Renewable and Sustainable Energy Reviews 97 (2018) 90–102

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy consumption levels and technical approaches for supporting development of alternative energy technologies for rural sectors of developing countries

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ARTICLE INFO

Keywords:
Developing countries
Energy systems
Rural off-grid
Energy consumption
Energy poverty
Renewable energy

ABSTRACT

The delivery of modern energy services in developing countries (DCs) remains a pressing challenge. The traditional energy choices of 2.67 billion people most of whom living in rural areas of DCs have far-reaching implications to health, the environment and economies. Rural areas in DCs have renewable energy resources, which are largely untapped due to lack of energy demand information of requisite load centres. This article formulates indicative energy consumption data to support the design and development of novel alternative energy technologies for rural off-grid areas in DCs. The study examines energy demand/consumption through an extensive literature review of quantified energy needs in rural sectors of DCs including households, institutions, infrastructure and productive sectors. Various energy needs are identified and their typical consumption levels analysed. The study will stimulate further research and support the design and development of alternative energy supply technologies to mitigate energy poverty, trigger development and support sustainable energy for all (SE4All).

1. Introduction

Access to clean, secure, reliable and safe energy services is essential for fighting poverty and achieving economic development in Developing Countries (DCs). However, many DCs have high deficits in modern energy access. There are 1.1 billion people worldwide with no access to electricity and 2.67 billion people relying on traditional fuels [1,2]. Fig. 1 illustrates that the majority of populations in rural areas of developing regions of the world depend on traditional biomass in lieu of electricity. This results in health dangers linked to air pollution resulting from using traditional fuels and inefficient technologies [3–6]. The challenges with the grid-based rural electrification approach, which include: expensive grid extension; unreliable infrastructure; lack of political will and institutional weaknesses, further complicates this scenario and impacts energy delivery to rural households, institutions and enterprises [7–9].

Another area gaining interest is quantifying energy needs in the various social units in DCs. Many have conducted studies and surveys to garner data concerning end-user demands in rural settings such as lighting and cooking [10–13]. Such micro-level data is essential in developing the design and sizing of novel energy technologies for DCs and can be instrumental in addressing some of the pitfalls that engineers face when designing for the resource-poor in DCs [14].

There are typically two kinds of problems when designing and developing energy technologies. The first involves design and development of new or novel energy technologies and associated components targeting specific energy end-uses. The second involves the sizing of existing energy supply systems to satisfy current and future energy needs. In the second case, designers have access to the facility being designed for; either physically or in blueprint form. From this, load/energy demand is ascertained. In the first case, this is not always possible and alternative approaches are sought such as a survey or a data collection exercise at the site of interest. This data would feed into the new/novel energy supply technology design process. However, where timelines, financial resources and administrative restrictions are involved such elaborate approaches would be difficult to undertake.

Therefore, an alternative approach could borrow from data generated by other authors. Such an approach could make use of quantified energy consumption metrics such as per capita, daily, monthly and/or annual concerning targeted end uses in rural energy sectors of DCs [15–18] as a crucial starting point. Other metrics such as energy consumption per unit floor area are useful when considering designing

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https://doi.org/10.1016/j.rser.2018.08.021
Received 3 November 2017; Received in revised form 1 August 2018; Accepted 15 August 2018

Nomenclature

AGECC	Advisory Group of Energy and Climate Change
CCHP	Combined Cooling, Heating and Power
CHP	Combined Heating and Power
EDI	Energy Development Index
GJ	Gigajoule
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kg	Kilogram
kgOE	Kilogram(s) of oil equivalent
kW h	Kilowatt hour
L	Litre
LPG	Liquefied petroleum gas
MEPI	Multi-dimensional Energy Poverty Index
MSMEs	Micro Small & Medium Enterprises
PV	Photovoltaic
PVT	Photovoltaic-thermal
SEforAll	Sustainable energy for all
USAID	United States Agency for International Development

systems for individual households [19]. Similar metrics can be devised for rural health centres [15,20], schools [16] and micro, small and medium enterprises (MSMEs) [21,22].

Due to rural sectors often being heterogeneous between countries, minor differences are inconsequential in a majority of DCs. Therefore, this data provides vital baselines for sizing and designing new technological interventions targeted at specific rural sectors in DCs. The macro-level metrics are distinct from aggregated macro-level metrics, which tend to be nationwide and mask greater error margins.

Researchers and development experts have quantified energy consumption levels in rural sectors of DCs. In particular, some have quantified minimum energy requirements for supplying the energy needs of the rural poor [23–27]. Others have conducted field surveys to ascertain the energy use requirements of the rural poor considering different energy carriers such as electricity, LPG, kerosene, biogas, ethanol, fuelwood and charcoal [8,28]. Energy requirements for rural schools, health centres, public buildings, irrigation and potable water service, among others are also considered but not as widely as for households [10,29]. Work by international organisations has also often mentioned the importance of these metrics [15,30–33].

This article is a step towards understanding the energy needs in sectors of rural areas with a goal of warranting innovative energy technologies that target specific applications in DCs. This article helps to harmonise published quantified micro-level energy use metrics pertaining to rural settings of DCs and to derive meaning from them. Since there's no research that analyses the context of quantified energy consumption/demand metrics for rural areas of DCs the paper is organised as follows. Section 2 reviews the concept of energy poverty and published data on energy consumption in DCs and provides examples of energy consumption metrics of interest. Section 3 defines a suitable classification framework for the rural energy sector. Section 4 presents the methodology and highlights research trends. Section 5 analyses and develops energy consumption baselines from published data. Section 6 presents a matrix of quantified energy needs for supporting the sizing of energy technologies for rural sectors of DCs. Section 7 proposes possible technological pathways for energy supply in rural areas of DCs and identifies future research challenges. Section 8 concludes with key highlights.

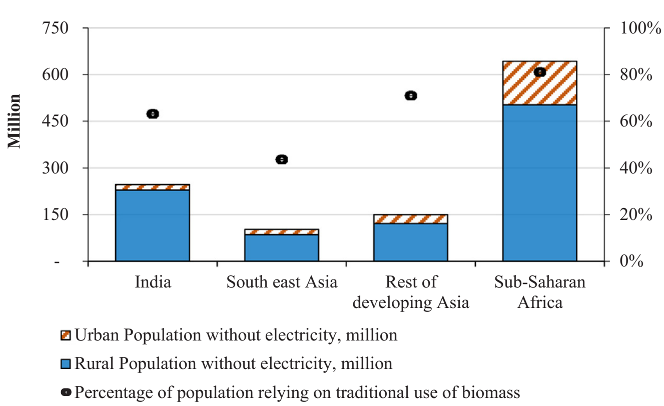

Fig. 1. Number and percentage of population without electricity and dependent on traditional biomass for cooking and heating needs (2016) [1,2].

