Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review

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Access to electric power supply has always had a significant role in promoting improvements in all the society sectors, nevertheless nowadays 1.3 billion of people still do not have electricity access. Moreover, most of them live in rural areas of developing countries which are often isolated, scattered populated and characterized by poor infrastructure and services. In this situation, the growing consideration towards the target of universal access to energy has emphasized the role of rural electrification, and off-grid small-scale generation represents one of the most appropriate options. As a consequence, the scientific literature has devoted attention to this topic with a large number of papers. In this frame, the present analysis focuses on off-grid systems for rural electrification and provides a general framework to this topic and an analytical review of the literature. The work is based on the review of more than 350 papers mainly published from 2000 to 2014 within selected journals, and it is organized in two sections. In the first one we describe the role of small-scale generation systems throughout the process of electrification, the main features of rural areas and their typical energy uses, and we propose a new comprehensive taxonomy for off-grid systems for rural electrification. In the second one we develop an extensive review of the selected literature according to the proposed classification and to five main research areas: Technology: layout and components; Models and methods for simulation and sizing; Techno-economic feasibility analyses and sustainability analyses; Case studies analyses; Policy analyses. The work results in a comprehensive review which organizes and capitalizes the main fundamentals of the addressed topic and provides elements to get acquainted with the literature.

Keywords: Distributed systems, Decentralized systems, Stand-alone, Micro-grid, Hybrid micro-grid, Renewable

Contents

Abbreviations: ac, alternating current; B, battery; BG, biogas; BM, biomass; COE, cost of energy; D, diesel; dc, direct current; DCs, developing countries; DG, distributed generation; FC, fuel-cell; GHG, greenhouse gas; H, hydro; HDI, human development index; HMG, hybrid micro-grid; IEA, International Energy Agency; ITC, information and communication technology; LCC, life cycle cost; LCoE, levelized cost of electricity; LPG, liquefied petroleum gas; LPSP, loss of power supply probability; MG, micro-grid; MHP, micro-hydropower; MSE, micro and small enterprises; NGO, non-governmental organization; OECD, Organisation for Economic Co-operation and Development; PAT, pump-as-turbine; PHP, pico hydropower; PV, photovoltaic; RE, renewable energy; SA, stand-alone; SHP, small hydropower; Wn, wind

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1. Introduction

Observing the development process of world countries throughout the 20th century, it is clear that electricity supply has had a significant role in promoting progresses in all the society sectors, thus leading to an improved well-being for people. Nevertheless, electric supply expansion has not been the same throughout the world, and hence nowadays it is possible to recognize many countries[1] which suffer for low rate of electrification (Table 1), low per capita consumptions [2–4] and low quality of the electric supply service [5,6]. Within this frame, dwellers of rural areas are the most affected by the problem [7,8]. Rural areas are generally scattered populated, isolated and characterized by high illiteracy rates, lack of access to health care and clean water supply which lead to *"standards of living that almost universally lag far behind urban areas"* [9]. This situation is exacerbated by the limited progress in rural electrification due to high costs for grid extension which is not balanced by a local market. Therefore the growing consideration towards the target of universal access to energy [10,11] has been drawing attention to rural electrification and to those technologies which go beyond the centralized system approach.

Off-grid small-scale electricity generation represents one of the most appropriate options to face this issue, both as a first step in the electrification process or as a building-block for future grid development [12–16]. The forecasts drawn by the International Energy Agency (IEA) reported that about 60% of the additional electricity generation requested to provide universal access to energy, is expected to be generated through off-grid systems. Furthermore, the analyses also report that off-grid systems are almost totally required for rural electrification and about 90% of them are supposed to rely on renewable-based systems and mini-grid [17,18].

The scientific literature has widely addressed the analysis of off-grid systems for rural electrification in developing countries (DCs). Nevertheless, to our knowledge, there are no papers which provide a general framework to this topic or an analytical overview of the literature. Such analysis, actually, may contribute (i) to define a common reference as regards the typical context of implementation and a general taxonomy for off-grid systems applied to rural electrification, and (ii) to review and capitalize the literature according to this taxonomy. The present paper addresses these two subjects and it is organized in two main sections. In the first one, we present the reference framework of off-grid systems for rural electrification. Specifically: (i) we describe the evolution of the role of small-scale electricity generation in the process of electrification and we enumerate the driving forces that are currently promoting it, (ii) we present the main features of rural areas providing an overview of the typical energy uses, and (iii) we introduce some definitions to realize a new taxonomy of off-grid systems in the specific context of rural areas of DCs. In the second one, we present a comprehensive review of the available literature. The review is focused on 14 Elsevier journals and it considers more than 350 papers mainly published from 2000 to 2014. We accomplish the literature analysis according to the taxonomy previously introduced, and to five principal areas of research recognized to be the most addressed ones in the literature: (i) Technology: layout and components, (ii) Models and methods for simulation and sizing; (iii) Techno-economic feasibility analyses and sustainability analyses; (iv) Case studies analyses; (v) Policy analyses.

2. Reference framework for off-grid systems in developing countries

2.1. The parabola of small-scale generation systems

Small-scale generation systems are gaining more and more consideration in electric utility planning of both developed and DCs. Nevertheless this is not a new approach. In fact at the sunrise of the electrical era, systems were quite decentralized, and small generation plants, together with batteries, supplied electricity via dc grids only to nearby limited areas of dense load [19,20].

The first era of small-scale generation was ended by the emergence of ac grids and by technical advancements in generation plants, which drove to the construction of huge transmission grids and large generation plants [19]. The resulting structure of the electrical industry was the *state-owned vertical integrated regulated monopoly* [21] which can be considered as the classical paradigm of *centralized electrical system* [22]. This approach has been followed both in developed and DCs, but while developed countries were able to extend the coverage area of the electric grid

[1] The majority of these countries fall in *low* or *middle-income economies* as regards the World Bank classification (which also refer to them as *developing countries*) [1]. The developing country definition does not imply that all economies in the group are experiencing similar levels of development or that other economies have reached a preferred or final stage of development. However, in this work we adopt this definition as an indication to locate the analysis for simplicity.

Table 1
Regional aggregates for electricity access (2011).*Source* [8]

	Population without electricity [millions]	Electrification rate [%]	Urban electrification [%]	Rural electrification [%]
Africa	600	43	65	28
Developing Asia	615	83	95	75
Latin America	24	95	99	81
Middle East	19	91	99	76
Developing countries	*1257*	*76.5*	*90.6*	*65.1*
Transition economies and OECD	1	99.9	100.0	99.7
World	*1258*	*81.9*	*93.7*	*69.0*

also to rural areas [20], DCs are still facing considerable difficulties in increasing power production and electrification rates (Table 1).

Rural areas are the most afflicted by this situation since governments paid more attention to urban areas where economic activities are relevant. Rural electricity supply generally results to be expensive within the centralized approach, and hence the utilities have always been reluctant to extend the service to rural areas. Typical actions taken up by DCs governments to address this issue, were the establishment of separate organizations – the *Rural Electrification Agencies* – that were made responsible for rural electrification programs [21].

The primacy of the centralized approach gradually decreased in developed countries during the '80s, due to the introduction of competition into the electric industry [20,21,23]. Also DCs pursued reforms trying to attract foreign private capitals in order to make more effective and efficient the existing power system and to increase the efficiency in the electrification process [21]. It is in the new post-reform frame that a second era of small-scale generation systems, mainly based on renewable sources, seems to arise [19, 24].

Besides the introduction of competition, other factors contributed to renew the interest towards a strategy based on small-scale generation systems. Revising the literature, we recognized and propose to group these factors according to five dimensions: environmental, economic, technical, political and social (Table 2). Most of the listed factors, are driving forces that support small-scale generation in developed countries as well as in DCs [23,25–27]. Nevertheless, further reasons can be associated specifically to DCs and rural areas:

- *accessibility*: small-scale generation, mainly based on renewable sources, is preferred for the remotest locations where costs make unfeasible the extension of the main grid [20,28,29];
- *load demand*: rural areas, especially when un-electrified, have very low demand and low load factors, thus fitting with small-scale generation systems [30,31];
- *poverty fight*: the shift by international institutions after 1995 towards poverty-based strategies with initiatives like the Millennium Development Goals or the 2012 as the International Year of Sustainable Energy for All, drew the attention on the links between modern energy and poverty (i.e. the importance of energy services to improve livelihood conditions by meeting basic needs). This has led to consider electricity as a main component within development rural programmes and small-scale generation as the preferable option for rural electrification [27,32,33];
- *leapfrogging*: the concept that DCs can avoid some of the steps originally followed in developed ones by incorporating the most advanced technologies, is still attractive despite critics had been advanced. Small-scale generation, specifically PV for rural areas, had been set out as example of leapfrogging [14,34,35].

In developed countries we are nowadays experiencing a growing integration between grid-connected small-scale generation systems (typically considered with the term *distributed generation* (DG)) and the main centralized grid, while in DCs off-grid small-scale generation systems can today play a pivotal role in the bottom-up electrification of rural areas (e.g. [2,12–14,17,18,31]).

Table 2
Major factors that contributed in a renewed interest for small-scale generation.

Environmental [19,24,27,36–40]:
- growing concern as for the GHG emissions
- public awareness as regards the impacts of the electric industry
- opposition to construct new transmission lines

Economic [19,23,36,39–41]:
- to avoid Transmission and Distribution related costs
- to tackle the current risky nature of large scale plant investments
- to reduce power plants costs with combined heat and power generation
- to better exploit profit margins within the competitive market

Technical [19,20,22,24,27,36,40,41]:
- increased performance of the small power technologies
- development of electronic metering and control equipment
- increased consumer demands for highly reliable power supply

Political [22,23,38–40]:
- to decrease dependence from fossil fuels
- to increase primary source diversification
- to reduce vulnerability of the supply chain in centralized systems

Social [22,36,38]:
- increasing public desire to promote "green technologies"
- growing interest towards energy autonomy communities and sustainability

2.2. *Rural areas as the main context for off-grid small-scale generation systems*

Despite there is no consensus about the definition of *rural areas*, which actually varies from country to country according to national statistical offices, their typical features are quite clear. In DCs, rural areas are generally scattered populated, geographically isolated and difficult to access [42]. The main sources of income for rural households are pastoralism, cattle raising, agriculture, fishing, tourism or forestry [43]. The road conditions and long distances from urban settlements exacerbate the limited accessibility, and hence service suppliers cannot guarantee regular visits, thus preventing local populations from participating in national or regional markets. Moreover high educated people (i.e. teachers, doctors, technicians, etc.) are despondent to dwell in such areas [44]. Rural areas are also affected by high illiteracy rate, gender inequality, lack of access to health care, infrastructure (roads, markets, information) and clean water supply [43].

