Long-term energy planning and demand forecast in rural areas of developing countries: classification of case studies and insights for a modelling perspective

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Abstract

More than half a billion people are expected to still lack reliable and affordable electric energy in 2040 and around 1.8 billion may remain reliant on traditional solid biomass for cooking. Long-term energy planning could help to achieve the energy access targets in developing countries, especially in remote rural areas.

Different studies exist on long-term rural energy planning, but the different foci, terminology and methodologies make it difficult to track their similarities, weaknesses and strengths. With this work, we aim at providing a critical analysis of peer-reviewed studies on long-term rural energy planning, to help researchers in the field move across the diverse know-how developed in the last decades.

The work resulted in the analysis of 126 studies and categorisation of 84 of them, under a number of rules clearly defined in the first part of the paper. The studies are then classified in two consecutive steps, first according to their type and afterwards according to the methodology they employ to forecast the energy demand, which is one the most critical aspects when dealing with long-term rural energy planning.

The work also provides specific insights, useful to researchers interested in rural modelling. Few studies assume a dynamic demand over the years and most of them do not consider any evolution of the future energy load, or forecast its growth through arbitrary trends and scenarios. This however undermines the relevance of the results for the purpose of long-term planning and highlights the necessity of further developing the forecasting methodologies. We conclude that bottom-up approaches and system-dynamics seem appropriate approaches to forecast the evolution of the demand for energy in the long-term; we analyse their potential capability to tackle the context-specific complexities of rural areas and the nexus causalities among energy and socio-economic dynamics.

Keywords:

Access to energy; rural energy planning; classification and analysis; energy modelling; energy demand models

Highlights:

- We collect case studies of rural energy planning in developing countries
- We classify rural energy planning studies according to five categories

- We focus on approaches adopted for modelling long-term energy demand
- We discuss the need to further the research on energy demand modelling for rural contexts

1. Introduction

Energy use and consumption are forecast to grow fast in developing contexts. Based on its New Policies Scenario [1], the International Energy Agency (IEA) estimated a rapid growth of the energy demand in sub-Saharan Africa and in rural and urban India in the next 25 years [2]. In the non-OECD regions, the total energy demand is expected to exceed the OECD regions' one by 89% in 2040 [3], especially in Southeast Asia, China and India. In developing countries (DCs), energy access-oriented policies and actions may contribute to the growth of the global energy demand. The World Bank estimates that 2.6 billion people should be electrified, and 4.4 billion should be served with modern cooking services by 2030 in DCs [4]. Nevertheless, more than half a billion people, increasingly concentrated in rural areas of sub-Saharan Africa, are expected to still lack of reliable and affordable electric energy in 2040 and around 1.8 billion may remain reliant on traditional solid biomass for cooking [5]. Rural energisation is therefore expected to largely contribute to the achievement of energy access goals, since people still living without electricity and modern energy fuels will live predominantly in rural areas [6][7]. In this context, the need to develop sustainable and appropriate approaches to energy planning clearly emerges.

As always in energy planning, also when dealing with rural energisation plans, a sustainable and reliable approach is advised. The latter may influence the architecture and the sizing of the implemented solutions, particularly where economic resources are scarce, as Kusakana discusses [8]. Much of the planning relies on good estimates of the energy demand and its evolution with time. Wrong predictions could negatively impact the local socio-economic development and cause an inappropriate sizing of local energy solutions, leading to supply shortages or cost recovery failure [9]. Cabral et al. [10,11] and Kivaisi [12] stressed the need to pay attention to the evolution of the electricity load when planning electrification programmes, since the marginal costs of energy services vary among supply alternatives (*i.e.* small photovoltaic (PV) systems when the load is low, grid-extension when it is high). Fuso Nerini [13] demonstrated how the cost of the energy system for reaching different tiers of electricity access (*i.e.* different levels of energy demand to satisfy) in the village of Suro Craic in the years 2010-2030 may vary from few hundreds to 8000 2010US$. Brivio et al. [14] demonstrate that in Photovoltaic-batteries based off-grid systems, the optimal size of the components are sensitive to the load evolution pattern, especially the capacity of the battery energy storage system. Hartvigsson [9] developed a system dynamics model to show how the power supply capacity should be accurately considered based on the forecasts of electricity demand: a demand larger than the capacity installed generates lack of power availability that may affect the willingness of people to stay connected and the utility revenues. Van Ruijven at al. [15] developed a bottom-up model to assess trends in electrification over the next decades in DCs, and they demonstrated how the potential of mini-grid technologies is highly dependent on the demand level.

Due to highly uncertain dynamics, strong non-linear phenomena, complex diffusion mechanisms, time-adjustments of technology perceptions, and low quality and availability of data affecting such remote contexts, the long-term forecasting of energy demand in rural areas is a complex issue. This is the reason why studies on local energy planning usually tackle demand forecasts by relying on multiple scenarios that follow regional policies or international guidelines (*e.g.* the OECD Environmental Outlook as in [15] or multi-tier categorisation proposed by the World Bank as in [13]).

This work reviews long-term rural energy planning studies on the basis of the application and the insights they provide, rather than their structural characteristics. The aim is to provide a synthesis of strengths and weaknesses, fields of applicability and insights which do not depend on the views of the authors or the specific terminology employed. Moreover, as a novelty, we try to combine the analysis of both the "demand" and the "supply" aspects of the rural energy planning studies, stressing the need to consider the two parts of the planning as linked and interdependent. Indeed, the aspect of long-term energy demand analysis and modelling within long-term rural energy planning is a poorly discussed and addressed topic in the reference literature, and we aim at opening a discussion about its importance in the field: we first introduce the approaches currently adopted to forecast long-term energy demand within the rural energy planning-based literature, and then we try to derive some useful insights and guidelines for tackling the issue in remote contexts.

The work intends to inform diverse groups of audiences, from researchers to energy planners, with different sets of information, levels of technical knowledge and involvement in the implementation aspects.

Section 2.1 reports the rationale and methodology we employed to carry out the review. Section 2.2 proposes a multi-criteria classification for the energy planning case studies and a description of the papers reviewed, while Section 3 analyses the methodologies to forecast the evolution of the energy demand employed in local energy planning case studies and it proposes guidelines for developing appropriate approaches to model rural energy demand.

2. Analysis of the long-term rural energy planning literature

2.1. Rationale and methodology

Different Authors have defined *energy planning* in several ways, emphasizing multiple important aspects. In general, the literature refers to energy planning as the process aimed at developing long-term policies for supporting the development, implementation and management of local, national, regional or even global energy systems. Prasad et al. [16] quote some authors underling that any energy planning needs to foster sustainable development. They consider energy planning "as a roadmap for meeting the energy needs of a nation [which] is accomplished by considering multiple factors such as technology, economy, environment, and the society that impact the national energy issues" ([16] p. 686). Hiremath et al. [17] write that the "energy planning endeavour involves finding a set of sources and technologies in order to meet the energy demand in an optimal manner" (p. 729). Deshmukh [18] suggests that energy planning aims above all at developing an optimal plan for the allocation of energy resources, by considering future energy requirements according to several technical, economic, social and environmental criteria. Yusta and Rojas-Zarpa [19] state that "energy planning implies finding a set of sources and conversion equipment that optimally satisfy the energy demand of all activities" (p. 67). In view of the above discussion and being aware of both the policy- and design-oriented concept of energy planning, in this study we refer to energy planning as that process aimed at (i) selecting (viz. identifying, sizing and designing) conversion technologies (ii) by performing an optimisation based on appropriate criteria (viz. either strictly mathematical programming or multi-criterial analyses if dealing with less quantitative objectives) (iii) for matching a certain demand with the available energy resources. Coming from an engineering and modelling background, we decided to emphasize the importance of objective criteria in order to confer a more scientific meaning and nature to the concepts of "optimal plan /optimally" that emerged from the literature. This definition is in line with the final aim of our research, which mainly focuses on the development of appropriate models for supporting the design phase of rural off-grid energy systems.

We discarded from our classification all the case studies which do not comply with the above definition of energy planning. For example, Díaz et al. [20] develop a comparative analysis between three off-grid technologies for the rural electrification of a group of families in Argentina, without introducing any optimisation criterion to select the most appropriate energy conversion system. Again, Johnson et al. [21] analyse the energy supply and use in a rural village in Mali and the dynamics of seasonal variation in the energy demand for one year, without employing any mathematical model to optimise the matching between supply and demand. Such case studies are not within the scope of the survey.