2. Energy poverty, energy use metrics and definitions of basic energy needs

2.1. The aspect of energy poverty

Poverty in DCs results in the lack of: means to satisfy basic needs; access to essential amenities; and opportunities [34]. Even if economic improvements are made at a country level, significant numbers of individuals may still lack adequate basic amenities such as shelter, food, health, education, clean water, clothing, sanitation, employment opportunities and energy. However, energy has been internationally recognised as an essential component to increasing social amenities, resulting in the adoption of 'energy poverty' as a commonplace phrase [32,35]. According to Bhatia and Angelou [32], 'energy poverty' is:-

> "the state of being deprived of certain energy services or not being able to use them in a healthy, convenient, and efficient manner, resulting in a level of energy consumption that is insufficient to support social and economic development."

This definition reveals that 'energy poverty' can be applied meaningfully to individuals, as well as entities, of rural settings in DCs such as households, education, health institutions and enterprises. Authors have attempted to determine the energy poverty line at a household level in several countries (see Fig. 2). Although typical micro-level energy demands in rural settings of DCs is insufficient, the need for innovative technologies to meet this and even higher demand levels, in a sustainable manner is irrefutable.

Efforts have been made to distinguish the energy poor from the non-energy poor, particularly for households [36,37], by using certain quantified energy use metrics or indicators. These indicators, often derived either from macro or micro-level data, have been commonly referred to as simple unidimensional quantities, for instance kW h consumption per capita [32]. Although the simple unidimensional quantities are widespread, there is a growing shift towards the use of multidimensional quantities, for instance Energy Development Index (EDI) and Multi-dimensional Energy Poverty Index (MEPI) [38,39] to enable comparability between countries.

This study does not focus on energy poverty or human development and does not consider multidimensional quantities. Also, it does not

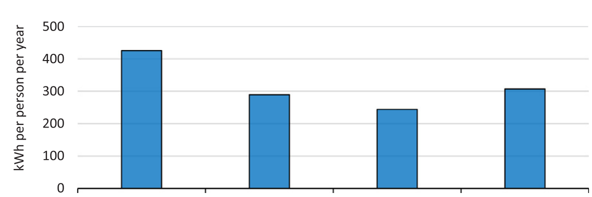

Fig. 2. Energy poverty line for different countries as estimated by researchers [24,25,36,97].

consider simple unidimensional quantities that are derived from macro-level aggregates of energy consumption data such as Goldemberg's [40] pioneering work on this topic.

However, it is essential to understand that the energy poverty aspect influences the quantity of energy required across the various rural sectors of DCs and will impact the sizing, design and development of new alternative technology interventions.

2.2. Energy use metrics and basic energy needs

Energy use metrics are measurement units often used to describe data representing consumption/demand quantities of electricity as well as solid and liquid fuels. Besides their use in specific country surveys, simple metrics have proved essential in defining the minimum energy amount for supplying basic energy needs. Basic energy needs are defined as energy for cooking, space heating, lighting as well as for basic services such as better health, education, communication, transport, and more [8].

Authors and global actors who have offered key quantified definitions of proposed and targeted direct energy needs include Modi et al. [41], The United Nations Secretary-General's Advisory Group of Energy and Climate Change (AGECC) [42] and Sanchez [8]. Table 1 summaries their proposals of minimum amount of energy needed to meet the basic needs of people in DCs. The frameworks and approaches for defining the basket of minimum energy needs adopted by these authors differs and have led to different proposals [43]. These quantities are often estimated for households as they have been the central focus of research and action over the years. Electricity is often considered for lighting, low power applications like phone charging, TV and radio while modern fuels consider energy for cooking with or without efficient cooking devices. Typical energy demand data assumed by Islam et al. [44] for households, health clinics, micro-enterprises and schools in remote communities of developing countries are reasonable but emphasise the need for detailed studies.

The International Energy Agency (IEA) utilised distinct energy consumption assumptions for rural and urban households in assessing the level of financial investment needed to attain universal access to electricity and cooking facilities by 2030 [45]. With an assumed average of five people per household, IEA [45,46] considered that newly electrified rural and urban households consume about 250 kW h and 500 kW h per year, per household, respectively which grows to an average regional consumption of 800 kW h per household per year over a period of five years. This analysis captured the fact that the rural poor too have potential to grow their energy demand overtime [47,48]. Such approaches demonstrate the importance of simple metrics in setting energy access goals and defining scenarios for analysing potential policies to meet energy access goals for the world's energy poor.

Although most of this literature focuses on energy use for households, there is evidence of research emerging in other rural energy sectors such in health centres, schools and agro-enterprises [15,16,20,49–51]. These simple metrics can provide essential rural energy sector-wide information for engineers, designers and researchers as benchmarks for creating alternative energy technologies. To illustrate this, when a benchmark value of consumption, say kW h per household per day is known, designers can use it as a starting point to inform technical specification of customised renewable energy supply technologies that are location and application specific.

3. Defining a classification framework for sectors of the rural energy economy

3.1. Rural sector stratification in the energy access context

Rural areas are an important sector in national development. For DCs in particular, rural areas are collectively home for large populations as compared to population aggregates of urban areas (Fig. 3). In rural areas, the most basic unit is a household[1] where the majority of the people live and thrive on opportunities within their communities. Like their urban counterparts, rural dwellers require the same kind of services to satisfy their survival needs (food, housing, and sanitation), affordable social services such as education, health, communication and transportation as well as employment. Improving the energy access levels of rural areas is just one way to provide rural people the best chance to escape poverty and promote development.