As regard electricity and fuel supplies, the typical situation can be depicted as in Fig. 1. Connection to the national centralized grid is generally limited to those towns and villages along major roads and to nearby areas. When it is available, often only the high-income households, few enterprises and community bodies can afford connections [35,43,45,46] since electricity may cost as much as 10 times more than in urban areas [47]. When there is no centralized grid connection, electrification occurs in those areas reached by local fuel supplies, and it is based on off-grid small-

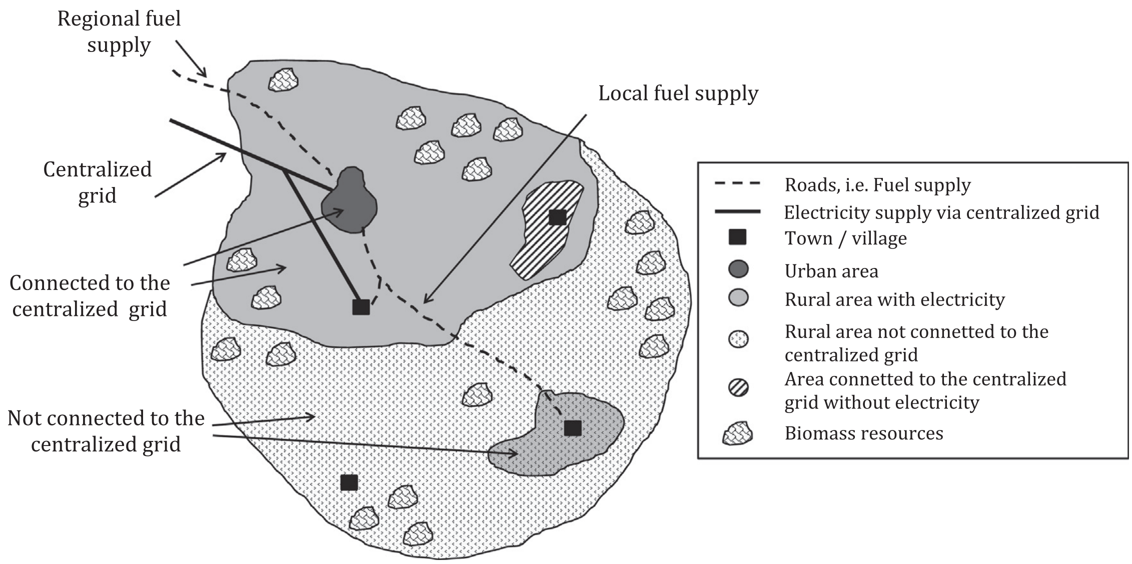


Fig. 1. Graphic representation of local disparities in electric supply in rural areas of DCs. Authors' elaboration based on [59].

scale generation systems; historically diesel generators [43,48] and recently renewable-based systems usually aid-financed [2].

Different categories have been employed in the literature to subdivide rural energy uses (e.g. [45,47,49]). Hereafter we revise and elaborate the categories already proposed by the authors in [50] and we suggest three energy uses: (i) energy for *household basic needs*, (ii) energy for *community services* and (iii) energy for *productive uses* devoted to income generating activities. Within each category over the last decades, a number of i*n-field* assessments as well as several estimates have been proposed to set quantitative power and energy loads associate to each local needs (e.g. [17,27,45,47,51–55]). More recently Practical Action has proposed the adoption of the Total Energy Access approach where rural energy uses are analyzed as for *energy for household needs*, *energy for community services* and *energy for earning a living* [56–58]. This approach offers a comprehensive understanding of the link between energy and development, and proposes evaluations of minimum standards of power and energy loads as well as indicators to assess the process towards access standards.

2.2.1. *Energy for household basic needs*

Households account for the majority of energy consumed in rural areas. They require energy mainly for cooking, water heating, lighting and space heating. Up to 80–100% of energy consumption is devoted for cooking and water heating that, in cold climates, indirectly can supply also space heating [45,47]. These needs are mainly covered by non-commercial or traditional biomass (i.e. firewood, crop residues, dung, etc.). The rest of the energy is consumed for lighting, while further appliances (fans, radios, TVs, etc.) are employed only when modern energies (electricity, gas or LPG) are available and households can afford it. Indeed although in few emerging countries the situation in the last decades has improved and a general shift to modern energy has been achieved, the rural households often do not benefit from it since modern fuels and the related technologies may have higher capital and maintenance costs.

When estimating the load power (which is a required datum for sizing small-scale off-grid generation systems) we may state that at household level the consumer load ranges between tents to hundreds of W.

2.2.2. *Energy for community services*

Electricity is the most important form of energy for improving access to community services, *education* and *health* being the most important. In education electricity is needed to improve schools facilities (lights, ITC, etc.) and to attract teachers to rural areas. Health clinics and hospitals require electricity to deliver adequate treatment and care, to operate the equipment and to manage the health-care waste. Moreover electricity contributes in improving access to clean and hot water and for the information and communication systems which are central for appropriate management of large hospitals.

Power requirements for these services experience a deep variation according to the number of beneficiaries and the quality of the service delivered: they can range from a few kW for rural dispensaries, to dozens of kW for large boarding schools or hospitals.

2.2.3. *Energy for productive uses*

From one side, the lack of access to energy (*quantity*) may affect the access to basic need and services, but on the other side, the lack of a reliable and affordable (*quality*) energy may prevent the poor to trace their way out of poverty since they cannot activate any productive activity. Productive uses of energy refer to productive activities and specifically include the needs coming from agriculture and rural industries.

In most DCs agriculture represents the primary earning activity [60], consequently improving agricultural practices is a critical element for DCs economies. Moreover in rural areas, food security and income generation highly depend on agricultural production. Therefore an increased use of modern energy services within the agro sector can deeply contribute to improve rural areas welfare. Energy uses for agriculture cover uses such as land preparation, primary and seedbed cultivation, irrigation, weeding, planting, harvest or post-harvest processing [61]. Moreover, small farmers may set up micro and small enterprises (MSE), often household-based, owned and managed by women [45]. Their activities include milling, fruit and vegetable processing, tobacco-curing, pottery making and other processes.

Also the development of rural industries is a key component of rural welfare improvement and an essential leverage to mitigate rural–urban migration [62]. They include a range of small and micro-businesses and industries such as small shops, kiosks, beer

OFF-GRID SYSTEMS MATRIX	DECENTRALIZED		DISTRIBUTED
Rural Energy Uses	**Stand-alone Systems**	**Micro-Grid Systems**	**Hybrid Micro-Grid Systems**
Household basic needs	Home-based Systems	Systems including a distribution grid	Systems including a distribution grid
Community services	Community-based Systems		
Productive uses	Productive-based Systems		
Consumer Number	Single	Multiple	Single OR Multiple
Energy Sources	Single		Multiple

Fig. 2. Off-grid Systems Matrix for rural electrification systems in DCs.

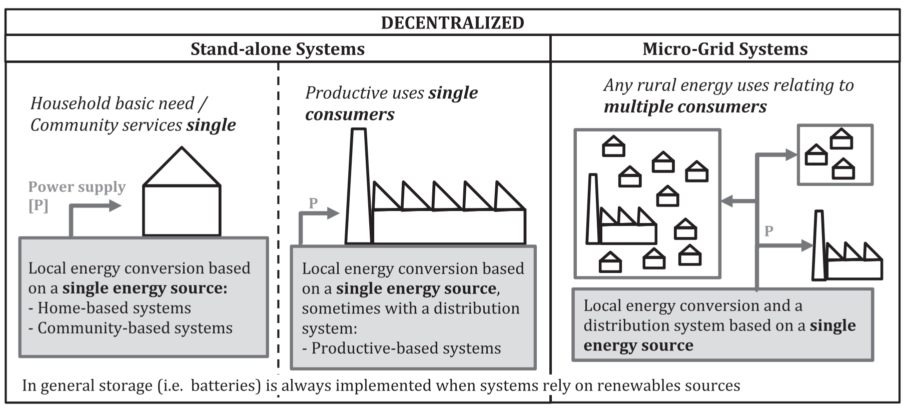


Fig. 3. Graphic representation of decentralized electrical system.

halls, inns, charcoal and brick manufacturing, potteries, bakeries, blacksmiths, etc. [45,47].

Each MSE has its own specific requirement: the amount of power and the form of energy supply may vary mainly depending on the activities and on the scales of operation. A reasonable range for electric supply considers power rate in a range from a few to hundreds of kWs.

2.3. *A taxonomy for small-scale generation systems in rural areas of developing countries*

When dealing with the concept of *small-scale generation systems*, a number of definitions and classifications have been developed and presented in the literature (e.g. [19,23,63–68]), nevertheless no consensus has been reached yet. Furthermore, the majority of this definitions and classifications address the context of developed countries with limited interest to the specific application for rural electrification. Therefore, in the following we propose a specific taxonomy for small-scale generation systems as regards the context of rural areas in DCs. Firstly we introduce the key elements that set the framework of our taxonomy, then we introduce the Off-grid Systems Matrix structure and afterwards we describe the new classification with the related definitions.

Two premises are essential to introduce the framework of the taxonomy:

- in the context of rural areas centralized systems often do not represent the appropriate option (e.g. [8,27,39,40,56–58,66,67]), and hence our taxonomy includes only those systems that operate detached from the national grid and which we call from now onward as *off-grid systems*;
- at the light of the energy situation in rural areas and reviewing the typical figures of systems power rates for rural electrification reported in literature (see tables in the Appendices), we limit off-grid systems power rate to 5 MWel that is the limit of *small-scale* distributed generation as defined by Ackermann [60].

We depict the classification of *small-scale off grid systems* for rural electrification by mean of the *Off-grid Systems Matrix* (Fig. 2) which we developed coupling a *system* perspective (the columns) with a *local context* perspective (the rows):

- the columns report the main classes of small-scale generation systems as defined by Alanne et al. [22]. Their approach stems from the observation that energy consumptions are decentralized by nature, while conversion, transmission and distribution[2] are not. Therefore, centralized systems, decentralized systems, and distributed systems differs since they are based on different layouts adopted for *conversion, transmission* and *distribution*[3];
- the rows report three additional essential categories which are essential for the local context. Thus, in addition to the *rural energy uses* already introduced (Section 2.2), we added the *consumer*

[2] Despite distinction between transmission and distribution systems varies from country to country according to specific voltage levels, we can consider in general *high* voltage lines as transmission system, while *medium* and *low* voltage lines as distribution systems.

[3] Grid connection regulations vary from country to country, however power systems up to 5 MWel are typically connected to medium or low voltage lines. Hence in our taxonomy we do not consider transmission systems.

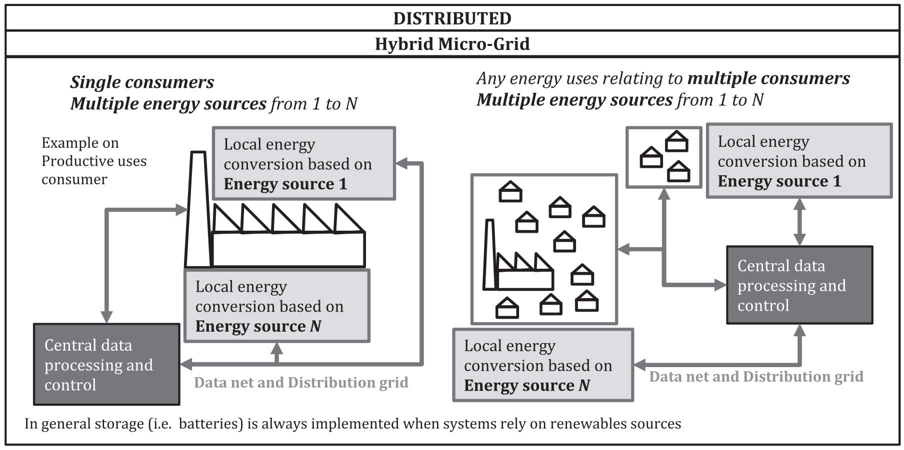


Fig. 4. Graphic representation of distributed electrical system.

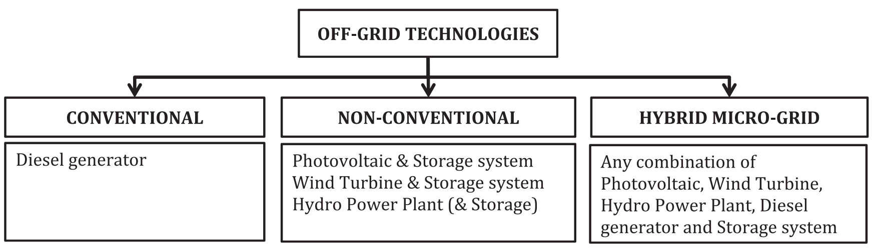


Fig. 5. Generation technology classification.

number which is connected by the off-grid system, and the *energy sources*, which the off-grid systems rely on, in order to differentiate single source from multiple-sources systems.

