POLITECNICO DI MILANO
DEPARTMENT OF ENERGY
DOCTORAL PROGRAM IN ENERGY AND NUCELAR SCIENCE AND TECHNOLOGY

STRATEGIES FOR ACCESS TO ENERGY IN DEVELOPING COUNTRIES: METHODS AND MODELS FOR OFF-GRID POWER SYSTEMS DESIGN

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2014 – XXVII Cycle

Abstract

This doctoral thesis is part of the research topic related to "energy for sustainable development in developing countries." In general terms this theme refers to the analysis of specific problems of the energy sectors of developing countries (DCs) and the resulting consequences on the sustainable development of these countries. Looking at the energy sector of DCs, a "problem of energy" is typically mentioned. This basically consists in the strong energy dependence on traditional biomass (firewood and charcoal) and low rates of electrification and low per capita consumption of electricity. From these two aspects derive a series of negative consequences that hinder the development process at local, but also at country level. In particular, the population of rural areas of DCs is one that most suffer the consequences of the problem of access to energy. In fact, these areas are often not reached by the electricity grid and the only energy source is traditional biomass. In particular the absence of electricity supply severely limits the ability to improve the capability to meet basic services both at home and community level. In many rural areas, however, strong technical and economic feasibility constraints limit the provision of electricity supply via the traditional paradigm of the centralized system. In these cases, off-grid systems based on renewable energy sources (RESs) are the only viable solution. Nevertheless, the process leading to the identification of the best technical off-grid solution within a specific application context is not trivial, and there are many research topics open in this regard.

In this context, this thesis mainly focuses on the problem of access to electricity in DCs and on the analysis of off-grid systems for electrification of rural areas. The thesis is organized into two parts which deal, through different chapters, with two specific topics respectively.

The first part offers an in-depth analysis and capitalization of the issue of access to energy in DCs with particular attention to the problem of rural electrification. This theme has attracted the interest of the academic sector in the last decade in particular, in consequence chapters 2, 3, 4 are concerned with collecting literature, analyzing it and structuring it as regards its fundamentals. Chapter 2 gives a description of the main characteristics and analysis in the light of the sustainability dimension of the problem of access to energy in DCs. Chapter 3 gives a detailed analysis of the energy situation in Africa by introducing an original analysis that combines the Energy Indicators for Sustainable Development with current energy policies of the continent. Chapter 4 describes the main features of the rural areas of DCs and introduces a taxonomy for off-grid systems applied in these contexts. This chapter also contains the analysis of an extensive review of the scientific literature related to off-grid systems for DCs. This revision is at the base of the methods and models developed in the other chapters of the thesis.

The second part introduces some methods and models that have been developed to respond specifically to some particular issues related to the process of designing off-grid systems for rural electrification. These issues have been identified through the analysis of the literature, but also through direct experience in contributing to the project Energy4Growing. This project deals with the design and installation of a hybrid

micro-grid for a school in a rural area in Tanzania. Chapter 5 describes the development, implementation and application of a procedure for the estimation of daily load profiles required by users of rural areas. The procedure wants to fill the gap in the literature about rigorous approaches that allow the calculation of load profiles. These are in fact essential information for the most advanced sizing methods for off-grid systems based on RESs. Chapter 6 introduces the first step of the development of a method for energy planning systems both off-grid and also for integration of distributed generation systems into the centralized grid. The proposed methodology, in contrast to those already available in the literature, allows the operator to intervene in the planning process working on the results of a series of mathematical-statistical indicators that consider the coupling of energy maps of load and generation. Chapter 7 presents a sizing procedure of off-grid system based on RESs which is appropriate for DCs. In particular, the classical approach based on the definition of the parameter that identifies the "loss of load probability" and "net present cost" has been modified so that both the procedure itself and the results, better fit with the conditions of the targeted context. In particular, the concepts of "value of lost load" and "levelized cost of supplied and lost energy" have been developed. Finally, Chapter 8 addresses the need for models that can simulate the operation of off-grid electro-mechanical systems allowing the analysis of dispatch strategies as well as the evolution of frequency and voltage during system operation. This chapter in particular has expanded the thesis research topics to those typically considered in electrical analyses and it tries to integrate the features of energy analyses with electrical analyses.

Estratto in Lingua Italiana

Questa tesi di dottorato si colloca all'interno del tema di ricerca relativo a "energia e sviluppo sostenibile nei paesi in via di sviluppo". In termini generali questo tema si riferisce all'analisi delle specifiche problematiche dei settori energetici di paesi in via di sviluppo (PVS) e alle conseguenze che ne derivano sul loro percorso di crescita sostenibile. Guardando al settore energetico dei PVS, si fa tipicamente riferimento ad un "problema dell'accesso all'energia". Questo sostanzialmente consiste nella forte dipendenza energetica dalla biomassa tradizionale (legna da ardere e carbonella) e in bassi tassi di elettrificazione con relativi bassi consumi pro capite di energia elettrica. Da questi due aspetti derivano una serie di conseguenze negative che frenano il processo di sviluppo sia a livello locale che nazionale. In particolare, la popolazione delle zone rurali dei PVS è quella che soffre maggiormente le conseguenze del problema dell'accesso all'energia. Queste aree spesso non sono raggiunte dalla rete elettrica e unica fonte energetica rimane la biomassa tradizionale. L'assenza di fornitura elettrica in particolare, limita fortemente la possibilità di migliorare il soddisfacimento di servizi primari a livello sia domestico sia di comunità.

In molte aree rurali si manifestano però forti vincoli di fattibilità tecnica ed economica della fornitura elettrica se promosssa tramite il tradizionale paradigma del sistema centralizzato. In questi casi, i sistemi in isola basati su fonti rinnovabili di energia sono l'unica soluzione percorribile. D'altra parte il processo che porta all'individuazione della soluzione tecnica migliore all'interno di un preciso contesto non è quasi mai banale, e numerosi sono i temi di ricerca aperti a questo riguardo.

In questo contesto, questa tesi di dottorato si concentra principalmente sul problema dell'accesso all'energia elettrica nei PVS e sull'analisi di sistemi in isola per elettrificazione delle aree rurali. Il testo è organizzato in due parti che rispettivamente affrontano, tramite diversi capitoli, due argomenti specifici.

La prima parte propone un'approfondita analisi e capitalizzazione del tema dell'accesso all'energia nei PVS con particolare attenzione al problema dell'elettrificazione rurale. Questo tema ha suscitato, specialmente nell'ultimo decennio, l'interesse del settore accademico, di consequenza i capitoli 2, 3, 4 si occupano di raccogliere la letteratura, analizzarla e strutturarne in maniera organica i fondamentali. Il capitolo 2 propone una descrizione delle caratteristiche principali e un'analisi, alla luce delle dimensioni della sostenibilità, del problema dell'accesso all'energia nei PVS. Il capitolo 3 riporta una dettagliata analisi della situazione energetica dell'Africa introducendo un'originale analisi che combina gli Indicatori Energetici per lo Sviluppo Sostenibile con le attuali politiche energetiche del continente. Il capitolo 4 descrive i tratti principali delle aree rurali dei PVS e introduce una tassonomia per i sistemi in isola applicati in questi contesti. Inoltre, qui è riportata una vasta revisione della letteratura scientifica relativa ai sistemi in isola per i PVS. Questa analisi è poi alla base degli sviluppi presentati nei capitoli successivi della tesi.

La seconda parte introduce alcune procedure e modelli che sono stati sviluppati per rispondere in maniera specifica ad alcune problematiche particolari relative al processo di progettazione di sistemi in isola per elettrificazione rurale. Queste problematiche sono state individuate attraverso l'analisi della letteratura, ma anche attraverso esperienza diretta tramite il progetto Energy4Growing. Questo progetto si occupa della progettazione e dell'installazione di una micro rete ibrida per una scuola in una zona rurale in Tanzania. Il capitolo 5 descrive sviluppo, implementazione ed applicazione di una procedura per la stima dei profili di carico giornalieri richiesti da utenti di zone rurali. La procedura vuole colmare la mancanza in letteratura di approcci rigorosi che permattono il calcolo dei profili di carico. Essi sono infatti un'informazione essenziale per i metodi di dimensionamento più avanzati per i sistemi in isola basati su fonti di energia rinnovabili. Il capitolo 6 introduce un primo sviluppo di un metodo per la pianificazione energetica di sistemi in isola, ma anche per l'integrazione in rete di sistemi di generazione distribuita basata su fonti di energia rinnovabili. La metodologia proposta, a differenza di quelle già disponibili in letteratura, permette all'operatore di intervenire sul processo di pianificazione operando sui risultati di una serie di indicatori statistico-matematici, i quali considerano l'accoppiamento di mappe energetiche di carico e di generazione. Il capitolo 7 presenta un procedura di dimensionmento di sitemi in isola basati su fonti rinnovabili che risulta appropriata per i PVS. L'approccio classico basato sulla definizione del parametro che identifica la "probabilità di non soddisfare il carico" e sul "costo attualizzato netto" è stato modificato in modo che, sia la procedura stessa che i risultati, rispondano maggiormente alle condizioni del contesto di applicazione. In particolare è stato sviluppato il concetto di "valore del carico non soddisfatto" e di "costo attualizzato dell'energia persa e fornita". Infine il capitolo 8 risponde alla necessità di modelli che possano simulare il funzionamento elettro-meccanico di sistemi in isola, permettendo l'analisi di strategie di dispacciamento e dell'evoluzione di frequenza e tensione durante il funzionamento degli stessi. Quest'ultimo capitolo in particolare ha ampliato gli argomenti di ricerca a quelli più trattati in ambito elettrico, cercando di integrare le peculiarità di analisi energetiche con analisi elettriche.

Contents

Notation

Main acronyms used in the text

DALYs	disability-adjusted life years
DCs	developing countries
EDI	energy development index
EISD	Energy Indicators for Sustainable Development
EMSs	energy management systems
GDP	gross domestic product
GNI	gross national income
HDI	human development index
IAP	indoor air pollution
IC	interface converter
ICTs	information and communication technologies
IEA	International Energy Agency
MHP	micro hydropower plant
PV	photovoltaic
RESs	renewable energy sources
SHS	solar home systems
TFC	total final consumption
TPES	total primary energy supply
UNDP	United Nations Development Program
WHO	World Health Organization

1 Introduction and Motivations

This doctoral thesis copes with methods and models for sizing and analysis of small-scale power systems for off-grid implementations. This theme is specifically developed within the frame of rural electrification in developing countries (DCs) with a particular emphasis on Africa.

1.1 Background

The thesis theme refers to the field of research in "energy for sustainable development in developing countries". It explicitly addresses a specific context and two main topics: (i) the frame of *developing countries*, (ii) the *problem of access to energy*, (iii) the concept of *sustainable development*:

- *developing countries* are affected by the lowest per capita values of total primary energy supply as well as electricity consumption. They mostly rely on traditional biomass as primary source of energy and they have weak power infrastructures. These conditions are exacerbated in rural areas where thousands of scattered villages are isolated and characterized by no access to any kind of service.
- tackling the *problem of access to energy* in DCs basically means to address (a) the problem of access to electricity (i.e. electrification) and (b) the problem of access to modern fuels and efficient use of traditional biomass.
- considering the concept of *sustainable development* means to recognize the link between energy and development and hence that the approaches in exploiting the energy resources contribute in determining the development process of any country. In this frame, specific energy strategies can be undertaken and appropriate energy technologies[1] can be implemented in order to promote sustainable development. This aspect is even more important in DCs where the impact on local development due to enhancing access to energy is more tangible.

Within this frame, this thesis deals with rural areas and with the problem of access to electricity (i.e. rural electrification). Specifically, it focuses on methods and models for

[1] This concept has been introduced by the economist E.F. Schumacher before the concept of sustainable development [477], but it can be considered as a part of [478]. It emphasizes the technology as people-centered: small-scale, decentralized, locally controlled, energy-efficient and environmentally sound.

sizing and analysis of small-scale power systems for off-grid implementations. Two main observations can be recognized as general motivations of this research theme:

- electricity supply is pivotal to promote development in rural areas, nevertheless the features of these areas bring about economic and technical constraints to the implementation of traditional technologies based on the centralized electrification approach. Therefore, rural electrification via off-grid small-scale power systems based on renewable energy sources (RESs) is often the most viable strategy;
- the design process of these systems is not straightforward and there are several issues that can be investigated. Therefore specific methods and models are required to tackle these issues. Moreover, achievements in off-grid rural electrification design can have favourable spin-off on applications in the developed world where there is nowadays a growing integration between grid-connected small-scale power systems (i.e. Distributed Generation) and the centralized grid.

Moreover, it is worthwhile to mention that the research field of small-scale power systems based on RESs, both off-grid and grid-connected, is quite new and has experienced a growing interest since the beginning of the past decade[2]. Furthermore, it involves a number of engineering disciplines, but also other subjects (e.g. social, environmental and economic sciences), leading to the development of several research areas. Within this context, the thesis contributes in the progress of the research field by revising the literature and capitalizing its main fundamentals in order to identify the main research themes and hence to provide scholars with a reference framework and.

1.2 Motivational Example and Problems Formulation

This thesis contributed to the research activities of the UNESCO Chair in Energy for Sustainable Development at Politecnico di Milano [1]. Thanks to the Chair network with NGOs, international organizations, private sector and academia, several collaborations have been initiated. In this frame, part of the research activities has been devoted to the project *Energy4Growing*. This project, started in October 2013, is promoted by a team of researchers of Politecnico di Milano, it is funded by the "5permille" Polisocial Award [2] and aims at studying, developing and implementing a hybrid Micro-Grid to supply power to a school in a rural area of Tanzania.

Looking at the different elements of Energy4Growing project, from the framework of the intervention to the aspects about the development of the technological solution, the main issues of rural electrification based on off-grid small-scale power systems can be identified. Therefore, in this paragraph, the project Energy4Growing is considered as motivational example of the thesis.

Motivational example

Access to energy and development in Tanzania

In this country, the population is affected by low life expectancy (61.1ys), low mean years of schooling (5.1ys) and low gross national income (GNI) per capita (1702$/y) [3] which determine a condition of *low human development* [4]. The poor situation of

[2] Well-known journals such as Energy for Sustainable Development and Renewable Energy & Sustainable Energy Reviews have experienced an increase of publications, while specific journals also appeared, e.g. Energy Research and Social Science, Sustainable Energy Technologies and Assessments, Sustainable Energy, Grids and Networks.

the energy sector contributes in hindering the process of development. Indeed Tanzania is afflicted by low electrification rates (24% on national basis), low electricity consumption per capita (92.15 kWh/y) and high dependence on traditional biomass (87.4% of total final consumption) [5]. These macro-figures describe a situation which deeply weighs on the everyday life of the population. In fact, poor electric supply service blocks health and education services development, limits the production capacities, and binds households to fuelwood dependence. Moreover, fuelwood dependence results in the exhausting and time-consuming task of wood collection (in Tanzania travelled distance is up to 10km [6]), in overexploitation of local biomass resources [7], and in severe exposure to toxic pollutants due to incomplete combustion of unprocessed solid fuels.
Tanzania as well as most of the sub-Saharan African countries are characterized by high rates of population and income growth, but have ineffective and inefficient energy sectors. Indeed, these ones are characterized by (i) low primary energy supply, (ii) low reliability of the power infrastructure, (iii) low electrification rates (mainly in rural areas), (iv) final consumptions driven by the domestic sector which relies on traditional biomass, (v) good availability of primary sources (either fossils, mostly exported, and renewables, mainly unexploited), and (vi) a pluralism of stakeholders, plans and policies which bring about fragmented and ineffective actions.

Energy situation in rural areas

Even in Tanzania, the worst situation occurs in rural areas. Here electrification rate is about 6.5% and more than 95% of the population relies on traditional biomass [8]. The power supply is available only among well off households and enterprises which employ diesel/petrol generators or small-scale renewable systems usually aid-financed. The interventions for rural electrification are responsibility of the Rural Energy Agency [9] which often works slowly and ineffectively [10], [11]. As a matter of fact, rural electrification is typically supported by cooperation programs led by international agencies, or local development projects led by NGOs [12].

Figure 1.1 Ngarenanyuki secondary school

Energy4Growing project

The Energy4Growing project acts in this context and specifically deals with the improvement of the electric supply service of the secondary school of Ngarenanyuki, a rural village in the Arusha Region (Tanzania). Here 460 students attend the school and 85% of them are resident in the school facilities which include classrooms, offices, dormitories, library, kitchen, teachers' houses, etc. (Figure 1.1). The centralized grid does not reach Ngarenanyuki area, but while the village is not provided with electric supply (only few households own small generators), in the school a number of off-grid power systems are available. These systems had been installed in the past years thanks to different project interventions (not coordinated) which supported the school.

Actual power supply system of the school

Currently the main power source is a run-off-river micro hydropower plant (MHP) based on a 3.2kW Banki turbine coupled with 1-phase synchronous generator (230V, 50Hz). The turbine always works at full capacity according to the stream flow and the frequency regulation is based on a 4kW dump load which dissipates the excess power into the air (Figure 1.2). The turbine water flow is diverted from a stream which is managed by local farmers. Therefore, water availability is highly variable during the day and according to the season. This requires having an operator of the plant who manually regulates the turbine distributor in order to keep the penstock pressure at proper level.

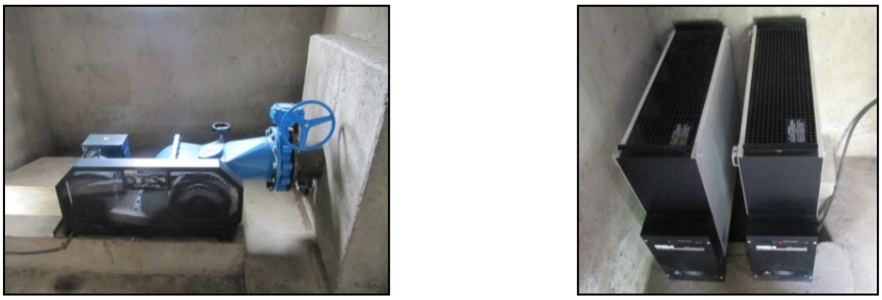

Figure 1.2 Banki turbine and generator – Dump loads

Owing to the unpredictability of the available water supply and hence to the discontinuity of the MHP generation, two back-up systems have been installed:

- a pack of 8 x 100Ah/12V Chloride Exide batteries that can be charged via the MHP plant thanks to a 2.4kW charger;
- a 5kW petrol generator which is manually switched on and off. Indeed, due to the high running costs, it is used when the MHP plant is off and the battery packs are discharged and only for special reasons.

Figure 1.3 Control panels: loads breakers (left), master switch (center), toggle switch (right)

The power supply is managed in the control room with a toggle switch that permits the choice of the power source to be used, and with a group of breakers that permits specific loads to be connected/disconnected (Figure 1.3). At the moment, the operation of the system is managed by an operator who checks the proper working conditions of the Banki turbine, selects the power source and operates the loads. Despite the operator (not being available h24) and the school staff have gained a fair practical experience about the system functioning, the system management is far from being effective and efficient, and hence several blackouts occur.

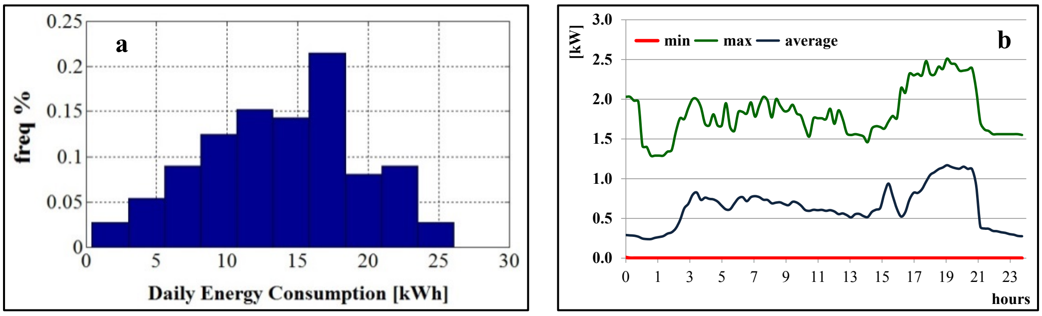

Figure 1.4 (a) Discrete probability distribution of daily consumptions. (b) Analysis of load profiles

Actual energy consumption patterns

Currently the number and type of the electric devices available in the school are determined by the limited generators and storage capacities. Moreover the current consumption patterns are deeply affected by the energy source availability (i.e. the water flow) which results in highly variable consumptions day by day and hour by hour. This is a typical feature of consumption patterns in rural areas where systems generating capacities are more often defined by economic constraints (i.e. capital expenditure availability) rather than on local needs. Therefore, these result to be defined by local resource and power rates limitations.

This observation together with preliminary analyses on school power consumption habits suggested to carry out a monitoring of the system functioning. Specifically, in these cases, in addition to investigate the consumption patterns of the users, also understanding the typical operational conditions under which the system works is mandatory to plan a proper intervention. In order to address these issues a meter has been installed on site and energy consumption data as well as electric functioning parameters have been monitored. Here, an analysis of the collected data of about 100 days from June to September 2014 is reported.

Figure 1.4 shows energy consumptions and load profiles data:

- the daily energy consumptions range from a few kWh to about 25kWh: this suggests a high variability of the water source availability on a daily basis;
- at each hour of the day the power loads ranges from 0W to values above 1.5kW. This suggests highly irregular water source availabilities on an hourly basis.

Functioning analysis of the current power system

Considering the analysis of the electro-mechanical behavior of the system (i.e. frequency and voltage), a wide range of operating conditions has been reported (Figure 1.5). This result from a number of elements such as the transient dynamics of the system during turbine overload, the inappropriate loads operation, the functioning of the petrol generator, etc. It is clear that the school staff tries to operate the system in order to fully exploit, when available, the hydro energy, but being unaware of the low quality of the electric supply, and hence to the detriment of the efficient functioning of the power systems and the electric load devices as well.

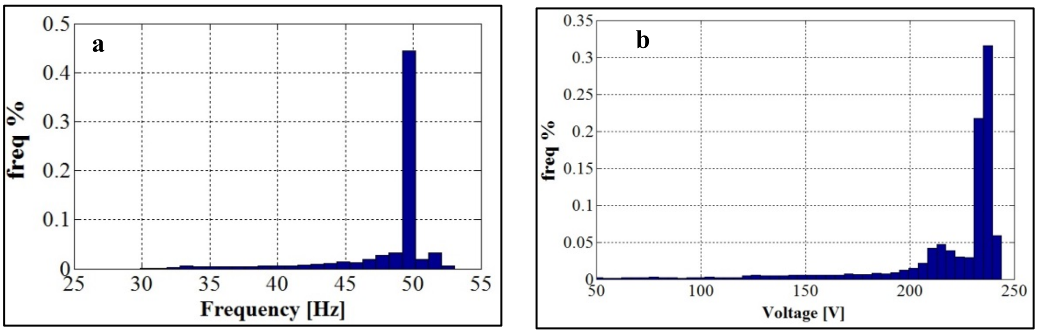

Figure 1.5 Discrete probability distribution (freq. %) of frequency (a) and voltage (b)

Proposed Hybrid Micro-Grid

With respect to the Energy4Growing project, a main purpose is to improve the power supply service of the school by increasing the generating capacity and by adopting an energy management system (EMS) capable of effectively and efficiently integrating the different power sources. According to this aim a specific architecture of the off-grid system has been developed in order to tackle some issues which have arisen from the specific context of Ngarenanyuki school, and others which are typical of rural electrification actions. Specifically the architecture:

- should allow the integration of already available different power sources which can operate in grid-following or grid-forming mode;
- should allow the integration of different power sources avoiding complex communication apparatus for system functioning control;
- should allow to be easily connected to the main centralized grid in case of grid extension to the area;
- should be cost effective, i.e. reaching high efficiency, assuring long life-time of main system components, lowering O&M costs;
- should allow future installations of power generation and storage capacity.

Accordingly, a hybrid Micro-Grid which combines the power systems already available with new installations of PV panels and lead-acid battery pack by means of an interface converter (IC) with specific control units has been developed (Figure 1.6):

- Q1 is the dc/ac control board which connects the PV and the batteries to a double ac busbars system via the IC. The IC permits two different operation modes: (i) PV and battery pack in parallel with the MHP plant or the petrol generator, (ii) PV and battery pack in stand-alone functioning. The double busbars configuration will allow a future easy connection to the national centralized grid;
- Q2 is the ac board which comprises: (i) the devices to monitor the status of the Micro-Grid, (ii) the PLC equipped with specific logics to manage the energy flows, (iii) the Human Machine Interface.

