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OVERVIEW

A critical review of modern approaches for multidimensional energy poverty measurement

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Recent efforts to measure energy poverty more comprehensively attempt to redress the shortcomings of binary metrics that remain in common use. However, significant challenges remain both with the construction of the new measurement frameworks and their application. The paper presents an analysis of recent multidimensional measurement approaches and applications to draw inferences on the implications of applying these for the measurement of energy access and in informing policies aimed at improving it. The assessment suggests that despite progress having been made in capturing the multidimensional nature of energy poverty, the new measures are currently too complex to operationalize at the global level and too prescriptive to gain acceptance in diverse national contexts. Further efforts are thus required to consolidate and simplify the new frameworks for global tracking purposes, and to adapt and modify these to specific country contexts to inform national policy and planning. A subset of key energy poverty dimensions and uniform set of indicators need to be shortlisted for the purposes of global comparisons, while specific national tracking efforts can apply dimensions and thresholds most suited to accurately capture energy poverty and its drivers in a given context.

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1 | INTRODUCTION

Energy poverty is only one dimension of deprivation and insufficient well-being more broadly. But it is important in itself because of the significance of energy for sustainable development and moving people out of poverty (AGECC, 2010; Groh, 2014; Jannuzzi & Goldemberg, 2012; Pachauri & Brew-Hammond, 2012; Practical Action, 2010; UNDP, 2005; UNDP and WHO, 2009). Universal access to modern energy services is thus central today to the international sustainable development agenda, with it a critical development challenge in itself and strongly cross-cutting with other sustainable development objectives and goals (McCollum et al., 2018).

The accurate measurement and tracking of energy poverty is a key aspect of efforts toward improving access to modern energy services for all. Early attempts at capturing the multidimensional nature of energy poverty include the development of the so-called access-use framework (Pachauri, Mueller, Kemmler, & Spreng, 2004; Pachauri & Spreng, 2004). This early effort derived from the theoretical contributions of Amartya Sen's capability approach and the Rawlsian tradition of justice as fairness (Rawls, 1971; Sen, 1992). The framework normatively distinguishes between people having less than sufficient energy for cooking one to two meals a day and very limited lighting from those having more than that. The two-dimensional access-use framework was further collapsed to a single dimension by weighting the fuel access dimensions, to derive a single access-use energy poverty rate that forms one of several energy indicators for tracking sustainability in developing countries (Kemmler & Spreng, 2007).

Building further on Sen's capability approach, there have been encouraging developments in conceptualizing and acknowledging the multidimensionality of poverty (Alkire, 2002; Alkire & Santos, 2014), and energy poverty (Nussbaumer, Bazilian, & Modi, 2012; Practical Action, 2010, 2012), more recently. However, efforts to operationalize multidimensional measures more broadly have so far been limited. In part, this is due to the existence of a broad diversity of views on how to define energy poverty and lack of consensus on which dimensions to consider in measurement, analysis, and policymaking (Bazilian et al., 2010; Pachauri, 2011; Pachauri & Spreng, 2011). Rudimentary indicators, such as percentage of population with an electricity connection and using nonsolid fuels as a primary cooking energy source, continue to be employed as the key international metrics in regular use to distinguish the energy poor from the energy nonpoor and to track efforts to achieve energy access and poverty-related goals. The latest in a series of efforts to define and measure energy poverty more comprehensively is the World Bank's Multitier Framework for Measuring Energy Access (MTF; Bhatia & Angelou, 2015). This builds on previous efforts at more comprehensive energy poverty measurement developed over the last decade, such as the Total Energy Access (TEA) approach by Practical Action (2010, 2012) and the Multidimensional Energy Poverty Index (MEPI) by other authors (Nussbaumer et al., 2012; Nussbaumer, Nerini, Onyeji, & Howells, 2013).

Measuring energy poverty and energy access remains challenging, both because of a lack of consensus on definitions and sparse data on its underlying causes in different contexts. Here, we review recent efforts at operationalizing multidimensional measures of energy poverty that move beyond the binary indicators currently in use to track it. We do not attempt to undertake a comprehensive review of individual energy poverty and energy access measurement frameworks or metrics, as several recent reviews already exist (Bensch, 2013; Bhatia & Angelou, 2015; Culver, 2017; Groh, Pachauri, & Narasimha, 2016; Kowsari & Zerriffi, 2011; Nussbaumer et al., 2012; Trace, 2015). Instead, we review how the new frameworks define and measure distinct aspects of energy poverty and discuss challenges in their application. We focus particularly on household energy services, as these are the most developed in existing measures. This also reflects the predominant focus on household energy access in literature and policy.

In the following, we first discuss methodological advances and limitations of the recent measurement frameworks. We then go on to review some recent empirical applications of these new measurement frameworks in order to derive lessons regarding how accurately they capture energy poverty and their ability to inform policy and planning. We conclude that while the new frameworks are a significant enhancement to simple binary indicators, they need to distinguish measurement objectives for global tracking and comparisons, from those aimed at informing utilities and local planning processes. Each of these distinct objectives demands further refinements and revisions to the frameworks, which we discuss in this work.

2 | CHALLENGES OF MULTIDIMENSIONAL ENERGY POVERTY MEASUREMENT

Existing measures to monitor multidimensional energy poverty include, single indicators, composite indices as well as dashboards of multilevel indicators and indices. Despite differences, some commonalities in recent approaches include framing energy poverty in terms of energy services and distinguishing between different household services or end uses, such as cooking, lighting, and space cooling (Nussbaumer et al., 2012; Practical Action, 2010, 2012), acknowledging the importance of energy service needs beyond those of households for development, such as community lighting, health facilities, mechanical power (Bhatia & Angelou, 2015; Practical Action, 2013, 2014), and the focus on multiple dimensions as well as threshold levels or cutoffs for each of these used to identify the energy poor (Bhatia & Angelou, 2015; Nussbaumer et al., 2012). However, issues and challenges remain, including how best to define and measure energy services, which dimensions to focus on and how to set threshold levels in ways that can facilitate achieving desired development outcomes (including achieving a desired distribution of the outcomes). Finally, issues regarding how to combine different dimensions and levels into a single measure, that is, issues of aggregation and weighting are always contentious. In the following, we discuss these aspects in more detail and the degree to which existing measures deal with them.

