rural areas	[140]
	Audits and interventions for poverty houses	Improve building energy efficiency to reduce energy expenditure for Housing of the Provincial Council	[141]
European Commission	Renovation Wave Strategy	Reduce energy poverty by improving the energy performance of buildings	[71]
Cyprus	Strength households with disabled people	Facilitate vulnerable consumers' social integration and aid in the energy transition	[142]
Italy	Building renovation measures	Tax deductions for expenses incurred to implement renewable energy and increase energy efficiency	[143]
Hungary	Benefits and bill reduction	People in energy poverty are practically assisted through social benefits, direct reductions in their energy costs, and a utility price reduction programme	[144]
	Renovation programme	The energy efficiency programme, which was launched in 2021, provides a 50 % subsidy for renovations for all families with children	[71]
Bulgaria	Energy Efficiency and Renewable Sources Fund	The fund covers the first 5 % of default risk, paid to lenders if homeowners associations fail to pay back their loans	[145]
Portugal	Support Program 65 – Elderly in Security	Social support organisations that work with the elderly and underprivileged people, particularly those who live far from populated areas	[83]
USA	Weatherization Assistance Program and the State Energy Program	Address energy challenges, promote sustainability, and enhance community resilience to energy-related impacts. They contribute to national goals by reducing energy consumption, lowering greenhouse gas emissions, and improving overall energy efficiency in homes and infrastructure	[146]

Table 6
Initiatives to approach energy poverty in some developing countries.

Country	Initiative	Objective	Source
Morocco	Rural Electrification Plan	Achieve universal electrification by reaching the remaining unserved 10 % of the population in remote areas through solar home systems	[148]
Kenya	Increased Grid Connections and Home Solar Systems	Rapidly increase electricity access from 20 % in 2013 to nearly 85 % in 2019	[149]
India	UJALA Campaign	Expand the penetration of high-efficiency lighting to low-income households affordably through an innovative repayment system	[149]
Poland	Clean Air Programme	Target low-emissions heating retrofits for households impacted by energy poverty	[149]
Colombia	Off-grid and Micro-grid Solutions	Bring power service to around 338,000 homes that are not connected to the main grid through off-grid and micro-grid solutions	[149]
Senegal	VAT Exemption for Renewable Energy Equipment	Increase electrification and penetration of renewables by exempting renewable energy equipment from VAT	[150]
Ghana	Strategic National Energy Plan (SNEP), the Renewable Energy Act of 2010	Promoting industrial crops as a means of rural development and offering rural communities in the nation decentralised renewable energy options, with biomass energy playing a prominent role	[151]
Mexico	Public Fund for Solar Panels in Rural Areas	Expand access and reduce energy poverty by contributing public funds toward the installation of solar panels in rural areas	[149]
Brazil	Biomass Gasification	Expand electricity access in rural areas using biomass gasification	[149]
Indonesia	Micro Hydropower Plants	Develop micro hydropower plants to expand access to electricity in rural areas	[152]
North Macedonia	Direct financial support and Habitat for Humanity Macedonia (HFHM)	Low-income households with vulnerable energy consumption receive grants and loans with favourable repayment terms through HFHM for energy bills and renovations	[153]

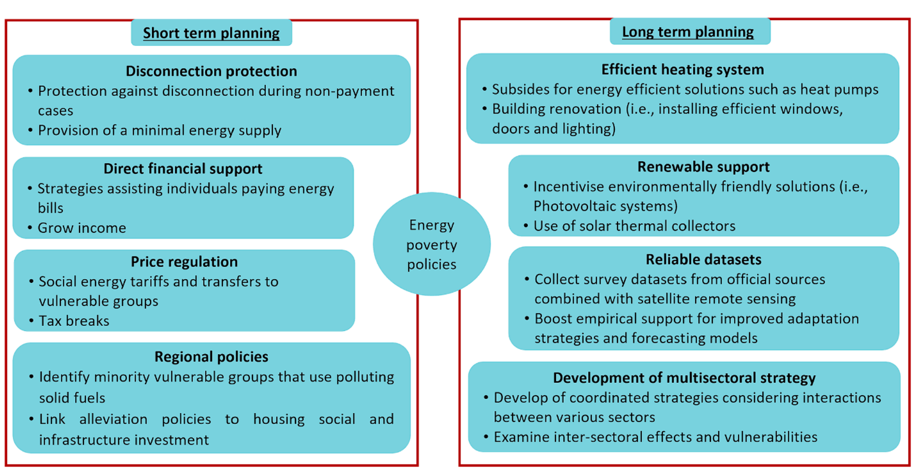

Fig. 3. Short term and long-term policy recommendations to alleviate energy poverty.

requires a comprehensive strategy, integrating ambitious climate policies with initiatives to reduce energy poverty.

This study proposes a framework and a set of policy measures outlined in Fig. 3 to maximize the knowledge gained from addressing energy poverty, forming the basis for a robust economic model prioritizing welfare. As shown, policies play a central role in shaping a well-rounded energy transition by fostering investments in clean energy, and innovation, promoting energy efficiency, and ensuring that the transition benefits all sectors of society.

In the context of short-term planning, addressing immediate challenges is essential. These solutions must establish a solid foundation for long-term sustainability. The proposed framework includes several key elements designed to alleviate energy poverty and promote a just energy transition.

One fundamental aspect of this framework involves providing direct financial support for low-income households. Initiatives such as energy bill discounts or subsidies specifically target low-income households, alleviating immediate financial pressures associated with energy bills. Emergency financial aid programs further provide short-term support for households facing disconnection or struggling to meet their energy expenses, ensuring that vulnerable populations are not left behind.