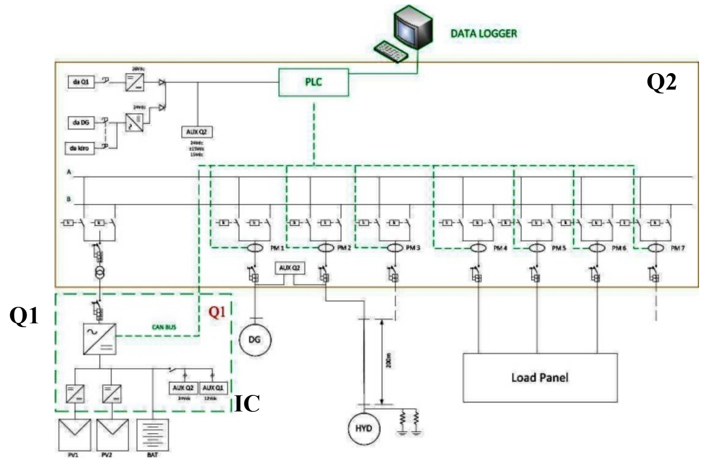

Figure 1.6 Hybrid Micro-Grid architecture for Ngarenanyuki site

At the moment of this thesis writing, lab tests are going on as regards the IC which is the core of the Micro-Grid. The implementation and the start-up of the system are expected for April/May 2015.

Problems formulation

Looking at the different elements of the Energy4Growing project, from the features of the intervention context to the specific aspects about the development of the technological solution, the main problems as regards rural electrification actions based on off-grid small-scale power systems can be identified. Table 1.1 summarizes the identified issues which are briefly described in the following.

Table 1.1 Main issues about rural electrification based on off-grid small-scale power systems

1	Analysis of the access to energy scenario in developing countries
2	Analysis of the energy framework where the electrification action takes place
3	Analysis of rural areas of developing countries: typical energy needs and technology solutions for rural electrification
4	Analysis and estimate of energy resources availability and electric consumption patterns
5	System selection and sizing
6	Optimization of the dispatch strategies and the real time power control
7	Monitoring and evaluation of the rural electrification intervention

1. Both for the Energy4Growing case and for any rural electrification action in DCs, improvements of power supply services aim at better addressing people needs thus triggering and supporting the process of development.
   Therefore the 1st issue refers to the features analysis of the energy–development link in DCs. Specifically, when aiming at sustainable development, it is required to analyze the relationships between the features of the access to energy scenario and the sustainability dimensions.
2. Once the general features of the energy–sustainable development link are described, the energy context of the electrification action has to be analyzed.
   For the Energy4Growing case, this means to consider the actual energy situation of Tanzania, its trends and the possible developments according to available resources. Therefore the 2nd issue refers to the analysis of the energy framework where the electrification action takes place. This means, at country or macro-region, to

acquire a picture of the current energy situation, to measure the state and the progress towards a sustainable energy system, and to understand the implications of selected energy strategies on local development.

3. Given the energy framework where the rural electrification action takes place, it is important to address the typical features of rural areas and the power system options.
   For the Energy4Growing example, having general information about the school, the neighborhood village, the available energy systems, the local technical skills and the energy habits, were mandatory in order to plan the intervention.
   Therefore the 3rd issue refers to the features analysis of rural areas of DCs. Particularly, this means to identify the typical energy needs and to acquire the state of the art of the technology solutions for rural electrification.
4. Once dealing with the design process of off-grid small-scale power systems, primary data required are about the user consumption patterns and about the availability of energy sources. Nevertheless getting this information is not straightforward. When dealing with the local available RESs metering stations are often unavailable. When dealing with the user consumption patterns: no data are available at all in un-electrified areas, consumption habits are deeply affected by resource availability and systems capacities rather than resulting from user choices, and rapid changes in the consumption patterns may occur.
   In the case of the Energy4Growing project, solar, wind and hydro availability data are not available due to lack of metering stations. Moreover even if consumption data have been metered, no typical trends can be recognized due to a number of elements: resource availability, systems power sizes, system management, school daily activities, etc. .
   Therefore the 4th issue refers to the analysis and estimate of the energy resource availability as well as of the electric consumption patterns (i.e. daily consumption and load profiles).
5. The 5th issue refers to the system selection and sizing. Indeed, given a rural area to be electrified, different system options are available (i.e. stand-alone, Micro-Grid, hybrid Micro-Grid) and rated powers and/or capacities of main system components have to be identified. Nevertheless these operations are not an easy task: loss of load and excess energy have to be limited while consumption and resource data uncertainty have to be considered.
   In the case of the Energy4Growing project, currently installed power capacity is limited when compared to the potential energy requirements thus leading to several black-outs and batteries severe exploitations. Nevertheless, when looking at the new installations, analysis as regards new power/energy availabilities and school desired consumptions (i.e. new devices use) is mandatory in order to exploit the new system within its limits while improving the power supply service.
6. The 6th issue refers to the optimization of dispatch strategies and to perform real time power control analyses. Mainly in hybrid Micro-Grids, these aspects require detailed information about system components features, involve developing complex control logics, may affect the system components sizing, and may result in uneasy system operating procedures for local people.
   In the case of the Energy4Growing project, optimizing the energy fluxes between batteries and dump loads leads to improving the systems efficiency, nevertheless this have not to compromise the quality of the power supply.

7. last but not least, rural electrification projects primary aim at triggering or supporting local development thus improving well-being of people.
   Therefore the 7th issue refers to the monitoring and evaluation of the rural electrification intervention in order (i) to understand to which extent local development has been promoted, (ii) to identify the encountered problems (technical and not), (iii) to plan intervention corrections and (iv) to capitalize experiences for future actions.
   In the case of the Energy4Growing project, the school is expected to benefit from the new plant by employing a water pump to improve water supplies, by increasing the available nightlights and evening study hours, by employing a freezer for meat preservation, by increasing the number of available computers, etc. .

Further issues refer to the analysis of economic, environmental and social features of the targeted context. Moreover, also testing and implementing the system with proper involvement of local technical people (i.e. from persons in charge of system operation, to technicians involved in system maintenance and local academia representatives) affect the action success.

1.3 Methodology

As already highlighted, the issues which have just been introduced represents the typical topics which concern rural electrification actions based on off-grid small-scale power systems. This thesis, in addition to specifically tackle these topics, also organizes them in a specific structure which has been followed in the research activities.

Figure 1.7 shows a schematic overview of this methodological frame. The introduced topics are arranged in two groups: (i) those which can be analyzed in order to develop a *Framework of Reference* of the targeted theme, and (ii) those which can be considered as building blocks of the *System Design Process*.

The *Framework of Reference* is defined:

1. by analyzing the access to energy scenario in developing countries;
2. by analyzing the energy framework where the electrification action takes place. Apart from the Energy4Growing case, this thesis considers the context of Africa to which most of the case studies presented in the thesis refer;
3. by describing the typical features of rural areas and the state of the art of systems for off-grid electrification.

The *System Design Process* is composed in macro-steps and building blocks:

- four consecutive macro-steps are identified according to four main technical issues to be sequentially tackled during the design process;
- each macro-step has been divided in a number of building blocks which represent specific tasks. According to the considered macro-step: (a) some building blocks are mandatory and others are useful only if particular features are embraced in the process, (b) some building blocks are consecutive (the output of one is needed by the other) and other are in parallel.

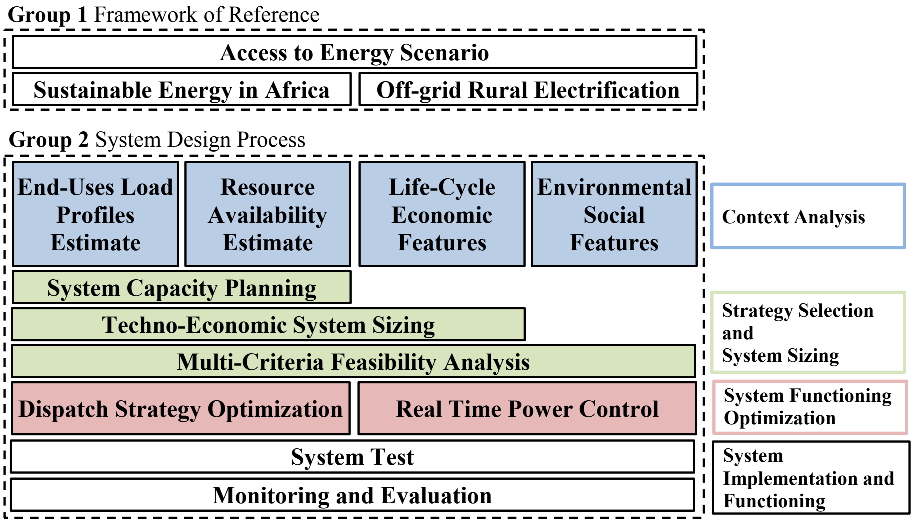

Figure 1.7 Schematic overview of the structure adopted to organize the typical topics concerning rural electrification interventions via off-grid small-scale power systems

The four macro-steps considered are: (1) Context Analysis, (2) Strategy Selection and System Sizing, (3) System Functioning Optimization and (4) System Implementation and Functioning.

(1*) Context Analysis*

It refers to the collection at local level of primary information and input data which drive the identification of the specific solution for the targeted context. It is composed by four building blocks in parallel which refer to: end-use consumption pattern estimate, energy resource availability estimate, economic features, and environmental and social features. Data about consumption patterns and energy resources are typically considered in terms of time series data (i.e. daily load profiles and hourly solar radiation, wind speed, water flow, etc.) which are mandatory in the design process. Economic data (e.g. system component costs, people willingness to pay) are often considered. Environmental (e.g. pollution constraints, space occupation) and social features (e.g. local technical skills, people acceptability, and cultural taboos) are employed only when aiming at "holistic" analyses.

(2) Strategy Selection and System Sizing

It refers to the identification of the proper off-grid power system type (e.g. stand-alone systems, Micro-Grid, hybrid Micro-Grid, a combination of them) and of the main power system components sizes (i.e. rate powers, storage capacities) according to one or more objective functions. It is composed by three building blocks:

- *System Capacity Planning* is based on *End-Uses Load Profiles* and *Resources Availability* and it performs the strategy selection and the system sizing considering a number of targeted energy performances (e.g. loss of load, excess energy);
- *Techno-economic System Sizing* considers also economic parameters (e.g. life-cycle systems cost, cost of electricity). Moreover, at this stage methods and models can embrace economic features by elaborating the outputs of *System Capacity Planning* model (i.e. being in sequence) or they can perform the analysis starting from the *Context Analysis* primary data*;*

- *Multi-criteria Feasibility Analysis* embraces also environmental parameters (e.g. pollutions and emissions, soil consumption, noises) and social parameters (e.g. created workplaces, services improvements). Moreover, at this stage methods and models can embrace environmental and social features by elaborating the outputs of *Techno-economic System Sizing* model (i.e. being in sequence) or they can perform the analysis starting from the *Context Analysis* primary data.

(3) System Functioning Optimization

It refers to the analyses which address the real interactions of all the system components (i.e. power sources, storage systems, power electronics, control systems, etc.) during the system working. This step is based on the *System Sizing* outputs, but it can entail a review of them (i.e. corrections/adaptations of rate powers and storage capacities).

It is composed by two building blocks in parallel:

- *Dispatch Strategy Optimization* performs the optimization of the power flows among the system components throughout a day or in particular conditions according to specific objectives functions (e.g. minimizing energy flows through the batteries, minimizing fuel consumptions).
- *Real Time Power Control* address the trends of electrical parameters (typically frequency and voltage) in order to verify the correct real interactions among all the systems components during system functioning.

The two building blocks are typically addressed by different mathematical models and they are mostly employed when dealing with complex system configurations (i.e. Micro-Grid) or immature technologies (i.e. advanced control and power electronics).

(4) System Implementation and Functioning

It refers to the analyses which address the real operation of the system in order to check, monitor and evaluate the system functioning on site, both from a technical point of view and from a local impact one. This step can entail a review of the modifiable functioning parameters. It is composed by two building blocks. Complex systems configurations require laboratory *Tests* before the installation to check the proper functioning. On the contrary, *Monitoring and Evaluation* should be performed for any systems addressing rural electrification actions in order to make modifications to the systems functioning settings and in order to understand the impact on local development.

1.4 Thesis Outline and Contributions

This thesis is a compilation of results published in books, and presented or submitted to scientific journals and conferences. It addresses the issues constituting the *Framework of Reference* group and some of the building blocks of the *System Design Process* group. With reference to the structure already proposed (Figure 1.7), the contributions are illustrated in Figure 1.8 and summarized in the following.

The thesis is divided in two parts:

- Part I Energy for Sustainable Development in Developing Countries which address the topics constituting the *Framework of Reference*;
- Part II Methods and Models for Off-grid Power System Design which address some of the topics constituting the *System Design Process*.

The element of originality of the former relies in the wide analysis, synthesis and capitalization of the scientific literature which has led to define and highlight the main fundamentals of this field of research and to set a reference framework for scholars.

The latter is composed by the descriptions of specific methods and models which address off-grid systems design process. Each of them has its own original contribution as for the specific research topic (which is often independently studied from the other). Therefore, each chapter of this part is structured according to: problem identification and literature analysis, method and/or model description, application(s).

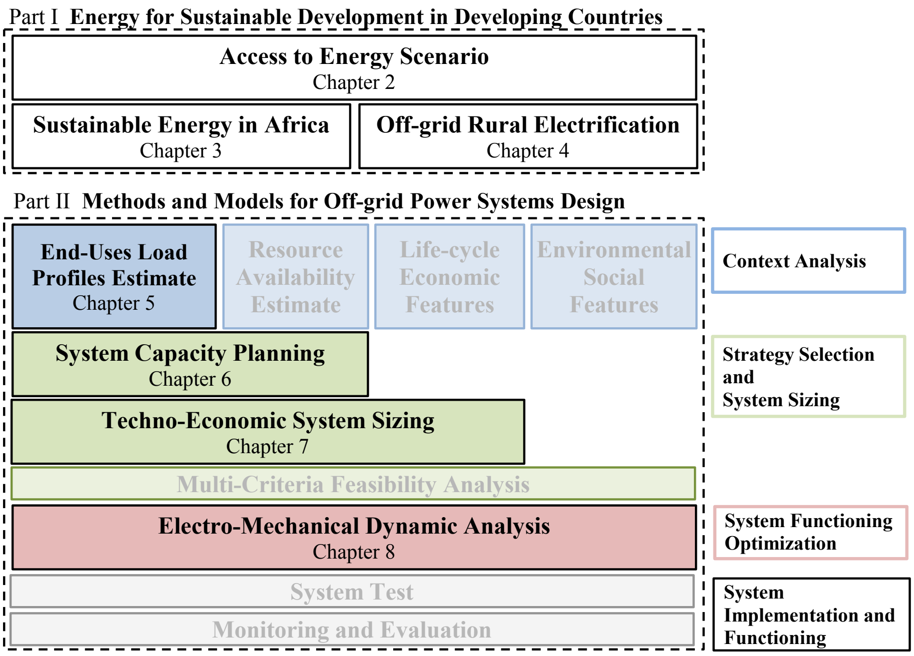

Figure 1.8 Summary of the thesis' contributions

Chpter 2: Global Dimension of Access to Sustainable Energy

This chapter introduces the theme of access to sustainable energy within a global perspective and in particular reference to DCs. The aim is to depict the background of this theme by describing the main issues as regards the topic of sustainability. In particular, the key energy challenges for high-income countries, emerging countries and DCs are highlighted. Then, focusing on the features of DCs, an analysis of the energy-sustainability dichotomy is carried out and two main issues, namely the problem of electrification (in particular rural electrification) and the problem of traditional biomass dependence, are introduced.

This chapter is based on the following publications:

E. Colombo, L. Mattarolo, S. Mandelli (2013). Global dimension of universal access to energy. In E. Colombo, S. Bologna, & D. Masera (Eds.), *Renewable Energy for Unleashing Sustainable Development (pp. 27-39). Springer International Publishing.*

E. Colombo, S. Mandelli (2012). Facts and figure a reasoned approach, In "Access to Energy: focus on Africa". *Ed. EDIPLAN*, ISBN 9788896726082, pp. 36-80, Milano.

Chapter 3: Sustainable Energy in Africa: Current Situation and Main Issues

This chapter depicts the current energy situation of Africa as far as the concept of sustainable development is concerned, and it analyzes if and how local energy policies fit with this asset. The energy situation of Africa is assessed by combining (i) data about final consumptions, electric sector and energy resources, with (ii) an analysis based on the Energy Indicators for Sustainable Development. Moreover, an overview of the energy-related action plans developed by different local players is also carried out with the goal of providing remarks by coupling such plans with the above mentioned energy analysis. In particular, emphasis is given to the issue of electrification which is pivotal in promoting local development and it is the focus of the following chapters.

This chapter is based on the following publication:

S. Mandelli, J. Barbieri, L. Mattarolo, E. Colombo (2014). Sustainable energy in Africa: a comprehensive data and policies review, *Renewable & Sustainable Energy Reviews*. 37:656-686.

Chapter 4: Review on Off-grid Systems for Rural Electrification

This chapter focuses on off-grid small-scale power systems which represent one of the most appropriate energy strategies to address rural electrification. Specifically, the chapter introduces the role of off-grid small-scale power systems in the process of electrification, describes the main features of rural areas (i.e. main targeted areas for these systems) and rural energy needs, depicts a specific taxonomy for off-grid systems (the *Off-grid Systems Matrix*) and reviews the related scientific literature.

The main aims are to deepen the analysis of the electrification issue in DCs with specific reference to rural areas and to introduce the research themes as regard small-scale off-grid power systems. These latter will be the basis, in the following chapters, for the development of methods and models which address more specifically the system design process.

This chapter is based on the following publication:

S. Mandelli, R. Mereu (2013). Distributed Generation for access to electricity: “off-main-grid” systems, from home-based to microgrid. In E. Colombo, S. Bologna, & D. Masera (Eds.). *Renewable Energy for Unleashing Sustainable Development (pp. 75-97). Springer International Publishing*.

S. Mandelli, J. Barbieri, R. Mereu, E. Colombo. Off-grid systems for rural electrification in Developing Countries: definitions, classification and a comprehensive literature review, *Renewable and Sustainable Energy Reviews. Under review.*

Chapter 5: Load Profiles Estimate with Stochastic Procedure

This chapter describes the development, implementation and application of a new procedure to address end-uses load profile estimate in rural areas. The procedure allows having a tool which is a support to develop the proper input data required by the most advanced off-grid systems sizing methods and software tools. Indeed, despite the growing interest, no methodologies are available in the literature capable to estimate load profiles for the System Design Process of off-grid systems.

The procedure works with the typical input data that are commonly considered in the approach for energy consumption estimates, but it employs a stochastic bottom-up approach with specific correlations between main load profiles parameters in order to build up the coincidence behavior of the considered electrical appliances.

The chapter briefly introduces the main definitions and parameters that characterize load profiles analyses and provides a short overview of the estimate methodologies available in the literature. Then the new procedure is introduced by highlighting the general approach, the required input data and by describing its mathematical formulation. The implementation of the procedure in a proper algorithm coded in MATLAB is also presented and finally, the procedure has been applied in two cases: (i) in forecasting the average load profile of an existing power supply system of a college campus in rural Cameroon, (ii) in developing stochastic sizing of an off-grid PV system based on the estimated load profiles.

Chapter 6: System Capacity Planning of both On-grid and Off-grid systems

This chapter deals with a first step development, implementation and application of a new procedure to perform System Capacity Planning. Particular features of the procedure are the capability to address both off-grid systems and Distributed Generation planning and the use of statistical-mathematical indicators to analyze and rank the available energy sources to be employed in the system planning. Moreover it is capable to adapt to many kind of contexts (i.e. multiple RESs, integration of storage systems and diesel generators) and it has been structured in a sequence of steps which have their specific mathematical formulations and which can be handled singularly by the procedure operator in order to adapt the process to specific planning judgments.

The overall procedure structure and the mathematical formulation of each specific step are described. Furthermore, examples of procedure application are described by means of an off-grid system capacity planning applied to a building of the Politecinco di Milano and an on-grid system capacity planning applied to the city of Legnano.

Chapter 7: Appropriate Techno-Economic System Sizing for Rural Areas

This chapter deals with a new methodology to perform appropriate Techno-Economic System Sizing for rural areas of DCc. The methodology can be applied to any off-grid systems, but it has been exemplified for the off-grid PV systems case. Specifically, in the chapter it is highlighted that the need as input datum – in the traditional sizing techniques – of the Loss of Load Probability parameter, may lead to un-appropriate sizing in rural areas. Therefore, an appropriate sizing methodology which embraces the new definitions of the Value of Lost Load parameter and of the Levelized Cost of Supplied and Lost Energy objective function is developed and described. Comparisons between the traditional methodologies and the new one are carried out in order to highlight the appropriateness of the latter as regards rural areas. Moreover, the new methodology is applied to perform optimum sizing of a Micro-Grid in Uganda.

This chapter is based on the following publication:

S. Mandelli, E. Colombo, M. Merlo, C. Brivio. A sizing methodology based on Levelized Cost of Supplied and Lost Energy for off-grid rural electrification systems, *Renewable Energy, Under review.*

S. Mandelli, E. Colombo, M. Merlo, C. Brivio (2014). A methodology to develop design support tools for stand-alone photovoltaic systems in Developing Countries. *Research Journal of Applied Sciences, Engineering and Technology*. 8(6):778-888.

Chapter 8: Electro-Mechanical Dynamic Analysis for Off-grid Systems

This chapter deals with a new approach to allow developing simplified integrated analyses of dispatch strategies and real time power control. This aim arises from the observation that dispatch strategy optimization and real time power control are performed by different approaches and hence different mathematical models. Nevertheless, both analyses may affect the desing of the system control. An example of this issue is presented by the case of the Energy4Growing project. In this frame the new approach is capable to simulate off-grid system functioning, working over medium term period (i.e. days) with typical time-steps of real time power control, and embracing simplified electrical models of system components in order to address dispatch strategy together with V and f trends analyses.

A first step development of the mathematical models of a 2-phase synchronous generator, of dump loads and user loads have been described and they have been employed to model the actual configuration of the MHP plant at Ngarenanyuki school.

This chapter is based on the following publications:

S. Mandelli, M. Merlo, E. Tedeschi, M. Molinas. A simple electro-mechanical model for understanding the operation and dynamic behavior of a Micro-Grid in Tanzania. *10th IEEE International Conference on Ecological Vehicles and Renewable Energies, Monaco 2015. Accepted paper.*

M. S. Carmeli, P. Guidetti, S. Mandelli, M. Merlo, R. Perini, G. Marchegiani, D. Rosati, C. Brivio, R. Di Molfetta. Hybrid Micro-Grid experimental application in Tanzania. *5th International Conference on Clean Electrical Power, Taormina 2015. Accepted abstract.*

Chapter 9 Conclusions and Future Work

A summary of thesis contributions is given and future research directions are discussed

Other Contributions

The following publications by the author had a significant influence on some of the contributions, but are not covered in the thesis.

E. Colombo, S. Mandelli, G. Cassetti, A. Berizzi, C. Bovo. Access to energy: mini integrated renewable systems for facing the technical problem. *Proceedings of the 2012 Tech4Dev International Conference, Lausanne, Switzerland.*

S. Mandelli, E. Colombo, A.D.C. Redondi, F. Bernardi, B.B. Saanane, P. Mgaya, J. Malisa. A small-hydro plant model for feasibility analysis of electrification projects in rural Tanzania. *Proceedings of the 2013 IEEE Global Humanitarian Technology Conference, San Jose, California.*

L. Mattarolo, S. Mandelli, E. Colombo, F. Romeo. An integrated monitoring & evaluation approach for the assessment of energy technologies-related projects.

Proceedings of the 2014 Tech4Dev International Conference, Lausanne, Switzerland. Selected for publication in Springer-Verlag book.

M. S. Carmeli, P. Guidetti, M. Mancini, S. Mandelli, M. Mauri, M. Merlo, R. Perini, G. Tomasini, G. Marchegiani, D. Rosati, Hybrid Distributed Generation system for a rural village in Africa. *Proceedings of the 3rd IET Renewable Power Generation Conference, September 2014. Napoli, Italy*

S. Mandelli, P. Guidetti, M. Merlo, S. Carmeli, R. Perini, G. Tomasini, M. Mancini, D. Rosati, M. Leonardi (2015), Elettrificazione nei paesi in via di sviluppo: il progetto Energy4Growing, *Energia Elettrica*. 5-1

D. Hakon, S. Mandelli, E. Colombo, F. Olav, M. Molinas. A methodology for supporting the planning of Micro-Grids based on composable tool: a case in Bhutan. *5th IEEE International Youth Conference on Energy, Pisa 2015. Submitted abstract.*

M. Merlo, S. Mandelli, M. Molinas, E. Park, M. Leonardi, E. Colombo. The role of storage in emerging countries scenarios. *EUROSOLAR 9th International Renewable Energy Storage Conference, Dusseldorf 2015. Accepted paper. Selected for publication on Energy Procedia.*

Part I Energy for Sustainable Development in Developing Countries

2 Global Dimension of Access to Sustainable Energy

The development of human society has been marked all throughout history by the role of energy resources. In particular, during the 20th century, the importance of energy in the global scenario and the interconnections with the environment and society has become more evident. Moreover, in the last decades, the need to fight poverty also by increasing access to modern energy services has been recognized. The designation of Year 2012 as the International Year for Sustainable Energy for All and the subsequent Sustainable Energy for All initiative [13], that fosters access to energy, energy efficiency and RESs, has contributed in raising awareness on these issues.

In this frame, this chapter introduces the theme of access to sustainable energy within a global perspective and in particular reference to DCs. The aim is to depict the background of this theme by describing the main issues as regards the topic of sustainability. In particular, the key energy challenges for high-income countries, emerging countries and DCs are highlighted. Then, focusing on the features of DCs, an analysis of the energy-sustainability dichotomy is carried out and two main issues, namely the problem of electrification (in particular rural electrification) and the problem of traditional biomass dependence, are introduced.