However, the situation in rural areas of most DCs is dire. Rural people are left behind by their urban counterparts. Progress for accessing many essential amenities such as clean water, equipped health facilities, electrical energy and efficient cooking appliances is slow. To enable targeted interventions, rural areas can be subdivided into key strategic sectors. Indeed, various subdivisions of the rural sector in the context of rural energy demand have been proposed [32,52,53] but there is no uniformly agreed upon categorisation framework for rural areas. Therefore, drawing from these prior efforts, this article proposes an overarching decomposition of the social energy end-use market into four main categories i.e. households, social services, infrastructure and productive use enterprises (Table 2). The quantified energy use metrics published in literature can be effectively categorised according to this classification. In the following subsections, each of the rural energy sector categories is briefly discussed. The methodological aspect of how these categories are applied in the present study is discussed in Section 4.

Table 1
Minimum energy quantities proposed/targeted by global actors for DCs (per person per year).

Author	Modern fuels	Electricity	Total amount (kW h)
Sachs et al. [30]	–	353 kW h	353
Sanchez [8]	35 kg of LPG (442)[a]	120 kW h	562
Modi et al. [41]	40 kgOE[b] (465)	10 kgOE (116)	581
AGECC [42]	100 kgOE (1163)	100 kW h	1263

Note: Values in parentheses are equivalent kW h.
[a] Used 45.5 MJ/kg of LPG, 1 kW h = 3.6 MJ.
[b] kgOE (kilogram of oil equivalent) is a metric of energy adopted when multiple fuel sources are combined.

3.1.1. Energy use in rural households

The rural household energy sector is fundamental as it constitutes the largest proportion of the energy demand of rural areas. However, electrical loads powered in households with access to electricity are typically small and end-uses are typically restricted to lighting, television, radio and phone charging [54,55]. For rural households without electricity, all their day-to-day energy needs are typically supplied by biomass for which they have to spend considerable time and labour gathering from near and afar [56]. Other fuels commonly in use are kerosene as well as dung and agricultural residues for cooking, water/space heating[2] and lighting. Research has shown that even within non-electrified households, there are diversities and nuances with regard to end-uses for biomass energy. For instance, in Cambodia, not only do households use fuelwood for cooking human food, they also commit a substantial amount of biomass energy towards repelling insects and preparing feeds for their piggery [17]. Elsewhere, studies suggest that if alternative modern energy carriers such as LPG and efficient appliances are accessible, rural households which can afford them will add them to their stack of total fuel mix [57,58]. Otherwise, poor rural households

[1] Persons per household vary significantly between geographical locations in a country as well as between countries, literacy levels being a key determinant for family size.

[2] Even if water and space heating end-uses are only needed in cold climates, those rural households that can't afford the fuel for meeting these needs live under excruciating weather conditions.

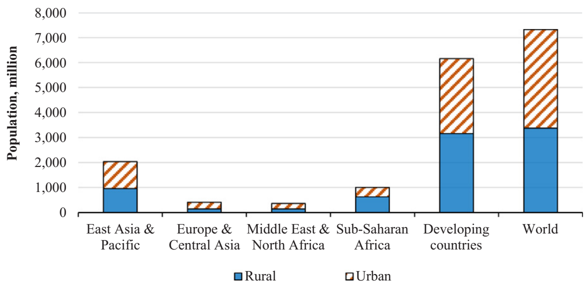

Fig. 3. Rural and urban regional population aggregates (2015) [2].

will maintain a stack of diverse low quality fuel sources to raise their fuel security [59]. Comparisons between world regions for all the biomass fuel types and electricity use (Table 3) indicates that rural households in Africa have the lowest aggregated electrification rate at 28% and the highest reliance on traditional biomass at 69%.

3.1.2. Energy for social services

The service provision sector of rural areas encompasses education institutions, health care facilities, church buildings as well as government and public institutions such as police posts and recreation centres [10,29]. Whichever of these facilities exist in an area, electricity is often necessary for powering lights, public address systems, television, information technology and others. Researchers have found a relationship between electrification of social service facilities and attraction and retention of professional workers. For instance, the lack of electricity in schools in Papua Guinea was identified as a significant issue contributing to the crisis of poor retention of elementary and secondary teachers in rural schools [29]. It is also essential to state that a significant amount of centralised cooking energy needs in this sector is derived from biomass fuel sources, particularly in schools where meals have to be provided to students.

Energy access is also crucial for improving the literacy levels amongst poor households since with it, higher enrolment levels are attained in rural schools, leading to improved income earning opportunities. In health clinics, energy for evening lighting to extend patient access hours, refrigeration of vaccines, sterilisation and autoclaving among others is essential for improving the health services standards in rural areas. Finally, electrification of public institutions strengthens service delivery, facilitates social gatherings and cohesion.

3.1.3. Infrastructure

Infrastructure energy needs in rural areas such as water pumping and street lighting for security at night are considered in this section. Water pumping infrastructure is essential in improving access to potable clean water to rural communities for institutional and household use. The World Health Organisation has reported that the lack of access to improved sources of drinking water contributes to over 3.4 million deaths annually of which about 99% occur in developing countries [60]. Due to most rural areas' remoteness from the national electrification networks, alternative technologies are essential for this sector. The commonly promoted technological interventions for water pumping include distributed energy generation configurations such as standalone solar [61] and solar-wind-generator hybrids [62].

Although, just as street lights are essential in facilitating night movement and safety in urban areas, they are also essential in rural areas and should be promoted as well. In rural areas without installed street lighting, people use handheld devices like torches to enable their night movement, spending their limited income on purchasing dry-cell batteries. A survey conducted in 568 rural households in Sierra Leone established that 93% of households used dry-cell battery powered torches as their main light source while 3% used kerosene lamps [63]. Provision of street lighting can be formulated for rural areas as either part of distributed community mini-grids or as standalone renewable energy technologies [64]. Either way, data is required concerning rural areas and street lighting infrastructure.

3.1.4. Productive activities/enterprises

This category of rural energy sector consists of rural activities that can contribute towards the development of the rural economy. Although most rural areas are a mix of informal non-farm enterprises as well as subsistence activities, agriculture is the most widespread [65]. Since outputs from agriculture are an essential aspect of developing a

Table 2
Proposed classification framework for rural energy sector [32,50,52].