2.1 | Definition and measurement of energy services

Existing literature on energy access and poverty recognizes that energy is valued not for its own sake but is rather instrumental to satisfying certain energy service needs such as a brightly-lit home, comfortable ambient air temperature, motorized mobility to one's place of work or education, and so on (Barnes, Khandker, & Samad, 2011; Bazilian et al., 2010; Goldemberg, Johansson, Reddy, & Williams, 1985; Pachauri & Spreng, 2004; Practical Action, 2010, 2012, 2013; Sovacool et al., 2012; UN Energy, 2005; UNDP, 2005). There are a myriad of ways energy serves to improve well-being and livelihoods and historical

TABLE 1 Definitions of basic energy services for human well-being

Year	Source	Basic energy service definition
1985	(Goldemberg et al., 1985)	Cooking, lighting, television, refrigeration, hot water, and clothes washer
2005	(UNDP, 2005)	Cooking, lighting, communications, water heating, refrigeration, water pumping, and transport
2005	(UN Energy, 2005)	Cooking, lighting, telecommunications, heating, motive power, mechanical power, and transport
2006	(Modi, McDade, Lallement, & Saghir, 2006)	Cooking, illumination and Information & Communication Technologies (ICT), appliances for household and commercial activities, and mechanical power
2012	(Practical Action, 2010, 2012)	Cooking and water heating, lighting, information and communications, space heating and cooling, and earning a living
2013	(Nussbaumer et al., 2012)	Cooking, lighting, services provided by means of household appliances, communication and entertainment
2014	(Bhatia & Angelou, 2014)	Cooking, lighting, entertainment and communications, space cooling and heating, refrigeration, mechanical loads, and product heating

definitions of basic energy services have often differed both in their scope and measurement. Table 1 provides an indicative list of definitions of basic energy services in literature. While these definitions reflect consensus that individuals can be energy poor in various aspects, they also reveal the historical lack of agreement on a normative set of basic energy services, which in turn has had repercussions for the development of a global measurement framework for multidimensional energy poverty measurement (Pachauri, 2011).

Among recent energy poverty measures, the MEPI defines basic household energy services as "cooking, lighting, services provided by means of household appliances, communication and entertainment" (Nussbaumer et al., 2012). It measures access to these through the use of proxy indicators derived from widely available Demographic and Health Survey (DHS; Figure 1). The use of proxy measures significantly reduces data collection costs but constrains the MEPI to measure only specific appliance ownership and physical access to specific energy carriers as those collected by the DHS surveys. As such, these proxy measures may not always be relevant in a given context, as also noted by the authors. This is because consumer preferences and cultural norms can have significant impact on energy service needs, appliances used to satisfy these needs, and consequently, energy demand and cost of delivery (Nussbaumer et al., 2012). The proxy measure for lighting, for example, inherently implies that household connection to an electrical energy carrier is sufficient to ensure reliable, affordable, and available lighting services[1] required in that context. The use of appliance ownership occurrence as a proxy measure assumes that ownership implies the ability to power the appliance reliably and affordably and thereby to satisfy desired energy service needs. The use of existing datasets to measure access to multiple energy services is a definite advantage of the MEPI. However, its inability to capture attributes of service, such as availability, reliability, and affordability is a shortcoming. We discuss some recent efforts at applying the measure and potential modifications made to enhance it in later sections.

In parallel with the development of the MEPI, pioneering efforts by Practical Action and the TEA framework developed by them (Practical Action, 2010, 2012), led to growing consensus on the need for a multitier definition for energy access. The development of a detailed tier-based approach within the MTF was a response to this demand and built further on these earlier efforts (Bazilian & Pielke, 2013; Bhatia, 2013; Bhatia & Angelou, 2014, 2015; World Bank; International Energy Agency, 2014). The MTF groups energy services in terms of electricity, cooking, and heating, while also drawing clear distinctions between energy service needs for household, productive and community end uses, proposing individual ordinal tier-based measurement matrices for each.

In the MTF, household electricity services are defined as follows: lighting, entertainment and communications, space cooling and heating, refrigeration, mechanical loads, product heating, and cooking. The measurement of electricity access through

Dimension	Indicator (weight)	Variable	Deprivation cut-off (poor if . . .)
Cooking	Modern cooking fuel (0.2)	Type of cooking fuel	Use any fuel beside electricity, liquefied petroleum gas (LPG), kerosene, natural gas, or biogas
	Indoor pollution (0.2)	Food cooked on stove or open fire (no hood/chimney) if using any fuel beside electricity, LPG, natural gas, or biogas	True
Lighting	Electricity access (0.2)	Has access to electricity	False
Services provided by means of household appliances	Household appliance ownership (0.13)	Has a fridge	False
Entertainment/education	Entenainment/education appliance ownership (0.13)	Has a radio OR television	False
Communication	Telecommunication means (0.13)	Has a phone land line OR a mobile phone	False

FIGURE 1 Multidimensional Energy Poverty Index dimensions and respective variables with cutoffs, including relative weights (in parenthesis) (Reprinted with permission from Nussbaumer et al., 2012 © Copyright 2012 Elsevier)

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Tier criteria	Not applicable	Task lighting Phone charging	General lighting Television Fan (if needed)	Tier 2 AND Any medium-power appliances	Tier 3 AND Any high-power appliances	Tier 4 AND Any very high-power appliances

FIGURE 2 Multitier Framework matrix for access to household electricity services (Bhatia & Angelou, 2015)

the MTF leans on the peak power requirements of selected bundles of typical appliances. These appliances are arranged in an ordinal framework as indicated in Figure 2, which describes the basis upon which the more detailed multitier matrix for household electricity supply is defined.[2] While the MTF does not explicitly measure ownership of appliances, the measurement of energy access through the implied ownership and usage of a set of typical appliances does play a significant role in establishing thresholds for dimensions such as peak power supply and activity levels used in establishing minimum daily energy supply thresholds. Earlier efforts in selecting typical appliances, energy carriers, and activity levels to develop engineering estimates of minimum energy requirements per capita[3] have proven informative (Barnes et al., 2011; Pachauri et al., 2004; Pachauri & Spreng, 2011). However, these results remain necessarily constrained to the national or regional context in which the analysis was conducted due to the country-specific differences in energy service needs and appliance availability. Noting these historical challenges, the reasoning behind the measurement of electricity services through a selection of typical appliances in the MTF could benefit from further empirical research into the potential heterogeneity of energy service, energy carrier, and energy conversion device preference in different national contexts.

The MTF matrix for measuring access to cooking solutions also consists of an ordinal framework with tiers distinguished by primary and secondary cooking stoves used in combination with the type of fuels combusted in these. Figure 3 depicts a simplified matrix within the MTF conceptualization report that indicates the distribution of access to modern cooking services across tiers. The inclusion of primary and secondary stoves in the framework is a welcome move as it explicitly acknowledges that many households stack stoves or in other words use multiple fuels and stoves. However, recent research reveals that other important energy-intensive end uses aside from meal preparation can exist (e.g., water heating, animal food preparation), which can necessitate stoves in addition to the one used to prepare meals. If these needs are not identified and are significant, intervention measures may not address them and use of polluting devices could persist (Lam et al., 2017). Given the wide variety of cooking stove and fuel combinations in use globally, the MTF's guidance on how a particular stove is to be allocated to a particular tier, and in the case of multiple stoves in use by a single household, how these can be assessed together to determine an overall tier rating of a household is insufficient. At minimum, clearer guidelines on these allocation rules would be useful to national planners to avoid subjective interpretation and application of these, particularly since actual measurement of air quality in kitchens is unlikely to be part of regular data collection efforts.