2.1 Energy Challenges

Access to modern energy is today considered essential to encourage development and to fight poverty [14]. Sustainable energy, being a basic condition to enable access to services, resources and public goods, therefore constitutes an essential prerequisite for human and social progress, along with environment conservation. Access to energy is essential for clean water supply and sanitation, for the development of agriculture (irrigation, mechanization, food processing and transportation), for the support of ICTs and for enabling access to healthcare, education and other basic social needs.

As indicated in the World Energy Outlook 2014 by the International Energy Agency (IEA), almost 1.3 billion people have no access to electric energy, almost 1.0 billion people are connected with unreliable electric grid and 2.7 billion people rely on traditional biomass for main energy needs [8].

International organizations have devised indicators to assess development with a comprehensive approach that goes beyond the single economic perspective: the human development index (HDI) and the energy development index (EDI). HDI was first presented in the UNDP Human Development Report in 1990 [15]; its aim is "*to shift the focus of development economics from national income accounting to people centered policies*", considering aspects such as life expectancy, access to knowledge and standards of living[3]. EDI has recently been devised by IEA [16], and further revised [17], in order to better identify the role that energy plays in human development. The index tracks the progress of a country or a region towards the use of modern fuels (electricity, LPG, natural gas, kerosene, paraffin, ethanol and biofuels) and modern energy services[4]. The correlation between EDI and HDI indexes is evident (Figure 2.1), thus confirming the importance that access to energy holds as a key basis to eradicate poverty, enable human promotion.

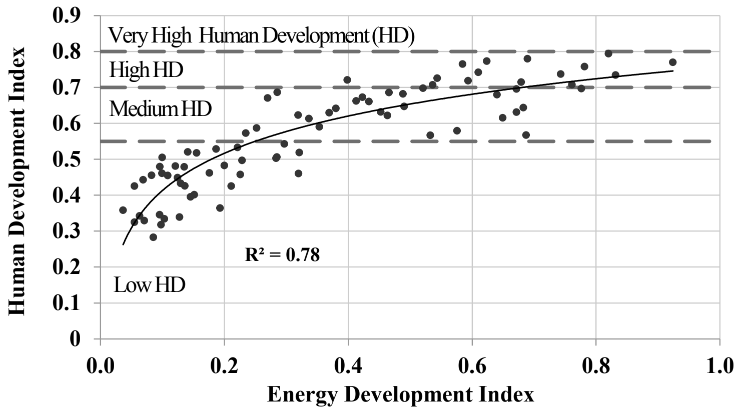

Figure 2.1 Nexus between HDI and EDI (2010). Author's elaboration based on [8], [18]

Energy consumption is increasing and, according to international forecasts, it is expected to increase further in the next decades. Energy has a global perspective, but it presents different faces according to the aggregated regions considered (Figure 2.2). In line with the classification of the World Bank, three macro regions can be identified depending on their GNI per capita:

- in countries with high-income economies, energy is available and relies mostly on fossil fuels. Current challenges are oriented to enhance sustainability through specific policies aiming to increase the share of RESs and to improve efficiency, while also reducing the impact on the environment;
- emerging countries with middle-income economies are facing high growth in both energy consumption and economic development. Their technologies often need to improve both in security and in reliability and the challenge of sustainable energy is directly related first to the efficiency and secondly to the environmental and social impact of their energy systems. These countries are now encouraged by the

[3]HDI aggregates [479]: Life Expectancy Index, Education Index, and Income Index. These consider: life expectancy at birth, mean years of schooling, expected years of schooling, and GNI per capita.

[4] EDI aggregates two indicators: household indicator and community indicator. These combine other indicators: access to electricity, access to clean cooking facilities (household indicator); access to energy for public service, access to energy for productive use (community indicator).

international community to focus their efforts on safety and environment, since the need to involve them in the global effort to reduce pollution and greenhouse gas emissions is becoming more and more urgent. In line with this direction, China and Brazil have promoted a number of national policies aiming at reducing their growth in emissions by 2010. More specifically, since the 2007 National Action Plan on Climate Change, China has committed to strongly reduce its energy intensity by 2010. Updated statistics from the IEA show that the energy intensity has been reduced by more than 20 %, thus reaching the declared target. As a consequence, a greater reduction in CO_2 intensity was experienced despite the plan did not include any quantified targets for carbon dioxide emissions [19], [20];

- DCs are characterized by low-income economies, with low energy consumption per capita. Access to electricity and use of modern energy service are not available for the majority of the population, especially in rural areas. Although these countries are often rich in primary resources, these are rarely used at local level. Current energy systems are still weak and characterized by low reliability. These countries are identified by a general low electrification rate and by a high percentage of population still relying on traditional biomass for their meagre energy needs.

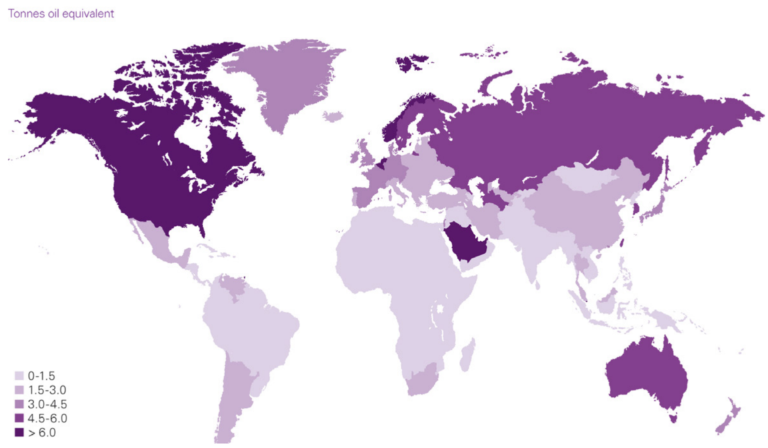

Figure 2.2 Total Primary Energy Consumption (toe/per capita) (2011) [21]

2.2 Energy and Sustainability

As discussed in the previous paragraph and more extensively in [22], the energy challenge presents different faces at the global level. Therefore strategies to tackle the related issues need to be tailored to the specific context where they have to be applied. Moreover, when looking for durable and long-term solutions such strategies have to be tackled from a perspective that includes the three main dimensions of sustainability (economic, environmental and social) [23].

Economic Dimension

Energy and economy are interrelated. Indeed, as shown in Figure 2.3, in all high-income countries the total primary energy supply (TPES) per capita is above 2 toe[5],

[5] toe (tonne of oil equivalent) is the amount of energy released by burning one tonne of crude oil, approximately 42 GJ.

while the remaining countries are mostly below this threshold. The correlation is more evident and distribution less scattered at low GNI, where DCs are located.

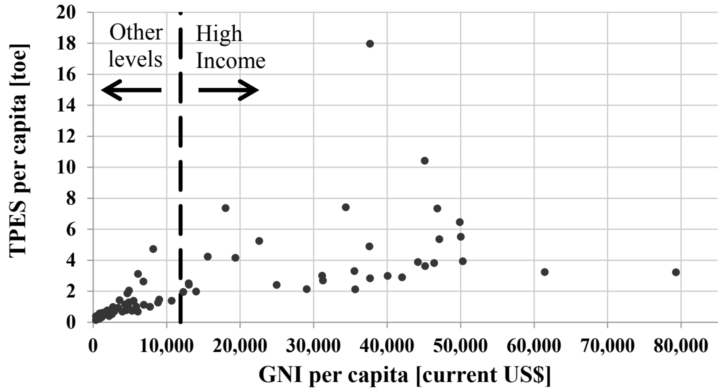

Figure 2.3 World countries distribution according to GNI per capita and TPES per capita (2012). Author's elaboration based on [24]

Considering the energy intensity (TPES per unit of gross domestic product (GDP), Figure 2.4), sub-Saharan Africa and China lead the classification with the highest values. Energy intensities in DCs are affected by underdevelopment of productive sectors (i.e. services, trades, industry) and high conversion system inefficiencies. As an example poor households often use three stones fires for cooking, with very low efficiency. Furthermore the national electric grid, when available, is also affected by a high percentage of outages which make the provision of electricity unreliable, with dramatic consequences on the local productive capabilities and productive costs.

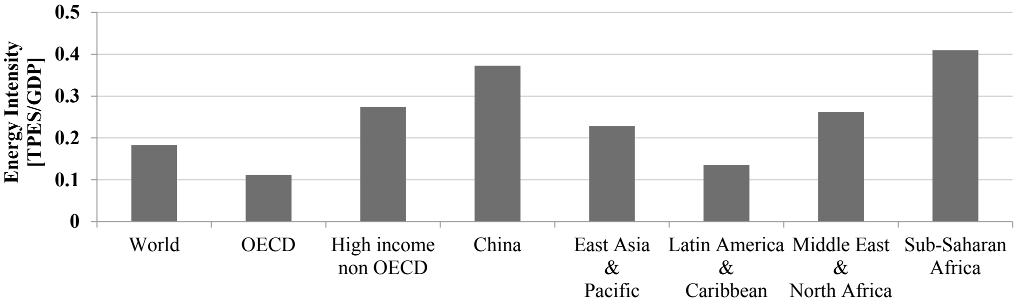

Figure 2.4 Energy intensity for the world's aggregate. Author's elaboration based on [24], [25]

Social Dimension

According to the World Health Organization (WHO), nowadays more than 1.4 million deaths per year (more than malaria and tuberculosis) are related to the effect of breathing smoke emitted by three-stone fires. Furthermore the number is expected to increase in 2030 to the point of overcoming deaths for HIV [24], [26]. Further health-related impacts associated with household traditional fuel use include: burns and scalds from open fires or semi-open stoves; poisoning of children who drink kerosene fuel stored in soft drink bottles; risk of injury and violence (primarily on women who walk far from their home to collect wood). In particular for three diseases (child pneumonia, chronic obstructive pulmonary disease (CODP), and lung cancer) the connection with solid fuel use is evident [27].

In general, these issues are relevant for DCs where more than 99% of the worldwide deaths attributable to solid fuel use occur (Table 2.1). A broader measure of the diseases is the disability-adjusted life years (DALYs) [28]. As shown in Table 2.1, of the approximately 40 million DALYs worldwide attributable to solid fuel use, almost 18,4 million (45 %) occur in least developed countries (LDCs) and 18 million (44 %) in sub-Saharan Africa. Since DALYs indicator detects the number of years lost due to deaths from child pneumonia, the highest impact of solid fuel use on health occurs in poorest countries where children under 5 years old are mostly affected by pneumonia.

Traditional fuel usage leads to considerations on the burden of biomass and raises a problem of equity, since low energy availability contributes to limit local development. In DCs women and children are in charge of fuel collection [29] which exposes them to health hazards and various risks. Furthermore, this activity prevents women and children from accessing education and being involved in income-generating activities, thus having an important social impact.

Table 2.1 Number and rates of deaths and DALYs per million population attributable to indoor air pollution from solid fuel use, for all causes (pneumonia, CODP, lung cancer), based on UNDP's classification of DCs and the UN's classification of LDCs [30]

	Attributable deaths per year		Attributable DALYs per year	
	N° (thousands)	per 1M population	N° (millions)	per 1M population
Developing Countries	1944	378	40.5	7878
LDCs	577	771	18.4	24,606
Sub-Saharan Africa	551	781	18	25,590
South Asia	662	423	14.2	9075
Arab States	35	114	1.1	3489
East Asia & Pacific	665	341	6.5	3308
World	1961	305	41	6374

Environmental dimension

In line with the 7th Millennium Development Goal which aims to ensure environmental sustainability, the promotion of energy usage has to be evaluated also in terms of ecosystem and environment damages.

On one hand, RESs are generally perceived as more sustainable compared to non-renewable sources, due to their reduced environmental impacts and benefits for local development [31]. However, RESs also have some environmental issues and therefore careful planning to address possible environmental impacts all along their life cycle is essential. For instance, the installation of large hydropower systems may significantly affect the involved ecosystems (flooding upstream and drought downstream). On the other hand, the use of fossil and traditional energy sources in DCs impacts global biodiversity, where ecosystems may be affected by an unregulated exploitation: an energy mix strongly unbalanced towards the use of traditional and non-commercial biomass can lead to local pollution and, if not properly controlled, to heavy consequences such as land degradation and deforestation.

Although the use of traditional biomass such as wood or charcoal is not the only contributor to deforestation at a global level, in some countries the link is more direct and evident. Production of charcoal from forest areas in response to urban demand, particularly in sub-Saharan Africa, is often not sustainable and could lead to deforestation and land degradation around urban centers. Scarcity of wood typically implies a greater use of agricultural residues and animal dung for cooking. However, when dung and residues are used as fuel, soil fertility is reduced and propensity to soil erosion is increased [32]–[35].

Overuse of natural resources through deforestation or increased extraction rates of forest biomass has also negative impacts on soil quality, carbon stocks and biodiversity. For instance, clearing of land for agricultural activities and production of timber for export are relevant causes of deforestation in DCs [36]. Other causes leading to deforestation and forest degradation are also represented by weak governance structures for forest conservation and by the absence of a sustainable management of forest resources [37]. A large number of countries are joining intergovernmental initiatives to establish criteria and indicators to monitor sustainable forest management, but they are not entirely based on common principles and do not yet have a mechanism for verifying compliance with the agreed principles. The adoption of sound land-use planning through the application of good management practices and use of well-adapted indigenous energy crops [38] can certainly contribute in addressing the problem.

2.3 Electrification and Modern Fuels

Two main problems need to be discussed with respect to energy access:

- access to electric energy, achievable through the extension of the national electric grid and/or by fostering off-grid systems;
- shift to modern fuels (gas, LPG kerosene, including paraffin, ethanol, biogas and biofuels) and efficient use of traditional biomass.

The increasing attention given by the international community during the past 5 years, which culminated with the declaration of 2012 as the International Year for Sustainable Energy for All, has supported a number of activities and projects for fighting against the energy poverty [13]. Despite the growth in the world's population, people without access to electricity and without access to improved or modern energy services for cooking have decreased respectively by 50 million and almost 40 million according to 2012 and 2011 IEA data [17], [25]. Main improvements occurred in countries such as India, Indonesia, Brazil, South Africa and Ethiopia, with the rest of sub-Saharan Africa remaining almost unaffected. Nevertheless, at the end of 2013, almost 1.3 billion people were still living without access to electric energy and 2.7 billion did not have access to improved or modern energy services for cooking [8]. Roughly 99% of this population lives in DCs in sub-Saharan Africa, Asia and Latin America and 80% of them live in rural areas.

Electrification

The World Energy Outlook 2012 [17] foresees an increase in the electrification rate in DCs from 76% in 2010 to 85% in 2030. The IEA projection states that in 2030 1 billion people will still be without electricity: Latin America will achieve universal access; developing Asia will halve the number of people affected while sub-Saharan Africa will keep a negative trend at least until 2025. Access will increase mainly in urban areas, where providing services is easier and more profitable for public utilities and private suppliers. In rural areas population with access to electricity is considerably lower than in urban areas (the ratio is 1 to almost 8) and providing electric energy to small and scattered settlements is more complex.

Various options for supplying electricity need to be considered, including grid connections and small-scale off-grid systems[6], with respect to the following factors:

- cost of energy delivered through an established grid may be cheaper, but the cost of extending the grid to sparsely populated areas can be very high and long distance transmission systems may have high technical losses [39];
- small-scale off-grid power systems based on RESs can instead provide cheaper electricity to rural communities, even though they require high investment costs. These systems can range from small home-based systems relying on a single source to Micro-Grids that can integrate more than one source of energy.

Micro-Grids in particular, seem one of the most promising approaches to rural electrification since they can rely on multiple local resources thus integrating and alleviating the pros and cons of each single source. Moreover, continual improvements in power electronics and EMSs in the smart-grid arena of developed countries may provide benefits also for applications in DCs (if properly adapted). Indeed, Micro-Grids can be designed and optimized at the local level (bottom-up approach) and then employed as building block for regional grid via appropriate interconnections [40], [41].

Biomass Dependence

The World Energy Outlook 2012 foresees an increase in the share of the world population with access to improved or modern energies for domestic cooking from 51% in 2010 to 61% in 2030. However, due to demographic growth, the total number of people with access will only slightly rise. According to IEA, the most significant improvement by 2030 will occur in Asia (led by China) while in sub-Saharan Africa the numbers will decrease by about 25%.

In DCs biomass is associated to all the different typologies of traditional fuels (firewood, agricultural residues, dung, and charcoal) that local population exploits for its livelihood and which are burnt into low-efficient and high-polluting conversion devices. In 2010 biofuels & waste primary source accounted for 10% of the world TPES, almost 80% of which coming from non-OECD countries. This high share of biofuels & waste supply confirms the reliance of DCs on non-commercial biomass.

Modern technologies refer to more efficient and cleaner cooking devices compared to the traditional three-stone open fires, such as improved or advanced cooking stoves, gas or electric cooking stoves and biogas systems. Although based on simple design, these technologies allow improvements mainly at household level with a positive effect on health, environment and the domestic economy. Specifically:

- improved cooking stoves (ICS) are based either on a more efficient combustion of traditional biomass or have chimneys, or a combination of both resulting on economic savings and reducing pollution. While their real impact is still being analyzed, experimental field campaigns are needed to prove their effectiveness and acceptability [42];
- advanced biomass cooking stoves usually work on innovative principles, such as the gasification of solid biomass, leading to high efficiency and clean conversion, although pilot experiences and research activities are still needed [43];

[6] A detailed disquisition as regard strategies and energy systems (i.e. grid extension – off-grid systems) for rural electrification is reported in Chapter 4.

- small-scale bio-digesters produce biogas by anaerobic fermentation of different organic waste origin (human and livestock, domestic, agricultural), thus allowing smokeless combustion and also the use of lighting devices [44].

2.4 The Role of Efficiency in Access to Sustainable Energy

Efficiency is often called *the sleeping giant* in the energy sector. From the primary energy sources to the final consumption, energy efficiency has a significant and high-potential role in improving energy security and reliability, reducing the environmental impacts and increasing the number of reached beneficiaries and available services.

Low and middle-income countries started to consider energy efficiency only recently. Nevertheless, the promotion of both efficiency and energy access should follow a more sustainable approach in order to avoid the recurrence of negative experiences of other economic regions. For example Europe, which after increasing its energy use for decades is now asking for a more rational use of it.

Improving efficiency has a great potential in DCs from many perspectives. For instance, it can increase accessibility both on the supply side, extending the provision of energy to households and reducing technical losses in generation and distribution, and on the end uses side, which is often neglected due to other major constrains.

Efficiency can also increase affordability and equity thus facilitating the lower income households to pay their energy bills. In [17] IEA states that in certain countries, including India, the energy that could potentially be saved through efficient uses would be enough to provide the additional electricity required to satisfy the basic energy needs for the entire population in 2030. Although in almost all countries these savings would not be sufficient to cover the energy needs, nonetheless they could free additional financial resources that could be dedicated to address energy poverty.

As barriers to energy efficiency depend on many circumstances a portfolio of measures needs both to be promoted by individual countries or regions and supported by global commitment. For instance, the improved energy performance of a device needs to be recognized by the market and by the governments, energy efficient technologies must become the standard, any improvement in energy efficiency must be monitored and investments in energy efficiency must be rewarded by appropriate financial mechanisms.

2.5 Summary

In this chapter an overview of the access to energy issue at global level has been developed in order to set the main background of the Framework of Reference where off-grid power systems act (Paragraph 1.3, Figure 1.7). Specifically the most important reports and databases of international organizations operating in this context have been reviewed and the link energy – development has been highlighted with the particular focus on the features of DCs. For these countries, a detailed analysis has been presented in order to assess the specific issues as regards energy and sustainable development. This has emphasized the burden of traditional biomass dependence and lack of access to electricity which both highly contribute in hindering the process of development.

3 Sustainable Energy in Africa: Current Situation and Main Issues

Observing features and data as regards the global dimension of sustainable energy, African countries are clearly affected by the most problematical situation which results in a heavy burden in the process of development. In this context, achieving sustainable energy development requires fostering the implementation of appropriate technologies, and hence the rational use of energy sources, by means of apposite policies. Three concerns are therefore required to achieve these issues: (i) to acquire a picture of the local current energy situation, (ii) to measure the state and the progress towards a sustainable energy system, and (iii) to have energy decision-makers aware of the implications of selected policies.

Table 3.1 List of countries considered in the analysis grouped according with UN sub-regions

Northern Africa	Middle Africa	Eastern Africa	Western Africa	Southern Africa
Algeria	Angola	Eritrea	Benin	Botswana
Egypt	Cameroon	Ethiopia	Cote d'Ivoire	Namibia
Lybia	Congo	Kenya	Ghana	
Morocco	Congo DR	Mozambique	Nigeria	South Africa
Sudan	Gabon	Tanzania	Senegal	
Tunisia		Zambia	Togo	
		Zimbabwe		

In this perspective, the objective of this chapter is to depict the current energy situation of Africa as far as the concept of sustainable development is concerned, and to see if and how local energy policies fit with this asset. The energy situation of Africa is assessed by combining (i) data about final consumptions, electric sector and energy resources, with (ii) an analysis based on the Energy Indicators for Sustainable Development (EISD). Moreover, an overview of the energy-related action plans developed by different local players is also carried out with the goal of providing remarks by coupling such plans with the above mentioned energy analysis. In particular, emphasis is given to the issue of electrification which is pivotal in promoting local development and it is the focus of the following chapters.

The analysis considers the African countries for which IEA provides data. They are 27 countries, which has referred as *Africa IEA* [45]. The analysis is carried out by grouping these countries according to the 5 African sub-regions. South Africa is separated from its own sub-region (Southern Africa) in order to highlight its marked differences. Table 3.1 shows these countries grouped according to the related sub-regions. When relevant, indicators for European Union 27 (Europe 27) are also computed in order to carry out comparisons with Africa IEA.

3.1 Socio-economic Profile

Nowadays Africa is characterized by a high rate of population and income growth.

The huge population growth began in the second half of the 20th century with almost a quadruplication of the population from about 230 to about 810 million people [46]. Despite this trend could probably have negative impacts on people's quality of life (e.g. higher pressure on the agricultural sector, risk of famine [47], slums dwellers increase [48], [49]), it will also lead to a huge expansion of the labor force [49].

Moreover, favorable demography, together with increasing revenues from natural resources and productive sectors, is a cause of the economy growth that appeared in Africa in the last decade. Over the ten years to 2010, six of the world's ten fastest-growing economies were in Africa [50]–[52]. Nevertheless, still large segments of the population live in poverty. Indeed, considering $ 1.25 a day as poverty line [53], 47% of total population of sub-Saharan Africa fell within this threshold in 2008 [54]. This figure is reflected at macro-economic level in the low values of income per capita (Table 3.2). Clear-cut disparities are also within Africa: (i) South Africa has the highest income and its economy drags the neighbor countries, (ii) Northern Africa follows with GDP per capita about 50% smaller than South Africa, (iii) Middle, Eastern and Western Africa are tail-end with GDP per capita about 80% smaller than South Africa.

Table 3.2 Brief profiles of Africa sub-regions, Africa IEA and Europe 27: selected indicators (2010). Author's elaboration based on [24], [55]–[57]

	Area [km^2]	Population [thousand]	GDP_{PPP} pc [2005USD]	TPES pc [toe]	TFC Electricity pc [kWh]	CO2 pc [ton]
Northern	8,258,700	199,049	5188	0.88	1134	2.06
Middle	4,676,670	110,195	1774	0.44	158	0.26
Eastern	4,692,320	222,446	1051	0.46	200	0.16
Western	1,853,040	229,864	1947	0.62	156	0.31
Southern	1,406,020	4290	8954	0.90	1518	1.85
South Africa	1,219,090	49,991	9497	2.74	4278	6.94
Africa IEA	**22,105,840**	**815,835**	**2969**	**0.74**	**667**	**1.11**
Europe 27	**4,324,782**	**502,334**	**27,696**	**3.42**	**6293**	**7.43**

A further feature of Africa, as well as of DCs, is the clear disparity between urban and rural areas. The majority of the Africa IEA population lives in rural areas (Table 3.3) and the distribution within the sub-regions between urban and rural varies according with the specific economy structure. While it is not correct to claim rapid urbanization of Africa, and instead the urban growth rates generally follow the national population trends [58], it is undoubtedly true that underdevelopment and poverty are predominantly rural phenomena: indeed about 70% of the poor people lives in rural areas [48], [59], [60].

In addition, large disparities also appear when comparing African urban areas with those in developed countries: to improve basic infrastructure and communication networks, to address public transport and environmental conditions and to respond to high inequalities (i.e. reducing proportion of slum dwellers) are among the main issues African cities have to tackle [61], [62].

Table 3.3 Shares of urban and rural population as % of total population (2010). Author's elaboration based on [24]

	Urban	Rural
Northern	51.2	48.8
Middle	43.0	57.0
Eastern	24.0	76.0
Western	48.5	51.5
Southern	48.7	51.3
South Africa	61.5	38.5
Africa IEA	42.5	57.5

3.2 African Reference Energy Framework

Hereafter a reference framework of the energy situation for Africa IEA is set by introducing: (i) TFC, (ii) electricity generation, (iii) power sectors, and (iv) fossil and RESs assessments.