In order to comprehensively investigate energy planning methods and applications (*i.e.* including input data processing, such as the load profile, and the final results), in our survey we analyse only real-life case studies or potential applications for real contexts, excluding papers that present only the theoretical methodologies. This adds value to the existing reviews and it is meant to address the research of a suitable and appropriate modelling framework for projecting the energy demand in real rural energy planning case studies. For example, Bernal-Agustin et al. [22] propose a multi-objective evolutionary algorithm and a genetic algorithm to find the most appropriate hybrid energy system to minimise the costs and the unmet demand. The rely on a reference daily load profile for implementing the optimisation. However, they do not provide any details about the daily demand or potential applications, therefore their study is not classified. Gupta et al. [23–25] analyse a hybrid energy system in order to determine its cost optimal operation. In the first [23] and second part [24] of the work they develop the mathematical model for the optimisation and the necessary algorithm to control the dispatch of battery storage systems. Only the third part [25] is here classified because it describes the application and simulation of the energy system for a real case study.

At a spatial level, only local rural energy planning for DCs (and BRICS) is here considered, whereby works referring to other contexts or to global and national scales are not included in the review. For example, Clark et al. [26] and Wies et al. [27] focus on a remote power system for a village in Alaska, so their studies have not been included. The same applies for Bala [28], who proposes a bottom-up approach to minimise CO2 emissions for Bangladesh, but at national level. Edmonds et al. [29] develop a long-term energy-economy model for assessing alternative energy evolutions over periods of up to 100 years at a global level, accounting for CO2 emissions. Parshall et al. [30] develop a national electricity planning model to guide grid expansion in countries with low pre-existing electricity coverage in Kenya. Alfaro and Miller investigate potential appropriate decentralised renewable energy schemes for Liberia at national level [31].

On the contrary, we do not put any restriction on the type of off-main grid system that the case studies propose: standalone systems, microgrids and distributed hybrid microgrids are considered, according to the classification given by Mandelli et al. [32]. Grid-based power is usually the least-cost option for large concentrations of household or industrial loads: it offers economies of scale, due to large fixed-cost investment in distribution lines and generation facilities. However, it is often the least attractive option at regional and village-size level [15], due to a number of economic, environmental, political, technical and social factors [32]. The selection of off-main grid case studies was not a prerogative stated at the beginning, but an outcome of the research, since they focus on rural areas where the population is highly dispersed and lives far from urban centres. For example, Zeyringer et al. [33] present an example of grid extension electrification in Kenya, comparing it with stand-alone PV systems. They find that, under current circumstances, the implementation of stand-alone PV systems is the most appropriate cost-effective solution in areas with low population density. As a matter of fact, because of high transmission and distribution costs, WEO-2013 [34] quotes that in the Universal Access scenario grid extension will be able to provide access only to 30% of rural areas. The remaining areas would rely either on mini-grids or small, stand-alone off-grid solutions.

The papers were selected starting from a web research on *Science Direct editorial platform* and *Scopus database,* and from references mainly taken from [19,32,35]. At the end, 126 papers have been studied and 84 have been selected for the analysis and classification.

Even if no range of publication date was fixed, Figure 1 shows how, among the papers selected in this study, the greatest number of publications is concentrated between 2004 and 2015.

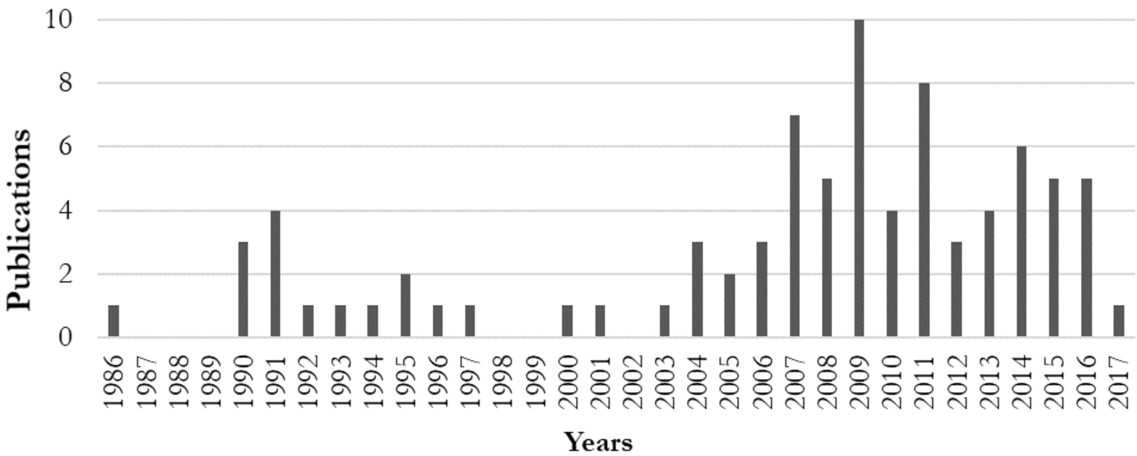

Figure 1. Publication on local energy planning over the years.

2.2. Classification and analysis of long-term energy planning case-studies

Within the energy planning literature, Prasad et al. [16] present the risks, uncertainties and errors involved in energy planning, as well as a review of models for energy planning (*econometric models*, *optimisation models*, *simulation models* and the related computer-assisted tools). In the context of rural electrification, Mandelli et al. [32] propose the most recent review of the scientific literature focused on off-grid systems according to five main research areas including *models and methods for simulation and sizing*. Hiremath et al. [17] present a classification of energy models for decentralised energy planning: *optimisation models*, *decentralised energy models*, *energy supply/demand driven models*, *energy and environmental planning models*, *resource energy planning models* and *models based on neural networks*. The same Authors [36] published more recently a review of possible decentralised renewable energy options for the Indian context. The review includes case studies of successful deployment of such options and opportunities (*e.g.* job creation) arising from the decentralisation of electricity generation. Nicole van Beeck [37] presents a decision support method for selecting appropriate energy systems for regions experiencing rapid growth, such as villages in developing countries. The Author proposes nine criteria to classify energy models: *purposes of energy models*, *model structure*, *analytical approach (bottom-up* vs. *top-down*), *underling methodology*, *mathematical approach*, *geographical coverage*, *sectoral coverage*, *time horizon*, *data requirements*. Yusta et al. [38] investigate the most utilised multi-criteria decision methods for electrification planning in rural areas and they review approximately 120 publications related to energy planning [19], focusing mainly on 50 cases studies of decentralised power supply plans. They classify them according to *referring country*, *mathematical model*, *methodology application*, *adopted criteria*, *implemented technologies*, and *target population*. Deshmuk [18] discusses how to develop an Integrated Renewable Energy System (IRES) to find the optimal energy resource allocation in energy planning processes, and suggests a classification of energy planning models based on *methodology adopted (bottom-up* vs. *top-down*), *spatial coverage*, *sectoral coverage* and *temporal coverage*. Trotter et al. [39] present a well-written comprehensive and systematic review of electricity planning in sub-Saharan Africa. They consider a broad definition of planning – i.e. “an integrated approach of analysing an economically, technologically, environmentally, socially and/or politically suitable equilibrium between electricity demand of a given unit of analysis and different available supply options across at least one element of the electrification value chain” ([39] p. 1189). They review the literature according to three categories: *value chain depth, decision criteria used* and *number of different decision alternatives*. Based on Deshmuk [18], Yusta et al. [19] and Nicole van Beeck [37], we introduce an extended and more comprehensive classification of more than 80 energy planning case studies in six categories: (i) spatial coverage, (ii) planning horizon, (iii) energy vector, (iv) energy uses and (v) decision criteria mathematical models. Categories (i), (ii) and (iv) are selected from Deshmuk [18] and Nicole van

Beeck [37]. Category (v) is based on Yusta et al. [19]. Appendix A reports a complete overview of the classification adopted for the collected case studies. In the following paragraph, we give an insight for each of the six categories. For each one we report some examples of case studies and the related models.

With this categorisation, we aim at proposing a framework containing all the most relevant aspects and information that rural energy planning studies should consider, state, and discuss. We also look at the topics that would need more investigation and might open new research opportunities, especially from an energy modelling perspective.