2.3.1. Decentralized systems

Decentralized systems (Fig. 3) are composed by autonomous units where *conversion* and *distribution* have no interaction with other units. Such systems are locally-based and need-oriented: they are usually tailored to specific local energy needs and they often rely only on local energy sources (i.e. renewables). Furthermore, this concept includes systems which supply electricity to nearby *single consumers* or a *number of consumers*. Using the *consumer number* category this leads to distinguish between *stand-alone systems* and *micro-grid systems*. The former refers to systems which supply power to nearby single consumers (e.g. a household, a kiosk, a rural industry, a school, etc.), the latter to systems which supply power to several, similar or different, consumers (e.g. a group of houses in a village, a number of kiosks in a market area, a group of farmer houses together with mills and water pumps, a village with houses, school, clinic, and rural industries) and embracing a distribution system. Moreover within Stand-alone systems, considering the *rural energy uses* categories we may thus distinguish among *home-based* systems, *community-based* systems and *productive-based* systems. Within the latter category, systems sometime require a local distribution system.

2.3.2 Distributed systems

Distributed systems (Fig. 4) are made by more than one decentralized *conversion* unit which are connected and interact each other through a *distribution* grid. This results in a *virtual power plant* consisting of several generation points and equipped with a central brain for centralized control, that receives data about the operational status of the system and determines how to manage it. We refer to these systems as *hybrid micro-grids*. Hybrid micro-grids embrace several conversion units which can rely on several different energy sources and which supply electricity to single of several consumers, comprising the latter even different energy consumer typologies. It is worth noting that in our classification micro-grids are different form hybrid micro-grids since the former are not constitute by more than one conversion unit and they rely on one single source.

Despite the Off-grid Systems Matrix does not deepen the technological dimension, it is worthwhile to make a distinction among generation technologies (Fig. 5) since they are often referred to in the literature. The technologies are classified as conventional, non-conventional, and hybrid on the basis of the energy source used [37,64,69]. Conventional technologies run fully on fossil fuel (typically diesel), non-conventional technologies run exclusively on renewable energy (RE) sources while hybrid micro-grids run with a coupling of sources (e.g. solar PV with diesel generators).

The unpredictable availability of renewable sources, especially solar and wind, makes the storage a necessary component of non-conventional generation systems. They are divided into three categories: components exploiting potential energy (e.g. pumped-hydro, compressed-air), kinetic energy (e.g. flywheels) or chemical energy (e.g. hydrogen from fuel cells, batteries, etc.) [37,70,71]. Batteries are the most common storage device in rural areas of DCs and in some cases they are also considered as the main electricity carrier [43,64]. Hybrid micro-grids try to overcome the need of batteries by coupling diesel generators to renewable-based systems while reducing the storage system size.

To close the paragraph an additional note is necessary. Among the technologies for rural electrification, we do not consider

Table 3
Selected Elsevier journals.

Applied energy	Energy Procedia
Electric Power Systems Research	Energy for Sustainable Development
The Electricity Journal	Int. Journal of Electrical Power & Energy Systems
Energy	Renewable Energy
Energy Conversion and Management	Renewable & Sustainable Energy Reviews
Energy Economics	Solar Energy
Energy policy	Sustainable Energy Technologies and Assessments

bioenergy-based technologies [75,81–92] (e.g. wood pyrolysis, gasification, direct combustion, and biofuels production and utilization such as bioethanol, biomethanol and biodiesel), even if biomass is considered one of the most important renewable sources in the near future [72–75]. Three are the main reasons:

- the minimum plant size for electricity production as regards economic feasibility in rural areas [76–78] is estimated to be 10–100 kW, fitting the micro-grid scale but not the stand-alone scale. Furthermore, the steam cycle technology is available for loads higher than 5 MW, hence suitable for grid-connected generation plants;
- the complexity of the supply chain [79] make the sustainable use of bioenergy for power generation quite difficult in rural areas. Such systems entail the development and management of complex biomass supply chain, and the adoption of specific systems for the reduction of pollutant emissions. Hence, this would require local capacity and a very specific and comprehensive analysis at local level;
- within the bioenergy arena there is the tendency of a "*flavor of the year*" which has passed from *Jatropha* to palm oil to algae to wood, and which has led to rush *"to develop new resources and prove new technologies often without the necessary forethought and policies in place"*. This issue has been analyzed by Amezaga et al. [80] who have also underlined that despite bioenergy production may play a pivotal role in rural development of several African and Asian countries, many countries *"still lack institutional structures able to articulate this development"*.

3. Review of the recent literature within the off-grid framework

3.1. Rationale and methodology

The main objective of this review is to introduce an analytical overview of the present situation as regards the selected scientific literature on the issue of off-grid systems for rural electrification in DCs. Since the global list of journals with relevant topics would be too wide, we decided for the moment to focus on journals belonging to the Elsevier group, and among these journals we carried out a selection according to the relevance of the aim and scope of each journal and the objectives of the review. Selected journals are given in Table 3.

The review have been organized according with the Off-grid Systems Matrix previously proposed, thus the selected papers are grouped as follows within the three *system categories*: stand-alone systems, micro-grid systems, and hybrid micro-grid systems. Then *topic categories* based on the most addressed topic in the analyzed literature have been introduced to further deepen the disaggregation: (i) Technology: layout and components; (ii) Models and methods for simulation and sizing; (iii) Techno-economic feasibility analyses and sustainability analyses; (iv) Case studies analyses; (v) Policy analyses. Descriptions of the topics categories are reported in Table 4.

The following key words (and their combinations) have been used to find matches in the key-words of each paper: off-grid, developing countries, stand-alone, rural electrification, home-based, community systems, micro-grid, mini-grid, renewable energy, wind, solar, photovoltaic, hydro, diesel, hybrid, sustainable energy, rural power systems, remote systems, decentralized systems, distributed generation, small-scale generation.

Among all the papers matching our key-words, a selection has been carried out and has been based on the following rules:

1. papers must deal with off-grid systems for rural electrification;
2. reference context of the papers must be related to DCs. We considered also South Africa and India due to the particular attention of local academia to rural areas and rural electrification issues;
3. publication date must be in the range from years 2000 to 2014.

Selected paper have been then grouped according to the five topic categories and assigning each single paper to a maximum of three of them. From Section 3.3 to Section 3.8 we present the literature review while in Appendices A–F we provide a summary of information for each selected paper: the location (i.e. the country) of the study, the addressed technology(ies), the power rate range or size of the analysed system(s) and a short description of the developed contents.

3.2. Analysis of the research trends and most addressed topics

Fig. 6 shows the trend over the years of the publications considered in this paper. As a general comment, a crescent interest in the field of off-grid systems in DCs is clear from the graph. As a matter of facts, regarding the papers included in this work, the number of publications per year in between 2000 and 2005, did not exceeded 17. Instead, the number of publications rose up to 35 in the 5 following years, and has been 41, 54, and 66 respectively in 2012, 2013, and 2014. A deeper analysis shows how, during the early considered years, the scientific literature mostly focused on the analysis of stand-alone systems followed by hybrid micro-grid systems. Later, the interest seems to have shifted more and more on systems characterized by a higher complexity, this bringing to a turn in the ranking. In fact, over the last years hybrid micro-grid systems have been the most addressed followed by micro-grid systems, while the interest for stand-alone systems has decreased in percent, even if in absolute terms the number of publications has been continuously increasing.

The second analysis we carry out on the selected papers is on the distribution of the energy technologies (i.e. PV, wind, hydro, diesel and others) within the considered *system categories* and *topic categories*. Indeed the histograms reported in Table 5 show, for each *topic category* (i.e. the rows of the table): (i) the number of papers for each *system category* (on the *x*-axis of the histograms), and (ii) the number of times each technology has been addressed in each *system category* as the share of the total.

Techno-economic feasibility analyses and sustainability analyses is the most populated sub-category, including a total of 124 papers, distributed as it follows: 29 papers addressing stand-alone systems, 31 addressing micro-grid systems, and 64 addressing hybrid micro-grid systems. In the first case, the most frequently studied technology proves to be PV, while in the case of micro-grid systems both PV and hydro play a significant role. Due to the fact of combining multiple sources, all the different technologies find a place in the case of hybrid micro-grid systems.

Models and methods for simulation and sizing, and *Case study analyses*, occupy the second and third positions in the ranking,

Table 4
Description of topic categories.

Topic category	Description
(i) Technology: layout and components	Analyses and descriptions of systems' layout and components; development of new technologies and/or components; advancements in technologies and/or components
(ii) Models and methods for simulation and sizing	Proposals of models and/or methods for systems simulation and/or sizing; improvement of models and/or methods for systems simulation and/or sizing. The models and methods can imply the use of both commercial or non-commercial software tools
(iii) Techno-economic feasibility analyses and sustainability analyses	Techno-economic feasibility analyses of systems and components; methods and studies about required data for this kind of feasibility studies (e.g. energy sources and energy demand assessments, costs assessments). Analyses with elements of sustainability (social, environmental parameters).
(iv) Case study analyses	Analyses of the performance of existing plants (reliability, efficiency, lifetime, technical or management problems, etc.); non-technical case studies, such as studies about environmental/social impacts of the considered technologies and/or systems
(v) Policy analyses	Analyses and/or proposals of policies about off-grid systems

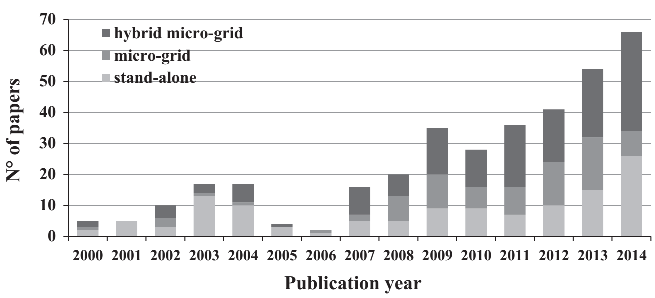


Fig. 6. Trend of publications over the years.

with a total of 61 and 53 papers respectively. In both cases, PV is once again the most studied technology in the case of stand-alone systems. On the other hand, in the case of micro-grid systems, hydro, PV and wind have been particularly addressed in the case of *Models and methods*, while in the *Case studies* topic wind is less considered. The situation for hybrid micro-grid systems is similar to the one previously described for *Feasibility studies*.

Looking at the *Technology: Layout and components* category, the situation tends to be similar to the precedent ones: the difference is that a higher importance is given to hydro, especially in the case of micro-grid systems, and of diesel in the case of hybrid micro-grid systems.

As regards *Policy analyses*, micro-grid and hybrid micro-grid categories are introduced together in accordance with the previous analysis, and the distribution appears to be very similar to that of Case studies.

Lastly, when looking at the number of papers per each system category, in the case of *Technology: Layout and components*, and *Policy analyses*, the share among stand-alone, micro-grid and hybrid micro-grid systems is quite balanced. On the other hand, in *Models and methods for simulation and sizing*, and *Techno-economic feasibility analyses and sustainability analyses*, hybrid micro-grids is the most studied category, because of a wider variety of possible combinations and solutions which allow adopting different approaches. Finally, in the case of *Case study analyses* the picture is the opposite, probably due to the small number of complex systems fully in operation.