As regards other energy services in energy access measurement, the TEA framework was the first to integrate productive use energy (PUE) services as a totally separate category (Practical Action, 2010, 2012). The MTF has built on this further, separating energy access for productive engagements and community facilities into distinct measurement indices (Bhatia & Angelou, 2015). The challenge of measuring access to energy services across a diverse array of productive engagements is tackled through assessment at the individual level, specifically, earning members of a household. The MTF defines electricity

HEALTH	LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
Primary cookstove Should have been formally tested and found to meet the required cookstove performance on indoor pollution AND Can be visually identified for performance using stove type, brand, or labeling	Untested three-stone fire, home-made stove, mud/earthen ring	Primary solution has met Tier 1 of generalized form of multitier indoor emission standards Potentially improved cookstoves but either untested or cannot be visually identified	Primary solution has met Tier 2 of generalized form of multitier indoor emission standards	Primary solution has met Tier 3 of generalized form of multitier indoor emission standards	Primary solution has met Tier 4 of generalized form of multitier indoor emission standards OR Cookstove using biogas, LPG, ethanol, or natural gas	Primary solution has met Tier 5 of generalized form of multitier indoor emission standards OR Electric or solar-based cookstove
Secondary cookstove		Any inferior secondary solutions are used for <20% of the cooking time, else shift one level below				Only BLEENS are used

Note | BLEENS = Biogas, LPG, etlmol, elcc/Ticily, natural gas, and solal.

FIGURE 3 Excerpt of the Multitier Framework matrix for measuring indoor air quality: Rough and conservative approach. (Bhatia & Angelou, 2015) access for community services across five different types of facilities and follows a similar measurement matrix to that for household electricity access. Notably both the access to energy for productive engagements and community facilities measurement matrices are silent on access to mobility and the energy services this requires, as these are considered public services or run by private operators that currently do not have a direct linkage with improving energy access (Bhatia & Angelou, 2015). Inadequate access to mobility has been highlighted as being particularly onerous on the poor and there have been earlier calls to include it in energy poverty metrics (Sovacool et al., 2012). Yet, there is little in the literature on ways to measure mobility poverty. A recent review, however, discusses indicators related to transport affordability, mobility, accessibility, and environmental justice that have been applied in different settings (Lucas, Mattioli, Verlinghieri, & Guzman, 2016). These could serve as a starting point to develop a measurement framework for access to energy for mobility services, which have clear implications for well-being and livelihoods.[4]

In summary, it is now widely recognized that a measurement framework must encompass energy services pertaining to household, community, and productive uses in order to accurately capture the range of needs that must be fulfilled to address energy poverty (Bhatia & Angelou, 2015; Nussbaumer et al., 2012; Practical Action, 2010). Both the MTF and the MEPI tackle this challenge in different ways, each with its own strengths and weaknesses. The measurement of access to electricity services based on a normative set of basic appliances; determined either through detailed surveys or secondary data, could benefit from further research on energy service preference and energy demand heterogeneity. Similarly, measuring access to cooking energy services requires a further refinement and clarity on how to designate primary and secondary stoves and end uses beyond meal preparation in vastly different environmental and socioeconomic contexts. At the minimum, assumptions made regarding the selection of typical appliances, end uses, and fuels and the resulting measurement within each framework should be transparently communicated. This can enable researchers, analysts, and national energy planners to select the most appropriate measurement framework for their requirements as well as review and improve the subjective aspects of a framework as the general understanding of energy service needs in a given context improve.

2.2 | Defining dimensions and thresholds for achieving desired development outcomes

The multidimensionality of energy poverty is now widely recognized, such that, alongside the continued prevalence of energy consumption, recent metrics consider more detailed dimensions including availability, reliability, affordability, quality, and safety. Nevertheless, there is still no consensus on which dimensions and thresholds are considered necessary for the measurement of energy poverty and tracking of desired development outcomes.

The Energy Supply Index (ESI) was the first ordinal framework to propose dimensions of energy supply, doing so on a largely qualitative basis (Practical Action, 2010, 2012). The ESI is split across household fuels (referring to cooking), electricity, and mechanical power, each having six quality levels (0–5). The household electricity supply measurement component is shown in Table 2. Although the dimensions of quality, intermittency, and reliability are mentioned within the framework, they are not explicitly defined, requiring subjective interpretation during the collection and analysis of data. This lack of clarity in the definition of chosen dimensions, while enabling some level of contextual adaptation, presents challenges in meaningful comparison of energy poverty over time and across countries and has thus far not found wider application.

Building on Practical Action's pioneering work, the MTF links the definition of energy services with a selection of typical appliances and finally detailed dimensions and thresholds[5] arranged into ordinal measurement matrices (Bhatia & Angelou, 2015). Each of the matrices for supply of energy, or access to household energy service, provides thresholds for seven dimensions distinguished across six tiers (Tier 0–5). Selected dimensions for household electricity supply and cooking solutions as defined by the MTF[6] are illustrated in Table 3.

The dimensions of peak capacity and availability in the electricity supply matrix and of indoor air quality (IAQ) and cookstove efficiency in the cooking solutions matrix are the most developed within the MTF in quantifying distinct thresholds to distinguish among tiers. A closer analysis of peak capacity reveals that this dimension is defined by a normative set of fixed appliance efficiency levels. This is illustrated in Table 4 below, which depicts the peak power consumption of specific electric

TABLE 2 ESI household electricity supply index—Excerpt from (Practical Action, 2012)

Level	Quality of supply
0	No access to electricity at all
1	Access to third party battery charging only
2	Access to stand-alone electrical appliance
3	Own limited power access for multiple home applications
4	Poor quality and/or intermittent connection
5	Reliable connection available for all uses

TABLE 3 Multitier Framework electricity supply and cooking solutions dimensions (Bhatia & Angelou, 2015)

Electricity supply	Cooking solutions
Peak capacity	Indoor air quality (IAQ)
Availability	Availability of primary fuel
Reliability	Cookstove efficiency
Legality	Convenience
Health and safety	Safety of primary cookstove
Affordability	Affordability
Quality	Quality of primary fuel

appliances as defined by the MTF. While these efficiencies may have been reasonable at the time of development, the rapid pace of technology innovation raises the question of whether tying energy access measurement to a universal set of appliances and stagnant efficiency levels can remain useful in mid to long-term electricity access planning and across vastly different contexts of implementation.

The constraints of appliance-based peak electricity supply thresholds are removed below Tier 3 through an "or" clause that recognizes the ability for high-efficiency appliances to deliver equivalent electricity services at lower peak loads. Justification for including such a clause only at the first two tiers of energy access is not provided and may reflect the lack of consensus on what energy services are needed next (after satisfying lighting, communications [mobile phone], space cooling [fan], and entertainment [television]) or a pragmatic decision based on the lack of information on the diffusion of high-efficiency appliances in developing economies. In either case, the need for further evaluation of fixed appliance-based electricity supply thresholds is apparent.