Total Final Consumption

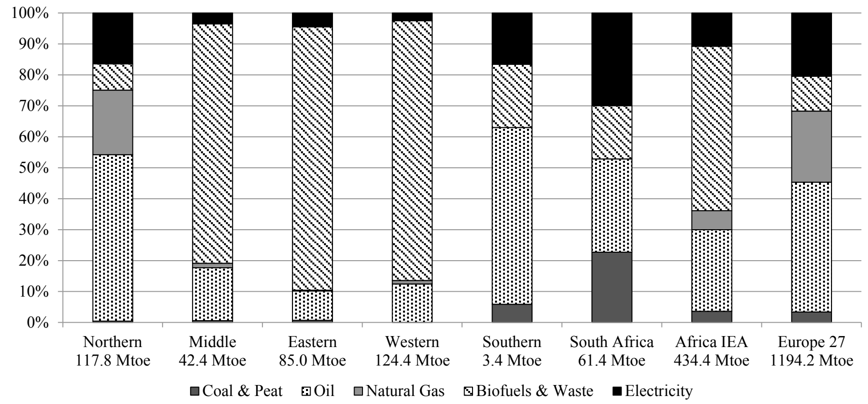

Figure 3.1 TFC total values (beneath region labels) and shares by resources (2010). Author's elaboration based on [57], [63]

Three main features can be highlighted when looking at the TFC of Africa (Figure 3.1):

- at continental level, TFC of Africa IEA was about 36% of Europe 27 and the energy mix is very different;
- *biofuel & waste* play a pivotal role with about 53% of TFC in 2010. Moreover they are the primary source in the poorest economies of the continent, i.e. in Middle, Eastern and Western Africa, with 77%, 85% and 84% of the TFC respectively;

- the final consumption of electricity becomes relevant only in Northern, Southern Africa and South Africa due to higher electrification rates (i.e. higher consumption within residential and service sectors).

Electricity generation

In 2010, electricity generated in Africa IEA was 647.1 TWh (about 19.5% of Europe 27); 81% was equally generated in Northern Africa and South Africa (Figure 3.2). Considering the energy mix, it can be noticed that each sub-region mainly relies on its own indigenous resources since inter-state trades of fossil fuels are minimal [64]:

- Middle, Eastern and Western Africa heavily rely on hydropower that is the cheapest, well-known, indigenous energy source;
- Western Africa has also a significant share of electricity generated with natural gas that is mainly related to the exploitation activities in Nigeria;
- Northern Africa relies on oil and natural gas, while South Africa relies on coal;
- South Africa is the only country in Africa that has a nuclear power plant that has two PWR reactors for 1.8 GW installed capacity.

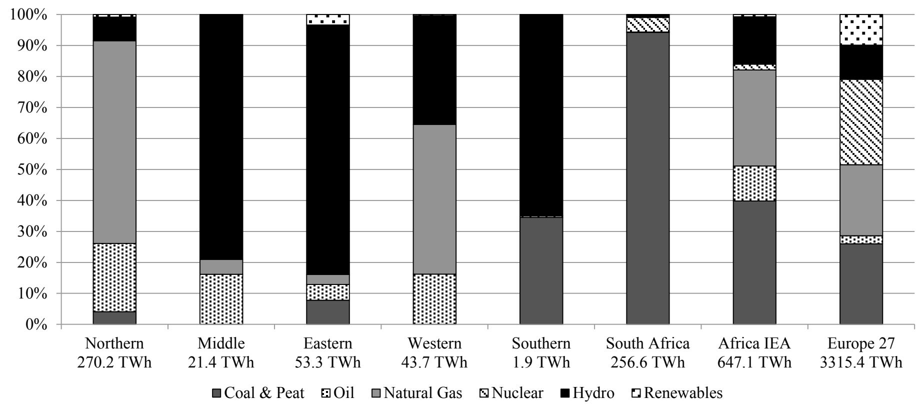

Figure 3.2 Electricity generation total values (beneath region labels) and share by resources (2010). Author's elaboration based on [57], [63]

Power sector

Within Africa there are five power pools that refer to the respective African Regional Economic Communities and that promote regional projects and trades: (i) the *Comité Maghrébin de l'Electricité (COMELEC)*, (ii) the *Central African Power Pool (CAPP)*, (iii) the *Eastern Africa Power Pool (EAPP)*, (iv) the *West Africa Power Pool (WAPP)*, and (v) the *Southern Africa Power Pool (SAPP)*. Table 3.4 shows the installed power within each power pool. Some countries play a pivotal role within their own pool: Algeria holds 41% of installed capacity in COMELEC, Egypt 78% in EAPP, Nigeria 60% in WAPP, and South Africa 82% in SAPP.

COMELEC and SAPP have the highest capacity per thousand habitants and this value drops significantly for the other pools. For comparison, Europe 27 in 2009 had a total installed power of about 840 GW with about 1670 kW per thousand habitants [65]. For Africa, the lower installed capacity per capita is an indicator of the poor access to electricity mostly among households which, in addition, in sub-Saharan Africa face tariffs about twice higher than other parts of the developing world [66].

Table 3.4 Total power installed capacity and key indicators for African power pools [67]

	COMELEC 2009	CAPP 2009	EAPP 2008	WAPP 2010	SAPP 2010
Installed capacity (GW)	27.35	6.07	28.37	14.09	49.88
Hydropower share	8%	86%	24%	30%	17%
Thermal share	91%	14%	73%	70%	83%
kW/1000 habitants	319	49	74	54	311

A major problem of the power infrastructure is the low level of reliability that is exacerbated by the lack of links between the regional networks [66]. According to the World Bank enterprise survey, which provides a useful measure of the reliability of grid-supplied power (Table 3.5), African firms often identify electricity as a main constraint in doing business and own generation facilities (i.e. diesel generators) are very popular. As a matter of fact, own generators constitute a significant proportion of the total power capacity of sub-Saharan sub-regions: while in East and Middle Africa own generation is about 8%, in West Africa it reaches 19% [68]. A further phenomenon caused by chronic power shortages is the use of grid-connected emergency power. In this case, countries enter into short-term leases with specialized operators that can quickly install new power capacity [66]. Emergency power in some cases constitutes a significant proportion of total installed capacity (even tens of percentage points) and related costs can reach a few percentage points of GDP [69].

Table 3.5 Electric outages and duration [70]

	Number of outages (days per month)	Duration of the outages (hours)
Sub-Saharan Africa	7.8	5.0
Middle East & Northern Africa	25.7	9.2
East Asia & Pacific	3.3	2.0
Latin America	2.8	1.5
South Asia	18.0	1.3
World	5.6	2.7

Fossil and renewable energy sources assessment

As a general figure, at the end of 2008, the continent had over 130 billion barrels of oil proven recoverable reserves, 14 trillion cubic meters of natural gas proven recoverable reserves[7], and 31 billion tonnes of coal proven recoverable reserves [71]. Nevertheless, most of fossil resources are exported to meet the needs of other areas of the world, mainly the United States, China and Europe [72]. Moreover, resources in Africa are unevenly distributed, and the interstate energy trade is minimal [64].

Specific figures concerning the assessments for coal, oil and natural gas are described by means of the following graphs. In each figure and for a given resource: the *x-axis* measures total production, *y-axis* compares net imports and production rate, and areas of the circles are proportional to the amount of proven recoverable reserves.

Considering coal (Figure 3.3), reserves are not particularly vast when compared to other world regions. As a producer, Africa occupies the third last place in the global ranking. Nevertheless, in absolute terms, the production is still significant: in 2008 the

[7] Even if no detailed data are still officially available, new important natural gas and oil fields have been discovered between 2009 and 2013. This concerns Eastern Africa, and in particular Mozambique and Tanzania (natural gas), and Kenya, Uganda and Madagascar (oil) [480], [481].

African continent produced more than 252 million tonnes, and exported about 48 million tonnes. More than 98% of the African production occurs in South Africa where more than 95% of the total reserves of the continent are located.

Considering oil (Figure 3.4), the 340 million tonnes exported in 2008 made Africa the first net exporter after Middle East. Major producers and exporters are Northern and Western Africa [73], while reserves and production are near zero in Eastern and Southern Africa. Top-four exporting countries are Nigeria, Angola, Libya and Algeria. Eastern and Southern Africa are the only net importers of oil.

Considering natural gas (Figure 3.5), in 2008 Africa produced more than 200 billion cubic meters (bcm) and exported more than 50% which makes the continent the second net exporter among all world areas. Morocco, Tunisia and South Africa are the only countries consuming imported natural gas. Top-four exporting countries are Algeria, Nigeria, Egypt, and Libya. In this frame it is important to mention the gas flaring practice which plays a significant role in Africa. At the continent level, more than 36 bcm of natural gas (20% of the marketable production) were flared [74].

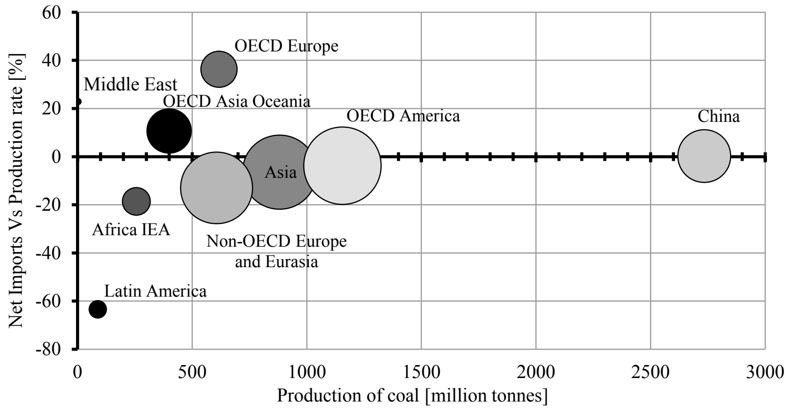

Figure 3.3 Net import, production and proven recoverable reserves of coal. Author's elaboration based on [71], [75]

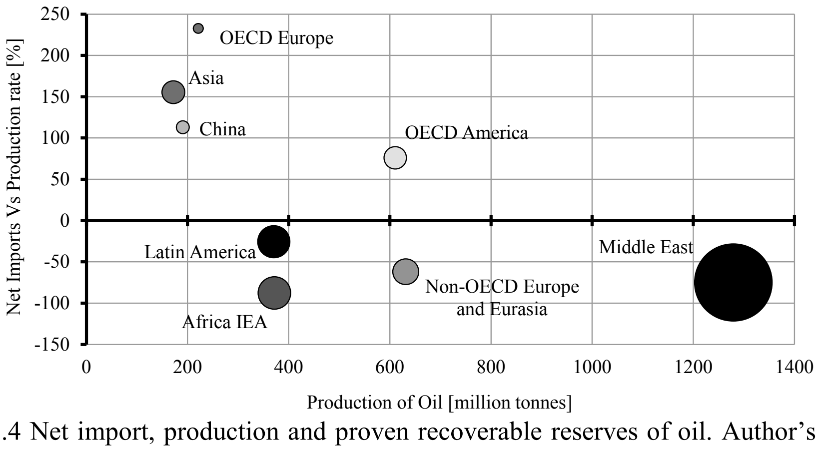

Figure 3.4 Net import, production and proven recoverable reserves of oil. Author's elaboration based on [71], [75]

As regards RESs, in Africa they are only minimally exploited. Indeed, as regards generation capacity they count for about 28 GW over a total capacity of more than 145 GW [76]. Hydropower accounts for more than 90% of total renewable energy capacity

(Figure 3.6). On the other hand, biomass is pivotal as a source of energy for heating and cooking: in 2010 biomass & waste provided about 207 Mtoe to the residential sector over a total residential fuel consumption of about 238 Mtoe.

Although at present the contribution of renewables is minimal (except for hydropower), the renewable energy potential of the continent is enormous: a total electricity generation potential of more than 13,700 TWh/year has been recently estimated by IRENA on the basis of a number of studies [76]–[78]. According to these estimates (Table 3.6), all African sub-regions are characterized by abundant resources: wind is particularly abundant in Northern and Eastern Africa, hydro and biomass in Middle Africa, solar energy is available in all areas, and geothermal energy is relevant in Eastern Africa (Great Rift Valley area).

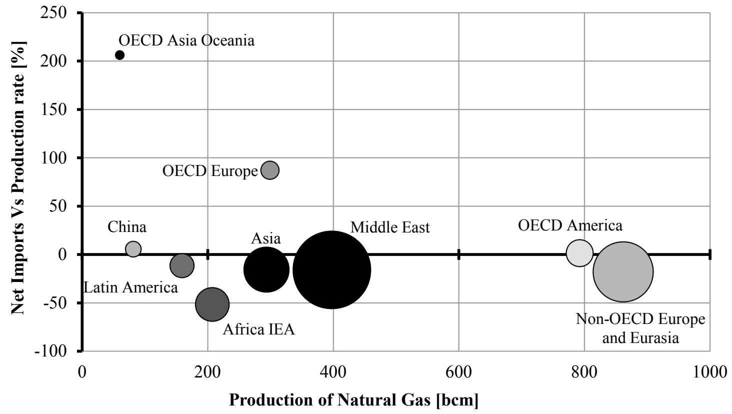

Figure 3.5 Net import, production and proven recoverable reserves of natural gas. Author's elaboration based on [71], [75]

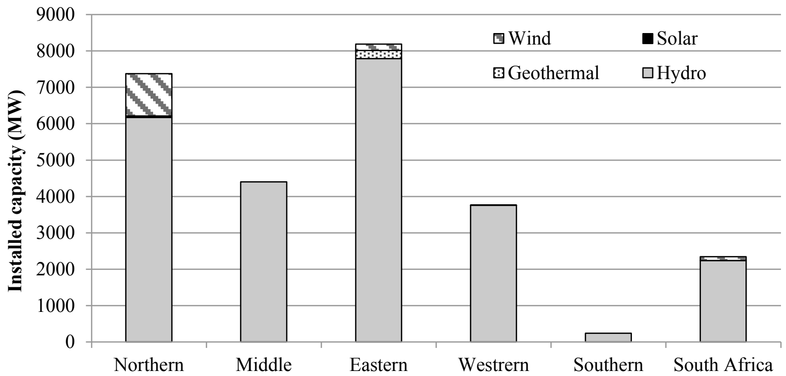

Figure 3.6 Installed powers for RESs (2012). Author's elaboration based on [79]–[81]

Table 3.6 Electricity potential from RESs (TWh/year). Author's elaboration based on [77]

	Wind	Solar*	Hydro	Biomass	Geothermal
Northern	1,014	2,025	78	257	-
Middle	120	915	1,057	1,572	-
Eastern	1,443	3,953	578	642	88
Western	394	1,265	105	64	-
Southern	852	3,128	26	96	-
Africa IEA	3,823	11,286	1,844	2,631	88

*Solar energy potential considers both photovoltaic and concentrating solar power systems

3.3 Energy Indicators for Sustainable Development Analysis

In addition to the previous figures and in order to deepen the analysis of the state and the progress towards sustainable energy systems in Africa, the EISD have been considered. In the framework of this work, only some EISD indicators (Table 3.7), which are grouped according to the social (SOC), economic (ECO) and environmental (ENV) dimensions [82], have been selected. Three reasons guided the selection: (i) relevance with the African specific context, (ii) data availability, (iii) relevance to the theme of electric energy.

Table 3.7 Selected EISD indicators

Acronym	Indicator	Description
ECO2	Electricity use per unit of GDP	Ratio of Electricity use to GDP
ECO3	Efficiency of energy conversion and distribution	Share of losses in total electricity generation, transmission and distribution
ECO9	Household energy intensities	TFC per capita in the residential sector
ECO11	Fuel shares in electricity	Shares of energy fuels in electricity generation
ENV2	Ambient concentrations of air pollutants	Data not available, considerations about the issue of Indoor Air Pollution (IAP) are introduced *
SOC1	Share of population without electricity or commercial energy	Share of rural and urban population without electricity access, or dependent on solid fuels*
SOC2	Share of household income spent on fuel and electricity	Data not available, a qualitative analysis is carried out
SOC4	Accident fatalities per energy produced by fuel chain	A proxy of SOC4 for households is computed as DALYs per 1000 people due to IAP for solid fuels combustion *

*The definition was modified by the author to make possible an evaluation using available data

ECO2: Electricity use per unit of GDP

Observing the trends of ECO2 indicator (Figure 3.7), some remarks can be introduced:

- Eastern, Middle and Western Africa have low values because of the very low electricity consumption (lower than 5% of TFC);
- Northern and Southern Africa have similar values to the sub-Saharan sub-regions, but do not have a similar electricity-economic figure. Indeed they have appreciable higher consumption of electricity mainly required by income generating sectors;
- South Africa has the highest electricity consumption which reflects in the ECO2.

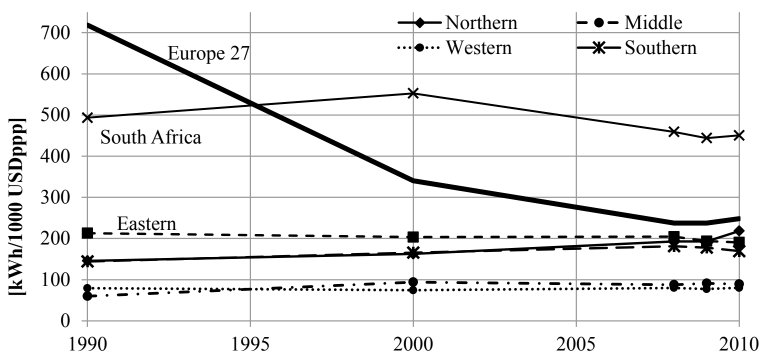

Figure 3.7 ECO2. Author's elaboration based on [24], [57], [63]

ECO3: Efficiency of energy conversion and distribution

ECO3 refers to electric system losses in generation, transmission and distribution. Table 3.8 shows ECO3 as losses as a share of total electricity generation. Taking as reference the Europe 27 value, the Africa IEA value is more than twice greater. South Africa, that has the most advanced electric systems, reaches 8% while all the other sub-regions have values above 10%. These figures bring out the poor conditions of transmission and distribution grids of Africa IEA, but also the widespread phenomenon of non-technical losses (i.e. illegal connections, metering inaccuracies, etc.) [83]–[86].

Table 3.8 ECO3 (2010) Author's elaboration based on [57], [63]

	ECO3		ECO3
Northern	12%	Southern	32%
Middle	13%	South Africa	8%
Eastern	14%	Africa IEA	11%
Western	16%	Europe 27	5%

ECO9: Household energy intensities

Figure 3.8 shows residential energy use per capita (ECO9) and also shares of the energy resources in the residential TFC:

- shares at continental level reflect the situation of Middle, Eastern and Western Africa that basically only rely on traditional fuels;
- South Africa and Southern Africa have higher penetration of electricity consumption at residential level than the other sub-Saharan sub-regions, but large segment of the population still rely on traditional fuels;
- electricity consumption increases when considering Northern Africa where it counted for 29% of residential TFC.

This situation arises from the following conditions: (i) subsistence residential sectors in Middle, Eastern and Western Africa that basically rely on the agricultural-based society, hence on traditional fuels, (ii) good rate of electrification in the coal-based power system in South and Southern Africa, (iii) large availability of natural gas and high rate of electrification in Northern Africa.

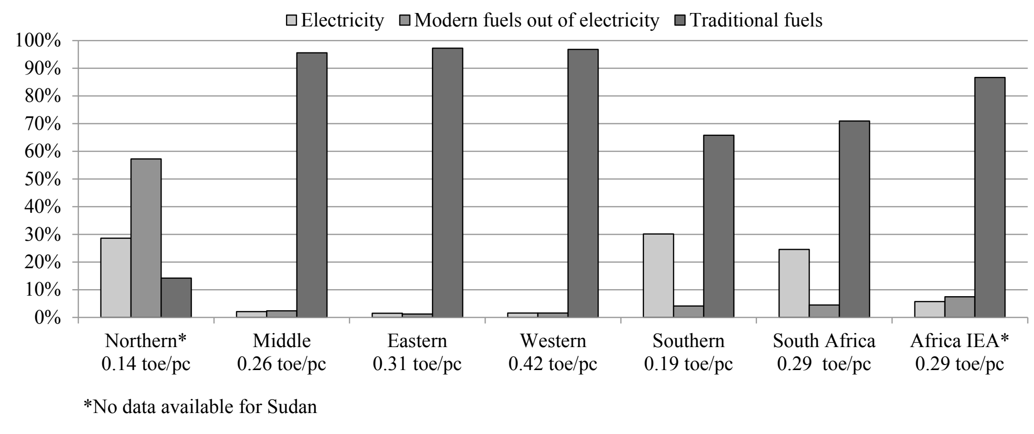

Figure 3.8 ECO9 (beneath sub-region labels) and shares of consumption of electricity, modern fuels out of electricity and traditional fuels. Author's elaboration based on [17], [24], [57], [75]

ECO11: Fuel shares in electricity

ECO11 monitors changes in fuel shares within electricity generation. The trend of electricity generation by fuel shares (Figure 3.9) shows that the natural gas consumption increase has been mainly driven by the power sector consumption (in Northern and Western Africa). As far as it concerns coal and peat, the consumption is associated only to South Africa, but due to the increasing pace of electrification in sub-Saharan sub-regions, the share of coal and peat is destined to decrease. Finally, it has to be mentioned that the small percentage of non-hydro renewable generation is based on geothermal power plants located in Eastern Africa. A focus on electricity generation by fuel shares for African sub-regions was provided through Figure 3.2.

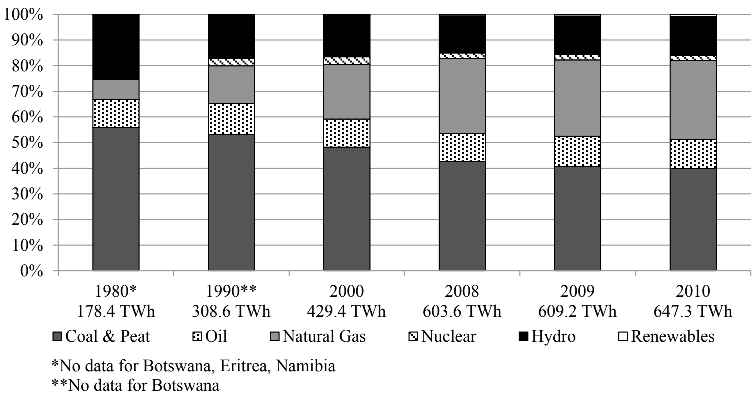

Figure 3.9 Electricity generation total values and fuel share trend for Africa IEA. Author's elaboration based on [57]

ENV2: Ambient concentrations of air pollutants

When discussing environmental issues (in this case pollution), on the one hand, DCs generally show small values since they use small amounts of energy in absolute terms and also because pollution due to household combustion of traditional fuels are not tracked. On the other hand, countries such as those belonging to Europe 27 have high energy consumptions in absolute terms, but also high energy conversion and end-use efficiencies. Furthermore, being all other factors equal, differences in the energy mix can have a strong influence on the emission values.

Provided this general remark, it is worthwhile to mention that for the African case the most problematic concern as regards pollution (ENV2) is Indoor Air Pollution (IAP). Several health diseases of DCs are related to ordinary exposure to toxic pollutants emitted by incomplete combustion of unprocessed solid fuels. Indeed, cooking and heating activities are traditionally done inside households using traditional three stone fires (i.e. open fires) and simple cooking stoves with limited ventilation. Hundreds studies have assessed levels of IAP in developing world. Findings of selected studies and comprehensive references can be found in [30], [87], [88]. Evidence from these studies shows that IAP often are order of magnitude higher than national standards and WHO recommendations for indoor or even outdoor concentrations [87], [89]. The mean 24-hour levels of carbon monoxide in DCs household are in the range 2–50 ppm, but during cooking values of 10–500 ppm have been reported. For comparison, the United States Environmental Protection Agency's 8-hour average carbon monoxide standard is 9 ppm [90].

SOC1: Share of population without electricity or commercial energy

SOC1 indicators have been calculated for urban and rural areas and considering: (i) electrification (i.e. population with electric connection) and (ii) use of solid fuels (i.e. population using solid fuels). With regard to electrification:

- in all sub-regions, excluding Northern Africa and South Africa, the total rate is 51% or less, while it is less than 80% in urban areas, and less than 25% in rural areas;
- in Eastern Africa rural electrification rate is about 7% (less than 4% in Mozambique, Tanzania and Zambia), while in Middle Africa is 6% (3.6% in Congo D.R.);
- in Northern Africa total electrification rate is 89% with a small difference between urban and rural areas;
- South Africa total rate is quite high (76%), but the difference between urban and rural areas is large thus showing an electric network not yet fully widespread.

Approximately the same considerations apply to solid fuels usage; indeed both accesses to electricity and to modern fuels are mainly related to the same issues, and mostly to infrastructures availability and to sufficient incomes at household level.