3.3. *Main existing reviews as regards off-grid systems for rural electrification*

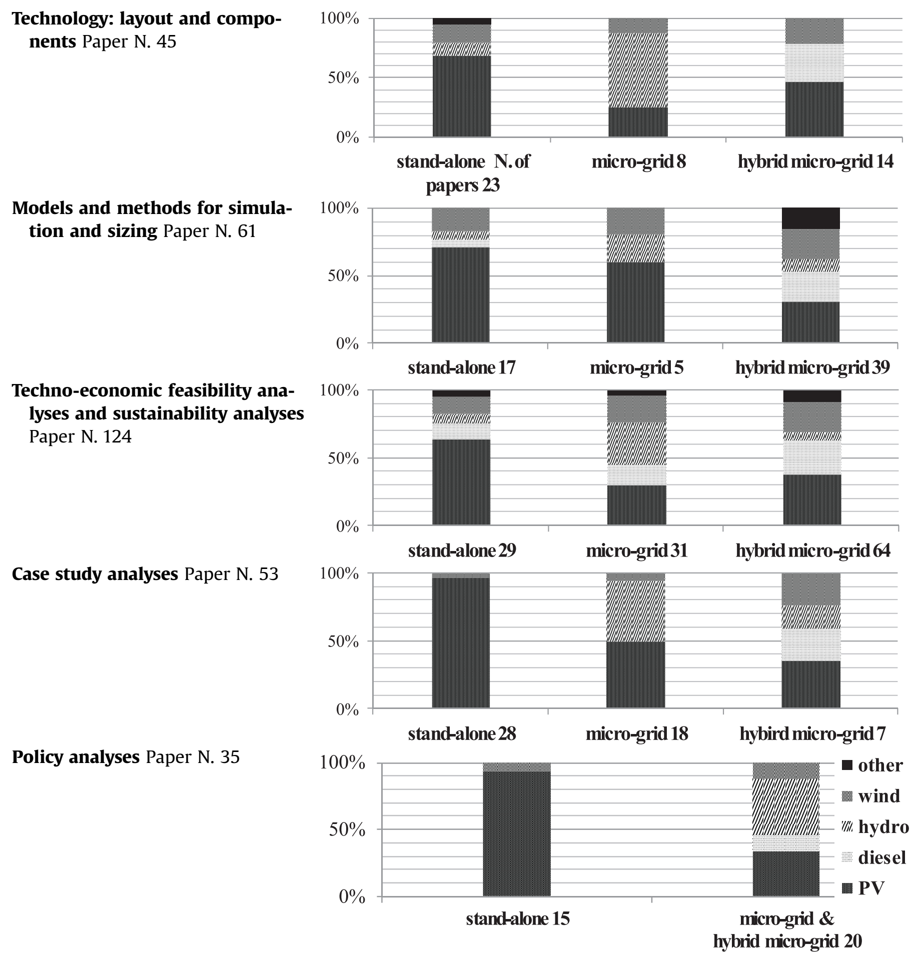
Despite, to our knowledge no papers provide a general framework to the issue of off-grid systems for rural electrification or an analytical overview of the literature, a number of reviews exist on various topics strictly linked with off-grid systems and other similar ones [15,28,81–100] .[4]

Among these publications, in our opinion, it is worthwhile mentioning those which contribute in providing broad description of specific topics. A complete synthesis of all the reviews is given in Appendix A, Table A.1. Chauhan and Saini [82] proposed a detailed overview that describes Integrated Renewable Energy Systems as regards configurations, storage technologies and system controls. Moreover, they review mathematical models for renewable-based technologies, typical design criteria and main sizing methodologies. Bhattacharyya [15] developed a comprehensive overview of methodologies to analyze technology options for rural electrification. He grouped them according with three classes: techno-economic feasibility, analytical approaches (indicator based, optimization techniques, multi-criteria decision making, systems analysis approach), and practice-oriented approaches. The final recommendation is that a hybrid option can complement the strengths and shortcomings of each approach. Rojas-Zerpa and Yusta [92] made an overview and an analysis of methodologies employed for electric supply planning in remote areas. They focus the attention on the evolution within the scientific literature arena of such methodologies towards the development of multi-criteria and multi-objective approaches which are capable to better address multiple benefits and sustainability in electric supply planning. Sinha and Chandel [94], and Connolly et al. [95] analysed respectively 19 and 37 software tools for hybrid RE systems. Sinha and Chandel concluded that HOMER is the most widely used tool due to its completeness. Connolly et al. found evidence there is no tool that addresses all issues: the *ideal* tool is clearly dependent on the objectives that must be fulfilled. Both papers provide information in order to direct the decision-maker towards a suitable energy tool for each kind of analysis.

Finally, there are publications which review specific off-grid systems within targeted countries or region and dealing with policies and strategies to promote rural electrification. For examples: Kusakana [96] reviews technologies for micro-hydropower technology in the context of South Africa, Pokharel [101] reviews off-grid technology options and analyses the case of policy interventions in Nepal searching for the barriers to promotion of such energy technologies, and Gurung et al. [102] review the energy situation, current policies and subsidies for the utilization of RE resources in rural areas of Nepal again, and concluding that RE systems will have an important role in providing reliable electricity supply to isolated and remote areas in the next future.

[4] In reviewing these papers we do not consider our classification as well as limit as regards the reference context of DCs.

Table 5
Distribution of papers among *topic* and *system categories.*



3.4. *Technology: layout and components*

The interest of the literature for the layout and components of specific technologies appears to have increased mainly since the last five years. We selected 23 papers referring to stand-alone systems [103–125] (for a complete synthesis refer to Appendix B, Table B.1). Referring to this category, PV is largely the most investigated technology, ranging from the smallest solar home systems (some Watts) up to the biggest community systems for water pumping or other needs. The most studied topic is the different layout of the systems, which is generally analyzed together with other specific characteristics. For example, Hoque and Kumar [116] and Diouf and Pode [110], provide a particularly complete analysis of the different components, layouts, and performances of a number solar home system (SHS) systems. Besides Muller et all. [123] provided an overview of MPPT charge controller for PV-based systems. The studies addressing bigger systems follow a similar pattern: Ramos and Ramos [106] work can be cited as an example of paper discussing the same topics for PV pumping systems. As per technologies other than PV, pico-hydropower (PHP) systems, as well as small wind ones, have been described in few studies. In this case, particular emphasis is on the development of appropriate solutions for the main system components according to the context, such as using pumps as turbines by Anyi and Kirke in [114], or locally constructing timber-blades wind turbines by Mishnaevsky in [111].

As per layout and components of micro-grid systems [126–133] (for a complete synthesis refer to Appendix B, Table B.2), the number of selected papers is much smaller compared to the ones referring to stand-alone systems. Moreover, all these publications are quite recent, having been published in between 2008 and 2012. These two facts could be considered as an index of a more recent interest of the literature for this kind of systems, which indeed require a more complex layout and technology. The typical sizes of the analyzed systems vary from some kW up to 20 kW. In this case, the most studied technology is small hydropower (SHP): different studies look for the layout definition and the installation methods according to the local context, as well as to the different kind of turbines. Locally manufactured wind systems have been addressed in a very complete manner by Leary et al. [132] giving a complete overview of different system configurations and components. As per solar based technologies, in addition to solar PV, Pikra et al. [133] focused on the more challenging option of concentrated solar power for remote areas.

The last group of papers is about hybrid micro-grid systems [134–146] (for a complete synthesis refer to Appendix B, Table B.3). The number of selected papers is slightly higher than the case of micro-grid systems. The size of the systems varies in a wide range, from some kW up to hundreds kW. It is interesting to look at the different systems configurations which different papers addressed. The coupling of a RE technology with a traditional one (PV-diesel) is the simplest typology. A second typology is obtained as an extension of the first one, by adding a storage system (PV-diesel-battery; wind-diesel-battery). An interesting example is given by Hrayshat [140], which presents the case of a system consisting of two diesel generators, a PV array and a battery. Systems made up by two RE technologies and a battery, constitute a third group (PV-wind-battery). Irwan et al. [144] give some information about such kind of systems. In addition to this, a more complex case is given Mondal and Denich in [136], where a PV-wind-diesel-battery system is compared to other simpler combinations of the same technologies (e.g. PV-diesel-battery). Finally, examples of papers which deal with specific issue related to the electrical control when integrating different power sources are [146,147] where Malla and Bhende analyzed the voltage control of wind-PV-battery system.

3.5. Models and methods for simulation and sizing

Considering papers which address the development and application of models and methods for the simulation and sizing of off-grid systems, it can be noticed that major attention has been devoted to hybrid micro-grid systems [134,137,139,148–183] and stand-alone [105,113,117,184–197], while a small number of papers focuses on micro-grid [198–202]. A complete synthesis of all the selected papers is given in Appendix C, Tables C.1–C.3.

Within stand-alone group, a number of papers deal with analyses relating to innovative technology solutions. For example Mathew et al. [184] developed a model to simulate wind-driven roto-dynamic pumps, Betka et al. [105] optimized the performance of PV induction motor pumping system, and Haidar et al. [113] simulate the performances of a real PHP system application. On the contrary, within hybrid micro-grid papers the main interest is devoted to the development of sizing methodologies which are able to embrace in an optimization problem the several variables which describe these highly complex systems. Moreover, the complexity of such systems highlights that this field of research has expanded in the last few years, together with the rise of advanced optimization and solver techniques. A few examples are given by Ashok [154] who optimized a wind-PV-hydro-diesel system with non-linear constrain optimization, Bala et al. [139] who employed a genetic algorithm to design a PV-diesel system, and Perrera et al. [174] who performed multi-objective optimization via evolutionary algorithm for wind-PV-diesel system. Moreover, in hybrid micro-grid systems attention is given also to modeling and analyzing the dynamic control of the different components, as presented by Ou et al. in [177].

Nevertheless, crossing the three categories (stand-alone, micro-grid and hybrid micro-grid), a common classification of the simulation and sizing techniques may be recognized. The techniques can be grouped in three categories:

- *intuitive*: simplified calculations of the system components size based on daily values of required electric load and resource data (e.g. [153,185]):
- *numerical*: several combinations of system components sizes are simulated typically on a year basis, employing hourly or daily load and resource availability profiles, and one or more objective functions are used to select the best components set (e.g. [194,200,203]);
- *analytical*: mathematical optimization problem with one or more objective functions subjected to one or more conditions. The objective function(s) and the conditions are the physical modeling elements of the system, defined by means of functional relationships between the component specifications and the economic and technical parameters (e.g. [162–164,179,182,199]).

Finally it can also be noticed that the PV is the most employed technology among the three categories: specifically it is often considered for pumping needs in Stand-alone applications, while in hybrid systems it is frequently supported by a diesel generator, which permits to increase the reliability of the supply, but also increases the complexity of modeling and defining the optimum system functioning.

3.6. Techno-economic feasibility analyses and sustainability analyses

Most of selected papers are characterized by description of technical design, optimization and economic evaluation of proposed energy systems. Three main categories for most of them can be identified: (i) technical design and sizing analyses with comparison among different available technologies, (ii) economic feasibility analyses with simulation and evaluation of different scenarios, (iii) techno-economic feasibility analyses which carry out systems optimization from technical, economic and environmental viewpoints. Some examples are respectively: Arriaga et al. [129] who studied the opportunity to introduce the Pump-as-Turbine as reliable and long term sustainable system instead of other RE technologies, Mirzahosseini et al. [204] who evaluated three different scenarios of energy supply via PV systems basing on energy subsidies in Iran, and Shaahid [205] where an optimization method for PV-wind hybrid systems to be installed in Algeria has been proposed considering four different locations. Moreover, a number of the analyses grouped in (i), (ii) and (iii) have been carried out by means of software tools, HOMER Energy in particular [206]. A comparison with traditional energy solutions (e.g. diesel generators, kerosene lamps, etc.) or the extension of the centralized grid is also present in many of them.