The availability dimension in the electricity supply matrix is similarly detailed and refers to the daily duration of supply, distinguishing between total daily hours and evening hours of supply. While availability is broadly recognized as a critical aspect of energy supply, both the distinction of supply in the evening and across the tier thresholds have not found consensus (Aklin, Cheng, Urpelainen, Ganesan, & Jain, 2016; Groh et al., 2016; Jain, Urpelainen, & Stevens, 2016). The contextual nature of minimum daily and evening duration of electricity across tiers of supply could be further explored through an analysis of electricity service time-of-use in a given context and may benefit from simplification if used in the context of global-level tracking, as will be discussed later in this paper. In either case, further research into defining appropriate thresholds for this dimension is desirable.

Within the cooking solutions matrix, the tier thresholds are set to be consistent with WHO's IAQ guidelines that are based on an assessment of the health risks associated with exposure to cooking-related emissions (WHO, 2014). This consistency with the WHO IAQ standards as well as the cookstove performance standards developed by the International Workshop Agreement (IWA) is a definite advantage of the approach. However, in fact only the top Tiers 4 and 5, as defined in the

TABLE 4 Electricity supply requirements for electricity services – Excerpt from (Bhatia & Angelou, 2015)

Electricity service and appliance	Power
Lighting	
Task lighting	6 W (min 1 W)
General lighting	12 W
Information, communication, and entertainment	
Radio	4 W (min 2 W)
Phone charging	4 W (min 2 W)
Television	40 W (min 20 W)
Food preservation	
Refrigeration	300 W
Mechanical/thermal load	
Food processor	200 W
Iron	1,100 W
Hair dryer	1,200 W
Water pump	500 W
Cooking and water heating	
Rice cooker	400 W
Water heating	3,500 W

framework are consistent with IAQ standards that significantly reduce the health risks of cooking emissions. Furthermore, guidance on how to operationalize the measurement of IAQ is less developed. The MTF proposes three potential approaches—through direct measurement; mathematical modeling using information about household characteristics, cooking stove type, and practices; or through a broad categorization of cookstove types and assumptions about cooking practices. However, given the difficulty and cost involved in the first two approaches, the third is the only one that has been applied in an empirical setting (Jain et al., 2016; Nerini, Ray, & Boulkaid, 2017). Further guidance on dimensions that can serve as proxies for IAQ would in this instance be desirable for aiding in the operationalization and application of this matrix.

The inclusion of normative thresholds for reliability, legality, and quality dimensions are difficult to capture through respondent surveys and have struggled to find consensus due to the widespread variance in politically and socially acceptable levels of disruption to supply in different country contexts (Aklin et al., 2016; Tait, 2017). Health and safety is also found to be especially challenging to accurately capture, relying on subjective respondent recall of prior incidences, which may not accurately reflect the real nature of current risk to health and safety due to energy supply, especially in the case of fuel stacking (Tait, 2017).

Finally, despite being a key decision factor in most energy access interventions, Affordability is not considered below Tier 3, and only rudimentarily defined above. The usage of a fixed share of household income as the denominator in an affordability dimension has received extensive criticism in the European context (Thomson, Bouzarovski, & Snell, 2017), while representing an even larger challenge in developing economies as it disregards the nonmonetary aspects of energy service acquisition costs due to lack of household market integration (Pachauri & Spreng, 2004). In many poor farming communities, asset or wealth indices might serve as a better denominator for measuring affordability than income or expenditures. The dimension in its current form does not capture the cost of energy services at lower tiers of energy supply in different environmental, cultural, and economic contexts, nor reflect the true cost of energy services (including the acquisition of appliances) at higher tiers of energy supply, which can have a significant impact of appliance acquisition and thus access to modern energy services (Pachauri, Scott, Scott, & Shepherd, 2013; Winkler et al., 2011).

Despite this broad criticism, it should be noted that dimensions and thresholds of the MTF in its current form have multiple levels of functionality. At the highest global tracking level, a normative set of dimensions and thresholds is almost certainly necessary to enable meaningful analysis and comparison of global progress toward SDG7 over time. However, an analysis of individual dimensions of the electricity supply and cooking solutions measurement matrices quickly shows that the complexity of dimensions as currently described by the MTF may create methodological challenges in their application that may not be necessary for this level of analysis. In contrast, recent efforts to understand factors influencing satisfaction with electricity supply have revealed the contextual nature of perceived importance of dimensions of household electricity supply measured by the MTF (Aklin et al., 2016). Clearly, a careful evaluation of pertinent dimensions and thresholds is needed for application in both global tracking and national or regional level energy planning.

2.3 | Aggregation and weighting

Despite widespread recognition of the multidimensional nature of energy poverty, aggregate indices continue to be favored at the global tracking level due to their simplicity and ease of communication (International Energy Agency (IEA) and World Bank, 2015, 2017; World Bank; International Energy Agency, 2014). This holds even for recently developed goals, such as SDG7. The nature of the aggregation and weighting remains a contentious topic, providing fertile ground for debate between the detail necessary for effective policy development and complexity of the measurement framework. Despite the prevalence of aggregate indices in policymaking, the use of these alone has drawn extensive criticism, specifically in their inability to capture trends at the community and household level necessary for effective policy development (Broto et al., 2017; Groh et al., 2016; Jain et al., 2015; Kowsari & Zerriffi, 2011; Practical Action, 2010, 2012; Tait, 2017). Moreover, as different dimensions of energy poverty and the respective interventions necessary to achieve specific development outcomes are unlikely to be substitutable, construction of any overall index or score should make very transparent the criteria for aggregation and weighting. In a significant step forward, most recent measurement frameworks capturing multiple dimensions of energy poverty propose a composite or hybrid approach, evaluating disaggregate data alongside aggregate indices.

In order to quantify the total energy poverty caused by deprivation in specific dimensions of energy access, individual dimensions of the MEPI are weighted as shown in Figure 1 based on a normative evaluation of their relative importance (Nussbaumer et al., 2012). The author's note that the weighting of individual dimensions of energy poverty described during the conceptualization of the MEPI is intended for demonstration only and must be evaluated for a given national context. Normative weights may draw from an empirical evaluation of consumer preference, global guidelines of basic energy service needs or reflect expert judgment of the analyst. As such, this aspect of the MEPI can make comparison across different studies challenging, as will be discussed later in this paper. In a reflection of its methodological roots within the Multidimensional Poverty Index (MPI; Alkire & Santos, 2014), the aggregate MEPI is designed to capture both the rate and intensity of energy poverty.[7] However, analysis of the aggregate alone may result in masking certain aspects and causal linkages and combining those that are not necessarily substitutable and that may require drastically different interventions, such as cooking and lighting. This strengthens the argument for evaluation of the MEPI aggregate alongside disaggregate data as demonstrated in recent applications, which we discuss later in this paper. Although the availability of the data necessary to determine the MEPI aggregate reveals its usefulness as an index to measure relative changes and trends in multidimensional energy poverty across the globe, the lack of empirical evidence or methods for the selection of proxy measures and individual weighting factors for each indicator reveals its vulnerabilities if used as a measure of absolute energy poverty in a given context.