2.2.1. Spatial coverage: local and regional coverage

Within this category, studies are classified based on the extension of the geographical domain they consider: *local coverage* considers a village, a community, and a group of small villages [40–42] or set of houses [25,43] located in the same region of the same nation; *regional coverage* includes islands, big cities or institutional divisions according to linguistic boundaries or morphological constraints. As already stated, national and global case studies are not covered in our analysis.

Authors identify and specify the spatial coverage of their work in different ways. Himri et al. [44] present a study for a remote village in Algeria, specifying the number of consumers living in the area. Musgrove [45] develops a dynamic programming model to find the optimal operating strategy for satisfying an electrical load of 1 kW, without specifying the number or type of user(s). Salehin et al. [46] combines a HOMER-based techno-economic optimisation with a RETScreen-based energy scenario analysis for assessing a PV-Diesel and a Wind-Diesel power system in a small locality of 1000 people in Kutubdia Island, Bangladesh. Gupta et al. [47] study a hybrid energy system for the Juanpur block in India, specifying the extension of the location and the number of households. Silva et al. [48] focus on the applicability of multi-objective methods to assess the introduction of renewable technologies for general “Non-interconnected Zones” in Colombia. Nakata and Kanagawa [49] apply the META-Net economic modelling tool to analyse the future energy supply options and end-use devices for the rural areas of Assam region, India. Zeyringer et al. [33] analyse the options of grid extension and stand-alone photovoltaic systems for the electrification of Kenya, dividing the entire national area in cells that vary in coverage, from local to regional.

From this first categorisation, it emerges that about 78% of the cases analysed are *local* energy planning, suggesting a lack of *regional* studies. Moreover, in some cases the spatial coverage of the study is vaguely defined. This might prevent the extension of the approach and the findings to other similar cases of energy planning in analogous contexts. From the analysis of the spatial coverage of all the case studies, it emerges that modelling frameworks for local planning (e.g. HOMER ®) allow detailed technical aspects of the planned energy systems to be analysed and taken into account; on the other hand, regional planning mainly concerns the selection of the optimal energy supply strategy, such as the identification of the energy mix and the solution of the off- / on-grid dilemma.

2.2.2. Planning horizon: short, medium and long term

The second category refers to the time scale considered for implementing the energy planning. Four subcategories are identified: *short-term* (from one month to one year), *medium-term* (from one to ten years), *long-term* (beyond fifteen years) and *not-specified* term. The distribution of the works between these subcategories is reported in Figure 2.

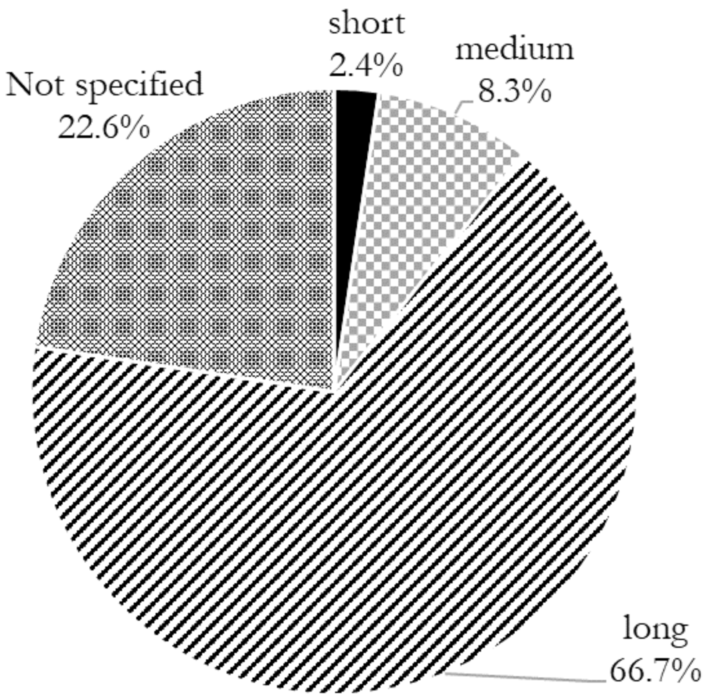

Figure 2. Classification of case studies: Planning Horizon.

Authors usually introduce the planning horizon in two different ways: some specify explicitly the lifespan of the project or lifetime of the energy system; others do not point out the planning period but report the lifetime of the components such as PV, diesel gen-set or wind turbine used to calculate the net present value or the discounted costs of the system. For example, Haddadi et al. [50] specify three different lifetimes for the systems implemented, equal to 10, 15 and 20 years. Similarly, Sen et al. [51] indicate a project's lifetime of 25 years. On the contrary, Silva et al. [48] do not point out the lifetime of the entire project but make the lifetime of the technologies explicit, in order to calculate the net present cost of the renewable energy system. Daud et al. [52] state clearly that the life cycle period of the system is assumed to be the maximum lifetime of the main components of the system. In cases where the project lifetime is not indicated, the maximum lifetime between all the system components defines the planning horizon of the study. This assumption is especially adopted to describe case studies where technical data of system components are listed, as Arun et al. do in [53].

Papers that do not specify any information for deriving the planning horizon are accounted for in the not-specified category. For example, Kanase-Patil et al. [54] apply the Integrated Renewable Energy Optimization Model (IREOM) for the electrification of dense forest areas in India in order to minimise the cost of energy generation over an amortisation period of *n* years. Again, Gupta et al. [47] generally note that the unit costs are calculated on the basis of the lifetime of the plants, without indicating a precise value.

This analysis highlights that about 67% of the studies refer to long-term energy planning, while almost one-quarter does not specify enough information to derive the planning horizon. This lack of information about the time horizon undermines the robustness of the planning results, since it prevents their replicability, as well as any uncertainty analysis on the evolution of the techno-economic parameters (e.g. energy demand, costs, efficiency). The classification of the case studies based on their planning horizon provides also useful insights about the details achievable by each energy model: short-term energy models allow the analyst to consider more precisely short time steps (seconds or minutes), specific operation constraints of the analysed energy systems and their response in case of unexpected conditions and phenomena (e.g. fluctuations, changes in weather conditions, variabilities of renewable resources). Long-term models usually rely on longer time resolutions (hours, days, weeks). This could prevent the analysis of short-term dynamics but allows the introduction of long-term variables (*e.g.* energy demands, useful life-time of the technologies, discount rates) that are pivotal to more complete economic analyses and sizing procedures.

2.2.3. Energy vector: electricity, thermal energy and oil products

The “energy vector” category classifies the case studies based on the energy output of the power systems subject to the planning. Three types of energy vector have been defined: *electricity*, *thermal energy* and *oil products*.

Electricity results as the most considered energy vector in the case studies (Figure 3), especially within those focusing on rural electricity planning and employing HOMER ® software for the optimal sizing of the off-grid system [40,44,46,55–72].

The thermal energy vector is the second most considered in the case studies, especially for the residential sector. This sub-category includes both thermal energy for space heating and cooking, often produced by systems fuelled by non-commercial energy (*e.g.* biomass and agricultural residues for cooking). For example, Malik and Satsangi [73] apply mixed integer/linear programming for optimizing the supply of energy for cooking in the rural areas in Wardha District, India. Joshi et al. [41] investigate the most appropriate fuels for cooking and for space heating in three villages of different zones of rural Nepal, among fuel wood, agriculture residues and animal dung.

Many case studies implement energy planning by considering more than one energy vector. Devadas [74] presents a linear programming-based model to optimally allocate energy resources to different end-uses such as household consumption, agriculture and transport, considering electricity for irrigation and lighting, liquefied petroleum gas for cooking, kerosene for the lamps of lower income consumers and organic and inorganic fertilizers for farming activities. Srinivasan and Balachandra [75] identify the most appropriate energy conversion technologies and non-commercial fuels for producing electricity for lighting and energy for cooking and thermal purposes. Hiremath et al. [76] optimise a decentralised bioenergy system to produce biogas for cooking and biomass for power generation. Fuso Nerini et al. [13] study the cost optimal energy supply options for different scenarios of energy demand in the village of Suro Craic, Timor Leste. Howells et al. [77] employ a MARKAL-TIMES model to plan household energy services in an African village considering both electricity and thermal energy for cooking.

In accordance with Pachauri et al. [78], this review indicates that rural energy planning studies mainly concern electricity planning, revealing that little quantitative analysis focuses on the other energy vectors. More comprehensive approaches would be needed to tackle all the challenges concerning sustainable rural energy planning, including the study of options to supply energy for cooking. This vector is highly prioritised in the Sustainable Energy for All (SE4All) global Agenda [79], as one of the pillars for achieving the SDG7 [80].