The majority of selected papers have been published recently, on the last 6 years (2008–2014) and independently they consider stand-alone, micro-grid or hybrid micro-grid systems. For stand-alone systems [106,110,129,140,193,194,204,207–225] (for a complete synthesis of selected papers refer to Appendix D, Table D.1) the PV technology is the most common: it reaches up to few kW [211,216] and it also covers the particular application of water pumping [193, 218]. In the micro-grid [25,42,54,198,200–202,226–248] and hybrid micro-grid [137,138,148,149,151–158,160,161, 165,166,169–171,173,205,209,230,232,242,243,249–296] categories (for a complete synthesis of selected papers refer to Appendix D, Tables D.2 and D.3) a relevant presence of SHP and MHP systems [229,230] is observed, as well as PV-wind [205,249,270] systems up to few MW are addressed. Moreover, more recently analyses of hybrid micro-grids architectures comprising micro-turbines and for trigeneration purposes have been presented (e.g. [278,279]). Stand-alone systems are usually analyzed for applications in sub-Saharan African and South-East Pacific Asian (mainly India) countries, whether studies and applications in Latin-American are often in the micro-grid category. Hybrid micro-grid papers are applied uniformly in the world macro areas; nevertheless additional studies for Saudi-Arabia carried out in the last 10 years are available.

Furthermore, some papers present more detailed analyses of environmental and social aspects related with the application of the proposed solutions [231,237,241,297]. Such papers may be considered as feasibility analyses accomplished within the framework of sustainable energy development. For example: Lhendup et al. [231] proposed a method to evaluate off-grid systems basing on weighted score of a set of criteria including social aspects, such as public and political acceptance, and interference with other utility infrastructure, while Vicente et al. [241] evaluated the location for PHP installation using social aspects such as reduction of health risks, improved social community services, new local working opportunities in order to define the priority ranking of intervention.

3.7. Case study analyses

During the considered years, a number of case studies about small stand-alone systems have been published [115,217,298–324], as reported in Appendix E, Table E.1. Most of these studies refer to SHS, with an installed power typically from 10 W up to 500 W. Moreover, some case studies exist on bigger systems for community services such as charging stations or water pumping. Most of the studies are located in Africa and Asia, and focus on a number of topics which can be grouped mainly under one or more of three key issues: (i) main causes of success and failure (techno-economic and social), (ii) economic expenditure and sustainability of projects/programs, and (iii) social benefits and other social aspects. Concerning the first group, some papers describe technical and social causes of systems failure, other describe local manufacturing and installation of the systems, and technical benefits such as improved reliability of telecommunications. For example, Green [321] gives a complete overview of technical and economic problems related to SHS programs in northern Thailand, as well as a description of social components such as income generation. Some examples in the second group are the assessment of consumption and expenditure patterns, as well as the analysis of economic sustainability of the project, and the cost of dissemination programs, such as the case of a rural electrification program in Morocco described by Carrasco et al. [320]. In the last group, social improvement coming from the use of these systems are reported, such as improvements in health and education (e.g. [314,319]), and, more in general, in quality of life.

Case studies of micro-grids are mainly located in Asia, and in particular India [132,139,232,236,267,325–341], as reported in Appendix E, Table E.2. The size of the systems varies in the very wide range from less than 1 kW up to 1 MW. Some of the main topics addressed are similar to those described for stand-alone systems. However, in this case the attention appears to be more on the feasibility and/or impact of the projects rather than on the three dimensions of sustainability (economic, environmental, and social) as separate dimensions. A significant example of this kind of analysis, considering all the three dimensions at once, is shown by Chakrabarti and Chakrabarti [341]. Nevertheless, factors influencing the implementation of such systems, including socio-technical and techno-economic barriers, have been assessed in many works, too.

As per hybrid micro grid systems, the number of case studies in the literature is really low [139,232,267,339,340,342,343], as reported in Appendix E, Table E.3. Probably, the reason is that a lower number of such systems have been implemented respect to micro grid ones due to the higher complexity of design, implementation, and operation, and of a more recent interest of the scientific literature. The locations of the seven studies which we selected are in Asia (Bangladesh, Thailand, and Nepal), Middle East (Iraq), and Latin America (Argentina and Perú). It is interesting to observe that we did not find any case study located in Africa. The size of the systems varies in a range from some kW to some hundred kW. The focus of the papers is somehow similar to the one for micro-grid systems, and mainly on the design and performances of the systems, and on the benefits achieved by their implementation.

Finally Terrapon-Pfaff et al. in [344] analyzed the effectiveness of 23 small-scale renewable projects in developing countries. Their approach was to consider energy needs, systems and technologies, socio-economic, gender and geographic factors to assess the sustainability of the interventions.

3.8. Policy analyses

Papers which present policy analyses often do not focus on a specific category of off-grid systems, while indeed they generally address more than one solution based on RE. Typical topic of these studies is the evaluation, the monitoring and the current status of governmental programs and / or projects that aim, at country, regional or local level, to promote rural electrification. Moreover the output of such analyses is usually a proposal of best practices or guidelines for future programs or projects. Nevertheless, within the literature, a group of studies which refers to the specific category of SHS can be recognized. Therefore we divided the papers which refer to the *policy analyses* topic in papers which refer to SHS (i.e. stand-alone systems) [107,305,317–319,345–358], reported in Appendix F, Table F.1, and papers which refer to miscellaneous analyses of micro-grid and/or hybrid micro-grid [31,32,45,102,132,239,245,258,312,330,331,334,359–366], reported in Appendix F, Table F.2.

Considering SHS, beside studies which address rural electrification policies and programs (e.g. [305,345,347]), some papers deal with specific topics such as the analysis of SHS impact on GHG emission reduction (e.g. [319,346]) or modeling the transition process from traditional technologies to SHS at local level (e.g. [357]).

Considering the miscellaneous analyses, a number of papers deal with the description of rural electrification programs at national level (e.g. [45,102,312]): in some cases they consider different off-grid systems (e.g. [245,359,362]) or they focus on a specific technology (e.g. MHP in Rwanda [331]). A further group of papers can be recognized which addresses the economic feasibility aspects of electrification programs via RE systems. A few examples are given by Thiam [32] and Solano-Peralta et al. [258] which propose new tariff schemes to incentivize RE systems, and by Bhandari [334] which performs an econometric analysis to compare SHS and micro-grid PV systems for a rural village.

Finally it is worthwhile to mention two studies which are exhaustive for the specific topics: Pode in [358] presented a comprehensive overview, from technology to financing models and current program, about SHS based on LED, while Sovacool et al. in [361] describe an accurate evaluation of the multi-functional platforms implementation program in Mali.

4. Conclusions

In this paper we proposed a review of more than 350 papers published from 2000 to 2014 within 14 international peer-reviewed journals by Elsevier addressing the topic of off-grid systems for rural electrification in DCs.

By means of a comprehensive Off-grid Systems Matrix, we introduced and formalized a taxonomy for small-scale off-grid systems coupling a *system* perspective with a *local context* perspective. The *system* perspective steams from the approach by Alanne et al., which relates electric systems to three main concepts: *centralized systems*, *decentralized systems*, and *distributed systems*. The *local context* perspective includes three criteria: the *rural energy uses* that are required, the *customer number* which need to be served and the *energy sources* used for fueling the systems. In the Off-grid Systems Matrix, *decentralized systems* are defined as composed by autonomous units where *conversion* and *distribution* have no interaction with other units because they are fueled by one single source of energy. In this category *home-based*, *community-based* and *productive-based* systems serve a single customer while micro-grids serve multiple customers. *Distributed systems* are defined as composed by more than one decentralized *conversion* unit which are connected each other and interact through a *distribution* grid. They are referred to as *hybrid micro-grids* since they never rely, whether serving a single or multiple customers, on a single source of energy.

The proposed Off-grid Systems Matrix may offer a structured reference framework to researchers of this sector since it capitalizes the fundamentals of this topic and it provides a structured approach for analyzing the last years of research in the sector.

Indeed, we also carried out an extensive review of the selected literature where papers are grouped according to the Off-grid Systems Matrix and to five main research areas identified within the literature itself: (i) Technology: layout and components, (ii) Models and methods for simulation and sizing, (iii) Techno-economic feasibility analyses and sustainability analyses, (iv) Case studies analyses, and (v) Policy analyses. From the literature, it emerges that in the first category the share among stand-alone, micro-grid and hybrid micro-grid systems is quite balanced while hybrid micro-grids are the most studied systems as far as *Models and methods for simulation and sizing* are concerned, because of wider variety of possible combinations and solutions they may offer in term of research perspective. On the other side, stand-alone systems are more present as *Case studies analyses* due to the higher number of on-going projects. We also observe that PV is largely the most investigated technology in general and specifically within stand-alone systems.

Finally, it is worthwhile to note that the growing scientific interest for off-grid systems recognized over the last five years well copes with the interest showed by the international community for off-grid solutions. Indeed, despite the cost of energy may not always be competitive with the centralized grid extension approach, the potential benefit to local development is recognized also from a sustainability perspective.

Acknowledgments

We would like to thank the anonymous reviewer for the valuable comments to the first submitted manuscript.

Appendix A

See Table A.1.

Appendix B

See Tables B.1–B.3.

Appendix C

See Tables C.1–C.3.

Appendix D

See Tables D.1–D.3.

Appendix E

See Tables E.1–E.3.

Appendix F

See Tables F.1 and F.2.

Table A.1
Overview of main review publications about off-grid systems.

N.	Publication	Off-grid system	Topic	Description
1	[28]	SA, HMG	Off-grid systems	Grid-connected and stand-alone decentralized systems concept, literature overview of system design as well as institutional/strategy analyses
2	[81]	HMG	Off-grid systems	Overview of structures, characteristics, components, energy flows, planning and analysis for decentralized multi-generation systems
3	[82]	HMG	Off-grid systems and Sizing/optimization	Exhaustive overview of hybrid micro-grid with configurations, storage technologies description, RE math models, techno-economic sizing/optimization techniques, system control strategies
4	[15]	SA, MG, HMG	Sizing/optimization	Comprehensive overview of methodologies to analyse technology options for rural electrification: techno-economic feasibility, analytical approaches (indicator based, optimization techniques, multi-criteria decision making, systems analysis approach), practice-oriented approaches, software tools.
5	[83]	HMG	Sizing/optimization	Overview of math models for hybrid renewable systems components
6	[84]	HMG	Sizing/optimization	Comprehensive overview and description of optimization techniques for RE hybrid systems: genetic algorithm, particle swarm optimization, simulated annealing, ant colony algorithm, artificial immune system algorithm
7	[85–87]	HMG	Sizing/optimization	Overview of design parameters (technological, economic, socio-politic, environmental) and main sizing/optimization techniques of hybrid systems
8	[88]	HMG	Sizing/optimization	Review of publications on multi-objective optimization for PV-battery, PV-wind-battery and PV-wind-diesel-battery systems
9	[89,100]	SA solar PV	Sizing/optimization	Publication review and description of sizing techniques for PV systems
10	[90]	HMG	Decentralized planning	Integrated Community Energy Systems concept and overview of software tools for energy planning and analysis
11	[91]	SA, MG, HMG	Decentralized planning	Extensive literature review on energy planning at decentralized level
12	[92]	SA, MG, HMG	Decentralized planning	Literature review and description of methodologies and technologies for electric supply planning in remote areas
13	[93,97]	HMG	Experimental tests	Overview of existing micro-grid test systems in the world, and overview of projects dealing with HMG for remote communities and small islands
14	[94,95]	SA, MG, HMG	Software tools	Comprehensive overview and description of software tools for RE systems planning and sizing
15	[98,99]	SA, MG, HMG	Sustainability analysis	Review of the impacts and the conditions that influence sustainability of small-scale renewable energy projects

Note: SA (stand-alone), MG (micro-grid), HMG (hybrid micro-grid).