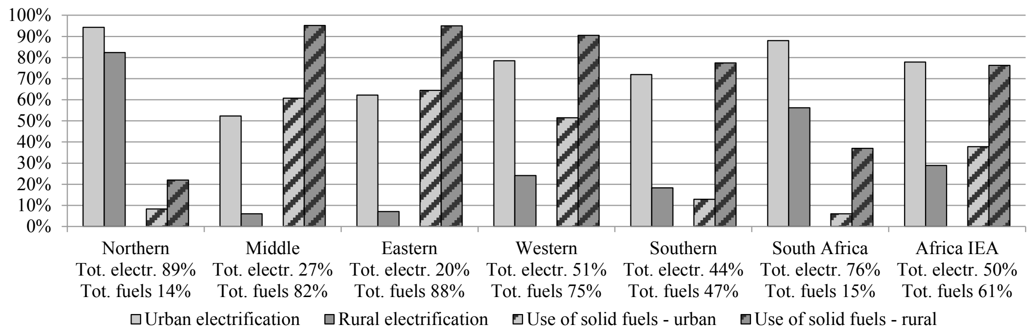

Figure 3.10 SOC1 total values (beneath region labels) and for urban and rural areas (2010). Author's elaboration based on [17], [24], [57], [63], [91]

SOC2: Share of household income spent on fuel and electricity

Considering the share of household income spent on fuel and electricity (SOC2), some studies are available in the literature (e.g. [92]–[96]). In general, the share of total expenditure due to energy needs decreases when the income level increases, but this pattern is not universal and depends on the context. The absolute value of the energy expenditure, instead, increases with the income level. Moreover, when looking at the geographical factor, some differences occur between urban and rural areas: in the latter, the impact of the energy expenditure is smaller. This is mainly due to the fact that in rural areas firewood is collected for free, while in urban areas the major difficulties in the supply (mainly the greater distance from areas where firewood is available) leads to a greater use of purchased firewood, charcoal or other solid fuels [94], [97].

Lastly, even if the absolute expenditure increases with the income, when considering commercial fuels the average cost of an energy unit can be much higher in the case of low-income households than in high-income ones. This is clearly due to the use of different energy resources, and mostly to the use and availability of electricity that substitutes paraffin, kerosene or other fuels for lighting: households using kerosene can pay up to 70 times more than households using electricity from the grid, and those using batteries can pay up to 30 times more [97]–[99].

SOC4: Accident fatalities per energy produced by fuel chain

As previously stated, in the developing world, health diseases due to IAP are a very important issue. Indeed, when looking at top-five causes of death in sub-Saharan Africa, respiratory infections occupy the third place, accounting for about 10% of total deaths, after HIV/AIDS and malaria, and followed by diarrheal diseases and perinatal conditions [100]. To give evidence of this fact, a proxy for SOC4 at the household level was computed as DALYs per 1000 people due to household IAP resulting from solid fuels combustion. The graph in Figure 3.11 shows data for each African sub-region. The significant decrease of DALYs between 1990 and 2010, especially in Middle, Eastern and Western Africa, is a positive figure. On the other hand, in these areas DALYs remain much higher than in Northern Africa, with values in-between 29 and 40 DALYs every 1000 people.

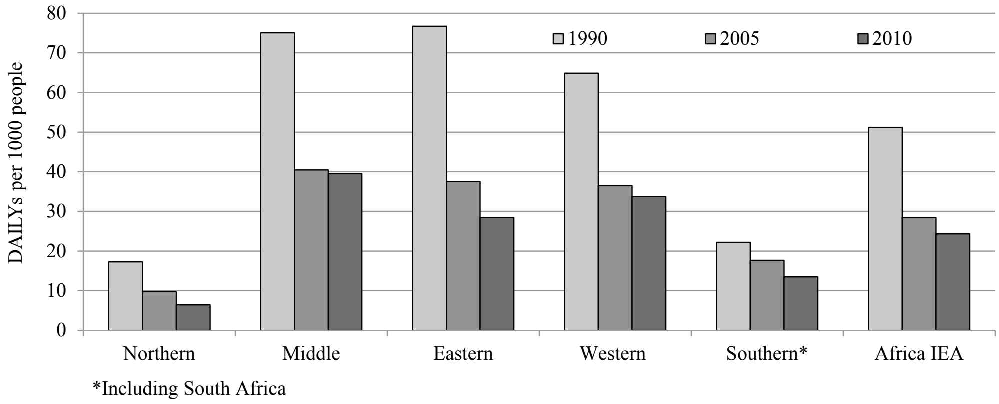

Figure 3.11 DALYs due to IAP in Africa. Author's elaboration based on [101]

3.4 Energy Action Plans Overview

As investigated in previous sections, Africa sub-regions differ even consistently in the resources disposal and utilization. Such differences bring about different sets of challenges which have lead in Africa to an evident pluralism of actors involved in the energy sector through several action plans. Governmental agencies and international organizations, development banks and funds, power utilities associations, NGOs and others, undertake actions addressing energy-related challenges.

In the light of this situation, the purpose of this section is to summarize and highlight the energy policies and action plans that main African entities have set and are intended to pursue in the next future. In particular the review considers and analyzes: (i) the African Union and its sub-agency NEPAD, (ii) the Forum of Energy Ministers of Africa (FEMA), (iii) the African Development Bank group.

The African Union (AU)

AU was established in 2002 and is composed by 53 African States [22], [102]. The commitment of AU in the energy sector is represented by the creation of the NEPAD Agency (New Partnership for Africa's Development). In the Agenda set in 2001 [103], NEPAD put forward a strategy whose energy priorities were resumed in the following objectives:

- to increase from 10% to 35% or more, access to reliable and affordable commercial energy supply by Africa's population in 20 years;
- to improve the reliability and lower the cost of energy supply for productive activities in order to enable economic growth of 6% per annum;
- to reverse environmental degradation due to use of traditional fuels in rural areas;
- to exploit and develop the hydropower potential of river basins of Africa;
- to integrate transmission grids and gas pipelines to facilitate cross-border flows;
- to reform and harmonize petroleum regulations and legislation in the continent.

The more updated action plan by AU and NEPAD is the Priority Action Plan (PAP) (2012). A main PAP objective is to guarantee access to electricity to more than 60% to any African Country by 2040 [104]. In order to address this objective one component of PAP consists in 15 energy projects which include: nine hydro power plants, four transmission corridors, and two pipelines (one for oil and one for natural gas).

The Forum of Energy Ministers of Africa (FEMA)

On institutional level, committees composed by Ministries of Governments have represented important channels to energy strategies development. The committees serve as common platform where energy interventions are linked to other infrastructural interventions, coordinating in this way energy development to a more wide extent [105]–[107]. FEMA proposed specific targets in line with addressed NEPAD strategies. As specified in [108], FEMA suggested a set of objectives acknowledging the role that modern energy plays in achieving the Millennium Development Goals. The path towards the achievement of the goals includes the following points:

- doubling of the consumption of modern fuels including increased energy access for productive uses;
- 50% of inhabitants in rural areas should use modern energy for cooking;
- 75% of the poor in urban and peri-urban areas should have access to modern energy services for basic needs;
- 75% of schools, clinics and community centers should have access to electricity;
- motive power for productive uses should be made available in all rural areas.

Fund agencies: the African Development Bank group

The African Development Bank Group (AfDB) was established in 1964 aiming at the promotion of economic and social development in Africa. In the last 40 years, the Bank Group assigned around 12% of funds to energy, 90% of which to power supply. Large-scale power generation projects were mainly supported, followed by fossil fuels projects, power transmission and distribution, multi-national grid interconnection and rural electrification. In 2008 the AfDB approved the Clean Energy Investment Framework [109], with the strategic goal of eradicating poverty conditions and constituting leverage for the development of different sectors: from household to social service institutions, from industries and business entities to infrastructure facilities. Objectives set to 2030 were the following:

- accelerating the reduction of energy poverty by increasing access of households and small economic operators to reliable and affordable energy supplies;
- facilitating sustained high rates of economic growth, by providing operators in the productive sectors with realistically priced electric power and energy supplies;

- contributing to world-wide energy security, by sustaining significant exports of energy resources, while increasing African countries' collective self-sufficiency and strengthening regional inter-dependence;
- promoting clean development and contributing to global emissions reduction, by raising energy efficiency on the supply side and encouraging energy saving on the demand side, increasing the contribution of renewable energy resources, and paying attention to environmental and social externalities of energy production.

The AfDB has also recently endorsed a Climate Change Action Plan for 2011-2015, which is based on three main aspects: Low Carbon Development, Climate Resilient Development and Funding Platform. The major targets related to Low Carbon Development are [110]:

- clean energy and energy efficiency providing advisory services and financing for supporting initiatives up to 5GW worth of clean energies or energy efficiencies;
- sustainable transport, with multi-modal transport infrastructure, mass rapid transit systems and railway transport;
- increasing the area under sustainable forestry management, reducing rate of deforestation and forest degradation, providing sustainable source of fuel wood for rural households;
- improving agricultural and land management to properly preserve ecosystems and biodiversity.

3.5 Energy Assessment and Action Plans Analysis

Purpose of this section is to summarize the main issues of the energy situation of Africa and to identify the action plans that address such issues. Moreover, the linkages among the selected EISD indicators and the unique picture of African countries are also analyzed. The result of the analysis is depicted by the scheme in Figure 3.12 where the cause-effect linkages between the groups of indicators are pointed by the arrows and relevant policies are shown for each group. As it is shown in the scheme:

- ECO11, ECO3 (which refer to the features of the power sector) and SOC1 (which refer to a feature of the household sector) are contributing factors for ECO2 and ECO9 (which refer to energy intensity features);
- ECO2 can be considered as a core indicator since it acts as a proxy of the overall economic-energy efficiency of the continent;
- ENV2 (which refer to pollution) is consequence of the overall economic-energy efficiency, but mainly of the type of energy systems used at household level (SOC1);
- SOC2 (which refer to household energy affordability) is related to energy intensity features;
- SOC4 (which refer to household energy-health) is a consequence of pollution (specifically Indoor Air Pollution).

Here below, the main features and issues of the African energy situation as previously described are summarized together with the relating action plans:

- the power infrastructure is affected by low level of reliability as well as low efficiencies in transmission and distribution. These issues are exacerbated by lack of interconnections between local power pools and high values of non-technical losses (i.e. mainly illegal connections).

Action plans pursued by local actors mainly have two modalities of intervention: (i) increase of power generation capacities, and (ii) construction and upgrade of transmission grids. New power plants usually result to have an installed capacity that exceeds the local needs since economies of scale push towards large size installations and they are often located far from urban areas. Therefore power plants projects have often regional or sub-regional dimensions and involve several countries. As a consequence cross-countries transmission systems are also planned;

- proven recoverable reserves of fossil fuels are always relevant in Africa even when compared with the other world regions. Moreover they are located in specific sub-regions: coal reserves are in South Africa, oil reserves are mainly in Northern Africa and Western Africa (i.e. Nigeria and Angola), and natural gas reserves are mainly in Northern Africa and Nigeria.

  The relevance of fossil resources is evident. Facing this situation, despite the necessity to reform the petroleum regulation and legislation was raised, investigated action plans have turned more attention to the connecting infrastructures like oil and gas pipelines rather than to the oil and gas exploration and production;
- at the moment the contribution of RESs (other than hydropower) to electricity generation is negligible. However, RESs potentials in electricity generation are huge and they could provide significant contribution in increasing electricity supply.

  The role of RESs is recognized to have higher importance, especially within clean energy policy frameworks. As highlighted by different plans, the selection of technologies has seen a predominance of hydropower large installations. It is worth nothing that no explicit endorsement or programs on geothermal energy have been declared despite the high potential in the Rift Valley region;
- biofuel & waste (i.e. traditional biomass) covers the largest share of Africa TFC, and specifically it is the energy resource used to meet the main energy needs in the residential sector (i.e. cooking and heating). A clear gap exists among Middle, Eastern and Western Africa, and Northern, Southern Africa: biofuels & waste accounts for most of the TFC in the first group, while the second group mostly relies on other fuels. Moreover, SOC1 highlights the issue of the rural/urban divide: except for Northern Africa, the difference in access to electricity and modern fuels is huge, with rural areas that lag far behind urban areas.

  Moreover large use of traditional biomass is also the main cause of IAP at household level. IAP causes an ordinary exposure to toxic pollutants, since cooking and heating activities are traditionally done inside households using three stone fires or simple cooking stoves. IAP is mainly responsible for the spread of respiratory infections and other diseases in the continent: DALYs per 1000 people due to IAP resulting from solid fuels combustion are very high in sub-Saharan Africa, affecting in particular women and children.
- The issues of traditional biomass consumption have been clearly recognized by institutions. Specifically actions plans mainly address this issue by (i) promoting the access to refined fuels (kerosene, petrol, diesel, biofuels or gas) and (ii) the shift to higher efficiency biomass stoves (improved and advanced cooking stoves)

  In order to address the issues rural/urban divide in the access to electricity, off-grid renewable systems have been proposed: including hydro, geothermal, wind, solar, biogas, and the promotion of micro-grids.

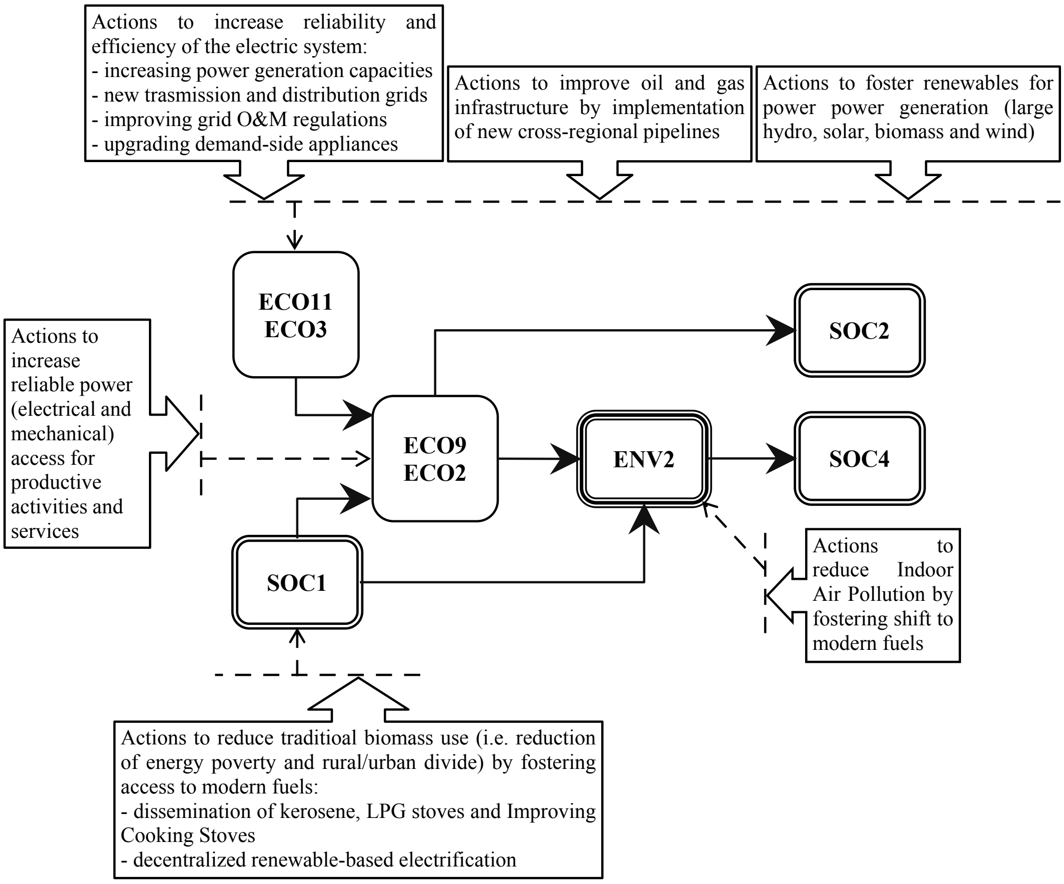

Figure 3.12 Linkages between selected indicators and relevant action plans

3.6 Summary

In this chapter a detailed analysis of the energy situation in Africa has been presented. It deepens the description of the link between energy and sustainable development introduced in Chapter 2, and contributed in defining the Framework of Reference of the thesis (Figure 1.7). Africa has been chosen as reference context of this thesis since it is the most affected by poor energy situations, its energy development will affect the global scenario in the near future, and most of the collaborations initiated during the thesis through the UNESCO Chair refer to Africa.
The energy situation of Africa has been assessed by combining data about final consumptions, electric sector and energy resources, with an analysis based on the EISD. Moreover, an overview of the energy-related action plans developed by different local players has been carried out.
Finally a framework connecting the EISD indicators has been presented in order to highlight the cause–effect linkages between some of them and to evaluate energy-related action plans according to the depicted energy situation.

4 Review on Off-grid Systems for Rural Electrification

At the light of the analyses carried out at global level and, specifically, for the case of Africa, it is clear how poor electric supply service has strongly contributed and still contributes in hindering their process of development. In DCs the electrification – development issue can be summarized by three figures:

- low electricity consumption goes along with low development (Figure 4.1);
- when available, the electric service is affected by low supplies quality (Table 3.5);
- rate of electrification are very low (Table 4.1).

These figures are particularly exacerbated in rural areas, thus leading to a growing attention toward the issue of rural electrification and to those technologies which go beyond the centralized system approach.

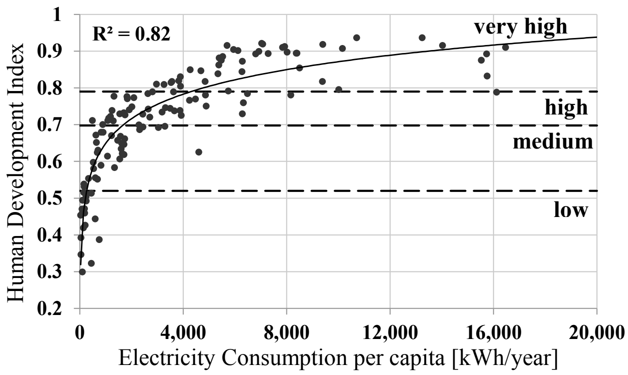

Figure 4.1 HDI and Electricity Consumption (2011). Author's elaboration based on [18], [24]

In this regards, this chapter deals with *off-grid small-scale power systems* which represent one of the most appropriate energy strategies to address rural electrification both as a first step in the electrification process or as a building-block for future grid development. Specifically the chapter is organized as follows:

- the role of small-scale power systems in the process of electrification is introduced;

- the main features of rural areas (i.e. main targeted areas for these systems) and rural energy needs are described;
- a specific taxonomy for small-scale off-grid systems for rural electrification is depicted by the Off-grid Systems Matrix;
- a comprehensive literature review as regards off-grid systems is accomplished. The review is structured according to five main research topics: (i) Technology: layout and components, (ii) Models and methods for simulation and sizing, (iii) Techno-economic feasibility analyses, (iv) Case studies analyses, (v) Policy analyses.

Table 4.1 Regional aggregates for electricity access (2011). Source [111]

	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	*1,257*	*76,5*	*90.6*	*65.1*
Transition economies & OECD	1	99.9	100	99.7
World	*1,258*	*81.9*	*93.7*	*69.0*

The main aims of the chapter are to deepen the analysis of the electrification issue in DCs with specific reference to rural areas and to introduce the research themes as regard small-scale off-grid power systems. These latter will be the basis, in the following chapters, for the development of methods and models which address more specifically the design system process of off-grid power systems.

4.1 The Parabola of Small-Scale Power Systems

Small-scale power 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 [112], [113].

The first era of small-scale power was ended by the emergence of *ac* grids which drove to the construction of huge transmission grids and large generation plants [112]. The resulting structure of the electrical industry was the state-owned vertical integrated regulated monopoly which can be considered as the classical paradigm of centralized electrical system (Figure 4.2) [114], [115]. 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 also to rural areas, DCs are still facing considerable difficulties in increasing power production and electrification rates.

Rural areas are the most afflicted by this situation since governments paid more attention to urban areas where economic activities are relevant. Moreover, 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 [114].

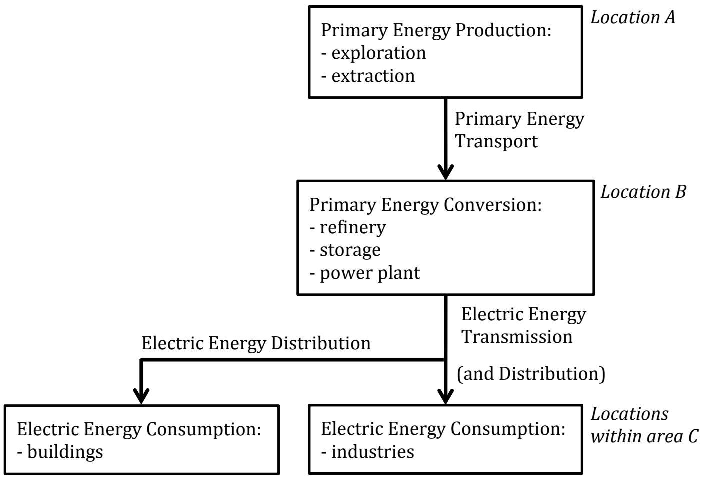

Figure 4.2 Representation of centralized electrical system. Author's elaboration based on [115]

Table 4.2 Major factors that contributed in a renewed interest for small-scale power system

Environmental [112], [116]–[122]	▪ growing concern as for the GHG emissions ▪ public awareness as regards the impacts of the electric industry ▪ opposition to construct new transmission lines
Economic [112], [116], [120], [121], [123], [124]	▪ to avoid Transmission & Distribution related costs ▪ to tackle the current risky nature of large scale plant investments ▪ to reduce power plants costs with CHP generation ▪ to better exploit profit margins within the competitive market
Technical [112], [113], [115], [116], [119], [121]–[123]	▪ increased performance of the small power technologies ▪ development of electronic metering and control equipment ▪ increased consumer demands for highly reliable power supply
Political [115], [118], [120], [121], [124]	▪ to decrease dependence from fossil fuels ▪ to increase primary source diversification ▪ to reduce vulnerability of the supply chain in centralized systems
Social [115], [116], [118]	▪ increasing public desire to promote "green technologies" ▪ growing interest towards energy autonomy and sustainability

The primacy of the centralized approach gradually decreased in developed countries during the '80s, due to the introduction of competition into the electric industry [113], [114], [124]. Also DCs pursued reforms trying to attract foreign private capitals in order to increase the efficiency in the electrification process [114]. It is in the new post-reform frame that a second era of small-scale power systems seems to arise.

Besides the introduction of competition, other factors contributed to renew the interest towards a strategy based on small-scale power systems (Table 4.2). Most of the listed factors are driving forces in developed countries as well as in DCs. Nevertheless, further reasons can be associated specifically to DCs and rural areas:

- *accessibility*: small-scale systems are preferred for the remotest locations where costs make unfeasible the extension of the main grid [113], [125], [126];
- *load demand*: rural areas have very low demand and low load factors, thus fitting with small-scale generation systems [127], [128];
- *poverty fight*: the growing attention on the links between modern energy and poverty has led to consider electricity as a main component within rural development programmes and small-scale systems as the preferable option [122], [129], [130];

- *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 systems, specifically PV for rural areas, had been set out as example of leapfrogging [40], [131], [132].

In developed countries we are nowadays experiencing a growing integration between grid-connected small-scale power generation systems (i.e. Distributed Generation) and the main centralized grid, while in DCs off-grid small-scale power systems can today play a pivotal role in rural electrification (e.g. [25], [40], [41], [128], [133]–[135]).

4.2 Rural Areas: the Targeted Context for Off-grid Systems

In DCs, rural areas are generally scattered populated, geographically isolated and difficult to access [136]. The main sources of income for rural households are pastoralism, cattle raising, agriculture, fishing, tourism or forestry [137]. The road conditions 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 [138]. Rural areas are also affected by high illiteracy rate, gender inequality, lack of access to health care, infrastructure and clean water supply [137].

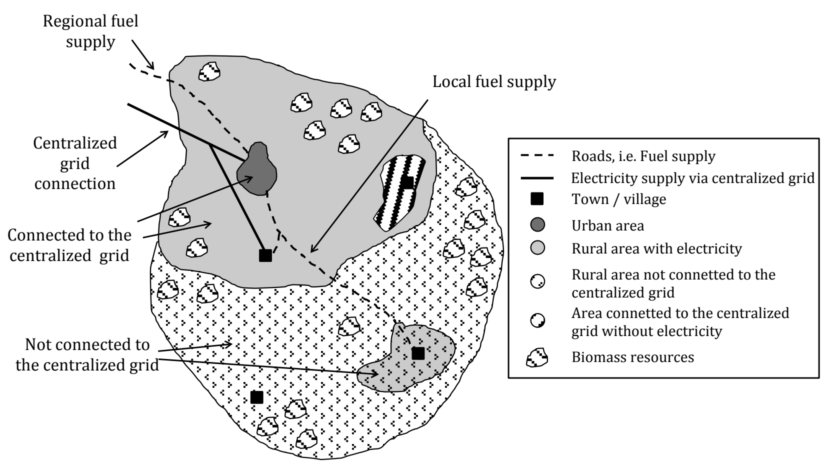

Figure 4.3 Representation of energy supplies in rural areas. Author's elaboration based on [139]

As regard electricity and fuel supplies, the typical situation can be depicted as in Figure 4.3. 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 since electricity may cost as much as 10 times more than in urban areas [132], [137], [140]–[142]. 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-scale power generation systems; historically diesel generators [137], [143] and recently renewable-based systems usually aid-financed [133].