The MTF in contrast does not define normative weights for each dimension of energy poverty, rather, the final energy access tier for each household is selected based on the lowest performing dimension (Bhatia & Angelou, 2015). A gap analysis to support policymaking is also proposed through a comparison of the lowest performing dimension, which is estimated as a simple average aggregate, across a given population. Such an approach avoids the methodological challenge faced by normative aggregates such as the MEPI as discussed above but raises the question of whether all dimensions can really be considered equal. For instance, the question of which specific dimensions a household needs to be deprived in to be considered multidimensionally energy poor is not really addressed on the basis of this current rule. This rule thus risks ignoring heterogeneity in attribute preference or collinearity between dimensions at the household level, which recent research suggests might be significant. This suggests that further work is needed to determine the appropriateness of this rule (Aklin et al., 2016; Baquié & Urpelainen, 2017; Urpelainen, 2016).

The MTF additionally proposes the aggregation of the distribution of tiers across a population into a single cardinal Access Index through weighting of tiers such that the Access Index $AI = \sum_{k=0}^{5} (20 \times P_k \times k)$, where P_k represents the proportion of population at Tier k (Bhatia & Angelou, 2015). The Access Index aggregate shown here distributes linearly increasing weights for each tier; *Weight Tier k* = 20*k*, such that *Weight Tier 1 = 20* and *Weight Tier 5 = 100* in order to preserve the ordinal nature of the tier-based distribution of a population in the cardinal Access Index aggregate. That is, it is assumed that moving from Tier 0 to Tier 1 (and gaining the respective energy services defined in these tiers) has the same absolute impact on energy access and by extension multidimensional energy poverty in a given context, as moving from Tier 4 to Tier 5 (and gaining access to the respective energy services this entails). Or, that moving from Tier 0 to Tier 4 is considered twice as beneficial as moving from Tier 0 to Tier 2. The problem with the implicit weighting of energy services underlying this assumption is noted by the authors, stating that an evaluation of weights assigned to each tier should be conducted at the national level (Bhatia & Angelou, 2015). However, a method describing how this should be done has yet to be developed.

In summary, aggregation is a necessary method by which to communicate complex interlinkages across several dimensions of energy poverty and enable goal setting beyond binary metrics. However, the trade-offs and methodological vulnerabilities of these aggregate indices should be made transparent and open to debate in both global and national contexts (Table 5). An analysis of the state of art across recent multidimensional energy poverty frameworks reveals the need for

TABLE 5 Summary of similarities and differences across multidimensional energy poverty measurement frameworks

	TEA/ESI	MEPI	MTF
Definition	The ESI separates energy supply across fuels, electricity, and mechanical power needs. The TEA combines electricity, cooking, and heating/cooling services into one matrix.	Evaluates deprivation across a normative set of basic household energy service needs.	Separates energy services across household, productive and community needs as well as electricity, cooking, and heating services.
Measurement	Requires detailed survey data. The ESI links energy supply with binary access to energy carriers and capabilities. The TEA links energy access to corresponding fuel consumption and capabilities.	Uses available DHS survey data. Relies on proxy measures including appliance ownership and binary access to energy carriers.	Requires detailed survey data. Establishes a strong link between energy service measurement and appliance/stove ownership.
Dimensions	The ESI does not explicitly describe dimensions of energy supply, whereas the TEA defines a unique set of dimensions for each energy service.	Does not describe specific dimensions or attributes.	Defines uniform dimensions (attributes) across each measurement matrix.
Thresholds	The ESI provides largely qualitative tier-based thresholds (0–5) for energy supply based on access to energy carriers and capabilities. The TEA establishes distinct qualitative and quantitative minimum thresholds for access to specific energy services.	Establishes the multidimensional energy poverty cutoff *k* used in aggregation.	Provides largely quantitative tier-based thresholds (0–5) based on a selection of typical appliances for electricity, and indoor air quality of stoves for cooking.
Aggregation	Encourages a disaggregate analysis of both TEA and ESI.	Uses normative weighting for household-level aggregation alongside the cutoff *k*. Suggests a simple average aggregate for a gap analysis of energy service deprivation across a population.	Uses a "worst-performing" dimension rule for ordinal aggregation at the household level and for gap analysis across a population. Suggests linear conversion of ordinal framework into cardinal Access Index across a population.

Note. MEPI, Multidimensional Energy Poverty Index; MTF, Multitier Framework; TEA, Total Energy Access, ESI, Electricity Supply Index.

further work into the selection of suitable aggregation methods and strengthens the argument for presentation and analysis of disaggregate data alongside aggregate indices.

3 | LESSONS FROM RECENT APPLICATIONS OF MULTIDIMENSIONAL METRICS

Capturing the relationship between energy and development and more broadly the state of energy poverty in a meaningful manner requires an analysis of trends, risks, and vulnerabilities at the household and community level (Barnes et al., 2011; Kowsari & Zerriffi, 2011; O'Sullivan & Barnes, 2007; Pachauri & Spreng, 2011). Although theoretical definitions of energy poverty have highlighted the multidimensional link between energy and broader development goals for several decades (Goldemberg et al., 1985; A. K. Reddy, 2000; UNDP, 2005), operational energy poverty measurement frameworks have historically relied on binary metrics for evaluating an inherently multidimensional concept.

Recent developments in multidimensional energy poverty measurement, such as the MEPI and MTF, are starting to close the gap between operational and theoretical definitions of energy poverty. Methodological advances in defining several dimensions of energy poverty, such as affordability and availability are getting closer to capturing more nuanced theoretical aspects. However, differences in the operational and theoretical definitions of energy poverty remain. Advances such as the refinement of the capabilities approach toward improving the definition of energy poverty (Day, Walker, & Simcock, 2016), the ongoing development of Decent Living Standards (N. D. Rao & Min, 2017), and the proposed decoupling of human need satisfaction and energy use (Brand-Correa & Steinberger, 2017) suggest that individual dimensions of energy poverty, such as those captured by the MTF, may be intrinsically linked and therefore cannot be assessed in isolation. These theoretical advances call for the introduction of indicators that do not necessarily require the selection of specific energy carriers and appliances or the quantification of energy consumption to evaluate necessary capabilities for human well-being. Naturally, such developments outpace operational definitions, however, their influence on independent applications of modern multidimensional energy poverty measurement frameworks can be seen. Here, recent applications of multidimensional metrics are analyzed in order to draw conclusions on their ability to capture energy poverty accurately, their relevance and meaningfulness in policy and planning, and the challenges of implementation and data gathering.