Sectors	Sub-sectors	Main end uses
Households	–	Electricity, Cooking, Space Heating
Social Services	Health posts, Clinics, Public Institutions	Definitions of differences between Health posts and clinics Energy end-uses in public institutions are located in such facilities as government administrative offices, police stations, religious buildings, prisons, community centres, public libraries, orphanages and sports facilities.
Infrastructure	–	Rural infrastructure energy end-uses including street lighting and water pumping (for irrigation, livestock watering, and potable water for human use). Excludes large-scale infrastructure such as transport and telecommunication towers.
Productive activities/ enterprises	Small shops, Micro, Small and Medium Enterprises (MSMEs), Farmers	Examples of farmer energy end use activities may include egg incubation, crop spraying, electric fencing, forced ventilation in greenhouses, crop dryers, lighting, refrigeration for veterinary applications, refrigeration (crops, products, and veterinary medicines), ice making, grinding, hulling of grains.

Table 3
Electricity access and traditional biomass use with emphasis on rural areas [1].

Region	Population without electricity (millions)	Rural electrification rate (%)	Population relying on traditional biomass (millions)	Population relying on traditional Biomass (%)
Africa	634	28	793	69
Developing Asia	512	79	1875	50
Latin America	22	85	65	14
Middle East	18	78	8	4
Transition economies & OECD	1	100	–	–
World	1187	71	2741	38

rural economy, they are mainly considered the central focus for this classification, as previously shown in Table 2. This is evidently the sector where energy access requires systems of higher capacity and cost than those needed for households, infrastructure and community services. For example, in a study by Practical Action [66], it was found that the size of the distributed energy system is an important factor for enterprises. While access through distributed energy systems such as mini-grids could be technically viable, they may generate electricity at a higher per kW h price than the price from a central grid [67] which can be a burden to enterprises. However, further knowledge is necessary in order to understand the sufficient energy consumption levels to facilitate agro-processing enterprises, trade between rural and urban areas and to create local employment in rural communities.

4. Review of energy end-use literature focusing on rural sectors of DCs

The specification of the quantity of energy requirements has presently dominated the global sustainable energy for all (SEforAll) and energy access debate particularly in the context of developing countries [32,68]. It involves determining the actual minimum quantity of energy sufficient for meeting people's basic energy needs. More specifically, it points to the lack of generally accepted quantified energy consumption baselines to guide action. Without suitable quantified energy consumption baselines, it is difficult to design adequate strategic policies and customise energy technology specifications for energy requirements of rural sectors in DCs. Country level aggregate quantities mask greater differences across countries than micro-level measurements owing to differences in climate, social and cultural norms and preferences (i.e. economic constraints and unpredictable choices of end-users). For instance, in Sri Lanka a survey established that high-income households, which could afford cleaner cooking fuels, chose slow cooking in clay pots using fuelwood burnt in wood hearths to preserve the food taste [69]. Such choices would definitely differ between countries. Additionally, the level of accessibility of fuels differs within developing regions of the world as well as by social income classes. Therefore, quantified energy use metrics determined at micro level as opposed to macro-level can provide a more representative picture.

4.1. Methodological approach

The literature search was rigorous and comprised two processes. The first process utilised Ei Compendex and Scopus to find all relevant publications. Search terms included all combinations of word forms and phrases deriving from “energy demand”, “developing countries”, “rural areas”, “off-grid”, “energy services” for all rural energy sectors as indicated in Table 2. During this process, a database created in NVivo version 11 [70] was used to store all relevant publications and to eliminate duplication.

The second process performed text search queries on the NVivo database combining metrics, energy sources, end uses and social sectors to locate energy demand data. Metrics included common reporting units for energy consumption data such as kilowatt-hour (kW h), kilogram of oil equivalent (kgoe), gigajoule (GJ) and megajoule (MJ) as opposed to units of instantaneous power but also considered mass and volume units used to report solid and liquid energy carriers e.g. kilogram (kg), litres (L) etc. This way, complexities that could arise from considering specific numbers of appliances, their types; hours of use and occupancies of rural facilities were avoided. Literature containing useful energy demand data was also located rapidly using the numeric filter functionality in Ei Compendex. Further searches utilised the reference sections of relevant publications.

Fig. 4 provides the methodological workflow adopted in this research. Careful reading of text surrounding each result ensured that the reported context for each data point matched the aim of this research. In some instances, literature reported household energy consumption on per person basis. Where the number of household members were not stated, a common reference occupancy of five persons per household was assumed [25,28,42,46,71–73]. Microsoft Excel provided the means for tabulating, analysing and presenting all data extracted from literature. The literature search considered scientific publications and grey literature (consisting of reports published by experts in international organisations working in the field of rural electrification and energy access) published in English and for the period 1980–2016.

4.2. Analysis of observations

The literature search identified 69 publications from which 147 data points representing quantified end use energy demand data in the four main highlighted rural sectors of DCs. Fig. 5 shows a graphical view of all data points for the period under review. The household sector has greater focus regarding quantifying end use energy requirements compared to other rural sectors. This is important because most of the research as well as international effort considering improving energy access in DCs has largely targeted households where improvements in people's wellbeing is most likely to be observed. When analysing formal energy access commitments made by DCs and international actors, Practical Action [74] made the same empirical observation as the authors that more focus was on households as compared to health centres, schools and productive enterprises and called for more attention in these areas.

Table A. 1 in the Supplementary data file reveals that although literature focused on local situations for different end uses in rural settings of different DCs, one can draw important conclusions on energy demand levels. Due to the scattered nature of energy consumption data in the different rural settings of DCs, data presentation and interpretations adopted the use of basic statistical measures. Moreover, where needed, end use energy consumption data for cooking and heating applications were further manipulated with conversion efficiencies as portrayed by Table 4. All the quantified end use data referring to electricity was converted to a uniform energy unit of kilowatt-hour (kW h) while other energy quantities for cooking or heating end uses (derived from solid and liquid fuels) were converted to a uniform energy unit of joule (J) using appropriate conversion factors.

Section 5 presents the analysis and synthesis of useful information capable of guiding the design and development of distributed energy technologies. Not only can creative efforts target specific rural sectors, energy consumers within the different percentiles can also be targeted. For instance, in a Latin American survey where it was found that a few families consumed a lot of energy while many consumed little, standardised technologies were considered an important solution. Families whose energy needs outgrew their technology capacity had options to obtain higher capacity standardised solar home systems [76]. This same approach is applicable in other rural sectors.