Different categories have been employed in the literature to subdivide rural energy uses (e.g. [140], [142], [144]). Hereafter three energy uses are suggested: (i) energy for *household basic needs,* (ii) energy for *community services* and (iii) energy for *productive uses*. Within each category 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. [25], [122], [140], [142], [145]–[149]).

Energy for household basic needs

Households account for the majority of energy consumed in rural areas. They require energy mainly for cooking, lighting and space heating. Up to 80-100% of energy consumption is devoted for cooking that indirectly can supply also space heating [140], [142]. 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 them.

Table 4.3 shows minimum standard proposed by Practical Action [150] for *household basic needs.* When moving to estimate of load power at household level, the consumer load ranges between tents to hundreds of W.

Table 4.3 Minimum standard associated to energy for household basic needs [151]

	Needs	Minimum standards
1	Lighting	300 lumens for a minimum of 4 hours per night at household level
2	Cooking and water heating	1kg firewood or 0.3kg charcoal or 0.04kg LPG or 0.2lit kerosene or ethanol per person per day, taking less than 30mins per household per day to obtain
3	Space heating	Minimum daytime indoor air temperature 18°C
4	Cooling	Householders have facilities to extend perishable products by a minimum of 50% over that allowed by ambient storage. Max indoor air temp. 30°C
5	ICT	People can communicate electronic information from their household People can access electronic media relevant to their lives and livelihoods

Energy for community services

Electricity plays a pivotal role 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. Moreover electricity contributes in improving access to clean and hot water and for ITC systems.

Table 4.4 Energy for community services [152]

Health services	Education services
1. Basic amenities and equipment: lighting, ITCs, radios, TV, water / space heating, fans, etc.	1. ITCs, i.e. computers, mobile, phones, music players, printers, photocopiers, etc.
2. Water supply: pumps, cleaning, sanitation	2. Indoor and outdoor lighting
3. Health-care waste management	3. Space heating and cooling
4. Immunization refrigeration	4. Water supply
5. Maternity: incubator, suction apparatus	
6. Laboratory and surgical equipment	

Table 4.4 shows the list proposed by Practical Action about electric services which help the improvement of the health and educational sector. 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.

Energy for productive uses

Productive uses of energy refer to productive activities and specifically include the needs coming from agriculture and rural industries. In most DCs, food security and income generation highly depend on agricultural production [153], consequently an increased use of modern energy services can 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 [154]. Moreover, small farmers may set up Micro and Small Enterprises (MSE), often household-based and managed by women [140]. 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 [155]. They include a range of small and micro businesses and industries such as small shops, kiosks, beer halls, inns, charcoal and brick manufacturing, potteries, bakeries, blacksmiths, etc. [140], [142].

Table 4.5 provides for each supply feature one or more indicators, as proposed by Practical Action, that should drive the designer attention to the energy supply system and its requirements. 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 kW.

Table 4.5 Enterprise Energy Matrix for electrical supply [152]

Reliability	(i) Availability (hours day), (ii) Predictability (timetabled or intermittent)
Quality	Voltage & frequency fluctuation (±10%)
Affordability	Proportion of operating costs (%), including capital cost payback if financed
Adequacy	Peak power availability (kW)

4.3 A Taxonomy for Small-Scale Power Systems in Rural Areas

When dealing with the concept of small-scale power systems, a number of definitions and classifications have been developed and presented in the literature (e.g. [112], [124], [156]–[161]), 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 a specific taxonomy for small-scale power generation systems as regards the context of rural areas in DCs is introduced. 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. [40], [123], [126], [136], [139], [152], [160]–[162]), and hence the taxonomy includes only those systems that operate detached from the national grid and which are called from now onward as *off-grid systems*;
- at the light of the typical figures of systems power rates for rural electrification (Paragraph 4.2), off-grid systems power rate is limited to 5 MWel that is the limit of *small-scale* Distributed Generation as defined by Ackermann [156].

The classification of *small-scale off grid systems* for rural electrification is depicted by mean of the *Off-grid Systems Matrix* (Figure 4.4) which has been developed coupling a “system” perspective (columns) with a “local context” perspective (rows):

- the columns report the main classes of small-scale generation systems as defined by Alanne et al. [115]. Their approach stems from the observation that energy consumptions are decentralized by nature, while conversion, transmission and distribution[8] are not. Therefore, centralized systems, decentralized systems, and distributed systems differs since they are based on different layouts adopted for *conversion, transmission* and *distribution*[9];
- the rows report three additional categories which are essential for the local context. Thus, in addition to the *rural energy uses* already introduced (Paragraph 4.2), the *number of consumers* which are connected to the off-grid system, and the *energy sources* which the off-grid systems rely on, are also considered.

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

Figure 4.4 Off-grid Systems Matrix for rural electrification systems in DCs

Decentralized systems

Decentralized systems (Figure 4.5) are composed by autonomous units where *conversion* and *distribution* have no interaction with other units. Such systems 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 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), the latter to systems which supply power to several, similar or different, consumers (e.g. 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, *Home-based* systems, *Community-based* systems and *Productive-based* systems can be distinguished.

Distributed systems

Distributed systems (Figure 4.6) 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

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

[9] Grid connection regulations vary from country to country, however systems up to 5 MW_{el} are typically connected to medium or low voltage lines. Hence the taxonomy does not consider transmission systems.

with a central brain for centralized control, that receives data about the operational status of the system and determines how to manage it. These systems are called *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 (even different energy consumer typologies).

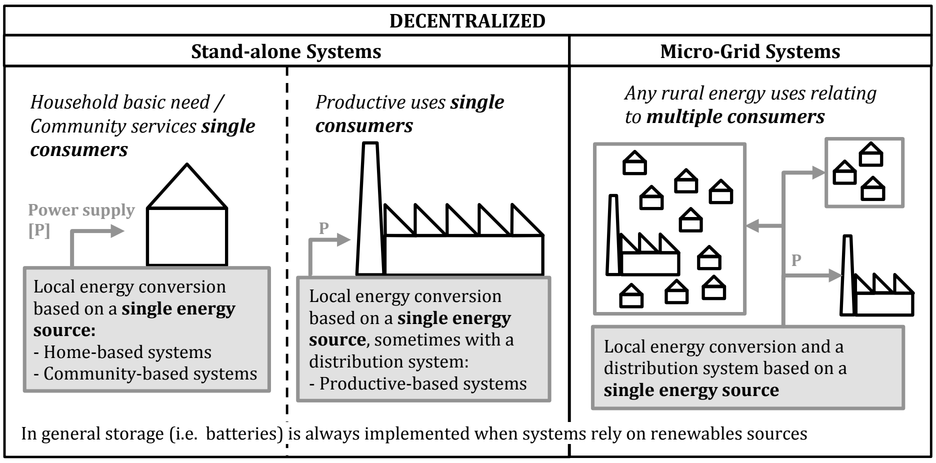

Figure 4.5 Graphic representation of decentralized electrical system

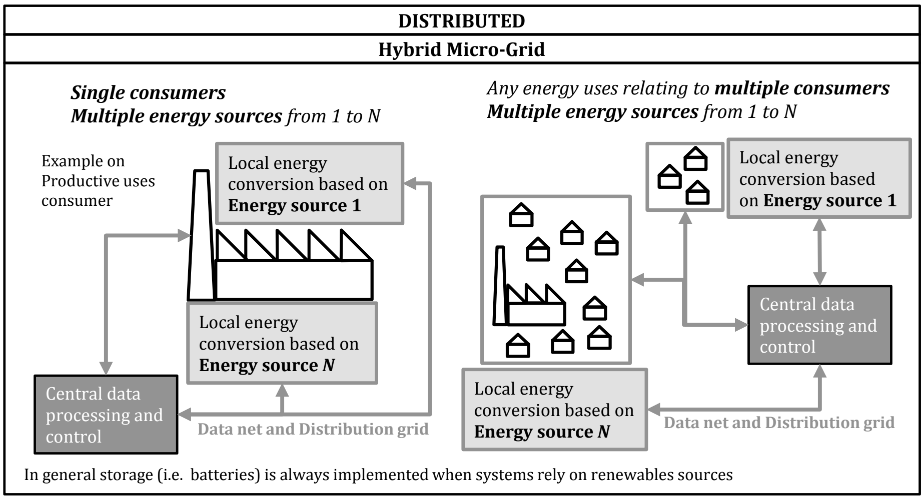

Figure 4.6 Graphic representation of distributed electrical system

It is worthwhile to make a distinction among generation technologies (Figure 4.7) 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 [117], [157], [163]. Conventional technologies run fully on fossil fuel (typically diesel), non-conventional technologies run exclusively on RESs 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.) [117], [164], [165]. 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 [137], [157]. Hybrid Micro-Grids try to overcome the need of batteries by coupling diesel generators to renewable-based systems while reducing the storage system size.

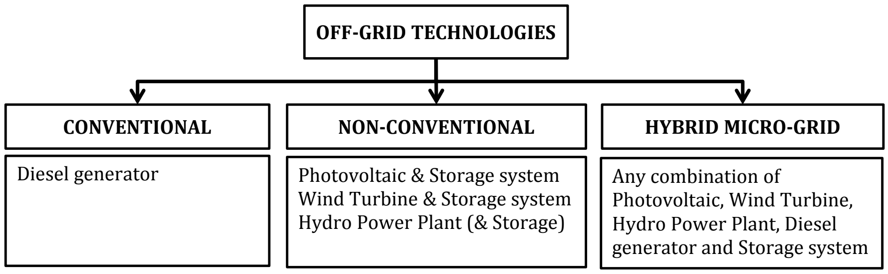

Figure 4.7 Generation technology classification

4.4 Research Themes and Literature Review for Off-grid Systems

The main objective of this section is to introduce an analytical overview of the main research themes, and relating scientific literature, on the issue of off-grid systems for rural electrification in DCs. This has been accomplished by carrying out a comprehensive literature review of the main international journals addressing this topic.

Table 4.6 Description of topic categories

(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:
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)
(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

Specifically, the review has considered 14 journals and more than 200 papers mainly published from 2000 to 2013. The methodology which has been followed in reviewing the literature and details about the selected papers are described in Appendix A. In the following the main outputs of the analysis are reported and have been organized according to:

- the Off-grid Systems Matrix previously described, thus the selected papers are grouped as follows within the three *system categories*: Stand-alone systems, Micro-Grid systems, and Hybrid Micro-Grid systems;
- five *topic categories* which are based on the most addressed research themes recognized in the analyzed literature: (i) Technology: layout and components; (ii) Models and methods for simulation and sizing; (iii) Techno-economic feasibility analyses; (iv) Case studies analyses; (v) Policy analyses. Descriptions of the topic categories are reported in Table 4.6.

Furthermore a review of the main reviews already available in the literature has also been accomplished in order to highlight the extent and the variety of this theme.

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

Despite to the author's 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 (Table 4.7).

Table 4.7 Overview of main review publications about off-grid systems

N.	Publication	Off-grid system	Description
	Off-grid systems		
1	[125]	SA, HMG	Grid-connected and stand-alone systems concept, literature overview of system design as well as institutional/strategy analyses
2	[166]	HMG	Overview of structures, characteristics, components, energy flows, planning and analysis for decentralized multi-generation systems
	Sizing & Optimization		
3	[167]	HMG	Exhaustive overview of hybrid Micro-Grid with configurations, storage technologies description, RE math models, techno-economic sizing/optimization techniques, system control strategies
4	[168]	SA, MG, HMG	Comprehensive overview of methodologies to analyse technology options for rural electrification: techno-economic feasibility, analytical approaches, practice-oriented approaches, software tools.
5	[169]	HMG	Overview of math models for hybrid renewable systems components
6	[170]	HMG	Comprehensive overview and description of optimization techniques for RE hybrid systems: genetic algorithm, particle swarm optimization, simulated annealing, ant colony algorithm, artificial immune system
7	[171]–[173]	HMG	Overview of design parameters (technological, economic, socio-politic, environmental) and main sizing/optimization techniques of hybrid systems
8	[174]	HMG	Review of publications on multi-objective optimization for PV-battery, PV-wind-battery and PV-wind-diesel-battery systems
9	[175]	SA	Review and description of sizing techniques for PV systems
	Decentralized planning		
10	[176]	HMG	Integrated Community Energy Systems concept
11	[177]	SA, MG, HMG	Extensive literature review on energy planning at decentralized level
12	[178]	SA, MG, HMG	Literature review and description of methodologies and technologies for electric supply planning in remote areas
	Experimental tests		
13	[179]	HMG	Overview of existing Micro-Grid test systems in the world
	Software tools		
14	[180], [181]	SA, MG, HMG	Comprehensive overview and description of software tools for RE systems planning and sizing

Note: SA (Stand-alone), MG (Micro-Grid), HMG (Hybrid Micro-Grid)

Among these publications it is worthwhile mentioning those which contribute in providing broad description of specific topics:

- Chauhan and Saini [167] 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 [168] 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**;**
- Rojas-Zerpa and Yusta [178] 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 [180], and Connolly et al. [181] analysed respectively 19 and 37 software tools for hybrid RE systems. Both papers provide information in order to direct the decision-maker towards a suitable energy tool for each kind of analysis.

(i) 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. When referring to *Stand-alone* systems:

- PV is largely the most investigated technology and it ranges from the smallest solar home systems (SHS), some W, up to the biggest community systems for water pumping or other needs;
- for SHS the most studied topic is the different layout of the systems, which is generally analyzed together with other specific characteristics. E.g. Hoque and Kumar [182] and Diouf and Pode [183] provide a complete analysis of the different components, layouts, and performances of a number SHS;
- studies addressing bigger PV systems follow a similar pattern. E.g. Ramos and Ramos [184] work can be cited as an example of paper discussing different components, layouts, and performances for PV pumping systems;
- as per technologies other than PV, pico-hydropower systems and 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 [185], or locally constructing timber-blades wind turbines by Mishnaevsky [186].

When referring to *Micro-Grid* systems:

- the number of selected papers is much smaller compared to the ones referring to Stand-alone systems. Moreover, these publications are quite recent having been published in between 2008 and 2012. These two facts are an index of a more recent interest for this kind of systems which require complex layouts and technologies;
- typical sizes of these systems vary from few kW up to 20 kW. In this case, the most studied technology is small hydropower: 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. [187] giving a complete overview of different system configurations and components;
- as per solar based technologies, in addition to solar PV, Pikra et al. [188] focused on the more challenging option of concentrated solar power for remote areas.

When referring to *Hybrid Micro-Grid* systems:

- the number of selected papers is similar to the case of micro grid systems, and the publication period is also the same;
- 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 RESs 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). E.g. Hrayshat [189] presents an interesting case of a system consisting of two diesel generators, a PV array and a battery;
- systems made up by two RESs technologies and a battery, constitute a third group (PV-wind-battery). Irwan et al. [190] give some information about such kind of systems. In addition to this, a more complex case is given Mondal and Denich in [191], where a PV-wind-diesel-battery system is compared to other simpler combinations of the same technologies (e.g. PV-diesel-battery).

(ii) Models and methods for simulation and sizing

As regards papers addressing 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 Stand-alone and Hybrid Micro-Grid systems.

Within *Stand-alone* group a number of papers deal with analyses relating to innovative technology solutions. E.g. Mathew et al. [192] developed a model to simulate wind-driven roto-dynamic pumps, Betka et al. [193] optimized the performance of PV induction motor pumping system, and Haidar et al. [194] simulate the performances of a real pico hydropower system application.

Within *Hybrid Micro-Grid* papers:

- 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;
- 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. E.g. Ashok [195] optimized a wind-PV-hydro-diesel system with non-linear constrain optimization, Bala et al. [196] employed a genetic algorithm to design a PV-diesel system, and Perrera et al. [197] performed multi-objective optimization via evolutionary algorithm for wind-PV-diesel system.

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. [198], [199]):
- *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. [200]–[202]);

- *analytical*: mathematical optimization problem with one or more objective functions subjected to one or more conditions. The objective function(s) and the conditions are defined by means of functional relationships between the component specifications and the economic and technical parameters (e.g. [203]–[206]).

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.

(iii) Techno-economic feasibility analyses

Most of selected papers are characterized by description of the feasibility analyses of the proposed energy system. Three main categories for most of them can be identified:

- technical design and sizing analyses with comparison among different available technologies. E.g. Arriaga et al. [207] who studied the opportunity to introduce the Pump as Turbine as reliable and long term sustainable system instead of other RE technologies;
- economic feasibility analyses with simulation and evaluation of different scenarios. E.g. Mirzahosseini et al. [208] evaluated three different scenarios of energy supply via PV systems basing on energy subsidies in Iran;
- techno-economic feasibility analyses which carry out systems optimization from technical, economic and environmental viewpoints. E.g. Shaahid [209] 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 have been carried out by means of software tools, HOMER Energy in particular [210]. 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 (2008-2013) and independently they consider Stand-alone, Micro-Grid or Hybrid Micro-Grid systems.

Furthermore, some papers present more detailed analyses of environmental and social aspects related with the application of the proposed solutions [211]–[213]. Such papers may be considered as feasibility analyses accomplished within the framework of sustainable energy development. For example: Lhendup et al. [211] 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. [213] evaluated the location for pico hydropower system 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.

(iv) Case study analyses

A number of case studies about *Stand-alone* systems have been published. Most of these studies refer to SHS, with an installed power typically from 10 W up to 500 W, nevertheless some case studies exist on bigger systems for community services such as charging stations or water pumping. These studies are mainly located in Africa and Asia, and focus on a number of different topics which can be grouped mainly under one or more of three key issues:

- main causes of success and failure (techno-economic and social): technical benefits such as the improved reliability of telecommunications, and poor local manufacturing and system installation. E.g. Green [214] gives a complete overview of technical and economic problems related to SHS programs in northern Thailand;
- economic expenditure and sustainability of projects/programs. E.g. 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. [215],
- social benefits and other social aspects. E.g. improvements in health and education (e.g. [216], [217]), and, more in general, in quality of life.

Case studies of *Micro-Grids* are mainly located in Asia, and in particular India. 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 sustainability aspects. Nevertheless, a significant example of this kind of analysis, considering all the three dimensions at once is shown by Chakrabarti and Chakrabarti [218].

As per *hybrid Micro-Grid* systems, the number of case studies in the literature is really low. 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 size of the systems varies in a range from some kW to some hundreds of kW. The focus of the papers is similar to Micro-Grid ones, and mainly on the design and performances of the systems, and on the benefits achieved by their implementation.

(v) 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.

Considering SHS, beside studies which address rural electrification policies and programs (e.g. [219]–[221]), some papers deal with specific topics such as the analysis of SHS impact on GHG emission reduction (e.g. [216], [222]) or modeling the transition process from traditional technologies to SHS at local level (e.g. [223]).

Considering Micro-Grid and Hybrid Micro-Grid analyses, a number of papers deal with the description of rural electrification programs at national level (e.g. [140], [224], [225]): in some cases they consider different off-grid systems (e.g. [226]–[228]) or they focus on a specific technology (e.g. micro hydropower in Rwanda [229]).

A further group of papers can be recognized which addresses the economic feasibility aspects of electrification programs via RESs systems. A few examples are given by Thiam [129] and Solano-Peralta et al. [230] which propose new tariff schemes to incentivize RESs systems, and by Bhandari [231] 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 [232] presented a comprehensive overview, from technology to financing models and current program, about SHS based on LED, while Sovacool et al. in [233] describe an accurate evaluation of the multi-functional platforms implementation program in Mali.

4.5 Summary

In this chapter the Framework of Reference of the thesis (Figure 1.7) has been completely depicted by a detailed description of rural areas of DCs and a detailed analysis of off-grid power systems. Specifically the growing interest towards off-grid systems in DCs has been emphasized. This has led to deepen the description of the energy features of rural areas by defining three main classes: energy for household basic needs, energy for community services and energy for productive uses. Off-grid systems have been later classified by means of the Off-grid Systems Matrix. This offers a structured reference framework to researchers of this sector since it capitalizes the fundamentals of this topic and it provides an approach for analyzing the last years of research in the sector. Accordingly a wide review of the scientific literature has been carried out. This has allowed identifying the main macro-steps and the relating building blocks which constitute the System Design Process for off-grid power systems (Paragraph 1.3). Moreover, the review has also allowed recognizing some relevant issues within this process and it is the basis which supports the development of the specific methods and models which are described in the second part of this thesis.

Part II Methods and Models for Off-grid Power System Design

5 Load Profiles Estimate with Stochastic Procedure

In Chapter 1, the Energy4Growing project has been considered as example to identify the main issues of rural electrification actions based on off-grid small-scale power systems. Beside those one that contributed in structuring the Framework of Reference for this theme, and indeed constituted the Part I of this thesis, other issues specifically address the design process of off-grid power systems (Paragraph 1.3, Figure 1.7).

The data collection at local level about available energy resources and energy needs is the primary and mandatory step in System Design Process. Nevertheless getting these data is not straightforward. Indeed, when dealing with local available energy sources (typically renewables) metering stations are often unavailable; while, when dealing with energy needs, data can lack at all (i.e. in un-electrified areas) and often they are deeply affected by resource availability and limited systems capacities rather than resulting from user choices. Moreover, while for RESs several models have been developed in order to perform availability estimates (e.g. [187], [234]–[239]), no particular attention has been devoted to models dealing with energy needs estimates.

Focusing on this latter topic, *load profiles* and *energy consumptions* are the two types of input data which are required by Strategy Selection and System Sizing methodologies as regards energy needs.

Energy consumption refers to the amount of energy (Wh) the targeted users require in a day. This type of data is employed by the simplest intuitive sizing methodologies which rely on average input data. Daily *energy consumption* (E_C) for several users having several electrical appliances can be estimated as follow:

$$E_C = \sum_{j}^{User\ Class} N_j * \left(\sum_{i}^{Appliance} n_{ij} * P_{ij} * h_{ij} \right) \quad [Wh/day] \qquad (5.1)$$

where:

- i refers to the type of electrical appliances (e.g. light, mobile charger, radio, TV);
- j refers to the specific user class (e.g. household, school, stand shop, clinics);
- N_j refers to the number of users within class j;

- n_{ij} refers to the number of appliances *i* within class *j;*
- P_{ij} refers to the nominal power rate [W] of appliance *i* within class *j;*
- h_{ij} refers to the duration of the period the appliance *i* within class *j* is on [h] (i.e. functioning time).

For energy consumption estimate, the trickiest required inputs data are the h_{ij}. values. They are typically defined on the basis of experiences about appliances usage habits in the specific context or by defining specific targeted amount of supplied energy. In any case the uncertainty related to these assumptions runs in parallel with the low degree of details of the intuitive sizing methodologies which employ these types of data.

Load profiles represent the electric consumption trends as a function of time (typically throughout a whole day) and are employed by the most advanced sizing methodologies (i.e. those based on system simulations throughout a year with hourly or even minute time-step energy balance).

Specifically, to perform load profiles estimates, in addition to define the same input data required to compute energy consumptions, it is also required to define the periods in the day each appliance works. In fact, these are needed in order to develop the "shape" of the profiles. It follows that different "shapes" of load profiles affect the System Design Process. Indeed, storage sizing and dispatch strategy optimization particularly depend on load profile features (e.g. peak values, hour of the day when power peak occurs, total daily energy, share of energy in the nigh hours).

Focusing on load profiles, it can be state that several methods and models have been developed to perform load profiles estimate or short term load forecast within the research themes of smart-grid and end-use efficiency (e.g. [240]–[242]). On the contrary, the development of estimates for load profiles to be applied in the design process of off-grid systems for rural electrification has not received attention within the scientific literature.

In this regards, this chapter describes the development, implementation and application of a new procedure to perform load profiles estimates to be employed as input data of the design process for off-grid power systems for rural electrification. The procedure works with the typical input data that are commonly considered in the approach for energy consumption estimates, but it employs stochastic bottom-up approach and specific correlations between main load profiles parameters (i.e. load factor and coincidence factor) in order to build up the coincidence behavior of the electrical appliances considered by the users.

In the following the main definitions and parameters typically used to characterize load profiles are introduced. Moreover a short overview of the available loads profile estimate methodologies available in the literature is presented with main focus on the applications for off-grid rural electrification. Then the new procedure is introduced by highlighting the general approach, the required input data and by describing its mathematical formulation. The implementation of the procedure in a proper algorithm coded in MATLAB is also presented. Finally, the application of the procedure in two cases is described: the first one to highlight the capability of the procedure in forecasting the average load profile of an existing power supply system of a college campus in rural Cameroon, the second one to highlight the use of the procedure, and particularly its stochastic nature, for the sizing of an off-grid power system.

5.1 Load Profiles Fundamentals

Use of the products created by electric power (e.g. light, heat, hot water, images on the TV, etc.) varies as a function of time of day, day of week, and season of year. As a result, the electric load varies. A *load profile* plots electric consumption as a function of time. Figure 5.1 shows a daily load profile for a college in a small city in Cameroon.

Load profile shape depends both on the connected load (appliances) and the activity and lifestyles of the consumers in an area. Nevertheless differences between the electric demand patterns of otherwise similar types of customers occur because of differences in climate, demographics, appliance preferences, and local economy.