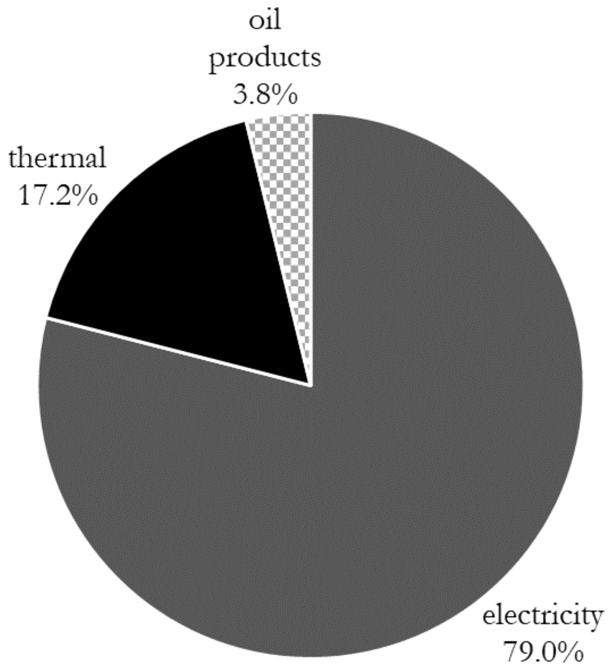

Figure 3. Classification of case studies: Energy Vector.

2.2.4. Decision criteria mathematical models: Linear Programming (LP), Multi-Criteria Decision Making (MCDM), Multi-Objective Programming (MOP), Non- Linear Programming (NLP), Dynamic Programming (DP), Enumerative Optimisation (EO)

In this sub-section, we examine the optimisation methodology lying behind the planning procedure. In accordance with Yusta and Rojas-Zerpa [19], decision criteria analysis has been classified into seven sub-categories (classes of models): *Linear Programming* (LP), *Multi-Criteria Decision Making* (MCDM), *Multi-Objective Programming* (MOP), *Non- Linear Programming* (NLP), *Dynamic Programming* (DP), *Enumerative Optimisation* (EO) and *other*.

LP is used to optimise a linear objective function subject to a set of linear constraints. In the analysed case studies, it is especially employed to minimise the cost of matching supply and demand [58,81,82]. The category includes also models using Mixed Integer Linear Programming (MILP). There are several modelling languages: LINGO is a modelling software developed by *Lindo Systems Inc.* and it is used by Kanase-Patil et al. [40] to calculate the cost of energy for an off- grid system in India. Fuso Nerini et al. [13] used OSeMOSYS [83], a linear model generator written in GNU MathProg language – a subset of the AMPL (A Mathematical Programming Language) –, to carry out the energy planning of Suro Craic village in Timor Leste.

MCDM solves problems involving more than one criterion of evaluation such as cost or price, efficiency and emissions. Analytic Hierarchic Process (AHP), Compromise Programming (CP), Goal Programming (GP), and Elimination and Choice Expressing Reality (ELECTRE) are MCDM-based techniques. Semaoui et al. [43] developed a Simulink-based model for the optimal sizing of a stand-alone photovoltaic system in Algeria, relying on a (i) reliability and (ii) economic criterion for the optimisation. Cherni et al. [84] implemented their multi-criteria decision-support system SURE to calculate the most appropriate set of energy alternatives for supplying power to a rural Colombian community, considering physical, human, social, natural and financial assets.

MOP is a method for solving optimisation problems with more than one objective function. For example, Hiremath et al. [76] set seven objective functions in their optimisation problem: minimisation of cost, maximisation of system efficiency, minimisation of use of petroleum products, maximisation of use of locally available resources, maximisation of job creation, minimisation of COx, NOx, and SOx emissions and maximisation of reliability.

NLP includes optimisation problems whose variables and constraints are linked by non-linear relations. Ashok [85] uses a Quasi-Newton algorithm to determine the optimal number of renewable energy units for a typical rural community in India. The META-Net economic modelling tool adopted by Nakata and Kanagawa [49] to analyse energy options in rural India is based on a NLP and partial equilibrium tool. Segurado et al. [86] relied on H2RES software to plan the future power generation for S. Vincent Island in Cape Verde; the model is based on a single-objective optimisation, i.e. the minimisation of the Levelised Cost of Energy (LCOE), subject to nonlinear relations and constraints.
DP is a technique for solving complex problems by splitting them into a sequence of smaller sub-problems, resolving and storing them in a data structure. Thus, DP does not identify a single optimisation algorithm: a variety of optimisation techniques can be employed to solve particular aspects of the main problem. It is applicable to problems that require a sequence of interrelated decisions to be made. Nahman and Spirić [87] determine the optimal long-term planning of various characteristic types of rural networks using a constrained DP technique. Bowe and Dapkus [88] formulate the problem of power systems expansion planning of a small utility in Midwest as a Markov decision process, and they use stochastic DP to solve the model. Das et al. [89] use DP to define the optimal investment plan for renewable energy technologies in Gajalia village, South-West Bengal.
More recently, EO stands out as a methodology of practical interest and straightforward application. Combinatorial optimisation models are also included in this category. This approach calculates numerically the optimal solutions based on one or more objectives. Usually, the objective is to minimise the cost of energy supply, by modifying the size of the supply technologies under a number of constraints (e.g. the availability of renewable resources). HOMER ® falls within this category: given the user-specified constraints and lower and upper limits on the size of the system the tool simulates every possible system configuration within the search space. The HOMER Pro's Optimizer ™ facilitates this operation, selecting the solution that satisfies the lowest total net present cost [90]. Türkay et al. [55] apply HOMER ® to find the lowest net present value for a stand-alone system composed of solar photovoltaic, wind turbines and fuel cells to supply electricity for a university in Turkey. Kolhe et al. [57] apply the same tool for optimally sizing an off-grid hybrid renewable energy system for electrifying a rural community in Sri Lanka. Akella et al. [58] compared LINDO ® and HOMER ® – respectively based on LP/NLP and EO optimisation methods – to define the optimal IRES for the Jaunpur block of Uttaranchal state of India. Mandelli et al. [91] develop a novel EO-based methodology for sizing PV-batteries power systems, which embraces uncertainty on load profiles. They apply it to electricity planning in a peri-urban area of Uganda.
Case studies that do not fit anyone of the classes or do not provide enough information are identified as "Others". For example, Phrakonkham et al. [92] minimises the annualised cost of energy for a remote village in Northern Laos with a genetic algorithm implemented in Matlab ®. Rana et al. [93] use an intuitive sizing method. They calculate and identify the system with the lowest total life cycle cost of six combinations of three possible technology alternatives (*i.e.* standalone PV, biogas system, gasifier system) to optimally match the energy supply and demand. Segurado et al. [86] rely on H_2RES software to maximise the penetration of renewable energy sources in the electricity system of S. Vicente Island in Cape Verde and they describe it simply as a "simulation tool".
Figure 4 illustrates the distribution of the reviewed works across the described decision criteria methods.

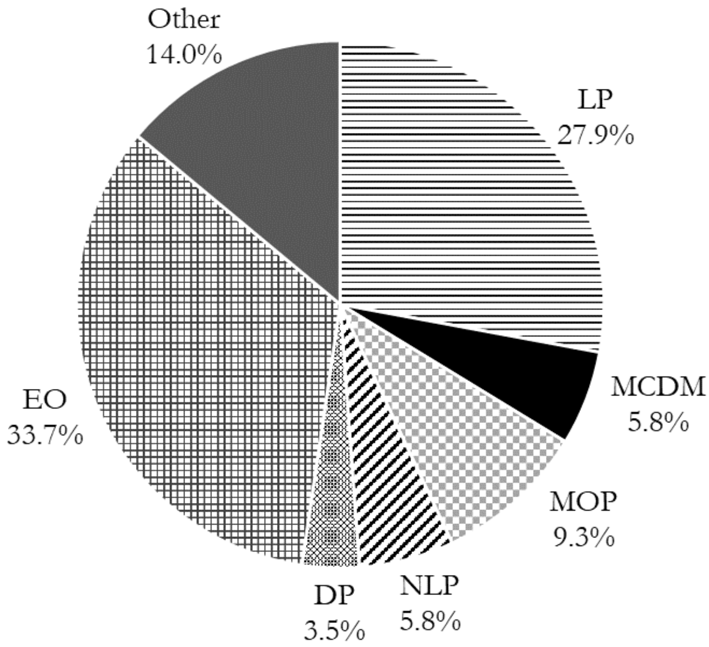

Figure 4. Classification of case studies: Decision criteria mathematical models.