3.1 | Capturing energy poverty accurately

Most independent applications of the MEPI concentrate on comparing and contrasting the multidimensional energy poverty assignment with various demographic variables and groupings similarly derived from existing datasets. Examples of these are societal (caste) groups, employment, education, gender, housing, health, and income (Ogwumike & Ozughalu, 2016; Sadath & Acharya, 2017; Sher, Abbas, & Awan, 2014). Contextual modifications to the weighting used in derivation of the aggregate MEPI have been carried out and can vary significantly from those provided in the original conceptualization of the MEPI. However, no consensus has been reached on a standard methodology or the theoretical framework underpinning their selection, making comparison across different studies challenging and sometimes impossible without redoing the analysis itself. While these applications demonstrate the wealth of analysis that is possible through the correlation of both the MEPI aggregate and disaggregate indicators to various potential explanatory factors, they also highlight the limitations of the MEPI in terms of identifying causal relationships between multidimensional energy poverty and the underlying correlates studied. That is, they show that it is possible to compare populations segments in terms of their ownership of specific appliances and access to energy carriers (in a disaggregate MEPI analysis) or to compare the overall multidimensional energy poverty level across several regions (through the MEPI aggregate). However, they also suggest that it is far more challenging to determine the cause of this level of energy poverty and translate this into recommendations for policy intervention and planning. Furthermore, issues such as the relevance and representativeness of employing dated datasets and correlation of proxy measures with true access to the final energy service for a household remain contentious.

A recent application of the MEPI in the Kenyan context discusses these challenges and proposes novel modifications to various indicators within the MEPI, such as the inclusion of Pico Solar Products as proxy measures for access to lighting and the incidence of fuel stacking as a proxy measure for cooking services (Olang, Esteban, & Gasparatos, 2018). The study also highlights the value of including additional dimensions for fuel or technology preference evaluation in addition to segregating the population through typical MEPI proxy measures in order to provide a more comprehensive analysis of possible determinants of the current level of household energy poverty. In a step forward, the authors discuss the challenge of solely occurrence-based (e.g., appliance ownership) evaluation that may fail to capture other important dimensions that impact multidimensional energy poverty, suggesting the need for research into the inclusion of new indicators such as the stability of the energy supply into the MEPI aggregate.

The largest publicly available primary data collection exercise dedicated to measuring energy access with the MTF conducted surveys at 8,566 Indian households from selected states in India (Jain et al., 2015, 2016). In this study, significant deviations have been made to the standard MTF approach, both in terms of dimension and tier threshold definitions as shown in Figure 4, as well as in the nature of survey questionnaire. The study concluded that the number of tiers should be reduced to just four out of the proposed six tiers since a finer differentiation was not considered to add any value in the Indian context. The authors also used subjective responses in lieu of objective thresholds when deemed necessary, reflecting the operational challenges of collecting the level of detailed data from survey respondents required by the MTF in its current form. An important finding of this application reveals that of the households placed in Tier 0, nearly 50% have an electric grid connection, highlighting the strengths of a disaggregate analysis enabled by the MTF in revealing the inadequacy of connection-based binary metrics predominantly used in global policy discourse.

A similar digression was undertaken in a study in South Africa (Tait, 2017), using subjective self-assessment as a complimentary evaluation tool, especially for the measurement of more complex dimensions such as affordability. In order to ensure suitability of the measurement framework for the local context, the dimensions were conceptualized in this case to represent the capabilities of the household to achieve certain standards instead of access to a particular appliance or energy carrier. The reasoning being that this helps to better capture the multifunctional nature of some energy services and energy carriers in their daily use in the South African context, where 'a focus on particular services or fuels may miss implications for others' (Tait, 2017). This application highlighted the dangers of aggregation in failing to capture the multidimensional nature of energy poverty, expressly rejecting the development of a single value to represent multiple dimensions. The study also found households of different size but similar median incomes showed dramatically different consumption levels and deprivations in different dimensions, highlighting the challenge of using household-level consumption-based metrics in evaluating energy poverty. Finally, while recognizing the importance of cross-country comparisons, the study strongly argues for assigning tier performance along a continuum rather than predefined thresholds based on the notion that each "particular context influences both how an indicator is conceptualized, as well as the choice of methods to operationalize it" (Tait, 2017).

These applications highlight the strengths and vulnerabilities of aggregate and disaggregate analysis using modern measures for capturing multidimensional energy poverty. Most recent applications underline the need for contextual adaptation and support the argument for the development of national tracking frameworks in order to capture the contextual drivers of energy poverty. The Global Tracking Framework (GTF) under SE4ALL promises to provide a wealth of data through the application of the MTF toward energy poverty evaluation and national energy planning under the World Bank's Access Investment Model through several benchmark studies currently being undertaken in over 15 countries around the world, (International Energy Agency (IEA) and World Bank, 2015, 2017). Recently released corresponding datasets will be incredibly valuable for the continued development and adaptation of modern measures to accurately capture energy poverty and its drivers within a given national context.

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Health and safety / Indoor air quality						
Indian framework	Only traditional fuel used	Mix of traditional fuels and nonsolid fuels (gas/elec)		Cook with gas/elec only		
World Bank		Still to be defined			<35 PM2.5 (µg/m3) <7 CO (mg/m3)	<10 PM2.5 (µg/m3) <7 CO (mg/m3)
Convenience						
Indian framework	Both difficult to use and time consuming		Either difficult to use or time consuming	Neither difficult nor time consuming		
World Bank			Tiers based on stove preparation and fuel acquisition and preparation time			
Affordability						
Indian framework	Not affordable		Affordable			
World Bank					Levelized cost of cooking solution (cookstove and fuel) <5% of household income	

Note: PM2.5 (µg/m3) is a measure of the amount of a particular size of particulate matter in the air; CO (mg/m3) is a measure of the concentration of carbon monoxide.
Affordability: The Indian framework uses 6% of household income as the affordability limit and only considers running costs

FIGURE 4 Comparison of the modified Multitier Framework for access to cooking energy services in India (Reprinted with permission from Jain et al., 2016 © 2016 Copyright Practical Action Publishing)

3.2 | Applicability, data needs, and relevance for policy and planning

As global efforts toward alleviating energy poverty by 2030 gather momentum, the role of measurement frameworks to provide accurate, tangible empirical evidence to support policy and planning is growing increasingly important (Bhanot & Jha, 2012; Pachauri et al., 2013; B. S. Reddy, 2015). Among the recently developed multidimensional metrics, the MTF has been most widely applied in energy planning and modeling. It has also been adopted in several SE4ALL Action Agendas, reflecting the shift away from solely grid-connection-based goal setting. This is driven by the strength of the multitier approach in simplifying and characterizing electricity demand across a set of dimensions and thresholds. This, in turn, supports the selection of least-cost electricity generation and distribution technologies for a given settlement, region, or country.