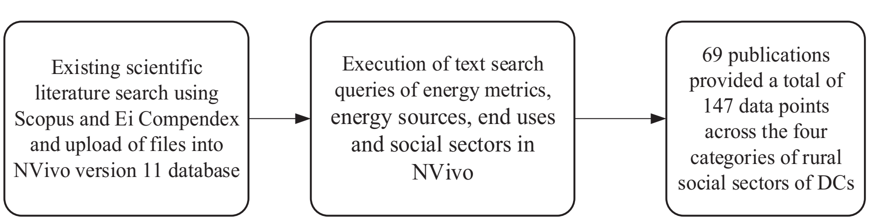

Fig. 4. Snapshot of overall methodological approach and outcome of the literature review.

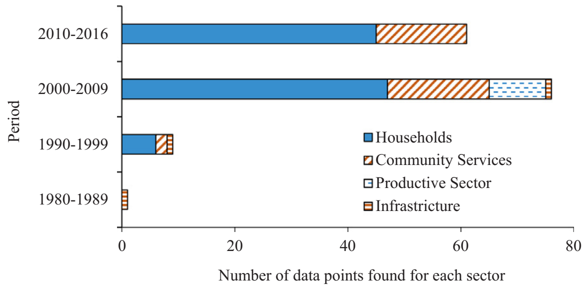

Fig. 5. Data points extracted from literature published over the last 36 years.

Table 4
Typical fuel conversion efficiencies on rural areas [75].

Fuel source	Energy content (MJ per kg)	Conversion efficiency (%)
LPG	45.5	60
Biogas (60% methane) (MJ/m^3)	22.8	60
Kerosene (cooking stove) (MJ/L)	35.5	40
Charcoal (efficient)	30.0	30
Charcoal (traditional)	30.0	20
Fuelwood (efficient), 15% moisture	16.0	25
Fuelwood (traditional), 15% moisture	16.0	15
Crop residue (straw, leaves and grass), 5% moisture	13.5	12
Dung, 15% moisture	14.5	12

5. Rationalisation of energy consumption metrics

Energy consumption is shown as minimum, maximum, mean and in percentiles with N being the number of observations extracted from literature. The 25th percentile suggests that 75% of the observations made state that energy consumption for a particular application amounts to at least the shown value. The 50th percentile (also median) suggests that half of the observations made state that energy consumption for a particular application amounts to at least the shown value and the 75th percentile suggests that 25% of the observations made state that energy consumption for a particular application amounts to more energy than the shown value. This interpretation is applied where several data observations are available for the household sector and the social services sector. For the infrastructure and productive sectors, a straightforward tabular interpretation is used owing to lack of sufficient observations stemming from lack of data. These documented results have the potential to act as an initial reference guide for sizing and designing alternative energy technologies for rural energy access of DCs.

5.1. Household sector

Table 5 shows a breakdown of energy consumption in the household sector. The calculations for obtaining the indicated data are included in a separate Supplementary data file. Three unstandardized end use categories are identifiable within the dataset. Lighting [10,36,37,76–88], multiple/combined end uses [10,12,27,36,78,88–96] (e.g. lighting, radio, television, phone charging etc.) and energy for cooking/high temperature heat using fuelwood sources [12,17,18,36,37,81,97–110] and LPG [27,36,37,81,111]. It is difficult to separate heat energy into the various end uses such as water and space heating because common practices such as open fire cooking can deliver more than one energy services (e.g. cooking and space heating as well as lighting).

Electricity consumption figures are significantly low partly due to disaggregation of end uses. In addition, electrified rural households of DCs lack the ability to obtain electrical appliances that would lead to increased energy use. For lighting, one-quarter of the observations suggest that households in rural areas of DCs require at least 59 kW h of electricity per person per year, half suggest at least 36 kW h per person per year and three-quarters suggest at least 15 kW h per person per year. For electricity demand for multiple applications, one-quarter suggest more than 244 kW h per person per year, half suggest more than 170 kW h per person per year and three-quarters suggest at least 125 kW h per person per year.

Energy requirements for cooking was explored considering various fuels i.e. Electricity, charcoal, fuelwood and LPG. It is commonly stated that the estimated total annual energy requirement for cooking needs in DCs is 1 GJ per person per year [28,112,113]. However, cooking energy proposals presented earlier in Table 1 (modern fuels column) from global actors works out as 1.56 GJ for Sanchez [8], 1.67 GJ for Modi et al. [41] and 4.19 GJ for AGECC [42] per person per year. The results shown are comparable, however, it is important to note that access to energy for cooking is still a major challenge in rural settings with accessibility and affordability being the major factors. The quantities of fuelwood energy consumed far exceeds the energy consumed in form of LPG while the use of electricity for cooking is still not affordable. The nature of the household fuel mix determines the proportions by which multiple fuel types are used. The differences in types of foods cooked in the different rural households of DCs as well as in cook stove efficiencies are also key determinants in the quantity of cooking energy needed. Table 6 elaborates further information from literature pertaining to the amount of primary and useful cooking energy that some authors have published, considering different cooking fuels. A contrast can be made between this and the analysis made by others for instance Sanga and Jannuzzi [28] who determined an annual LPG demand of 1.05 per person per year from published literature.

5.2. Productive/rural enterprises

Quantified energy metrics of rural productive enterprises in DCs are considered according to the observations made from literature. Table 7 describes energy consumption/demand levels whist Table 8 presents thermal energy temperature ranges for specified productive activities in rural areas of DCs as cited from indicated sources. An important gap is that for certain activities, for instance, grain mills, key data; such as production throughput per year corresponding to the shown energy consumption values was not available. In Table 7, the energy consumption values are provided by Kirubi et al. [10] from a case study in Kenya. Bhatia and Angelou [32] proposes an energy requirement for productive uses ranging from 500 to 1000 kW h but does not clearly delineate issues of number of people involved, production throughput and size of establishments which makes this information less informative.

In Table 8, Giovannucci and Weingart [50] provided expert guidance about required temperature ranges for productive activities

Table 5
Energy consumption levels in rural household sector of DCs.

	Lighting	Multiple applications	Energy for high temperature heat including cooking (GJ per person per year)	
	kW h (electricity) per person per year		Fuelwood	LPG
Minimum	7	24	0.2	0.07
25th Percentile	15	125	1.3	0.11
(50th) Median	36	170	1.8	0.14
75th Percentile	59	244	3.4	0.53
Maximum	84	344	13.2	0.95
Mean	39	183	2.6	0.36
N	23	15	55	5

Table 6
Estimated cooking energy requirement from literature considering different fuels.