EO results to be the most used mathematical method. It is adopted in 33.7% of the case studies, especially those that rely on HOMER ®. LP follows, used in 27.9% of the case studies. LP is based on analytical optimisation, requiring less computational time and effort than EO methods. On the other hand, EO is not constrained by the need to set only linear equations, sometime overly simplistic [94]; they therefore result in a better representation of the actual dynamics and phenomena that characterise the operation of energy systems (e.g. the charge-discharge dynamics inside the batteries).
This part of the review results suggests that the literature has been mainly limited to mono-objective optimisation models so far. Considering the multifaceted issue of sustainable rural energy planning [39] – which includes important socio-economic and environmental aspects, such as technology appropriateness, indoor air pollution, local know-how and capabilities –, MCDM and MOP models may provide more comprehensive frameworks for rural energy planning. Interesting options can consider the soft-linking with behavioural approaches, in order to take into account complex social aspects. As a pioneer example in this field, Moresino et al. [95] couple OSeMOSYS with a share of choice in order to take into account the consumers' real behaviour. In their case study, they focus on the consumer's preferences regarding the purchase and use of electric bulbs.

2.2.5. Energy uses: residential, communitarian, agricultural, industrial, commercial and not-specified

We classify the case studies based on both the type of energy users and the end-use of energy: *residential*, *communitarian*, *agricultural, industrial and commercial* and *not-specified*. In accordance with IEA's definition [96], such categories are the most comprehensive ones of all energy uses. The energy consumption for the residential sector includes demand for lighting, cooking and powering domestic appliances such as radios, televisions, fans, etc. The communitarian use of energy refers to schools, medical centres, radio stations, small shops, churches, and restaurants. Ferrer-Martì et al. [97] design an electrification plan for a community in Peru, considering households and five institutions as direct beneficiaries, namely the church, the school, the health-centre, restaurants and shops. The agricultural sector includes energy for farming activities: pumping water, ploughing, supplying tractors and other agricultural uses. The industrial sector considers rural industries and income generating activities, such as grain mills, coal kilns, small vans for products transportations, etc. The energy demand for the commercial sector refers to energy used for all the activities that need roads, telecommunication infrastructure, water and irrigation networks, bank and credits facilities; transportation (unless otherwise specified) is included as well, with the hypothesis that few people use cars or mini-vans as private use in rural contexts.

Very few case studies specify the sector covered by the planning [58,71,91], but they provide a the description of the type of technology and appliance to supply [13,88] or the end-uses of energy [77,98] – such as lighting, cooking, pumping, heating, cooling and transportation –, whence the demand sector is derived. Mandelli et al. [91,99] simulated the planning of a PV-based power system for a rural village in Uganda, investigating the effect of the uncertainty of the load profile on the optimum sizing; they employed a novel stochastic tool called “LoadProGen” to derive the load curves, which requires the definition of all the classes of users as input and consequently their end-use load profile. Amutha [71] explicitly estimates the electricity uses for the households, the industries, the agricultural activities, and the local Base Transceiver Station (BTS) (*viz*. a device that facilitates wireless communication) for the electricity planning of a remote Indian village.

Figure 5 illustrates how case studies are distributed among the five demand sectors.

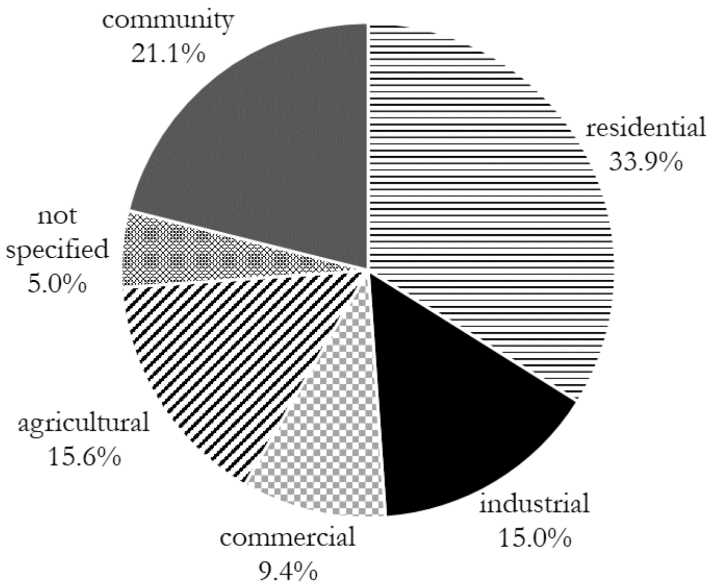

Figure 5. Classification of case studies into the five Demand Sectors.

It emerges that energy planning deals more with residential demand, in accordance with Bhattacharyya [35], who stated that “the demand in rural areas arises mainly from the use of domestic appliances” (p. 678). However, the literature concerning the nexus between energy and local development shows the need to increase the focus on the industrial use of energy, elsewhere called *productive use of energy*. Specifically, it indicates that access to energy, when it is supported by complementary activities – e.g. educational activities, capacity building and awareness campaigns –, can be a pivotal driver in developing new business [100–107], with a consequent increase in the industrial energy demand. In line with this finding, Homer Pro ® has a new interesting feature, which allows the user to select default “Commercial” and “Industrial” types of load in the simulation.

3. Approaches to forecast the long-term evolution of the energy demand

This section focuses on methods and approaches for the long-term forecasting of energy demand, which is a pivotal aspect for implementing a reliable and appropriate planning of the energy supply options, as discussed in the Introduction [9–14].

3.1. Overview of energy demand models for rural energy planning

The scientific literature has addressed the classification of models to forecast the energy demand. Bhattacharyya and Timilsina [108,109] propose a literature review of existing energy demand forecasting methods and highlight the methodological diversities among them. Their purpose is to investigate whether the existing energy demand models are appropriate for capturing the specific features of developing countries. They find that mainly two approaches are used: econometric (or top-down) and end-use (bottom-up) accounting; the latter is able to produce more realistic projections as compared to the former; on the other hand, it suffers from data deficiencies ([109] p. 1979), while econometric accounting does not. Suganthi et al. [110] present a comprehensive review of the various energy demand models, as well as applications for both developing and developed countries. Swan et al. [111] focus on the residential sector to present a review of existing approaches to model energy household consumption, classifying them into top-down and bottom-up approaches.
Among the existing reviews, very few applications of energy models for forecasting energy demand refer to rural contexts: Hartvigsson [112] developed an end-use system dynamics model to project the electricity demand of a rural community of Tanzania by accounting for the nexus between income, economic growth and electricity needs. S. Mustonen [113] built an end-use LEAP (*Long-range Energy Alternative Planning System*)-based model to generate long-term scenarios of energy demand evolution for a rural village in Lao People’s Democratic Republic, for a time domain from 2006 to 2030. Van Ruijven et al. [114] developed a bottom-up simulation model for investigating the growth of household energy demand in India and Daioglou et al. [115] extended it to other emerging regions: China, South East Asia, South Africa and Brazil. They named it global residential energy model (REMG) and applied it for both rural and urban areas. Fuso Nerini et al. [13] modelled 4 scenarios of energy demand growth in the rural village of Suro Craic in Timor Leste, based on the ESMAP/World Bank multi-Tier framework for measuring energy access and the long-term objectives set by the Timorese government.
In this section, we assess how the existing approaches for long-term forecasting of the energy demand are employed in the previously reviewed case studies, in the attempt to derive insights and guidelines for supporting future rural energy planning studies in DCs.