Table B.1
Technology: layout and components. Stand-alone systems.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[103]	Saudi Arabia	PV, B	–	Design and usage of a PV system for automated irrigation
2	[104–106,122]	Bangladesh, Algeria, Saudi Arabia	PV, B	0.2–10	Components, layout and performance analysis of different PV pumping systems
3	[107–110]	Senegal, India, DCs	PV, B	0.02–0.08	Development of new SHS systems and components for lighting. Different layouts are introduced, such as portable solar lamps, multiple-lights systems, rechargeable lamps coupled to centralized solar charging station, as well as design features are discussed
4	[111]	Nepal	Wn	–	Results of mechanical testing and choice of timber for wind blades, testing of different coatings and blades, and installation
5	[112]	Thailand	Wn, B	0.002	Development of a roof-ventilator-based power generator
6	[113,114]	Malaysia, Bangladesh	H	1–2	Components and layout design of different SHP systems for off-grid remote communities (impulse and kinetic type). Particular attention given to locally appropriate solutions such as PAT
7	[115,116,124,125]	Bangladesh, Ethiopia, Tanzania	PV, B	0.0010.05	Components, layout and performance analysis of different micro utility systems such as lanterns, LED systems, LED submersible units and multifunctional devices
8	[117]	Iraq	PV, B	–	General description of typical Stand-alone PV system's components. A particular focus is given on the different possible configurations of the charge controller
9	[118]	Algeria	PV, B	–	Performance analysis of a dc–dc converter assisted by MPPT control in comparison with other approaches (perturb & observe, proportional-integral-derivative and fuzzy logic control)
10	[119]	–	solar stirling	–	Control of solar powered stirling generator for off-grid power supply
11	[120,121]	–	Wn, B	1–10	Modeling and simulation of electrical machines, control and storage for stand-alone wind power system
12	[123]	–	PV	DCs	State of the art in MPPT charge controller technology in PV-based systems

Note: PV (photovoltaic), Wn (wind), B (battery), DCs (developing countries).

Table B.2
Technology: layout and components. Micro-Grid.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[126,127]	Algeria, Thailand	PV, B	–	Experimental determination of the characteristics and behavior of PV systems, such as *I–V* curve, modules degradation, and operating cell temperature
2	[128–131]	DCs, Laos	H, B	0.2–20	Investigation of main types of SHP installation methods and local adaptations, including different turbine (PAT also considered) and penstock types, and a number of different layouts
3	[132]	–	Wn	0.19–5	A complete overview of different options for locally manufactured wind technology: different materials, and possibilities to adapt objects and devices as components of a wind system
4	[133]	Indonesia	Solar thermal	10	Development of a small scale concentrated solar power plant using Organic Rankine Cycle for remote areas

Note: PV (photovoltaic), Wn (wind), B (battery), DCs (developing countries).

Table B.3
Technology: layout and components. Hybrid Micro-Grid.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[134]	Cameroon	Wn, D, B	5.6	Modeling of wind-diesel-battery hybrid power systems for electrification of rural areas
2	[135,136]	Bangladesh, Senegal	PV, Wn, D, B	5–16	Design and layout of different PV-wind-diesel-battery hybrid plants, and comparison with wind–diesel-battery and PV-diesel-battery plants
3	[137–140]	Jordan, Argentina, Bangladesh	PV, D, B	1.5–41	Design, layout, energy productivity and fuel consumption of different PV-diesel-battery hybrid plants
4	[141,142]	Burkina Faso	PV, D	12–55	Design and performances of a new PV-diesel-battery hybrid system without storage
5	[143]	DCs	PV, Wn, B	–	Design of a new series-parallel resonant high frequency inverter for Stand-alone PV-wind systems
6	[144]	Malaysia	PV, Wn, B	–	Design of new components and of a PV-wind-battery hybrid system: a cooling system for PV modules and a wind turbine combining Savonius and Darreius layouts
7	[145]	Algeria	PV, Wn, B	5	Analysis of performances of hybrid micro-grid systems installed in Saharan areas
8	[146,147]	India	PV, B	15	Voltage control in hybrid micro-grid based on PV and wind generators: modeling and analysis of the systems with different parameters

Note: PV (photovoltaic), Wn (wind), D (diesel), B (battery), DCs (developing countries).

Table C.1
Models and methods for simulation and sizing: stand-alone.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[184]	India	Wn	–	Modeling and simulation of wind-driven roto-dynamic pumps to compute instantaneous and integrated performances
2	[185]	Bangladesh	PV, B	~0.3	Intuitive sizing technique for PV-battery systems
3	[105,186–188]	Sahara	PV	–	Optimal operation and sizing of PV pumping systems with optimization of the induction motor efficiency
4	[189]	Algeria	PV	–	Model for current–voltage curves of PV modules and loss of load probability computation for PV pumping systems
5	[190]		PV, D, B		Development of sizing curves for PV-battery and diesel-battery systems via simulations
6	[191]	Turkey	PV	3	Analyses of power output errors due to use of solar radiation correlations in PV pumping sizing
7	[192,196]	Iran	Wn	85–90	Simulation and sizing of wind turbine considering instantaneous wind speed variations – modeling of novel voltage and frequency controller
8	[193–195]	Algeria, Nigeria	PV	20 kW	Numerical sizing and Particle Swarm optimization techniques for solar pumping systems with storage
9	[113]	Malaysia	H	2.85	Matlab-Simulink model for simulation of real PHP plant in university campus
10	[117]	Iraq	PV, B	~3	Visual Basic tool to design PV-battery systems based on an intuitive sizing technique
11	[197]	Tunisia	PV, B	13	Fuzzy logic control (modeling and analysis) for off-grid PV systems considering variable load

Note: PV (photovoltaic), Wn (wind), H (hydro), B (battery), D (diesel).

Table C.2
Models and methods for simulation and sizing: Micro-Grid.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[198]	India	H	1000–10,000	Analytical approach to determine the correlations for the cost of different components of SHP schemes
2	[199]	India	PV, B	1–700	Design space approach for the optimum sizing of PV-battery systems incorporating solar resource uncertainty
3	[200]	Malaysia	PV, B	<1	Numerical sizing technique for PV-battery system
4	[201]	Algeria	PV, B	~1	Matlab-Simulink PV-battery model for optimal sizing with energy management of load
5	[202]	Tunisia	Wn, B	13–16	Integrated Optimal Design for selection and sizing of the system components of wind turbine and batteries

Note: PV (photovoltaic), Wn (wind), H (hydro), B (battery).

Table C.3
Models and methods for simulation and sizing: Hybrid Micro-Grid.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[148–153]	Saudi Arabia	Wn, PV, D, B	~15	Intuitive sizing technique based on monthly energy balance, and numerical technique based on hourly simulations to size system components for a household, a supermarket and a commercial building
2	[154]	India	Wn, PV, H, D, B	25	Mathematical modeling development, dispatch strategy analysis and simulation for system sizes optimization (non-linear constrain) via cost minimization
3	[155–158]	India	Wn, PV, H,BG, BM	~100	Optimization model for decentralized energy planning based on simple technology modeling, reliability and economic parameters. Application to rural area comprising several villages
4	[134]	Cameroon	Wn, D, B	5.5	Wind availability characterization and intuitive monthly-based sizing technique, economic analysis
5	[159]	Algeria	Wn, PV, D, B	~10	Matlab-Simulink model of the system, and techno-economic optimization for 6 rural sites
6	[139,181]	Bangladesh	PV, D, B	~ 3–30	Genetic algorithm to perform simulation and optimum sizing (minimization of costs), HOGA tool used
7	[160]	Senegal	Wn, PV, B	~40	Multi-objective optimization (LCoE, reliability) with genetic algorithm. Analysis of load profile influence
8	[161–164]	India	PV, H, BG,BM, D, B	~150	Math model development, dispatch strategy analysis, optimization algorithm and case study for system simulation and sizing. C++ model, minimization of cost with mixed integer linear programming
9	[165,178,179,183]	Senegal Algeria Iran	Wn, PV, D, B	5–100	Mathematical modeling development, dispatch strategy analysis and simulation for system sizes optimization via cost minimization using Dividing RECTangles optimization algorithm - cuckoo algorithm and fuzzy logic – Partical Swarm Optimization
10	[166]	Algeria	PV, D, B	~200	System simulation based on electrical models of components and economic feasibility analysis
11	[167]	Laos	PV, H, D, B	~10	System modeling and optimization via genetic algorithm based on LCoE, given a target system reliability
12	[168]	Iran	Wn, D	~300	New control strategy for wind turbines coupled with diesel generator, simulation of the system
13	[169]	Palestine	Wn, PV, D,B	~15	Numerical technique for system simulation and optimization based on Cost of Energy and autonomous days
14	[170,171]	Senegal	PV, Wn, D, B	~ 50	Multi-objective optimization (LCoE, CO_2) with genetic algorithm, analysis of the influence of load profile

Table C.3 (*continued*)

N.	Publication	Location	Technology	Size range [kW]	Description
15	[172]	Perù	Wn, PV	–	Geographical and technology configuration optimization for rural electrification planning based on heuristic indicators assessment
16	[173]	Philippines	PV, D, B	~10	Sizes and dispatch strategy optimization via system simulations: linear programming with Matlab
17	[174]	Sri Lanka	Wn, PV, D, B	~10	Multi-objective optimization with evolutionary algorithm based on economic and environmental parameters, analysis of different dispatch strategies
18	[137]	India	PV, D, B	~40	Multi-objective optimization with economic - environmental parameters, analysis of different dispatch strategies
19	[175]	-	PV, Wn, BM	~10	Design and capacity allocation for hybrid system using MILP approach and transhipment model
20	[176]	Malaysia	PV, BM, B	1–5 MW	Analysis of self-sufficient energy eco-village based on PV, BM systems and employing load shifting and storage
21	[177]	-	FC, PV, W	~50	Modeling and simulation of dynamic control (active/reactive power) of hybrid micro-grid based on Simulink
22	[180]	India	PV, Wn, B	–	Analysis of system reliability by means of probabilistic modeling of storage

Note: PV (photovoltaic), Wn (wind), H (hydro), BG (biogas), BM (biomass), D (diesel), B (battery).

Table D.1
Feasibility analyses: stand-alone.

N.	Publication	Location	Technology	Size range [kW]	Software	Description
1	[207]	Nigeria	PV	0.06	–	Assessment of the domestic load demand in small villages sited in rural areas. Data collection of domestic load via questionnaire
2	[208]	Kenya	PV, H	0.012–0.02	–	LCC comparative analysis of off-grid electrification via SHS and PHP systems. PHP using Pelton and PAT technologies
3	[209]	Palestine	PV, B	~0.35	–	Potential of PV applications in Palestine, design and sizing method for a PV system for a rural clinic. On-field application and verification of reliability after two years
4	[210]	Vietnam	PV, Wn, B	0.1–0.15	–	Economic feasibility study of RE technologies (wind turbine and PV) for households needs in remote and rural areas
5	[211]	India	PV, Wn, BG	~1	–	Comparative study for economic evaluation of PV, windmill, biogas and gas-driven dual fuel engine for water pumping and irrigation
7	[140,212–214]	Cameroon, Egypt, Bangladesh, Jordan	PV, D, B	2–8	HOMER	Feasibility analysis of a PV plant: comparison with diesel generator and grid extension costs for the whole energy demand
8	[204,215,216]	India, Iran, Kenya	PV, B	0.01–0.07	RETScreen, HOMER	Comparison of off-grid PV system performance in 3 different scenarios for electricity market in Iran by using the RETScreen. Feasibility study for Stand-alone PV systems via energy production and LCC evaluation. Sensitivity analysis of number of households and length and cost of distribution network via HOMER
9	[129]	Laos	H	2	–	Feasibility of PHP system and SHS. PAT system as alternative to propeller and cross flow turbines. Overview of the off-grid power scenario in Laos
10	[106,193,194, 217,218,221]	Algeria, Zambia, Indonesia	PV, B	0.1–3	–	Feasibility studies and related simulations focusing on PV pumping. Design, sizing and optimal configurations. Reliability and economic analysis based on LPSP and LCC methods, respectively. Sensitivity analysis of tank storage size
11	[110,219,223]	Senegal, Tanzania, DCs	PV	0.02–0.92	–	SHS with LED lamps and a mobile phone charger system for domestic use. Survey after 2 months from the installations to evaluate the users' satisfaction
12	[220]	Mali	PV, B	1–3.5		Classical sizing process based on reliability and cost performed for different simulation time-steps: analysis for the results with reference to cost decreasing
13	[222]	Saudi Arabia	Wn	1–80		Evaluation of potential for installation of wind turbines with regards to wind data
14	[225]	India	PV, B	1.2		Feasibility assessment of potential and market availability for solar battery charging stations

Note: PV (photovoltaic), D (diesel), H (hydro), W (wind), BG (biogas), B (battery), DCs (developing countries).