Ref.	Type of energy flow	GJ per person per year				
		Fuelwood	Charcoal	LPG	Kerosene	Electricity
[113]	Primary energy	2.5–20	2.5–10	–	–	1.1–1.4
[114]	Useful energy	–	–	–	–	0.5–1.4
[115]	Useful energy	1.46	0.99	0.40	1.04	–

Table 7
Energy consumption levels in rural productive sector of DCs [10].

Productive activity	Quantity (kW h/year)
Retail and repair shops	473
Grain mills	8800
Petrol station and welding garages	2271
Bars, lodging and hotels	2880
Carpentry workshops	3300
Small tea/food café	180

Table 8
Thermal energy temperature requirements in rural productive sector of DCs [50].

Productive activity	Energy source	Proposed values (°C)
Small-scale agriculture	Solar/biomass	40–70
Production of high-value fruits spices	Solar	20–30
Crop drying (coffee, tea, fruit)	Solar/biomass	40–70
Poultry processing (high-temp water)	Solar	40–100

based on experiences of related projects in DCs. Although less specific, these could be referred to for high level planning of low and high-grade heat applications. Overall, the data arising from the observations in literature for productive enterprises in rural areas of DCs was not sufficient to construct a strong narrative of utility in light of the goal of conducting this literature review. These results signal a need for further research regarding quantification of energy consumption metrics for specific applications in productive enterprises of rural areas in DCs.

Specific energy requirement for solar crop drying was addressed by Weisis and Buchinger [116] as shown in Table 9. Although vast literature exists specifying temperature requirements and air heating technologies [117–126], there's minimal data on specific solar thermal energy requirement. The few studies which have explored the subject of specific thermal energy requirement for crop drying include Fudholi et al. [127] and Grube and Böckelmann [128]. The major challenge with determining the specific energy requirement for solar thermal dryers is that this value is inextricably dependent on the climate and weather conditions in a particular location as well as the drying temperature and air velocity. These effects have been observed and reported in literature for specific crops such as grapes [129] and cornelian cherry [130]. Otherwise, the energy requirement for solar crop drying is often reported on per unit amount of moisture evaporated [131,132] which would require additional manipulation to convert into specific energy requirements for drying.

5.3. Social services sector

For energy consumption levels in the social services sector of rural areas, the observations are summarised in Table 10. Consumption levels for several end use types are shown for rural clinics, health posts, educational institutions and public/government institutions. In addition, where several data points were available [10,15,31,49,77,92,96,133,134], measures of central tendency were utilised.

For each of the institutions, it would be essential to have information pertaining to building sizes, number of people accessing the services, number of daily operating hours and detailed information about particular appliances and their frequency of use. For rural clinics, the United States Agency for International Development (USAID) defined pertinent categories of rural health clinics and their estimated energy requirements and typical equipment loads as shown in Table 11. However, in light of the ideal information highlighted in the foregoing, the data offered by USAID is also partial. The authors did not find other specific details for helping to describe essential characteristics for education and public institutions. Examples of public institutions which were encountered by Kirubi et al. [10] in the Kenya study included religious buildings, post office, police station, commercial bank and district offices.

Moreover, there is emerging emphasis for rural health facilities to invest in better and energy efficient medical devices [133]. In fact, the adoption of energy efficient lighting, cooking and other efficient electrical appliances within the various rural sectors and how it might influence the portrayed energy consumption levels is of significance. Therefore, further research is needed in this area to generate insight about energy requirements in relation to specific building characteristics, number of consumers, operating hours and end use applications for the social services sector of rural areas in DCs.

5.4. Infrastructure sector

Finally, a dearth of energy consumption information pertaining to energy access for the rural infrastructure sector is a glaring reality. Table 12 is an illustration of the few observations made from literature.

Table 9
Low temperature thermal energy requirement in sun drying of various crops [116].

Crop	Initial moisture content (%)	Final moisture content (%)	Maximum temperature (°C)	Required drying temperature (°C)	Required drying time	Energy required (W h/kg)
Apricots	85	15–25	65	45–65	4,5 days	463
Bananas	70–80	7–15	70	30–75	4–6 days	466
Cassava	75	14–17	–	30–60	Days–Weeks	307
Cassava leaves	80	14	–	30–60	Several days	441
Chillies and peppers	75–80	5–14	90	40	6–8 days	447
Coffee	45–65	9–12	–	30–60	3–7 days	238–240
Grapes	75–80	15–20	70	45	8–10 days	410
Maize	20–35	8–15	66	35	Several weeks	71–157
Mangoes	80–85	12–18	70	55–70	1–2 weeks	434
Potatoes	70–75	8–13	75–85	30–70	Several days	404
Rice	20–30	12–18	66	< 50	Days–Weeks	61–98
Tea	60–80	25–3	140	30–60	Several days	334
Tobacco leaves	70–85	11–25	70	30–60	30–40 days	442–555
Tomatoes	75	35	–	30–60	36 h	268
Wheat	15–20	13–14	66	45	Days–Weeks	15–54

Table 10
Energy consumption levels in rural social services sector of DCs.

Institution	End-use type	Type of fuel	Unit	Value	Min	25th percentile	Median	75th percentile	Max	Mean	N
Clinics and health posts	Lighting	Electricity	kW h per year	2000–8000[a]							
Clinics and health posts	Cooking	LPG	GJ per year	10.92–27.30[a]							
Clinics and health posts	Multiple loads	Electricity	kW h per year		266.0	624.2	766.0	2217.4	11,534.0	2221.7	11
Education institutions	Multiple loads	Electricity	kW h per year		180.0	425.6	675.3	1763.8	5803.5	1521.2	8
Education institutions	Cooking	LPG	GJ per year	191[b]							
Public institutions	Multiple loads	Electricity	kW h per year		82.0	600.0	900.0	1140.0	1500.0	852.6	11

[a] Minimum to attain development for clinics (lower value) and health posts (upper value), cited from Sachs et al. [30].
[b] Minimum to attain development for cooking in a school, cited from Sachs et al. [30].