3.2. Energy demand forecasting approaches: categorisation and adoption

Few case studies explicitly state the model adopted to predict the energy demand, like for instance Malik et al. [42,73]. We classified the others based on the mathematical forecasting approach adopted; we identified eight categories of long-term energy demand forecasting approaches: *fixed load*, *arbitrary trend*, *scenarios, regression*, *time-series*, *extrapolation*, *system dynamics* and *input/output* (*I/O*). Regression, time-series and I/O approaches refer to the classification proposed by Suganthi et al. [110]; the others have been proposed by the authors and refer to the specific function or mathematical technique adopted.
Appendix B reports a complete overview of the categorisation adopted for the collected case studies. The *fixed load* category is introduced for those energy planning case studies that consider a fixed value of energy load – i.e. no evolution of energy consumption – along all the planning horizon. For example, Zhang et al. [82] consider a constant electricity demand throughout the whole lifetime of the system (15 years) and they generate random weekly load profiles based on typical values of load for rural villages of Southeast Asia. Borhanazad [116] develop a MOP-based planning of three micro-grids in rural Iran. Here, they consider a constant hourly load profile for a typical rural area ([116] p. 300), derived by local assessments, without considering any evolution along the planning period. Cherni et al. [84] propose a model to supply sustainable energy for a community in Colombia. They do not introduce any demand forecasting model but they state that the energy system is designed to support a potential growth of the community and its electric consumption. Almost all the case studies that employ HOMER ® software to design electricity microgrids belong to this category [40,44,46,55–72], since the software considers a fixed load curve along the planning horizon, and the only variability

lies at a daily and seasonal level. Also case studies that do not specify how they project the demand along the planning horizon are considered within the ‘fixed load’ category. For instance, Tegani et al. [117] apply a genetic algorithm to size a hybrid wind/PV/diesel power system for a small isolated area of few houses in Algeria without reporting any information about the evolution of the load along the lifetime of the system.

The *arbitrary trend* method is characterised by the assumption that the energy demand would evolve with at a constant pace during each year of the planning; the trend is often estimated from historical data series, as in [13,118–120], derived from local data, national plans and “goals” of energy access. Such arbitrary trends are frequently combined with multiple scenarios of energy demand. Fuso Nerini et al. [13] set arbitrary trends of energy demand growth in the rural village of Suro Craic depending on the different Tiers of electricity access defined by the World Bank [121]. Domenech et al. [97] investigated the current energy demand of a community of Alto Peru with local surveys. They derived arbitrary trends of growth from considerations on the “development of small productive activities and/or enjoyment of some domestic comforts” ([97] p. 280). For a case study focusing on India, Nakata and Kanagawa [49] assume that the total energy demand increases linearly during the planning horizon according to the expected annual growth of population in the country: 1.4% from CIA data in 2015.

The *scenario*-based approach refers to a set of descriptive pathways that indicate how future events may occur. It is a particularly suitable method in contexts characterised by high uncertainty. A number of case studies adopted this approach to develop possible long-term pathways of energy demand evolution: Ferrer-Martì et al. [122] couple a “low-demand” scenario characterised by constant demand for energy for households, the school and a health centre, and a “high-demand” scenario to consider a wider fulfilment of the basic needs and possible production uses. Nayar et al. [70] use HOMER ® to design an innovative wind/PV/diesel hybrid system for three remote islands in the Republic of Maldives. They gather data from monthly records and by evaluating the load profile for a period of one day, and they state that “several scenarios of […] load growth were examined” (p. 1079).

The *regression* models perform the forecast through a regression function where a dependent variable is obtained by a combination of some parameters or coefficients and independent variables. The regression function is usually linear and the parameters are usually estimated from data with the least-squares technique. Zeyringer et al. [33] implement a regression and Tobit model for evaluating the monthly electricity demand per household as a function of a number of independent variables. These are non-food expenditures per household per month, the number of servants employed in the household, the flush toilet as main toilet facility, the age of the household head, the formal education of the household head and the number of people living in the household. For the regression, they use data from a 2005/2006 survey, and they project the demand to 2020 by employing forecasts of future GDP (rural, urban), population (rural, urban), and share of educated population (over 15 years of age).

Time-series models use historical panel data for extrapolating the future energy requirement. This marks a difference with the regression analysis, which investigates how the current values of one or more independent variables can affect another current or future dependent parameter. Different techniques are used in time-series models to predict the electricity demand: simple first-order autoregressive time-series models, logistic curves, Markov models and other models for technology diffusion, like Gompertz. The results of these sophisticated methods seem to depend on the structure of the model itself and the strategies employed for data analysis. Bowe and Dapkus [88] developed a Markov model for solving the problem of power systems expansion planning, simulating a case study of a small utility in Midwest in the '90s., In this case, the complexity, uncertainty and dynamics of the problem affect also the future demand levels.

System dynamics (*SD*) models are used to capture the nonlinear behaviour of complex systems over time, by relying on the use of causal and feedback relationships. SD models are characterised by stocks, which are the state variables of the dynamical system, and their inflows and outflows (rates), which increase or decrease the value in the stock. In the field of rural electrification, Steel [123] developed a SD model to simulate the decision-making process of electricity consumers in rural Kenya, while choosing between grid and off-grid power options. Jordan [124] uses SD to compute endogenously the electricity demand in a long-term power capacity expansion model for Tanzania.

Hartvigsson et al. [9] attempt to study how the initial planning of capacity generation affects cost-recovery, electricity usage and user diffusion in rural areas. Zhang and Cao [125] simulate the nexus between rural economic development, social development (*viz.* growth in population) and energy consumption to analyse the future energy supply mix for a rural Chinese region. Among the analysed case studies of rural energy planning, only Zhen [126] applied a SD approach to model energy demand: he developed a model to predict the developmental changes of the energy supply and demand for a rural village in the North China.

The *Extrapolation* technique corresponds to the method used by Malik et al. [42,73], which approximates data of future energy consumption by a probability distribution function starting from historical surveys. We did not find any other use of this technique in other cases studies, probably due to the problem of data scarcity, which prevents the use of this method in studies of rural energy planning.

Input-output models (I/O) have long been used for macro-economic and top-down analysis, with scarce application to local energy planning. They are usually not employed for modelling informal activities and non-monetary transactions, due to the lack of reliable data. Subhash et al. [127] carry out an energy planning for an Indian village cluster by developing an I/O model, which adopts inter-sectorial relations for projecting sector scenarios of the economy in the long-term.

3.3. Observations from literature and guidelines to forecast rural energy demand

Figure 6 summarises the distribution of the reviewed studies across the different demand forecasting approaches. It clearly emerges that two thirds of the case studies do not consider the variation of demand over the planning horizon, weakening the reliability and robustness of the design phase of the planning, especially for long-term approaches. One-third of the reviewed case studies employ HOMER ® software or its improvements to carry out the electricity planning; here, the electricity demand is fed as a daily average load profile, with the possibility to introduce a daily and monthly variability; however, no variability over the years can be introduced. Only Prasad and Natarajan [128] justify this modelling choice due to the fact that the surveyed variation of the distributions of the load resulted insignificant between the period 2000 and 2004 for the site Pompuhar, in India. Among the case studies with a long-term planning horizon, our study reveals that only 23% of them apply at least one of the remaining forecast techniques for projecting energy demand. Among these, the most used approach assumes a fixed growth every year (*arbitrary trend*) justified by previous studies, historical trends or specific assumptions, that may fail in capturing the complexities behind the evolution of energy demand in rural contexts. Therefore, they are often combined with a *scenario*-based approach, which is very useful to deal with uncertainties in the demand; nevertheless, the use of the *scenario*-based approach must be compatible – at reasonable computational effort and time – with the decision criteria mathematical models employed for the energy planning.

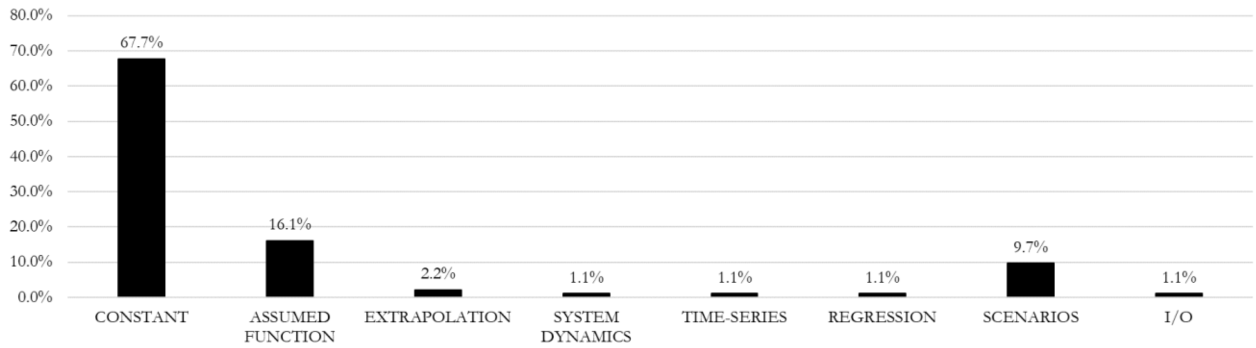

Figure 6. Percentage of energy demand forecasting approaches adopted in the case studies.