The characterization of electricity demand and supply beyond binary indicators has also led to significant advancement in geospatial electrification modeling and planning tools, enabling both public and private stakeholders to make use of spatially visualized electricity generation technology mixes and access strategies in their decision-making processes (Dagnachew et al., 2017; Mentis et al., 2015; Mentis et al., 2017; Moksnes, Korkovelos, Mentis, & Howells, 2017; Nerini et al., 2016; Nerini, Dargaville, Howells, & Bazilian, 2015; Practical Action, 2016, 2017). In contrast to electricity access, however, the multitier measurement framework for cooking services has been largely used to set a minimum tier target in the SE4ALL Action Agendas, with some use in the development of least-cost cooking energy service models and cooking technology selection (Nerini et al., 2015; Nerini et al., 2017; Practical Action, 2016, 2017). These exercises have been limited to cooking services for meal preparation alone, reflecting the ongoing challenge of characterizing cooking and heating end uses and demand, quantifying nonmarket costs and selecting appropriate least-cost technologies in a given context. The remaining metrics for community and productive energy use are yet to see broader application in the context of energy access planning and policy development.

In the context of global tracking, the GTF proposes a simplified three tier matrix as shown in Figure 5 (World Bank; International Energy Agency, 2014). This simplified matrix focuses on characterizing access in terms of household energy generation technology access and does not capture or communicate the different attributes or dimensions of energy access. While this represents an improvement over the binary indicators used in global tracking of SDG7.1, the wider adoption of this simplified matrix in global tracking has yet to been seen. Some might argue that the exclusion of affordability and reliability/availability attributes of energy service supply in this simplified framework might limit its usefulness, given that these attributes characterize observed energy poverty in many regions of the globe.

Metrics must seek balance between accuracy and meaningfulness of a measurement framework, and the cost and ease of the corresponding data collection and analysis methods. Using readily available DHS data, as required by the MEPI, is certainly cost-effective, but the lack of its application in policy development and energy planning highlights the need for further research to overcome challenges in its usage beyond correlation and trend analyses. In contrast, carrying out dedicated surveys that collect information on different dimensions and drivers of energy poverty, as required by the MTF, is certainly desirable for improving data quality and availability. However, undertaking such surveys regularly and for a large sample of countries is financially expensive and administratively challenging. Additionally, local policy priorities and contextual realities will naturally create strong incentives to adapt detailed and prescriptive frameworks. Progress in characterizing energy demand and supply technologies to support national energy policy development and planning through a multitier approach must now be mirrored in efforts toward evaluating which dimensions and thresholds are most suitable to accurately capture energy poverty and its drivers in a given context. Alongside national efforts toward adaptation, clearer guidelines on which indicators are deemed suitable and necessary for global comparisons and what feasible survey instruments for data collection might be applied are necessary.

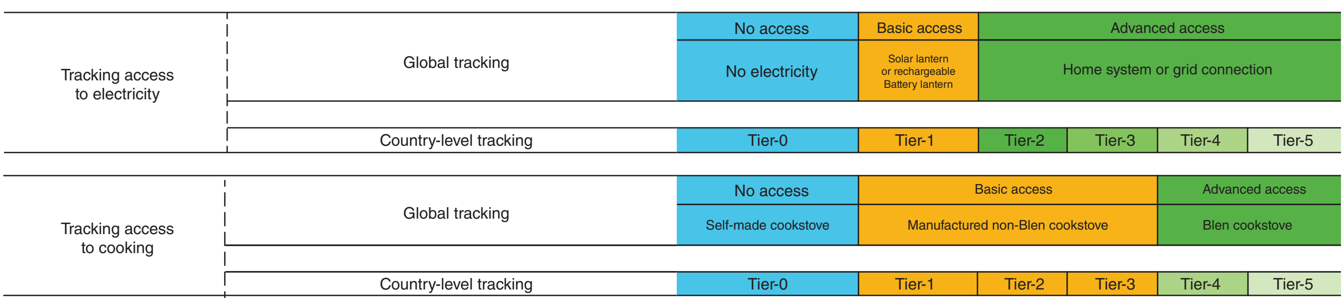

FIGURE 5 Tracking access at global and national levels (World Bank; International Energy Agency, 2014)

3.3 | Potential improvements and future research needs

Measures to track energy poverty are needed for both benchmarking progress toward global development goals, as well as providing a deeper understanding of the drivers of energy poverty, which are likely to be context specific (Best, 2013; N. Rao & Pachauri, 2017; Riva, Ahlborg, Hartvigsson, Pachauri, & Colombo, 2018). In order to improve on the status quo, we argue that it is necessary to distinguish between measurement objectives for broader development goal tracking needs such as for SDG7, and contextually defined national energy planning requirements. Following a separation of measurement objectives between the global and national tracking levels, we propose an alignment of the respective measures such that an appropriate balance between effort and detail is achieved for both levels of tracking, as shown for electricity access in Figure 6.

In order to enable global-level tracking beyond binary indicators, the MTF could be simplified to a standard set of globally uniform dimensions, thresholds, and tiers that each country-specific national-level tracking framework must provide in order to ensure international comparability. The simplification of the framework, data requirements, and clarification of survey methods may then enable smoother integration into existing country-level survey processes, such that each country-specific national-level tracking framework would generate the same data subset that is used at the global tracking level. National energy planners could then have the freedom and responsibility to develop a suitably complex, politically and socially acceptable national tracking framework based on their needs, while still reporting standard dimensions for global tracking and comparison.

This is in itself an incredibly complex challenge, where the MTF in its current form could be seen more as a toolbox of potential dimensions and suggested thresholds that can be selected depending on which are most applicable to capture the real nature of energy poverty for the given tracking objective. Methods to improve the selection of relevant dimensions within a global or national context may draw from a contextual understanding of user needs, demographic, geographic, and environmental factors (Aklin et al., 2016; Baquié & Urpelainen, 2017; Graber, Narayanan, Alfaro, & Palit, 2018) or from a theoretical understanding defining normative measurement dimensions and minimum thresholds below which the benefit or developmental impact of the energy service is not met (Day et al., 2016; N. D. Rao & Min, 2017). In all likelihood, a combination of such approaches will be necessary to achieve consensus for global tracking indicators and developing suitable national multidimensional energy poverty measures.