This does not mean that these areas have been entirely neglected by scholars but when they are considered, their share of energy consumption is often not separated as exemplified in the study by Munoz et al. [135]. Additionally, some researchers have indicated that low capacity systems may not be suited for meeting the rural sector needs of this category [136]. While some researchers are in favour of PV microgrids [137] as the best suited systems for meeting rural energy needs such as street lighting and water pumping, others have proposed minigrids since they can also be extended to serve social services facilities such as schools, clinics etc. [138]. It is recommended that more research should be conducted in this area, particularly with a focus on energy consumption levels to generate useful data for energy technology designers.

6. Quantified matrix of energy service estimates for DCs

This section summarises the information gathered from literature regarding the energy requirements of rural off-grid communities in DCs. With the data summarised in the form of a quantified energy needs matrix shown in Table 13, the current work has endeavoured to establish guiding facts for needs-based design and development of energy supply technologies targeting rural sectors of DCs. Knowing the quantity of energy typical in the various rural social sectors is essential for designers, researchers and funders to develop energy technologies. Narula et al. [140] observed it would be cheaper to achieve universal rural electrification by 2030 with distributed generation technologies as opposed to central grid extension.

Initially, local renewable energy resources must be established, and targeted demand levels estimated before sizing potential systems. This quantified energy needs matrix may serve as a reference guide for facilitating designers of novel distributed energy technologies. The mean, median and range of monthly energy requirements have been determined from a series of published data for various energy needs in rural settings of DCs.

Typical energy requirements for rural infrastructure which comprises water pumping and public/street lighting; and energy demands in rural enterprises require purposeful consideration by researchers. Practical research regarding the investigation of actual energy demand profiles of new and existing distributed energy systems in rural settings of DCs is essential. The existence of this information for various geographical regions of DCs could support a fast tracked approach to energy technology interventions for achieving the sustainable development goals in rural off-grid communities that are currently disadvantaged.

Table 12
Energy consumption levels in rural infrastructural sector of DCs.

Author/Source	Application	Unit	Quantity
Volpi [80]	Water pumping	kW h/person per year	2[a]
Krugmann and Goldemberg [26]	Water pumping	kW h/person per year	12.7–21.2
Reinders et al. [84]	Street Lighting	kW h per year	65.7[b]

[a] Considered a delivery rate of 5 L of potable water per person per day.
[b] For a single low-pressure sodium street light rated 18 W for 10 h daily.

7. Rural energy needs, potential technologies and future research challenges for DCs

In this section, potential technological pathways for addressing the energy needs in the context of off-grid locations of DCs are highlighted. First, the energy needs are clearly identified for the various rural sectors by creating six categories as shown in Table 14. The energy needs categories represent enablers for security, entertainment, social service delivery, wellbeing and rural economic activity.

The International Renewable Energy Agency (IRENA) proposed several potential renewable energy technologies for off-grid locations [144]. Table 15, is an expanded list with regrouped energy needs that suggest potential research areas. The checkmarks indicate confirmed applications while the question marks indicate areas of interesting research. Solar photovoltaic-thermal (PVT) systems are included as an interesting technology for further research and development for energy needs of off-grid locations of DCs. PVT systems are a class of solar energy harvesting technologies that can generate electricity and low-grade heat simultaneously thereby attaining higher solar conversion efficiencies [145]. For instance, PVT systems could be developed to energize a variety of combined low power electrical [146] and thermal energy [147] applications thereby replacing kerosene and biomass use in remote off-grid households. Although most of the work to-date has largely focused on the development and experimentation of PVT collectors as building integrated elements [148], Tiwari and Dubey [149] have demonstrated through case studies that systems can be constructed to fit the context of rural energy access for electricity and low temperature heat applications. Solar energy harvesting technology is particularly of interest owing to a number of benefits. It is

Table 11
Categories of rural health clinics of DCs and their estimated energy requirements.Source [139].

Category	No. of beds	Typical end uses	Demand (kW h/year)
I (low energy requirement)	0–60	Evening light, cold chain for vaccines, blood and medical supplies, basic lab equipment (centrifuge, haematology mixer, incubator)	1825–3652
II (medium energy requirement)	60–120	More sophisticated diagnostic medical equipment, communication device, separate refrigerators for food storage and cold chain in addition to Category I loads	3650–7300
III (high energy requirement)	> 120	Information technology equipment, x-ray machine,CD4 counters, blood typing equipment etc.	7300–10,950

Table 13
Matrix of quantified energy use/service estimates and energy use opportunities in rural areas of DCs.

Rural unit/sector	Use/Service	Demand estimate (kW h per month)			Comment
		Mean	Median	Range	
Households	Electrical lighting	16.2	15.0	2.8–35.0	Mostly at least 3 h/day of lighting after sun-set and/or small TV, radio and phone charging
	Various electrical appliances[a]	76.3	70.7	10.1–143.5	Electrical loads including lighting and may include refrigeration but exclude cooking
	LPG heat	41.9	16.4	8.7–109.6	Typically LPG demanded for supplementing predominant cooking fuels
	Fuelwood heat	295.2	213.9	17.4–1526.7	Heat energy requirement with fuelwood may be for space heating, water heating and cooking at least two meals a day or a combination of these uses.
Health posts	Various electrical appliances[a]	112.1	63.8	22.2–261.9	167 kW h monthly minimum electrical energy consumption for electrical needs to achieve MDGs[b]
	LPG heat	–	–	252.8–631.9	LPG energy proposed to achieve MDGs; lower end refer to health posts[b]
Clinics	Various electrical appliances[a]	–	–	152–912	Considered the baseline for low power electrical loads for average rural clinic
	Vaccine refrigerator	–	–	15.2–18.3	Considering clinic availability for all the days in a month[c]
	LPG heat	–	–	252.8–631.9	LPG energy proposed to achieve MDGs; upper end refer to clinics[b]
Schools	Various electrical appliances[a]	89.7	45.6	26.6–212.9	Values close to the median are typical of small primary schools of between 200 and 400 students with no boarding facilities[d]
	LPG heat	–	–	–	4424 kW h monthly minimum thermal energy consumption proposition by development practitioners for cooking with LPG to achieve MDGs[b]
Public institutions	Various electrical appliances[a]	84.9	75.0	33.0–125.0	Needs may cover lighting, recreation and entertainment in rural institutions such as churches, mosques, community centres and rural police units.
Enterprises	Cottage crop/fruit drying	338.5	404.0	54.0–555.0	Estimated thermal energy requirement for 1 tonne of dry crop per month[e]
	Ice production	–	–	31–65	Corresponding to a freezer with gross volume capacity of 387 L[f]
	Refrigeration in bar/cafeteria	–	–	82.1–584	Lower indicative consumption values refer to modern energy efficient refrigeration while greater values refer to less efficient refrigeration[g]

Sources:.
[a] Combined low power DC/AC loads (e.g. lighting, radio, TV and phones charging) in varying quantities.
[b] Sachs et al. [30].
[c] Kivaisi [141].
[d] Finucane and Purcell [31].
[e] Weisis and Buchinger [116].
[f] Shields et al. [142].
[g] Campana et al. [143].