These results highlight that the use of appropriate and reliable models for long-term energy demand forecast in rural energy planning studies is quite limited. Based on the literature, we try to propose some guidelines that aim at enhancing the future research on this topic. When modelling energy demand in DCs, Urban et al. [129] list the main characteristics of the energy system of developing countries that should be captured by energy models: the supply shortages, the transition from traditional to commercial fuels, the role of income distribution, the urban/rural split, the underdeveloped markets and informal activities, structural changes in the economy and subsidies. Bhattacharyya and Timilsina [109] criticise most global energy models that forecast future residential energy demand based on relatively simple relationships between energy consumption and income or GDP per capita, since they neglect such specific dynamics of developing countries and use aggregate macro-data. Table 1 presents an abstract of the main features, strengths and weaknesses of the two most diffuse approaches discussed by Bhattacharyya and Timilsina: top-down or econometric and bottom-up or end-use approach.

Table 1. Characteristics of bottom-up and top-down models.

	Bottom-up	Top-down
Strength	- detailed sectorial representation of energy demand - realistic projections - local demand representation	- identification of the relationship between economic variable and aggregate demand - reliance on aggregate data easy to obtain - reliability on historical trends able to drive the model
Weakness	- huge data deficiency especially for DCs - not able to capture price-based policy and price signals	- inability to capture technological diversity and technical progress

Especially in rural areas, energy access planning should firstly consider the structural change in the socio-economic dynamics caused by the introduction of new energy technologies, such as the leapfrogging of economies (*e.g.* new income generating activities and opportunities) [108,109]. Secondly, an appropriate model for demand forecasting in rural areas must account for the demand for end-use appliances [115]. This in turn depends on acceptability, deeply-rooted consumer behaviours, social networks-based diffusion mechanisms, affordability, elasticity of the demand and the inertia of the stock of available appliances. This is why Swan at al. [111] state that bottom-up end-use approaches are more suitable for contexts where there is a rapid technological development as in DCs. Ruijven et al. [114] and Daioglou et al. [115] integrated some of the typical features of energy systems in DCs mentioned by Urban et al. [129] in their Residential Energy Global Model (REGM). The model is able to capture many of the specific dynamics of DCs (*viz.* underdeveloped markets and informal activities, the transition from traditional to commercial fuels, the role of income distribution and the urban/rural difference). It also adopts deterministic correlations derived from econometric studies and regression analysis on national data to project the energy use of households: this results a function of exogenous factors and drivers such as population, household size, household expenditures and temperature [130,131]. The use of such approaches for local applications might be prevented by the lack of local long-term data, as frequently happens in rural areas. In this context, the need to move towards mathematical approaches and instruments able to capture both the technical and the socio-economic-related dimensions of energy demand evolution emerges, as we summarise and propose in Table 2.As Khandker et al. [132] state, "the dynamics of growth and electrification are complex, involving many underlying forces" (p. 666) and feedback mechanisms: rural electrification is expected to positively impact new economic and educational opportunities, which in turn might make electricity and appliances more affordable, increasing the local electricity demand.

Table 2. Socio-economic- and energy-related dimensions of energy demand evolution in rural contexts

Economic dimension

- Considering the informal activities/economies that may bias available aggregate data on income [129]
- Considering income distribution and inequity among users, who may behave differently among different socio-economic classes [129]
- Modelling the new income generating activities and possibilities driven by more reliable access to energy [108,109]

Social dimension

- Modelling the urban and rural demand separately, since people have different needs and constraints [129][114]
- Considering also non-monetary factors that may influence the users, such as past experience, social norms, and trust-based information and perceptions of quality, satisfaction and social network [133][134][135][9]

Energy dimension

- Modelling the demand for end-use appliances following a bottom-up approach [115].
- Considering the "user choice" of fuels and transition from traditional to modern energies, and vice-versa [129], especially for energy for cooking [136]

To this end, SD seems an appropriate candidate tool, given its ability to represent complex socio-economic, techno-economic and socio-technical nexus causalities. Hartvigsson [9,112] highlights how SD can be a valuable methodological approach to capture the dynamics behind the evolution of energy demand in developing contexts, since the latter are affected by high uncertainty, strong non-linear phenomena, complex diffusion mechanisms, time-adjustments of technology perceptions [137]. SD models have some limitations in modelling the social interactions that ensue within social networks and impact on consumers' energy behaviours, since individuals are assumed to be always well-mixed and in many cases the interactions between compartments are assumed to occur at random [138]. Rai and Henry [134] indicate therefore that "agent-based modelling (ABM) is a powerful tool for representing the complexities of energy demand, such as social interactions and spatial constraints" (p. 1). As already stated by other studies in different research fields [139–142], we therefore conclude that coupling ABM and SD may be useful also to investigate in a comprehensive way the multi-faceted complexities behind energy choices and uses in rural areas.

Conclusions

In developing contexts, the number of people affected by lack of reliable and affordable energy sources may be only slightly reduced in the incoming decades in spite of the many efforts and investments in the sector [5]. A number of studies was carried out on long-term rural energy planning since around the '80s, but the different foci, terminology and methodologies make it difficult to track the similarities, weaknesses and strengths of these works. Moreover, the aspect of energy demand is

far from being carefully addressed and analysed in rural energy plans. This in turn can constitute a barrier for researchers to build on the whole experience and findings of the authors. Indeed, most of the studies and the reviews focus only on the “supply” aspect of the rural energy planning.
Coming from a modelling background and being interested in the prompt applicability of the existing know-how on long-term rural energy planning, we aimed at providing a critical analysis of the literature on the topic. The specific objective of the review is to provide a synthesis of strengths and weaknesses and fields of applicability of the approaches used so far, as well as the main modelling insights that can be derived from their applications.
The work resulted in the analysis of 126 studies and categorisation of 84 of them, under a number of rules clearly defined in the first part of the paper: (i) the implemented energy planning must be aimed at selecting energy conversion technologies able to match a certain demand with certain energy resources in an optimal manner; (ii) studies refer to real-life cases or potential applications for real contexts; (iii) only local rural energy planning for DCs (and BRICS) is considered, excluding works referring to other contexts or to global and national scales; (iv) in case of electricity planning, all the on- and off-main grid electrification options (standalone systems, microgrids and distributed hybrid microgrids) presented by the case studies are considered; (v) the papers must come from the scientific peer-reviewed literature, without any constraint on the publication period. These rules are meant to indicate the scientific ground of the analysis and to provide a benchmark to replicate and extend it.
As a novelty, we combined the analysis of both the “demand” and the “supply” aspects of the rural energy planning studies, stressing the need to consider and model these two parts of the planning as linked and interdependent. For this purpose, the studies have been classified in two ways:

i. Firstly, in accordance with their type: subcategories of spatial coverage, planning horizon, energy vector, decision criteria mathematical models and energy uses were identified and the studies classified under each of them;
ii. Secondly, in accordance with the methodology they employ to forecast the evolution of the energy demand, if any.