Table D.2
Feasibility analyses: Micro-Grid.

N.	Publication	Location	Technology	Size range [kW]	Software	Description
1	[226,227]	Nigeria, Bangladesh	PV, D	0.3–10	–	Economic evaluation of PV and PV-diesel systems via Life Cycle Economic Analysis and Net Present Worth methods. Influence of subsidies and prices taken into account
2	[228,229]	Turkey	H	1800–5000	–	Investigation of the sustainable development of Turkey's SHP plants, especially from run-off river plant. Feasibility study of SHP plant
3	[230]	India	PV, H, BM, Wn	5	–	Evaluation of economic feasibility of MHP systems, dual-fuel biomass gasifier systems, small-wind electric generators and PV systems as alternative to grid extension

Table D.2 (*continued*)

N.	Publication	Location	Technology	Size range [kW]	Software	Description
4	[231]	Bhutan		4.5–12-3	–	New methodology for DG evaluation based on multi-criteria method. Criteria include technical features, government regulations and social and environmental aspects
5	[232]	Argentina, Chile	Wn, D	Up to 5	HOMER	Simulation and measurement systems for wind and hybrid (wind-diesel) systems in south Patagonia. Wind resource measurements via loggers to validate simulation results
6	[198,233]		H	2–10	–	Economic correlations for evaluating the cost of different components of canal-based and run-of-river SHP projects for different heads and capacities
7	[234,235,246–248]	India, Ghana Malaysia, Gambia	Wn	3.2–250	–	Assessment for wind energy potential in Penang Island. Techno-economic evaluation of small wind plants already implemented or under implementation in India.
8	[200,201,236,283]	Algeria, Malaysa, India	PV, B	0.7–25	–	Model for sizing optimization of PV system with batteries. Method based on the energy efficiency model, the LPSP and minimum system cost
9	[25]	Senegal, Africa	PV, Wn	130–150	–	Feasibility study via LCC: LCoE computed considering environmental costs
10	[237]	Iran	H	50–200	–	Sites selection for MHP plants in remote areas based on natural resources and electricity situation basing on different techno-environmental-social-economic parameters
11	[238]	Thailand	H	320–6000	–	Potential MHP sites in Thailand for both reservoir and run-of-the-river schemes
12	[239]	India	H	Up to 25,000	–	Analysis of SHP systems sustainable development in India
13	[240]	Nigeria	H	1000–6000	–	Assessment of potential of SHP in Nigeria evaluating capital, operating and maintenance costs and government initiatives
14	[241]	Laos	H	Up to 5	–	Feasibility study for suitable communities where install PHP systems basing on social, environmental and technical aspects
15	[54]		PV, BM	25	–	Model for choosing among PV, biomass gasifier and conventional grid extension using Economical Distance Limit from the existing grid access, based on LCC analysis
16	[242]	India	H	400–900	–	Methodology approach for feasibility of MHP run-off-river scheme
17	[202]	Tunisia	Wn, B	2–16	–	Systemic optimization approach for the design of wind turbine plant coupled with storage for rural area electrification
18	[224,243]	Indonesia	PV, H, B	25–100	–	Techno-economic model for evaluate off-grid RE technologies use. Review of recent literature on the economics of RE-based electricity generation in Indonesia and Liberia
19	[244]	Malawi	H	4500–7600	–	Review of the energy situation and SHP potential, and application status in Malawi basing on government reports, informants and on-site visits
20	[42]	AfganistanNepal	PV, H, Wn, D	20–400	–	Comparison among different RE systems for electrification of rural areas. LCoE to evaluate the cost effectiveness of present electrification processes
21	[245]	Africa	H, PV, D	15	–	Spatial-economic analysis identifying least cost electrification options

Note: PV (photovoltaic), D (diesel), H (hydro), Wn (wind), BM (biomass), B (battery).

Table D.3
Feasibility analyses: Hybrid Micro-Grid.

N.	Publication	Location	Technology	Size range [kW]	Software	Description
1	[148,151,153]	Saudi Arabia	Wn, PV, D, B	10	–	Wind speed and solar radiation measurements to determine sizing variables such as PV array area, number of wind machines, and battery storage capacity. Feasibility study for a hybrid system supplying twenty houses and a typical commercial building
2	[155]	India	PV, Wn, BM	100	HOMER	Model for hybrid system optimization using LINDO software. Results of the model are compared and tested using TORA and HOMER tools
3	[249]	Saudi Arabia	Wn, D	4000	HOMER	Pre-feasibility analyst to evaluate the wind potential instead of a diesel generator for a village
4	[250]	Cameroon	PV, D, B	5–180	–	Modeling of a typical rural community load supplied by a PV-diesel system with storage
5	[251]	Cameroon	PV, H, D	12	HOMER	Techno-economic feasibility study for a typical rural village load profile
6	[230]	India	H, BM, Wn, PV	5–100	-	Preliminary assessment to identify potential areas for hybrid RE system installation in India. Economic feasibility analyses carried out
7	[232]	Argentina, Chile	Wn, D	> 1	HOMER	Simulation and measurement for wind-diesel systems application in south Patagonia. Available wind resource evaluation with network of automatic loggers and definition of an integrated power curve

Table D.3 (*continued*)

N.	Publication	Location	Technology	Size range [kW]	Software	Description
8	[149,152,252–254,287,289]	Saudi Arabia, Nigeria, India	PV, D, B	> 10	HOMER	Evaluation of potential of RE technologies for typical residential and commercial building loads. Techno-economic feasibility study for PV-diesel hybrid systems with storage
9	[154,255]	Ethiopia, India	PV, H, Wn	> 6	–	Design, sizing and optimization studies for basic needs in rural villages. Application to selected villages loads
10	[256,280]	Iran	Wn, FC, BG	1–200	–	Method for sizing hybrid systems consisting on fuel cells, wind turbines, electrolyzers, reformer, anaerobic reactor and hydrogen tanks. The system is fed by biomass (via reformer) and wind energy
11	[257]	Senegal	PV, Wn, BM, B	10–45	–	Potential of RE evaluation in three regions basing on local energy sources and energy demand. Energy demand estimated by surveys to local rural communities' households
12	[258,290]	Ecuador, Tanzania	PV, D	20–660	–	Techno-economic model for the introduction of PV-diesel hybrid systems in rural areas. Sensitivity analysis of fuel cost
13	[259]	Cameroon	PV, H, BG	~8	HOMER	Hybrid system composed by PHP plant, PV, and biogas. Subsystems simulation considering the load profile of a hostel
14	[161]		PV, H, BM, BG, D, B	> 10	–	Techno-economic feasibility study with mixed integer linear programming model
15	[260]	Indonesia	PV, H, FC, D	> 500	HOMER	Feasibility study for supplying energy to an ICT center comparing PV-hydro, PV-hydro-fuel cell, PV Stand-alone and diesel systems
16	[138,209,242,261,262]	Argentina, Chile, Palestine, Saudi Arabia	PV, D, B	0.84–800	–	Feasibility study of PV system coupled with diesel and storage. COE and Present Value of Cost evaluation. Long-term performance of PV-diesel-battery system in rural areas
17	[157,158,293]	India	H, BM, BG, PV, Wn, B	1–100	HOMER	Four different scenarios using RE for supplying energy in rural area are modeled and optimized. Reliability, total system cost and COE are evaluated via LINGO software and HOMER. A model for choosing components, sizing and optimize a hybrid renewable system in order to minimize the COE is proposed
18	[160,281,284,292,294]	Senegal, Cape Verde, Tunisia, Nepal, Iran	PV, Wn, B	2- 100	–	Method based on a multi-objective genetic algorithm and mixed integer linear programming for PV-Wind system with storage sizing and optimization. Minimization of the annualized cost system and LPSP – minimization of investment cost, network balance (voltage drop and maximum current)
19	[250,263]	Cameroon	PV, D	> 10	–	Feasibility study of a hybrid PV-Diesel system. System optimization via an iterative method based on desired annual number of generator hours and Net Present Value
20	[88,166,264,265]	Algeria, Bangladesh	PV, Wn, D	27–68	–	Techno-economic feasibility studies and optimization of PV-Wind-diesel and PV-diesel hybrid systems including sensitivity analysis of fuel cost and annual capacity of shortage
21	[266]	Algeria,	PV, Wn, D	< 1	HOMER	Optimization method for PV-Wind system. Sensitivity analysis for 4 different locations
22	[267]	Iraq	PV, D	4	HybridRO	Design of a hybrid power supply system for a Reverse Osmosis desalination plant. HybridRO software for optimization
23	[156]	India	PV, H, BM, Wn	> 40	–	Techno-economic model for sizing and optimization of hybrid RE systems. Seasonal variations of loads taken in account. Application to seven un-electrified villages
24	[205]	Saudi Arabia	PV, Wn, D	> 10	–	Feasibility analysis of hybrid systems including PV and Wind technologies for supplying typical commercial building loads
25	[169,268,285]	Buthan, Palestine, Congo	PV, Wn	> 5	HOMER	Sizing and optimization models for hybrid systems. Minimization of the total cost installation, dump load and CO_2 emissions
26	[165,170,171,269,270]	Egypt, Ethiopia, Senegal	PV, Wn, D	10–15, > 100	HOMER	Design, sizing and optimization of hybrid systems for small rural villages via deterministic algorithm, multi-objective genetic algorithm and HOMER software. Sensitivity analysis of solar radiation, wind speed and fuel cost
27	[271]	Laos	PV, H, D, B	0.5–5.5	–	Design of a hybrid P/MHP turbines, PV panels, a water reservoir as an energy storage device and a backup diesel generator system. Genetic algorithm use for the system optimization based on the minimum annualized COE
28	[272,273]	RD Congo, Cameroon	PV, Wn, D	~1	HOMER	Feasibility study of hybrid RE systems to supply mobile telephone Base Transceiver Stations. Evaluation of Initial Capital, total Net Present Cost, COE, System Capacity Shortage and Net Present Value
29	[274,275]	Indonesia,Taiwan	PV, Wn	1–100	HOMER	Techno-economic feasibility and optimization studies for hybrid systems and Micro-Grids via HOMER and GAMS/PATH software
30	[137,173]	India, Philippines	PV, D, B	3–40	–	Methods for components sizing and optimization of hybrid systems minimizing LCC and COE. Application to typical families' load of un-electrified villages

Table D.3 (*continued*)

N.	Publication	Location	Technology	Size range [kW]	Software	Description
31	[243]	Indonesia	PV, H	> 10	–	PV and MHP systems evaluation via LCoE in comparison with traditional diesel systems
32	[276]	Iran	PV, D	> 10	HOMER	Techno-economic feasibility analysis for PV-diesel system potential in rural areas of Iran
33	[277]	Algeria	PV, Wn, D	0.1–1	HOMER	Feasibility analysis and comparison of hybrid systems based on PV, diesel and wind
34	[278,279]	Malaysis	PV, micro-tg	10–1000		Feasibility analysis of hybrid system based on PV and micro-turbine for off-grid trigenartion
35	[282,291,295,296]	United Emirate Arab, Somaliland, Libya, Sudan	PV, Wn, D, B	500	HOMER	Optimization method for PV-Wind-Diesel Battery systems, grid extension and sensitivity analysis
36	[283,286]	India, Ghana	PV, Wn, B	100	HOMER	System sizing based on balance between financial viability and beneficiaries affordability

Note: PV (photovoltaic), D (diesel), H (hydro), Wn (wind), BG (biogas), BM (biomass), FC (fuel cell), B (battery).