Another critical component is the implementation of consumer protection measures. These measures include constraints on disconnections to prevent vulnerable households from losing access to essential energy services during times of financial hardship. Additionally, regulating energy providers ensures fair pricing and transparent practices, safeguarding vulnerable consumers from exploitation. Establishing dispute resolution mechanisms offers accessible channels for resolving billing disputes, further enhancing consumer rights and protections.

Furthermore, energy efficiency initiatives are essential for mitigating energy poverty and promoting sustainable energy consumption patterns. Programs such as emergency weatherization assistance provide basic repairs and weatherization improvements to enhance energy efficiency in low-income homes, thereby reducing energy costs and improving living conditions. Appliance exchange programs incentivize the adoption of energy-efficient appliances by offering discounts or vouchers for replacing older, less efficient models, contributing to long-term energy savings and environmental sustainability.

Region-specific approaches are also essential to address distinctive energy challenges across different geographical areas. Urban policies may focus on increasing access to affordable, reliable grid-connected electricity, while rural policies prioritize off-grid and micro-grid solutions, catering to the specific needs of each community.

Identifying and analyzing energy poverty vulnerability requires a comprehensive approach that considers various indicators encompassing building stock, energy performance, socioeconomic characteristics, population dynamics, thermal comfort, well-being, and environmental aspects. A comprehensive assessment should ideally encompass the type, extent, and severity of energy poverty, utilizing multidimensional indicators and finer spatial scales to capture nuances and address disparities effectively.

Long-term planning involves designing a coordinated strategy that promotes sustained growth and environmental sustainability by considering interactions between various ecosystem elements and sectors. Action based approaches, forums for debate, collaboration, and evaluation of energy poverty mitigation strategies are recommended for achieving a socially and environmentally sustainable transition to net zero. Integrated policy options should consider economic, social, and environmental vulnerabilities, coordinating efforts throughout all government levels, and inclusively involving all communities and demographics, including low-income households, rural communities, and marginalized groups. This holistic approach is essential as short-term solutions that fail to address the root causes of energy poverty may have limited impact and sustainability.

Within the proposed framework, long-term policy plans incorporate multifaceted strategies to address energy poverty sustainably over time. These strategies involve investing in affordable and accessible energy solutions, including community-owned renewable energy projects. Furthermore, expanding access to energy efficiency financing plays a crucial role. This facilitates loans and grants for home energy upgrades for low-income households, ensuring they can invest in energy-saving measures without facing undue financial burden.

The long-term strategies also focus on improving building energy performance. This involves implementing mandatory energy efficiency standards for rental properties and enhancing the energy performance of existing housing stock. Moreover, investments in public housing energy retrofits upgrade public housing units to meet modern energy efficiency standards, ensuring that residents benefit from comfortable and energy-efficient living environments.

Lastly, long-term policy plans emphasize the importance of data collection and analysis to improve understanding of energy poverty's scope and target interventions effectively. Collaboration and partnerships between government entities, energy providers, Non-Governmental Organizations (NGOs), and community organizations are encouraged to develop and implement sustainable solutions collaboratively. This collaborative approach is important for developing comprehensive and sustainable strategies to address energy poverty, ensuring that interventions are effective, equitable, and sustainable in the long term.

7. Conclusions

In conclusion, the study highlights the complex nature of energy poverty, which is influenced by a variety of drivers and manifests differently in developed and developing countries. The study also discussed the different definitions and indicators used to measure energy poverty and the challenges associated with these methods. As such, the study underscores the need for a comprehensive and nuanced understanding of energy poverty, considering the diverse drivers and manifestations of the issue, as well as the limitations and biases of different measurement methods.

When examining energy poverty, two main factors come into consideration. The first involves limited access to energy sources, stemming from factors like inadequate infrastructure or barriers preventing individuals or households from connecting to the electrical grid or obtaining energy through alternative means. The second aspect pertains to the inability to utilize modern energy resources due to financial constraints or other limitations that curtail general energy consumption. The significance and intricacy of energy poverty highlight the need for precise quantification, but devising solutions is typically complex and multifaceted. One potential approach to define and measure energy poverty involves the use of MEPI indicators, which represent a valuable method for understanding the outlined phenomenon.

A specific emphasis is required for the most impoverished regions and individuals, with a considerable number found in Sub-Saharan Africa. Efforts from different organizations can be directed towards alleviating the numerous deprivations that profoundly affect the well-being of low income people, aiming to reduce severe multidimensional poverty. This can be achieved by leveraging MEPI data, encompassing details such as MEPI values, the percentage of deprived individuals, the severity of their poverty, the overall count of people in poverty, and the composition of indicators.

Furthermore, the study demonstrated that energy poverty specifically has a significant impact on health, education, and gender quality, emphasising the critical need for effective policy interventions. While both developed and developing countries have made progress in addressing energy poverty through various policies and programmes, much more remains to be effectively implemented. As a result, future research could focus on determining the independent effect of energy poverty on education by developing a more robust methodology to determine the causal relationship between energy poverty and education, because as the old saying goes 'you can lead a horse to water, but you can't make it drink.' Education is key in solving the issue, not just more policy directions based on indicators. In sum, the real action urgently needed is education on energy efficiency and saving measures, true energy costs, energy and it's place in the environment and viable technology options considering SDGs and climate change targets.

CRediT authorship contribution statement

Dlzar Al Kez: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Aoife Foley:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Christopher Lowans:** Writing – review & editing. **Dylan Furszyfer Del Rio:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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