We came to the conclusion of performing such multi-layer categorisation based on the observation that the diversity of the studies spans over multiple dimensions and that selecting only few categories would have been simplistic and inconclusive.
From our classification, it emerges that about three quarters of the cases analysed refer to local rural planning (i.e. a village, a community, a group of small villages or a set of houses located in the same region of the same nation) and about two thirds carry out a long-term energy panning analysis (i.e. beyond fifteen years). Nevertheless, we found several case studies that did not report enough information for assessing the spatial coverage and planning horizon, preventing the findings to be extended to other similar cases of energy planning in analogous contexts. Electricity is found to be the most considered energy vector (79.0 % of the studies), followed by thermal energy (17.2%) and oil products (3.8%). The results reveal the need to increase the energy planning-based research on the other energy vectors, especially regarding thermal energy for cooking, given its priority in the Sustainable Energy for All (SE4All) global Agenda. Household end-use of energy is considered by most of the case studies, followed by communitarian, agricultural and industrial uses. Regarding the modelling approaches adopted to develop the planning, LP and EO result to be the most used, respectively by 27.9% and 33.7% of the reviewed studies. However, considering the multifaceted issue of sustainable rural energy planning – which includes important socio-economic and environmental aspects such as acceptability, technology appropriateness, indoor air pollution, local know-how and capabilities –, we suggest to enhance the research on MCDM and MOP models for more comprehensive energy planning studies.
Interesting conclusions emerge particularly from the analysis of the methodologies to forecast the energy demand. Few studies assume a dynamic demand over the years and most of them forecast its evolution through arbitrary trends and scenarios. This, however, undermines the relevance of the results for the purpose of long-term planning, as also remarked by [109]. We therefore encourage

future researches to pay more attention to this topic and consider carefully the importance of energy demand evolutions within rural energy planning studies, as inferred from [10–12]. We finally highlight the necessity of further developing the forecasting methodologies. To this end, we attempt to highlight the main socio-economic aspects that should be considered when modelling the evolution of rural energy demand: informal activities/economies, income distribution and inequity among users, new income generating activities and possibilities, difference between urban and rural demand, non-monetary factors such as past experience, perceptions of quality, satisfaction and social network, end-use energy consumption of appliances, user's choice of fuels and transition from traditional to modern energies. In this context, bottom-up approaches and system-dynamics seem potential appropriate approaches to tackle the context-specific complexities of rural areas, the nexus causalities among energy and socio-economic aspects, as well as the possibility to deal with high uncertainties and data scarcity. Such conclusion sets a starting point for our modelling work on enhanced demand forecasting methodologies and it is meant to contribute to the same effort of other researchers.

Acronyms – Subscripts

AHP	Analytic Hierarchic Process
AMPL	A Mathematical Programming Language
BRICS	Brazil, Russia, India, China and South Africa
CIA	Central Intelligence Agency
CP	Compromise Programming
DC	Developing Country
DP	Dynamic Programming
ELECTRE	Elimination and Choice Expressing Reality
EO	Enumerative Optimisation
ESMAP	Energy Sector Management Assistance Program
GP	Goal Programming
IEA	International Energy Agency
IREOM	Integrated Renewable Energy Optimization Model
IRES	Integrated Renewable Energy System
LCOE	Levelized Cost of Energy
LP	Linear Programming
MCDM	Multi-Criteria Decision Making
MOP	Multi-Objective Programming
NLP	Non- Linear Programming
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaic
REMG	Residential Energy Model Global
RET	Renewable Energy Technology
SD	System Dynamics

Appendix A

Table 3. Systematic classification of long-term energy planning case-studies.

	SPATIAL COVERAGE		PLANNING HORIZON				ENERGY VECTOR			ENERGY USES						MATHEMATICAL DECISION CRITERIA						
Reference	*local*	*regional*	*short*	*medium*	*long*	*n.s.*	*electr.*	*therm.*	*oil prod.*	*resid.*	*ind.*	*comm.*	*agric.*	*commun.*	*n.s.*	*LP*	*MCDM*	*MOP*	*NLP*	*DP*	*EO*	*Others*
[143]	x					x	x	x		x								x				
[87]	x			x			x			x	x	x	x	x						x		
[144]		x			x		x	x	x	x	x		x			x						
[126]	x				x		x	x		x						x						
[76]	x				x		x	x		x		x	x					x				
[145]		x			x		x			x	x						x					
[81]		x		x			x			x	x	x	x	x		x						
[77]	x				x		x			x						x						
[146]		x			x		x			x								x				
[55]	x				x		x							x							x	
[13]	x				x		x	x		x						x						
[74]		x	x				x	x	x	x	x	x	x			x						
[40]	x				x		x			x	x		x	x		x					x	
[147]	x				x		x			x	x		x				x					
[89]	x					x	x			x			x							x		
[33]	x				x		x			x						x						
[56]	x				x		x			x	x	x	x	x							x	
[127]	x				x		x			x	x	x	x			x						
[148]	x			x			x	x		x	x	x	x			x						
[57]	x				x		x			x	x	x	x								x	
[97]	x					x	x			x				x			x					
[12]	x				x		x			x				x								x
[149]	x					x	x			x						x						
[150]		x		x			x	x		x	x	x	x	x						x		
[53]		x			x		x								x						x	
[117]		x			x		x								x							x
[50]		x			x		x			x									x			
[151]	x					x	x			x				x								x
[152]	x				x		x	x							x							x

[82]	x				x		x			x						x					
[25]	x					x	x			x	x	x		x							x
[43]	x				x		x			x							x				
[153]	x				x		x								x						x
[116]	x				x		x			x								x			
[85]	x				x		x			x									x		
[128]	x				x		x								x						
[47]		x				x	x			x	x	x	x			x					
[84]	x				x		x			x			x	x			x				
[48]		x			x		x			x								x			
[154]	x					x	x			x				x		x					
[155]		x				x	x								x			x			
[156]	x					x	x			x	x		x			x					
[157]	x				x		x	x		x				x				x			
[158]	x					x	x				x		x			x					
[75]	x			x			x	x	x	x			x			x					
[122]	x		x				x			x				x		x					
[44]	x				x		x								x					x	
[58]		x			x		x			x	x	x	x			x				x	
[93]	x				x		x	x		x	x		x								x
[159]	x					x	x			x				x		x					
[160]	x					x	x						x			x					
[161]	x					x	x			x						x					
[59]		x			x		x							x						x	
[60]	x				x		x			x										x	
[61]	x				x		x							x						x	
[62]	x				x		x							x						x	
[63]	x				x		x						x	x						x	
[64]	x				x		x						x	x						x	
[65]	x				x		x						x	x						x	
[66]	x				x		x							x						x	
[67]	x				x		x							x						x	
[68]	x				x		x						x	x						x	
[54]	x					x	x	x		x	x		x	x						x	
[69]	x					x	x							x						x	
[162]		x			x		x			x											x
[70]	x					x	x							x						x	
[163]	x				x		x	x		x				x					x		

[120]	x				x	x			x				x			x			
[52]	x			x		x			x				x						x
[164]	x				x	x			x										x
[118]	x			x		x								x			x		
[41]	x		x			x	x	x	x						x				
[49]		x	x			x	x		x								x		
[57]	x			x		x			x	x			x					x	
[91]	x			x		x			x	x			x					x	
[71]	x			x		x			x	x	x	x	x					x	
[117]	x			x		x			x										x
[46]	x			x		x			x	x			x					x	
[72]		x		x		x	x		x	x	x	x						x	
[86]		x		x		x								x					x
[99]	x			x		x			x	x	x			x				x	
[165]	x			x		x			x	x	x			x				x	
[166]	x			x		x			x					x	x				
[14]	x			x		x			x	x	x			x				x	

754 **Appendix B**

755 **Table 4.** Long-term energy demand forecasting approaches adopted within case studies.

	LONG-TERM DEMAND FORECAST							
Reference	*Fixed load*	*Arbitrary trend*	*Extrapolation*	*System Dynamics*	*Time-series*	*Regression*	*Scenarios*	*I/O*
[143]	x							
[87]		x						
[144]			x					
[126]				x			x	
[76]		x					x	
[145]		x						
[81]		x					x	
[77]		x					x	
[146]	x							
[55]	x							
[13]		x					x	

[74]	x							
[40]	x							
[147]		x						
[89]	x							
[33]						x		
[56]	x							
[127]		x					x	x
[148]			x					
[57]	x							
[97]		x					x	
[12]	x							
[149]	x							
[150]					x			
[53]	x							
[117]	x							
[50]	x							
[151]	x							
[152]	x							
[82]	x							
[25]	x							
[43]	x							
[153]	x							
[116]	x							
[85]		x						
[128]	x							
[47]	x							
[84]		x						
[48]	x							
[154]	x							
[155]	x							
[156]	x							
[157]	x							
[158]	x							
[75]		x						
[122]	x						x	
[44]	x							
[58]	x							
[93]	x							
[159]	x							

[160]	x		
[161]	x		
[59]	x		
[60]	x		
[61]	x		
[62]	x		
[63]	x		
[64]	x		
[65]	x		
[66]	x		
[67]	x		
[68]	x		
[54]	x		
[69]	x		
[162]	x		
[70]			x
[163]	x		
[120]	x		
[52]	x		
[164]	x		
[118]	x		
[41]	x		
[49]		x	
[57]	x		
[91]	x		
[71]	x		
[117]	x		
[46]			
[72]	x		
[86]		x	
[99]	x		
[165]	x		
[166]	x		
[14]			x

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