Table E.1
Case studies: Stand-alone systems.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[300]	Kenya	Wn	–	Case studies of wind pump projects: local manufacturing and installation, benefits, and challenges to be faced for the dissemination in Africa
2	[217,301]	Sudan, India	PV	0.9–7.3	Case studies on solar energy for water pumping and irrigation. Benefits as well as costs are reported and discussed
3	[298,299,302]	El Salvador, Zambia	PV, B	0.02–0.05	Different private companies and NGOs project approaches and results for the introduction and diffusion of SHS
4	[303,304,321]	Thailand, Cuba,	PV, B	0.01–0.5	Analysis of the frequency and main causes of failure of SHS in different projects. Technology as well as social factors and flawed implementation strategies are considered
5	[209,305]	Botswana, Palestine	PV, B	0.05–0.4	Analysis of different factors acting as barriers for the application and diffusion of SHS
6	[307,308,322]	Bangladesh, Thailand, DCs	PV, B	0.02–1	Economic and financial sustainability of SHS and charging stations: techno-economic determinant factors
7	[309–312]	Ghana, Nigeria, Indonesia, Bangladesh	PV, B	0.1–87	Impact of community services PV electrification and/or commercial and productive activities in terms of socio-economic conditions such as extension of the working hours or improvement of the reliability of the tele-communications network
8	[367]	Perú, Brazil	PV, B	0.03–0.15	Results of a study on the electric power consumption patterns in SHS installed in some rural communities
9	[313]	Malawi	PV, B	0.01	Case study on the introduction of solar LED lanterns in rural Malawi in terms of enterprise development, community interactions, and lighting use and expenditure patterns
10	[115,314,315,319]	Ethiopia, Ghana, Zambia, Bangladesh	PV, B	0.001–0.13	Impact of SHS adoption in terms of improvement in education and health, and other socio-economic topics
11	[316–318,320,324]	Morocco, Jordan, Bangla-desh, Fiji	PV, B	0.04- 0.13	Analysis of different large-scale SHS programs in rural areas: implementation, costs results, and feedback from users
12	[338]	Philippines	PV, B	0.05–0.08	Study on the relevance of an appropriate match between technology and users' capacities for the success of SHS projects based on a case study in the Philippines
13	[323]	Morocco	PV, B	4	Monitoring and analysis of the functioning parameters and performances of PV system

Note: PV (photovoltaic), Wn (wind), B (battery), DCs (developing countries)ll), B (battery).

Table E.2
Case studies: Micro-Grid.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[341]	India	PV, B	25	Feasibility of a PV system, compared to other conventional systems, considering the socio-eco-nomic and environmental perspective
2	[325–327]	Tanzania, Algeria, India	PV, B	3–7	Performance analysis and ex-post considerations on the effects of proper/improper sizing of PV systems based on different case studies
3	[328–330]	India, Nepal, Peru, Kenya, Thailand	H	3–1000	Evaluation of the impact of SHP plants from the economic, environmental and social perspective, and comparison with other alternatives such as diesel generator or grid connection
4	[331]	Rwanda	H	100–500	Aspects such as the institution arrangement, local people participation, and private-financial sector collaboration are discussed by comparing four MHP plants based case studies
5	[332]	Afghanistan	H	7	The opportunities and challenges associated with widespread adoption of a distributed approach to developing country power provision are discussed on the basis of the analysis of a MHP project
6	[333]	Bolivia	H	15–100	Performance analysis of a set of rural MHP plants and considerations on their implementing organization, also regarding the management perspective

Table E.2 (*continued*)

N.	Publication	Location	Technology	Size range [kW]	Description
7	[334]	India	PV, B	–	A comparative evaluation of household preferences among PV Stand-alone and Micro-Grid systems
8	[335]	Nepal	H	27	Present status and perspective of MHP plants, and the dynamics of the relationship between electricity and socio-economic development for the case of Nepal
9	[236,336,337]	India, Philippines	PV, B	0.01–45	Impact of PV electrification in terms of socio-economic conditions such as education and social life quality improvement, and decrease in the kerosene expenditure for lighting
10	[132]	DCs	Wn, B	0.19–5	Identification and analysis of socio-technical issues influencing the sustainability of wind-based rural electrification projects (e.g. system level planning, consistency of supply, stable institutional support)
11	[338]	Philippines	PV, B	45	Study on the importance of an appropriate match between technology and users` capacities in order to guarantee success and sustainability of PV-based electrification projects
12	[368]	Malaysia	H	7.5–35	Comparison of techno-economic and social aspects of MHP projects with regards to to sustainability

Note: PV (photovoltaic), Wn (wind), H (hydro), B (battery), DCs (developing countries).

Table E.3
Case studies: Hybrid Micro-Grid.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[139,339]	Bangladesh, Thailand	PV, D, B	4–180	Analysis of PV-diesel-battery systems' performances in a techno-economic and social perspective
2	[232]	Argentina	Wn, D, B	4–10	Results of experience with measurement systems applied to wind-diesel-battery systems in south Patagonia.
3	[340]	Nepal	H, PV	0.5	Analysis of the benefits for remote villages in Nepal due to hybrid systems electrification
4	[267]	Iraq	PV, Wn, D, B	11–55	Design of an off-grid hybrid system for powering Reverse Osmosis desalination units in Iraq. PV-wind-diesel-battery, as well as other combinations of the above mentioned technologies are described
5	[342]	Nepal	PV, H, Wn, B	10 kW	Description of system architecture and specifications of components, analysis of the system hybridization with connection to the main grid
6	[343]	Perú	PV, H, Wn	3.5	Description of technical design for electrification system of a remote community. Adequate technology used according to micro-scale resource evaluation and the socioeconomic requirements of the population

Note: PV (photovoltaic), Wn (wind), H (hydro), D (diesel), B (battery).

Table F.1
Policy: Stand-alone.

N.	Publication	Location	Technology	Size range [kW]	Description
1	[345]	Indonesia	PV	–	Description and evaluation of governmental SHS rural electrification program
2	[346]	–	PV	0.05	Qualitative analysis of impacts of SHS in GHG emission reduction in a rural context
3	[347]	–	PV	–	Analysis of social issue relating to solar pumping, proposal for a new type of pump
4	[348]	Nepal	PV	0.04	Status, programs and experiences of SHS distribution in Nepal
5	[349]	Bangladesh	PV	–	Qualitative description of a business model to promote sustainable rural development via PV systems
6	[350]	Sri Lanka	PV	0.025	Analysis of socio-economic impacts of SHS within monitored households
7	[351]	Sri Lanka	PV	–	Quantitative analysis and discussion of factors contributing in changing the perception of PV technology for rural electrification
8	[319]	Ghana	PV	–	Survey and impact evaluation of SHS system on indoor air pollution, recommended policy
9	[305]	Botswana	PV	–	Comparison and evaluation of SHS distribution project for 3 villages, recommendations for further projects
10	[352]	India	PV	0.02–0.07	Estimate of CO_2 mitigation potential due to SHS implementation under Clean Development Mechanism
11	[317,318,353–355]	Bangladesh, Fiji, India	PV	0.02–0.05	As for rural electrification with PV: status, potentialities, monitoring and analysis of national programs, success stories, challenges and incentive issues
12	[356]	Mongolia	PV, Wn	–	Status of electricity in Mongolia, history, development, challenges and benefits analysis of Rural Electricity Access Project
13	[107]	East Timor	PV	0.01–0.08	Comparison of benefits between 3 sizes of SHS for rural areas, policy implications
14	[357]	Kenya	PV	–	Modeling and analysis of energy transition to SHS for lighting needs in rural areas of Kenya
15	[358]	Asia, Africa	PV	0.02–0.15	Overview of LED SHS: technology, aid and programs in the world, models and best practices of financing

Note: PV (photovoltaic), Wn (wind).

Table F.2
Policy: Micro-Grid, Hybrid Micro-Grid and miscellaneous analyses.

N.	Publication	Location	Technology	Off-grid system SA	MG	HMG	Size range [kW]	Description
1	[45]	Sub-Saharan Africa	PV	√	√	√	–	Energy situation in rural areas of Africa and discussion about the hypothesis of PV as the main RE for rural electrification
2	[312]	Nigeria	PV	√	√		–	Rural electrification with PV: potential, situation, benefits and policy issues
3	[31]	India	-	√	√	√	–	Rural electrification status in Rajasthan region, qualitative analyses of electrification options and proposal for a sequential distributed generation-based approach for electrification
4	[331]	Rwanda	H		√		100–500	History, analyses, project results and considerations about a program for MHP plants implementations in Rwanda
5	[258]	Ecuador	PV, D		√		110	Description of innovative feed-in incentive system for hybrid system promotion. RE Premium Tariff. Use of HOMER tool.
6	[334]	India	PV	√	√		–	Econometric analysis to compare SHS and Micro-Grid PV systems within specific rural village population (Sundarban)
7	[359]	Nepal	H, PV	√	√		–	As for rural electrification in Nepal: review of financing approaches for MHP and SHS, survey and analysis of RE market development.
8	[32]	Senegal	PV, Wn	√	√		–	RE Premium Tariff to boost RE systems. Econometric model developed, policy implications analysed
9	[239,360,366]	TanzaniaIndia, Central Africa	H	√	√	√	10–5000	As for rural electrification with S/MHP plants in Tanzania, India and Central Africa: situation, expectations, challenges and policy recommendations
10	[330]	Nepal, Perù, Kenya	H		√		22–40–135	Sustainability assessment of 3 existing MHP plants in rural areas and discussion of existing barriers and policy implications
11	[132]	Perù, Nicaragua, Mongolia	Wn	√	√	√	0.185-1	Analysis of appropriateness of locally manufactured wind turbine: 3 case studies description and evaluation
12	[102]	Nepal	–	√	√	√	–	Review of rural electrification in Nepal with RE as regards: status of technology development, policy interventions and incentives, impediments
13	[361]	Mali	D	√	√		~7	History, benefits, challenges, and lessons learned about a program of multi-functional platforms implementations in Mali
14	[245]	Africa	PV, H, D	√	√		–	Mapping best economic solution for rural electrification over the African continent, policy and financial implications
15	[362]	Malaysia	PV, Wn, H	√	√	√	–	Rural electrification in Malaysia: potential of and barriers to RE, policies and issues
16	[363]	Bangladesh	–	√	√	√	–	Review and analyses of rural electrification in Bangladesh, factor hampering and contributing to success for off-grid and on-grid interventions, suggested actions to promote rural electrification
17	[364,365]	Mozambique Tanzania Indonesia	Renewables	√	√	√	–	Analysis of options for rural electrification: comparisons between on-grid and off-grid approach and the use of renewable energy technologies

Note: SA (stand-alone), MG (micro-grid), HMG (hybrid micro-grid), PV (photovoltaic), D (diesel), H (hydro), Wn (wind), RE (Renewable Energy).

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