Table 14
Rural sector energy needs breakdown for DCs.

Energy needs category	Typical rural sector load centres
Lighting and ICT	Street lights, TVs, radios, phones, internet in households, social service facilities, enterprises
Refrigeration/freezing	Households, social service facilities, enterprises
Cooking	Households, social service facilities, enterprises
Heating/cooling	Hot water, crop drying, fans etc.
Process power	Small enterprises
Water pumping	Potable water, watering livestock, irrigation

environmentally benign, durable, has low maintenance and operating costs, low investment risks, draws on permanently abundant resource, and can facilitate the initiation of income generating activities capable of developing local technical expertise and boosting the rural economy in DCs.

Another pressing issue for rural areas of DCs concerns the aspect of access to modern heat [150]. Health effects, time losses and gender inequalities that accrue to persistent dependence on traditional cooking fuels have been widely investigated [151,152]. Interesting studies have emerged where the potential of solar electric cooking is being investigated [114,153–156]. Results of these studies indicate that this technology would be potentially viable by the year 2020 with the advancement and decline in costs of electric storage technology. Couture and Jacobs [113] have investigated cooking by comparing costs for traditional fuels (fuelwood and charcoal), gas (LPG) and levelised generation cost of solar home systems (SHS) and hybrid mini-grids for electric cooking. They found that mini-grids compete well with traditional fuels and that SHS are potentially viable for rural households since the cost of solar panels and battery storage are declining. Several fascinating studies show the practical significance of direct solar cooking [157–159], a potentially beneficial application for households and institutions in developing countries endowed with solar energy resources.

The availability of energy efficient appliances for the off-grid energy market is a theme of increasing importance as they influence the affordability of the overall system. International development experts [160] know too well that energy by itself will not change lives, but rather, what people can be able to do with it, will. Craine et al. [161] have challenged the status quo of electrical appliances in off-grid systems and shown that a move from business as usual appliances to energy efficient appliances can significantly reduce system cost and transform the effectiveness and widespread use of modern energy in rural locations. Low voltage super-efficient DC appliances powered by off-grid solar systems are available [162] and are likely to receive significant support in programs funded by governments and international development agencies [163].

Finally, future research activities could modernise certain traditional activities in rural areas of DCs through novel ways by capturing, utilising and storing various forms of energy. Low-grade heat naturally existing in air and water and heat stored under the earth's surface can be of significant use in many developing countries. Researchers from high-income countries are demonstrating promising concepts in agriculture [164,165], space cooling [166] and space heating [167] among others. Agro-processing activities are a source of significant organic wastes and could be important supplementary fuel sources in waste-to-energy technologies [168,169] particularly Combined Heating and

Table 15
Distributed renewable energy technologies for targeting rural sectors needs of DCs.

Potential systems	Typical rural energy needs					
	Lighting and ICT	Refrigeration/freezing	Cooking	Heating and cooling	Process power	Water pumping
Solar Home Systems (SHS)	✓	✓	?		✓	
Pico-scale solar PV	✓					
Solar thermal				✓	✓	
Solar cookers			✓			
Solar crop dryers				✓		
Solar PV pumps						✓
Small hydro	✓	✓				
Small wind	✓					
Mechanical wind pumps						✓
Domestic-scale biogas digester	✓	✓	✓	✓		
Biomass gasifier	✓	✓			✓	
Improved cook stoves			✓			
Hybrid mini-grids	✓	✓	?		✓	
Solar PVT	✓	?	?	✓		

Adapted from IRENA [144].

Power (CHP) and Combined Cooling, Heating and Power (CCHP) systems. Other research efforts may advance techniques for harnessing waste heat in such decentralised energy systems to improve their techno-economic viability.

8. Conclusion

This article focused on reviewing literature documenting typical energy consumption levels in sectors of rural areas in developing countries (DCs) and creating quantified energy consumption/end use metrics to guide the sizing of novel energy technologies. The research found that rural energy needs of household and community service locales in DCs seem to attract greater research interest as compared to energy requirements for rural infrastructure and productive sectors. In general, analysis has shown that the energy needed across the rural sectors of DCs is of small amount. Basic electrical energy needs such as lighting and small appliances in a 5-person household is in the range 2.8–35.0 kW h per month with mean and median values of 16.2 kW h per month and 15 kW h per month respectively. Once electrified, energy needs for rural households in DCs may grow to the range 10.1–143.5 kW h per month with mean and median values of 76.3 kW h per month and 70.7 kW h per month respectively. Fuelwood is the dominant fuel in rural settings of DCs. The present analysis has shown that the useful energy obtained from fuelwood for meeting high temperature heat requirements ranges from 17.4 to 1526.7 kW h per month, with average and median values of 295.2 kW h per month and 213.9 kW h per month. Within the community services sector, attention appears to focus on the energy needs of rural health posts and schools compared to clinics. The quantification of energy needs for rural infrastructure and productive activities appear to be the least researched areas. Owing to a dearth of research outputs in these two areas, only essential literature is highlighted and further research to generate quantified energy use data in these sectors is recommended. Creative design effort can target either specific end uses within the rural sectors or energy consumers based on their energy consumption ranges. An energy technology design reference framework is proposed. This framework, together with the presented quantified energy needs matrix are a contribution towards guiding and facilitating research and development of alternative energy technologies for rural energy access in DCs.

Acknowledgements

This research was enabled by the funding support provided by the Department of Learning and Employment by way of an International Studentship. Credit is due to the anonymous reviewers who provided detailed constructive comments during the peer review process. Authors thank Jason Olsen for critical proofreading of the manuscript and Deborah Cully for commenting on earlier versions. Authors also thank The UK Data Service for providing World Development Indicators and the International Energy Agency for providing the energy access database.

Declarations of interest

None.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2018.08.021.

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