Finally, it has been argued that any effort to capture energy poverty must include a conceptual approach of energy vulnerability, implying a certain degree of poverty mobility in the energy access space (Bouzarovski & Petrova, 2015). Downward mobility can be triggered by political interventions, most obviously through a cut in subsidies as shown in the case of liquefied petroleum gas (LPG) subsidies in Brazil (Lucon, Coelho, & Goldemberg, 2004), but also based on seasonal effects of renewable energy solutions, price volatility of fossil fuels, or aging effects and lack of maintenance of existing energy service systems leading to a worsening service supply. Multidimensional energy poverty metrics such as the MTF could evolve appropriate tools to take these dynamics into consideration if their continuing applicability can be proven. Such an analysis inherently requires ongoing data collection and evaluation over time at the disaggregate level to capture the dynamics of energy poverty, and risks and vulnerabilities at the household level. No doubt ongoing data collection efforts through bespoke

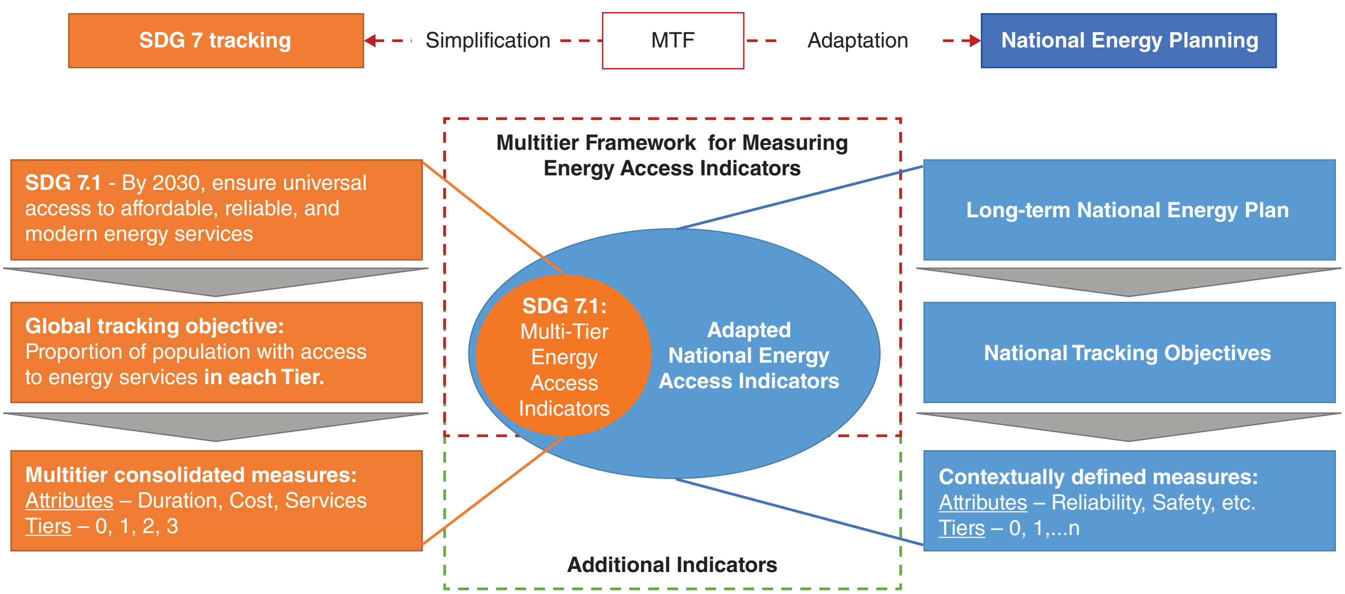

FIGURE 6 Modifying the multitier framework for distinct global tracking and national planning purposes

surveys being rolled by the World Bank and MTF developers will reveal lessons and insights that result in further improvements to the frameworks over time.

4 | CONCLUSION

The measurement of energy poverty is fundamental to shaping ideas on appropriate policies for addressing it. Advances in multidimensional energy poverty measurement, most recently with the development of the MTF, represent a significant leap forward from the predominantly binary perception of energy poverty in global policy discourse and national energy planning. Although global tracking indicators such as those for SDG7, as well as national energy planning measures remain largely constrained to binary metrics, the MTF provides strong evidence and methodological support for moving this rhetoric forward. At the same time, the level of detail proposed through the MTF can be critiqued on two fronts, it is both too complex to operationalize at the global tracking level, and too prescriptive to gain acceptance in national energy planning. It is here that a distinction between measurement objectives might prove useful. At the global tracking level, some form of consolidation is necessary to simplify the measurement framework while retaining its meaningfulness. At the same time, adaptation of measurement dimensions and thresholds is necessary in order to truly capture the nature of energy poverty and develop policy and planning strategies to increase access to modern energy services in a specific country context. In some way, this has already been discussed in the conceptualization report of the MTF, describing different levels of application of the framework and corresponding survey requirements, however, the discussion falls short of expressing concrete steps toward a separation of these measurement and tracking objectives and what is required for each.

While the selection of a representative set of basic household energy services seems to be reaching consensus with the MTF, accurate measurement of access to these energy services at the global level and their link to national development goals within a given context requires further work. These challenges find parallel in the analysis and measurement of basic needs and estimation of minimum requirements for general welfare improvements. Much can therefore be learnt from debates about how basic needs are defined and estimated in other domains, and the mix between objective measurement and elicitation of subjective needs to determine these. Inherent in the choice of these methods lies the social and ethical philosophy underpinning them. Introducing a sufficient degree of simplicity to enable the integration of global tracking metrics into existing surveys such as the DHS and Living Standards Measurement Surveys (LSMS) and providing necessary freedom to choose a set of contextual dimensions that can be adapted by national planners and implementers, could enable the alignment of both global and national tracking frameworks toward broader development goals. Nonetheless, unless mandatory data collection requirements within multidimensional energy poverty metrics such as the MTF are more easily implementable, the SDG 7 indicators will likely remain binary, and with this of limited use to inform policy.

In an ultimate analysis, the value of any metric lies in its ability to inform policies that deliver the greatest welfare benefits. Newer multidimensional frameworks, such as the MTF, make great strides from the binary lethargy in energy policy discourse. However, a clear separation of global and national tracking objectives and corresponding enhancements that can also capture dynamic movements into and out of energy poverty, and the depth of energy poverty are still needed. Metrics must better inform targeting of policies to assist those most in need, particularly women and children, whose vulnerabilities are often masked by measures that track energy poverty at a household level, and thus ignore intrahousehold distributions and divisions of privilege and responsibility. While such intrahousehold distributions have not been the focus of discussion in this work, recent reports suggest that the application of the newer multidimensional energy poverty frameworks must allow for the collection of sex and age disaggregate data so that these vulnerabilities can be better understood and addressed (Alem, Hassen, & Köhlin, 2017; UN Women, 2018).

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

NOTES

[1]The DHS historically does not differentiate between the sources nor the availability or affordability of electricity, be it a national grid connection, mini-grid connection, or a solar home system.

[2]A detailed selection of typical appliances across all energy access tiers can be found in the MTF conceptualization report (Bhatia & Angelou, 2015).

[3]Useful energy—that which is equivalent to the service provided, end-use energy—that which is consumed by the device to provide the service and primary energy—that which is consumed to produce the end-use energy (Pachauri et al., 2004; Pachauri & Spreng, 2004).

[4]The contextual realities of specific cases, such as charging requirements of half a million electric vehicles (e-bikes and rickshaws) operating in rural Bangladesh, could serve to further inform a mobility energy measurement framework (Rasel, 2017).

[5]The MTF replaces what we term dimensions with attributes.

[6]Detailed definitions of each dimension and respective thresholds discussed here are available in the original MTF conceptualization report (Bhatia & Angelou, 2015).

[7]A more detailed description of the MEPI aggregate calculation can be found in the MEPI conceptualization articles (Nussbaumer et al., 2011, Nussbaumer et al., 2012).

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