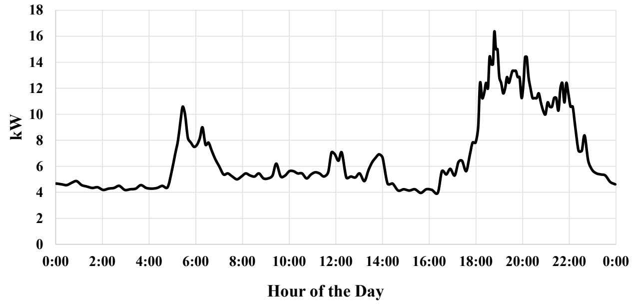

Figure 5.1 Daily load profile for the Cameroon Presbyterian College in Bali (October, 23 2014)

A number of definitions can be introduced to characterize load profiles.

Demand and peak load

Demand is the average value of load over a period of time (i.e. the *demand interval*). Demand can be measured on any interval (seconds, one minute, day, etc.). The average value of power during the demand interval is found by dividing the kWh accumulated during the interval by the number of hours in the interval. The peak and minimum usage rates during the interval may result quite different from this average. *Peak demand,* also called *peak load* is the maximum demand measured over a measurement period. This value is often used as a capacity target in engineering studies, i.e. the maximum amount of power the system must deliver.

Load factor

Load factor (f_L) is the ratio of the average demand to the peak demand during a particular period. Load factor is usually determined by dividing the total energy accumulated during the period by the peak demand and the number of demand intervals in the period. Considering hourly demand periods over a day, load factor is defined as:

$$f_L = \frac{E_L}{24h \; x \; p_L} \qquad (5.2)$$

where:

- E_L represents the total electric usage during a day
- p_L represents the peak load during the day

Load factor gives an indication of the degree to which peak demand levels were maintained during the period under study. It is typically calculated on a daily, monthly, seasonal, or an annual basis.

Customer's class

Usually, electric consumers are grouped into classes of broadly similar demand behavior. A class is "*any subset of customers whose distinction as a separate group helps identify or track load behavior in a way that improves the effectiveness of the analysis being performed*" [243]. Usually all customers in a class have similar daily load profile shapes and peak demands because they employ similar types of appliances, and have similar needs and habits.

Customer's class peaks occur at different times

Often, the various classes do not demand their peak energy at the same time. As a result, the system peak load may be less than the sum of the individual customer class loads. This is called *inter-class coincidence* of load.

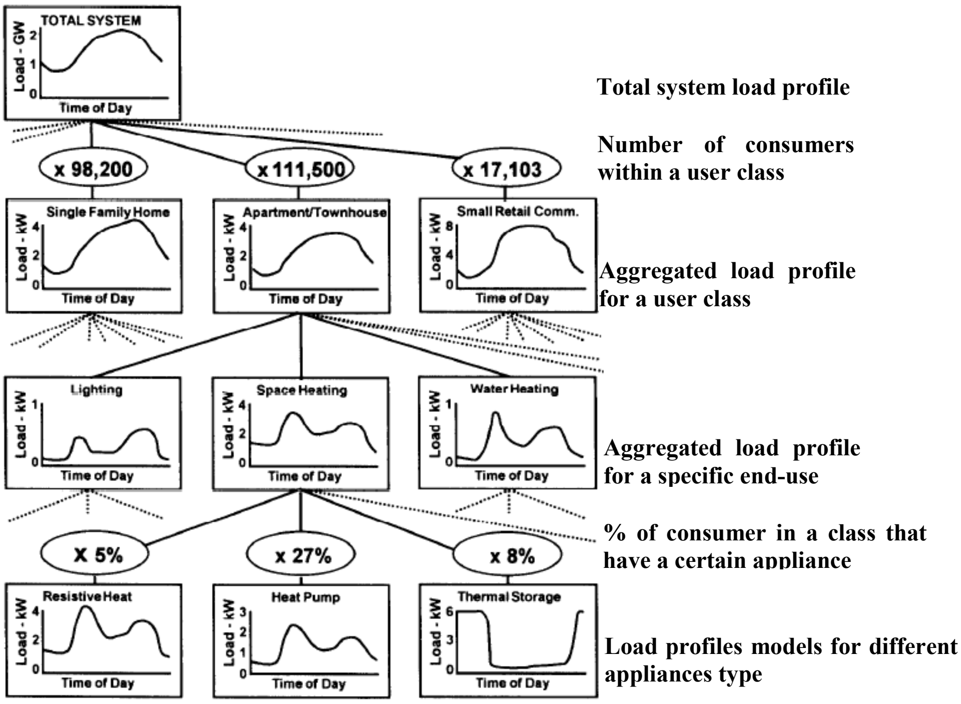

Figure 5.2 Bottom-up end-use analysis. Source [243]

End uses analysis

Each end-use is satisfied through the application of appliances or devices that convert electricity into the desired end product. All of these devices require electric power to function, and create an electric load when activated. The term load refers to the electric power requirement to accomplish some purpose (opening a door) or to convert that power to some other form of energy (light, heat). Loads are usually rated by the level of power they require, measured in units of W or VA. Power ratings of loads refer to the device at a specific *nominal voltage.*

The electric load in any end-use category depends not only on the number of customers and their aggregate demand for the end-use, but also on the types of devices they are using. Detailed analysis of electric load in a utility system generally proceeds into subcategories within each customer class's end-use categories, with the subcategories characterized by *appliance type* (**Error! Reference source not found.**).

Coincident load behavior

Most of the main loads in any home or business behave in a manner similar to the on-off. As a result, individual household load profiles, and many commercial and industrial site load profiles, display the blocky, on-off load behavior shown in Figure 5.3A. When a group of similar loads (homes in this case) is considered as a single load, the load profile becomes smoother, the peak load drops, and the minimum load rises.

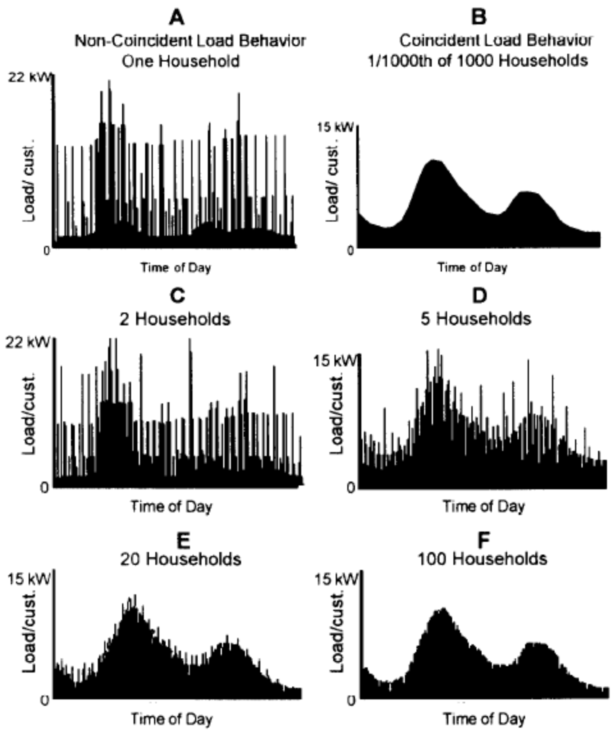

Figure 5.3 Non-coincident (A) and coincident (B) load profiles for a household. Profiles B through F show the transformation from non-coincident to coincident behavior as group size increases. Source [243]

This highlights that the interpretation of coincident load behavior as the expectation of non-coincident load behavior is generally applicable. Indeed, with reference to Figure 5.3, while no single customer within the represented group would have an individual load profile that looked like Figure 5.3B (i.e. every customer's load profile looks something like Figure 5.3A), the smooth coincident load profile for the group has two interpretations:

- the profile is an individual customer's contribution to system load. On the average, each customer of this class adds this load to the system;
- the profile is the expectation of an individual customer's load. Every customer has a load that looks something like the on-off behavior shown in Figure 5.3A, but each has slightly different on-off times that vary in an unpredictable manner from day to day. Figure 5.3B gives the probability-weighed value of daily load that one could expect from a customer of this class, selected at random. The fact that the expectation is smooth, while actual behavior is erratic, is a result of the unpredictability of timing in when appliances switch on and off.

Coincidence factor

Usually, coincident load behavior is summarized by the *coincidence factor* (f_C). Coincidence factor is defined as "*the ratio of the maximum coincident total power demand of a group of consumers to the sum of the maximum power demands of the individual consumers comprising the group, both taken at the same point of supply and for the same period of time*" [244]:

$$f_C = \frac{p_{L,class}}{\sum_j^{N_j} p_{L,j}} \tag{5.3}$$

where:

- $p_{L,clsss}$ represents the total power demand of a class of consumers;
- $p_{L,j}$ represents the maximum power demands of the individual consumers comprising the class.

Population habits, community and business practices, weather and other climatic conditions exert a great influence on the degree of coincidence in the consumers' use of electric service. These conditions are not subject to precise mathematical formulation, and their resultant effect will be different for different communities and different climatic, social, and political conditions. But for any given community, operating under a given set of conditions, the resultant effects of population habits community and business practices, weather and other climatic conditions on the manner of use of electric service usually fall into some general pattern and thus result in some determinable values of degree of coincidence of individual consumer's use of service [243], [244].

Despite the complexity of elements which affect the coincidence factor, experience has demonstrated the existence of two general phenomena relative to the behavior of group coincidence factors:

- relationship between class coincidence factors and number of consumers in a group;
- relationship between group coincidence factors and average load factors of individual consumers of a class.

Coincidence factors vs Number of consumers

This relationship can be formulated as follows [244]: "*for consumers of equal size, with not artificial restrictions placed in the way of their service use, and with all the other things equal, the degree of coincidence of the maximum power requirements of a class of consumers decreases along a path resembling that of a rectangular hyperbola from unity for one consumer in a class to values approaching the asymptote of the rectangular hyperbola for an infinite number of consumer in a group*".

The equation of the rectangular hyperbola is reported hereafter, while Figure 5.4 depicts the hyperbola and demonstrates that test observations for various types of consumers general follow the mathematical relationship.

$$f_{C,j}(N) = f_{C,j}(\infty) + (1 - f_{C,j}(\infty))\frac{1}{N} \tag{5.4}$$

where:

- $f_{C,j}(N)$ represents the coincidence factor for N consumers of the class j;
- $f_{C,j}(\infty)$ represents the coincidence factor for infinite consumers of the class j.

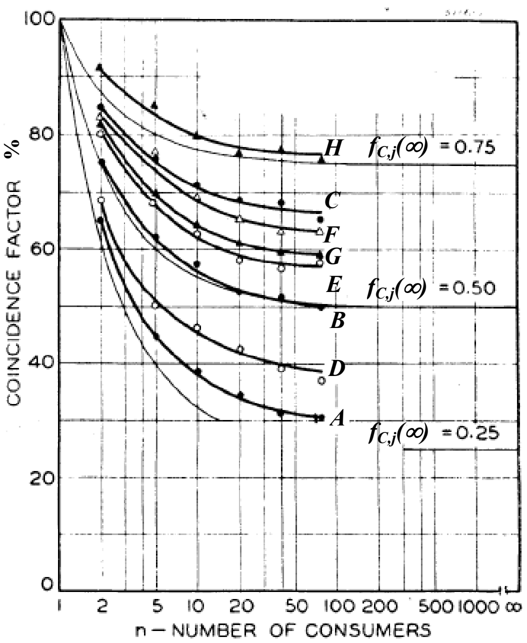

Figure 5.4 Probable trend in relation between group coincidence factor and number of consumers in group. Domestic: A 12% L_F, B 23% L_F, C 31% L_F, D 10% L_F, E 16% L_F; Retail light and power: F 17% L_F , G 18% L_F, H 28% L_F.Source [244]

Coincidence factors vs Load factor

It is obvious that a group of consumers, each having a 100% load factor, has a coincidence factor equal to unity. Furthermore, it may be demonstrated that a group of many consumers, each having a load factor approaching zero, and being unrestricted in the manner of operation throughout the entire period under consideration, will have a coincidence factor which will approach the value of one divided by the number of consumers, and which will approach zero for small demand intervals and for a very large number of consumers in a group.

Hence, whit these two extreme values known, it may be expected that, for a large number of consumers and under natural conditions of load behavior, there will exist some probable relation which will connect these two points. It may also be demonstrate that under no conditions can the value of the coincidence factor of a group of consumers, each having the same load factor, drop below the load factor, nor can it, by definition, exceed the value of unity. With these conditions set, the probable relations should lie between these limits (upper and lower limits in Figure 5.5). Theoretically, for any given value of consumers' load factors, the group coincidence factor can have any value between these limits. Nevertheless, from theoretical as well as empirical observations, it is possible to formulate qualitatively the coincidence factor–load factor relationships as follows [244]: "*for a large number of consumers, of equal size, with no artificial restrictions placed in the way of their service use, and with all other things equal, the degree of coincidence of the maximum power requirements of individual consumers in a group changes with the change in their individual load factors.*

In the low load factor range the coincidence factor increases rapidly with the increase in the individual consumers' load factors. In the medium range of load factors the magnitude of the group coincidence factor remains substantially fixed, until very *high load factor values are reached, when the relation between load factor and coincidence factor approaches the lower limit possible relationship*" (Figure 5.5).

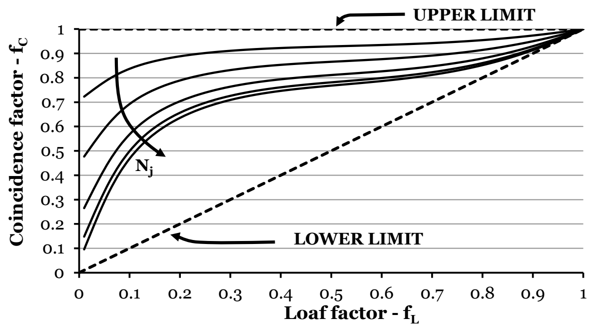

Figure 5.5 Relationship between coincidence factor and load factor. Effect of number of consumers is also highlighted

Effect of number of consumers on the coincidence factors vs load factor relationship

For one single consumer in a group, by definition the coincidence factor is unity with no regard to the load factors, while for an infinite number of consumers the coincidence factors may be expected to be lower than for groups of *N* consumers, throughout the entire load-factor range. Therefore it is possible to construct a set of curves depicting the coincidence factors–load factor relationship for various numbers of consumers in a group ranging from one to infinity.

This relationship is basically a generalization of Eq. 5.4 and is formulated as [245]:

$$f_{c,j} = a * f_{L,j} + \left(1 - a * f_{L,j}\right) * N^{-1/\alpha} \qquad (5.5)$$

where a is the ratio between $f_{C,j}(\infty)$ and $f_{L,j}$ and it can be expressed as regards the probability p that single consumers' peaks occur at the same time:

$$a = \frac{1}{p}\left[1 - (1-p)^{1/f_{L,j}}\right] \qquad (5.6)$$

$$p = b + c * e^{-h^2 * g(f_{L,j})^2} \qquad (5.7)$$

where p is formulated to conform to Gauss' normal probability distribution. Different relationships between coincidence factor and load factor are shown in Figure 5.5 for different number of users *N*.

5.2 Literature Review

Estimate of load profiles is a topic addressed within two research themes:

- power system engineering refers to *load forecasting* as the domain of models able to provide data for setting the best operating and planning of Transmission and Distribution grids. Load forecasting is divided in three categories: (a) short term which is used to predict loads from 1 hour to a week ahead, is required to solve unit commitment and economic load dispatch problems, is based on historical data and employs a variety of techniques (statistical, Artificial Intelligence, etc.); (b) medium term which is used to predict weekly, monthly and yearly peak loads up to 10 years ahead and is required for efficient grid operational planning; and (c) long term which is used to predict loads up to 50 years ahead and is required for grid expansion planning(e.g. [240], [246]–[252]);

- energy planning research refers to *energy consumption modeling* as the domain of models able to support energy-related policy decisions. Energy consumption modeling deals with energy consumptions for a country, a region or a sector. Energy consumption techniques can be grouped into two categories: (a) *top-down* which is used to determine the effect on consumptions due to ongoing long term changes in order to assess future supply requirements, and is based on econometric or technological models; (b) *bottom-up* which is used to model consumptions of each end-use and hence to identify areas for efficiency improvements at user level, and is based on statistical or engineering models (e.g. [241], [253]–[257]).

Despite the large number of scientific papers that have addressed these themes, only few of them specifically focus on the estimate of daily load profiles which are required in the system design process of off-grid systems. Moreover, most of them deal with the particular case of domestic electric consumptions in developed countries and they are mainly devoted to support decisions as regards Distributed Generation integration in the power system, analysis of Demand Side Management measures, impacts of various scenarios on local power demand, etc. .

A recent review of models to perform estimates of daily load profiles within the residential sector, has been published by Grandjean et al. [242]. They revised and described 12 domestic load profiles models. These models have been classified in three main categories: bottom-up, top-down (Figure 5.6) and hybrid. Then further five sub-divisions have been proposed according to the way coincidence behavior is modeled:

- deterministic statistical disaggregation model: this approach consists of disaggregating measured load profiles to identify various appliances. Coincidence is not modelled since it is embedded in the measured data;
- statistical random model: the calculation of the coincidence makes use of statistical data. To generate variations for a given scenario, a random procedure is applied;
- probabilistic empirical model: from real collected data concerning domestic habits of people, probabilistic procedures are defined and applied to generate coincidence;
- time of use based model: coincidence is constructed thanks to data coming from time of use surveys (real and precise data concerning the behavior of people);
- statistical engineering model: in this case, coincidence is partly embedded in the measured data that serve as input (dwelling characteristics, weather data, penetration rates, etc.). Then, coincidence is also in the statistical coefficients that adjust the original results. These coefficients are calculated with the help of measured load curves and socio-economic data.

Despite to perform detailed sizing of main components in off-grid systems, load profiles are required as primary input data, to the author knowledge a dedicated section within the scientific literature is not present. This is even true when looking at the literature which poses focus on specific sizing methods and models rather than on their applications, but also when looking at feasibility or prefeasibility analyses. Only Celik [258] brought about the issue of load curves and systems sizing. Moreover, as a matter of fact, analyzing the reviewed literature in Chapter 4, researchers generally introduce load profiles in sizing analyses in three manners:

- load profiles are defined without any explanations about the origin (e.g. [196], [259]–[261]);
- adapting load curves from similar contexts (e.g. [262]–[266]);

- computing the load profiles without any defined procedure, but employing assumptions on electric device functioning windows and/or load factors in order to build up a coincidence behavior (e.g. [267]).

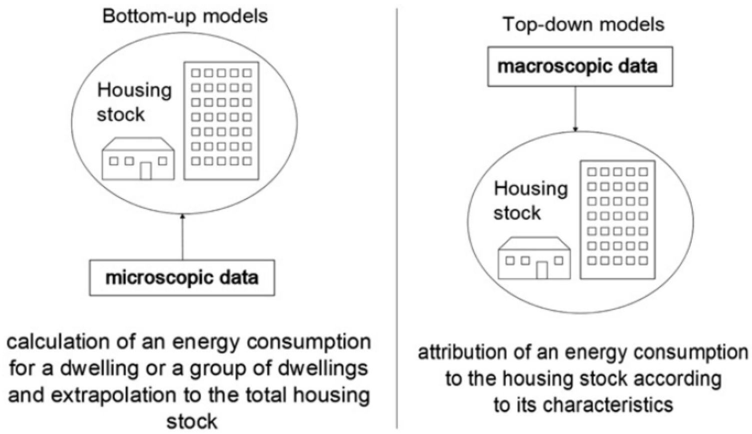

Figure 5.6 Bottom-up and top-down models. Source [242]

Considering the last manner, despite no formal procedures are reported in the literature, two possible approaches which are *unintentionally* employed can be formalized. They are briefly described in the following.

In order to develop a load profile a further input parameter is required besides those already introduced with energy consumption definition (Eq. 5.1); that is the *functioning window(s)* of a consumer class appliance ($W_{F,ij}$).

The functioning window(s) represent the period(s) during the day when an appliance can be on (Figure 5.7).

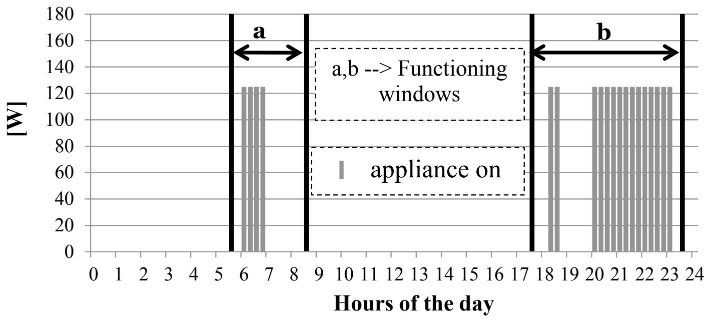

Figure 5.7 Graphical representation of functioning windows for a single appliance

The first approach that can be formalized is based on the same input data required in the energy consumptions definition (Eq. 5.1), plus the assumptions for each appliance i within each user class j about the functioning windows. Specifically this approach is based on the following condition:

$$\sum duration(w_{F,ij}) = h_{ij} \qquad (5.8)$$

i.e. the sum of the assumed functioning windows is equal to the functioning time $h_{ij.}$ Accordingly, all the n_{ij} appliances result to be on at the same time. Figure 5.8 shows the load profile resulting from this approach for the assumed load data of a peri-urban area of Uganda (detailed data available in Appendix D).

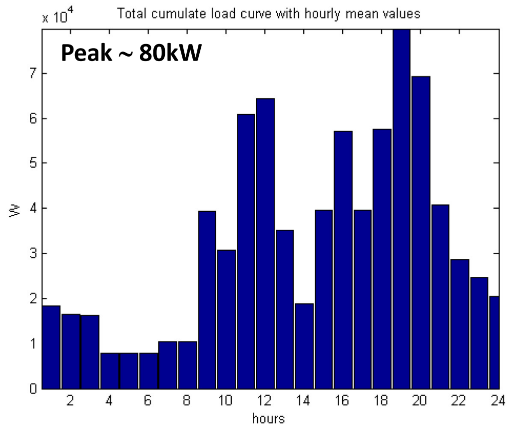

Figure 5.8 Estimated load profile for Uganda case according to the assumption of functioning windows matching the functioning time

The second approach that can be formalized is based on the same input data required in the estimate of energy consumptions definition (Eq. 5.1), except that the functioning times (h_{ij}) are not considered, while functioning windows and load factors ($f_{L,ij}$) for each appliance type are assumed.

In this case, firstly the energy consumption associated to each appliance i within each user class j ($E_{L,ij}$) is computed (Eq. 5.9), then the average power associated to each appliance ij ($P_{av,ij}$) which contributes to build up the load profile is evaluated as in Eq. 5.10. Figure 5.8 shows the load profile resulting from this approach for the assumed load data of a peri-urban area of Uganda (detailed data available in Appendix D).

$$E_{L,ij} = f_{L,ij} * 24h \; x \; P_{ij} \tag{5.9}$$

$$P_{av,ij} = \frac{E_{L,ij}}{\sum duration(w_{F,ij})} \tag{5.10}$$

Considering the two approaches and looking at the resulting load profiles for the specific case, some considerations can be made:

- despite both profiles account for the same daily energy consumption, the shapes are quite different. Looking at the peak loads the values as well as the time are different;
- in the first approach, basically it is defined how long and when the appliances are on without considering any coincidence behavior. Indeed, according to the leading equation (5.8), all appliances ij are on at the same time and hence the coincidence is equal to one. Thus the peak power is overestimated, and in general the profiles are not flat, but have high values or low values;
- in the second approach, input load factors are found in literature or more often are assumed. Then, the power contribution of each appliance ij to the load profile refers to the average power computed by "spreading" the consumed energy on the total duration of the functioning windows. In this way the coincidence factor assumes the minimum value possible given by the input load factors and functioning windows. Hence, the power peaks are underestimated, and in general the profiles are flat.

As a consequence the two approaches are not satisfactory to perform a proper off-grid system sizing, indeed:

- no attention is devoted to appropriately compute the coincidence factor values whose results do not relate to the number of consumer considered and to the load factors. Overestimates and underestimates of power peaks can deeply affect the system sizing;
- to assume values of load factors (in the second approach) is not the most proper approach. Indeed: literature values mostly refer to developed countries context and in any case, assuming load factor values, is an harder task than assuming functioning time h_{ij};
- they do not embrace uncertainty of load demand which is typical for DCs and rural electrification actions. In both approaches, the input data allow computing only a single load profiles, but not different stochastic profiles within the same input parameters. A random noise may be considered to add uncertainty, but the coincidence appliances behavior is not considered as well.

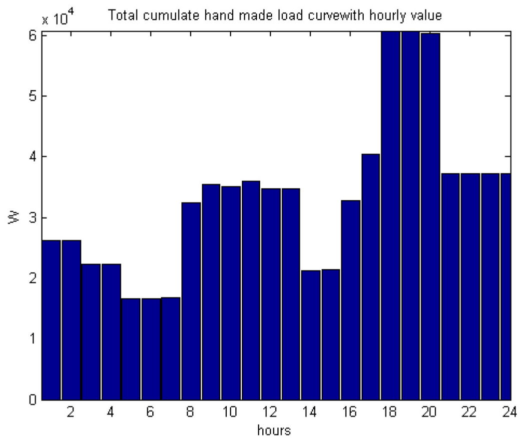

Figure 5.9 Estimated load profile for Uganda case according to the assumptions of load factors and functioning windows

5.3 Development of the New Procedure

At the light of the issue about lack of appropriate methods to estimate load profiles for supporting the off-grid system design process, a new procedure has been developed, implemented and applied. In this paragraph the procedure is introduced as regards: the general features considered in the development, the required input data, and finally the mathematical formulation.

General features

In setting the frame to develop the new procedure, the characteristics of an ideal method for load profiles estimate, as introduced by Grandjean et al. [242], have been taken as a reference. In their opinion, an ideal model should present the following features:

- it has to be parametric in order to simulate various scenarios;
- it has to be technically explicit, i.e. the different specificities of the simulated appliances must impact the load profile results;
- it has to be evolutive, i.e. new elements can be introduced so as to be simulated;

- it has to be aggregative so that results can be obtained at different levels (household, area, city, region, etc.);
- all end-uses can be considered in the load profile calculations.

At the light of this reference, the new procedure has been developed in order to embrace the following features:

- it has to be based on input data that can be assessed or assumed by looking at the typical conditions of rural areas;
- it has to be based on a rigorous mathematical formulation which allows developing the load profile shape, i.e. apart input data, the designer judgments should not affect the profile shape;
- it has to be bottom-up, i.e. the load profile computation has to rely on microscopic input data referring to each appliances features within a specific type of user class;
- it has to build up the coincidence behavior of the appliances and the power peak value with regards to the existing correlation between number of users, load factor and coincidence factor;
- it has to be stochastic in order to embrace uncertainty, i.e. given the input data, the procedure output has not to be unique, but it should embrace the uncertainty given by the fact that a single correct load profile does not exist in rural areas.

Input data

Table 5.1 shows the input data of the new procedure, while Table 5.2 shows an example of input data for a specific user class.

i refers to the type of electrical appliances (e.g. light, mobile charger, radio, TV), j refers to the specific user class (e.g. household, school, stand shop, clinics).

Table 5.1 Input data required by the new procedure

Nj	number of users within class j
n_{ij}	number of appliances ij
P_{ij}	nominal power rate [W] of appliance ij
h_{ij}	functioning time [min] or [h], i.e. duration of the period the appliance ij is on in a day
$W_{F,ij}$	functioning window(s), i.e. period(s) during the day when an appliance ij can be on (Figure 5.7). Defined by a starting window time and a ending window time
d_{ij}	functioning cycle [min], i.e. minimum continuous functioning time once appliance ij is on
Rh_{ij}	% random variation of functioning time appliance ij
RW_{ij}	% random variation of functioning window appliance ij

Considering the input data, some considerations can be made:

- all the appliances are modelled with on-off functioning mode and considering a minimum continuous functioning cycle (d_{ij}), i.e. the functioning behavior of each appliance is simply considered by setting different d_{ij} values. For example, a functioning cycle of 45 min can be considered for the oven while a functioning cycle of only 10 min can be considered for the iron;
- it always results that $d_{ij} \leq h_{ij}$;
- in order to consider a degree of uncertainty in the values of h_{ij} and $W_{F,ij}$,which are usually a input assumed by the designer, random parameters Rh_{ij} and RW_{ij} are introduced respectively. They set the maximum percentage of Rh_{ij} and RW_{ij} subjected to random variation;
- obviously Σ $duration(W_{F,ij}) \geq h_{ij}$;

- given all the input data, the total required daily energy of each user class is defined. Indeed it can be computed by means of Eq. 5.1;
- given all the input data, a possible maximum power peak of each user class is defined. Indeed overlapping the functioning windows for the different appliances within a class, a window (*peak window*) will result to be embraced by a number of appliances hence defining a possible maximum power peak (Figure 5.7). For the example shown in Table 5.2, the peak can occur from 5pm to 2am and the maximum value can be 1.35kW;
- according to the previous considerations, a load factor relating to the maximum possible peak power can be computed.

Table 5.2 Example of assumed load demand data for a user class

User class	N_J	App Name	P_{ij} [W]	n_{ij}	h_{ij}	$W_{F,1-ij}$ h_{start}	h_{stop}	$W_{F,2-ij}$		$W_{F,3-ij}$	
Family_1	50	Lights	3	4	6	0	2	17	24	-	-
		Phone Charger	5	2	3	0	9	13	15	17	24
		Security Lights	5	1	12	0	7	17	24	-	-

Mathematical formulation

The procedure can be formulated according to the following objective function and constraints:

Objective function

The load profile of each appliances *ij* is computed by defining, in a stochastic manner, the moments *t* the appliance is switched on within the vector of the daily minutes [1:1440]. Hence, having the moments *t* and the input d_{ij}, the load profile of each appliance is defined. Then the user class profile results from the aggregation of single appliance profiles.

Constraints

- the number of switching on moments *t* (n_t) is defined as follows:

$$n_t = \frac{h_{ij} + random(h_{ij} * Rh_{ij})}{d_{ij}} \qquad (5.11)$$

  where random(h_{ij}*Rh_{ij}) refers to the computation of a random value defined in [-(h_{ij}*Rh_{ij}), +(h_{ij}*Rh_{ij})];
- starting from each *t* , the appliance is on for the following d_{ij} minutes;
- the functioning window(s) $W_{F,ij}$, which define the periods when moments *t* can occur, is defined as follows:

$$W_{F,ij} = W_{F,ij} + random(W_{F,ij} * RW_{ij}) \qquad (5.12)$$

  where $random(W_{F,ij}*RW_{ij})$ refers to the computation of random values for the starting and ending times of the functioning window;
- power peak time is randomly chosen with uniform probability distribution within the *peak window*, Figure 5.10;

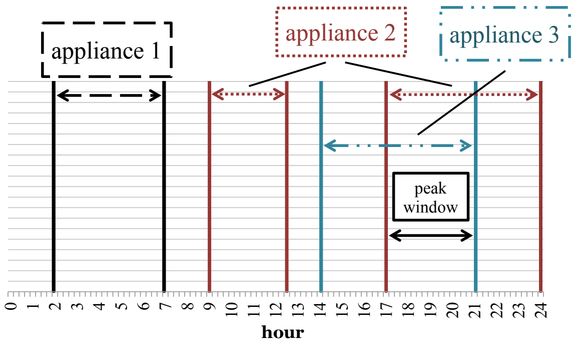

Figure 5.10 Peak window definition: it is assumed that the cumulated power rate of appliance 2 and 3 is higher than power rate of appliance 1

- the moments t are defined by random sampling within the functioning windows with two probability distribution: (i) for appliances which do not contribute to the peak (e.g. appliance 1 in Figure 5.10) sampling is carried out with uniform probability distribution, (ii) for appliances which contribute to the peak (e.g. appliance 2, 3 in Figure 5.10) sampling is carried out with normal probability distribution having mean value on the peak time;
- standard deviation of the normal probability distribution for appliances contributing to the peak is defined in order to obtain, within each user class, a power peak value which comply with the peak power obtained via the correlation between coincidence factor, load factor and number of user. The employed correlation refers to the one presented by Bary in [244]. The coincidence factor is calculated by Eq. 5.5. and 5.6 where p is computed as follows:

$$p = 0.187 + 0.813e^{-4[(1-f_{L,i})^2+(1-f_{L,i})^{16}]} \quad (5.13)$$

5.4 Implementation of the New Procedure

An algorithm which computes load profiles in accord with the described formulation has been implemented in MATLAB. In Figure 5.11 a block representation of the algorithm is presented.

It is worthwhile to highlight two main features:

- the algorithm develops the profiles of each single user class defined by the designer with a bottom-up approach, and then the final load profile is given by aggregating each user class load profile;
- the algorithm is divided in three sections: (i) *input data* which highlights different groups of required inputs, (ii) *operational elements* which considers the different computational steps performed within the algorithm, and (iii) *output data* which highlights different groups of outputs computed throughout the algorithm.

Input data

They can be divided between those which are not subjected to randomization and those which can be randomly modified according to designer parameters (i.e. Rh_{ij} , RW_{ij}).

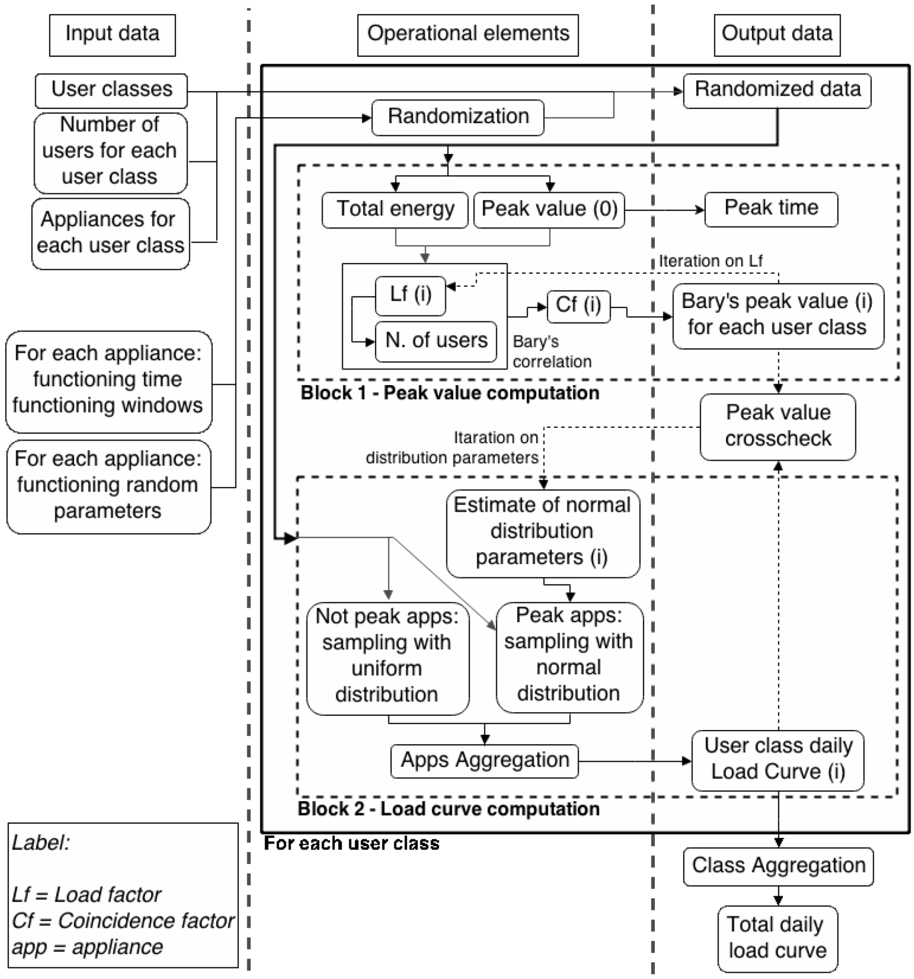

Figure 5.11 Block representation of the algorithm for load profile estimate

Input data

They can be divided between those which are not subjected to a first randomization and those which can be randomly modified according to designer parameters (i.e. Rh_{ij} , RW_{ij}).

Operational elements and Output data

1. the algorithm elaborates the input data in order to obtain them in the proper form to compute the load profile: functioning times and functioning windows are randomized and then aggregated with the other inputs;
2. *peak value computation*. In this block the total required energy, the peak window(s), the maximum possible power peak (i.e. *peak value(0)*), and the peak time are firstly computed. Then with an iterative process the load factor and the coincidence factors are computed according with Eq. 5.5 until convergence is reached for their values. Hence the reference value of the power peak for the considered user class can be computed;
3. *load curve computation*. In this block, for each appliance, the switching on moments *t* are randomly selected according to the appropriate probability distribution (i.e. uniform if the appliance does not contribute to the peak, normal if

the appliances contribute to the peak). Accordingly, the load profile for the user class can be computed. Nevertheless the resulting peak may not comply with the estimated one (step 2). Therefore iterations are performed by operating on the parameters that define the normal probability distribution which guides the random sampling of moments *t* of the peak appliances (i.e the parameters which define the normal distribution are relaxed);

4. once the resulting peak value matches, with an error defined by the designer, the computed power peak the iteration are stopped and the final load profile is identified;
5. repeating steps 2,3,and 4 for each user class and aggregating the different user class load profiles allows computing the final load profile.

The algorithm implements the new procedure and complies with the proposed features introduced in Paragraph 5.3. In particular, it is worthwhile to highlight that:

- by developing the load profile of each single appliance and then by aggregating them (i.e. bottom-up approach), the coincidence behavior within a user class is achieved in a similar way as it occurs in real power systems (Figure 5.3);
- due to the stochastic approach in defining the peak time and the switching on moments *t*, the algorithm computes a different load profile each time it is run. Specifically, sensible differences can occur as much as the parameters Rh_{ij} , RW_{ij} are large.

5.5 Applications of the New Procedure

In the following two applications of the new procedure are described. The first one aims at showing the capability of the procedure in matching metered daily load profiles of a college in a peri-urban area of Cameroon, the second one aims at introducing an application of the procedure in performing stochastic sizing for an off-grid PV system in Uganda.

Application 1

Despite the procedure has not been developed with the aim of addressing load forecast, a first application of the procedure has been devoted to compare the resulting load profiles with metered load profile values of existing users in DCs.

Metered load profiles

The reference context is the Cameroon Presbyterian College in Bali, Cameroon. At the moment the power supply of the college is provided by the national grid, but also back up diesel generator are locally available. As part of a study to perform an energy planning of the school aiming at identifying possible solution towards the college energy self-sufficiency, actual load profiles have been metered.

Specifically eight days have been monitored by considering the local meter installed at the connection of the electric system of the school with the local distribution grid. Accordingly, both for the power (kW) and energy data (kWh) only one decimal has been considered relevant. The relating load profiles are reported in Figure 5.12. The power peak ranges between 11.5 and 15.4kW, while the daily energy consumed ranges between 139.5 and 161.2kWh.

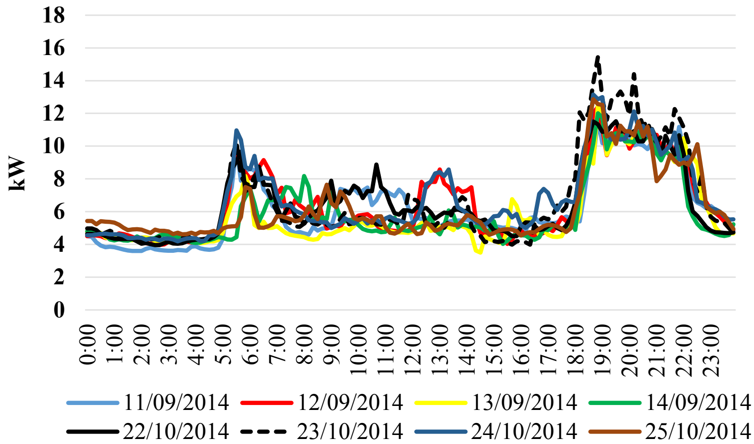

Figure 5.12 Metered load profiles for Cameroon Presbyterian College in Bali

The profile to be employed for the comparison with the new procedure is the average of the metered ones (Figure 5.13). The power peak is 12.6kW, while the consumed daily energy is 151.3kWh.

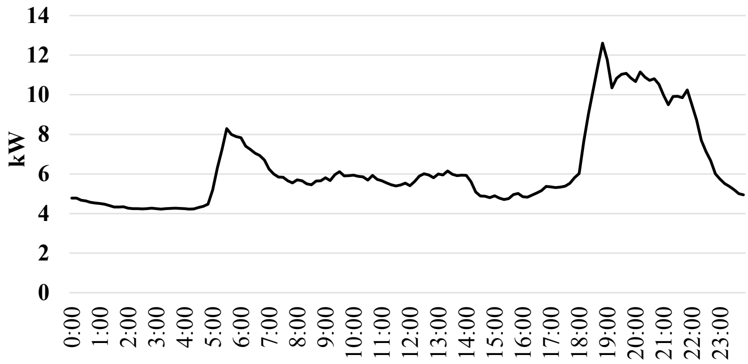

Figure 5.13 Average metered load profile for Cameroon Presbyterian College in Bali

Estimated load profiles

Thanks to local surveys and interviews with the college staff and students, the input data to be provided to the new procedure have been defined.

In Table 5.3 the list of the defined user class and a summary of the input data in terms of energy are reported. Moreover, the detailed input data required by the procedure are reported in Appendix B. Finally both Rh_{ij} , RW_{ij} have been set to 30%.

Table 5.3 Summary of energy consumptions for the defined user classes

	Class Type	N_{US}	$E_{class,day}$ [kWh/day]	$E_{user,day}$ [kWh/day]	$E_{pc,year}$ [kWh/year/pc]
1	Family_1	18	51.9	2.9	131.7
2	Family_2	14	20.0	1.4	65.2
3	Family_3	11	7.6	0.7	31.5
4	Students' Dormitories	1	10.4	10.4	-
5	Classrooms	1	13.8	13.8	-
6	Kitchen	1	4.4	4.4	-
7	Bakery	1	1.0	1.0	-
8	Dining hall	1	0.7	0.7	-

9	Canteen	1	1.3	1.3	-
10	Workshop	1	0.7	0.7	-
11	Dispensary	1	0.4	0.4	-
12	Church	1	1.7	1.7	-
13	Administration Office	1	7.9	7.9	-
14	Library	1	3.8	3.6	-
15	CCU	1	13.2	13.2	-
	Total Load		138.8	64.3	

Due to the stochastic nature of the procedure, the estimated load profile to be compared with the metered one has to refer to an average profile given by the procedure. As a matter of fact this should represent the profile to which the procedure converges. Therefore, the considered profile is the average of *N* estimated profiles, when *N* is identified when both the following conditions are met:

$$\frac{\bar{y}(k)_N - \bar{y}(k)_{N+1}}{\bar{y}(k)_N} \leq 0.5\% \;\; for\; k \geq 80\%\; of\; time\; steps$$
$$and \qquad (5.14)$$
$$\frac{\overline{std}[y(k)_N] - \overline{std}[y(k)_{N+1}]}{\overline{std}[y(k)_N]} \leq 0.5\% \;\; for\; k \geq 80\%\; of\; time\; steps$$

where:

- k refers to the profile time steps, in this case the load profiles are build up according to 10min time steps, i.e. a full day is composed by 144 values;
- $\bar{y}(k)_N$ refers to the average load profile value of *N* generated profiles at the time step k;
- $\overline{std}[y(k)_N]$ refers to the average standard deviation of the load profile value of *N* generated profiles at the time step k;

According to this approach, the procedure converges by generating at least 99 profiles. The resulting average profile based on 100 profiles is shown in Figure 5.14. The power peak is 16.3kW, while the consumed daily energy is 138.1kWh.

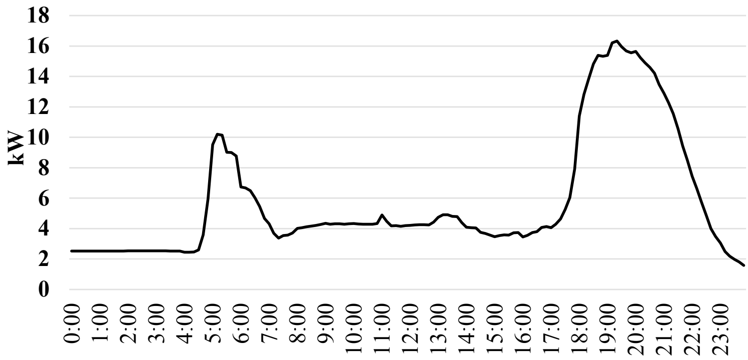

Figure 5.14 Average load profile estimated by the new procedure

Metered Vs estimated profile

Figure 5.14 shows the comparison between average metered profile and average estimated load profile. A number of observations can be made:

- the estimated profile generally tends to overestimate power peaks, and underestimate the flat part of the profile;
- power peaks occur at the same time;
- considering the values of the estimated profile at the end of the day and at the beginning, they do not exactly match;
- the “bell” which embraces the power peak of the estimated profile, clearly remind the normal distribution profile.

Moreover, it is worthwhile to mention that the metered profile does not exactly represent the average profile of the college since it is based on only eight metered profiles. Nevertheless, despite this limitation, and despite the above mentioned considerations, in the author’s opinion the comparison shows that the new procedure is based on a sound approach: the input data have been easily collected or assumed at local level by survey and observation of the consumption habits, the coincidence behavior of the appliances simulated by the procedure fairly matches with the metered one, and the peak power computation is appropriately addressed both in term time and value.

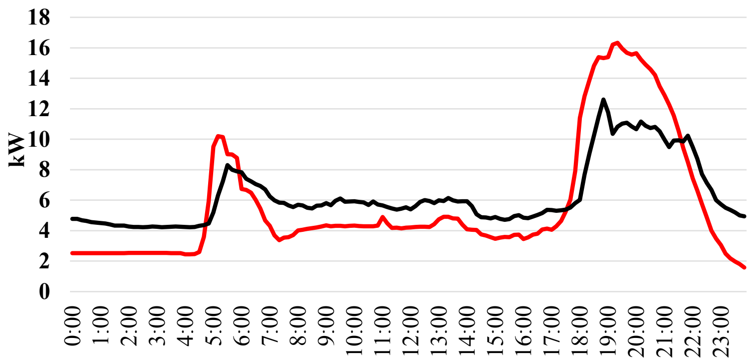

Figure 5.15 Comparison between average metered profile (black line) and average estimated load profile (red line)

Clearly further developments are required in order to improve the procedure. This can only be addressed by a number of comparisons between metered and estimated data. Moreover, a rigorous approach is required also in order to assess the “match” between metered and estimated profiles. In this regards a set of indicators have been identified and are reported in Table 5.4, while in

Table 5.5 they have been evaluated for the application to the college in Cameroon,

Specifically the indicator I_S account for the differences in each time step between the value of the metered and the estimated profile, hence assessing the shape match between the two profiles.

Table 5.4 Proposed indicators to assess the match between metered and estimated profiles

1	Daily energy [kWh]
2	Power peak value [kW]
3	Power peak time [hh:mm]
4	Shape indicator: $I_s = average\left(\frac{\lvert \bar{y}(k)_{metered} - y(k)_{estimated} \rvert}{\bar{y}(k)_{metered}}\right)_{k=1}^{Daily\ time\ step}$

Table 5.5 Values of the proposed indicators for the considered application

		Metered	Estimated
1	Daily energy [kWh]	151.3	138.1
2	Power peak value [kW]	12.6	16.3
3	Power peak time [hh:mm]	18:5	19:2
4	Shape indicator	0.32	

Application 2

Load profiles are an input which can deeply affect the results the sizing process of the main components of any off-grid system. Moreover, given a targeted context for off-grid system implementation, the expected load profile is not unique, i.e. uncertainty can be associated to the load profile. This is even truer when dealing with rural electrification. Therefore the possible different load profiles related to a context can lead to different system sizing. A possible approach to this issue is to look for the system sizing which fits with the majority of the possible load profiles.

This second application of the new procedure aims at a first step system sizing which address the issue of uncertainty of load profiles. Indeed, as already highlighted, the new procedure is based on a stochastic approach, which allows, given a set of input data, to compute different load profiles which all match with the imposed constraints, i.e. the uncertainty of load profiles for off-grid systems sizing is considered.

This case study has been applied to the sizing of the main components of a PV Micro-Grid in a peri-urban area of Uganda according to the following features[10]:

- 10 scenarios for load input data have been identified. Appendix E shows the main input data which have remained constant for each scenario. The different scenarios are based on different values of Rh_{ij} , RW_{ij} (Table 5.6);

Table 5.6 Definition of the 10 load profile scenarios

	Rh_{ij}	RW_{ij}
Scenario 1	0	0
Scenario 2	0	10
Scenario 3	0	20
Scenario 4	0	30
Scenario 5	10	0
Scenario 6	20	0
Scenario 7	30	0
Scenario 8	10	10
Scenario 9	20	20
Scenario 10	30	30

- 100 load profiles have been computed for each scenario with the new procedure;
- for each load profile within a scenario, the main system components sizes of the PV Micro-Grid (i.e. PV peak power and storage capacity) have been defined by mean of a numerical optimization approach based on life-cycle Net Present Cost and minimum Loss of Load parameter [201];
- since for each estimated load profile within a scenario, different optimum system sizes may result, the optimum system configuration for a scenario (i.e. the optimum

[10] Further details as regards the input data and the numerical approach for system sizing are reported in Chapter 7 which specifically focus on the Uganda case study and the numerical sizing approach.

sizes of the PV panels and the storage) is identified as the one that fits with the majority of the employed load profiles;

- beside the uncertainty embraced by the procedure in developing different profiles for a given set of input data, further degree of uncertainty has been introduced by considering different scenarios based on different values of Rh_{ij} , RW_{ij};
- in addition to identify the best system sizes within a single scenario, the overall best system sizes can be recognized by overlapping the results of each single scenario.

Figure 5.16 and Figure 5.17 show graphical representations for the sizing results of the Scenario 1. In particular, Figure 5.16 highlights the distribution on the search plane of the optimum system configurations: going from blue to cyan, to yellow and red, the configurations have resulted the best ones more often. It can be noticed that, even if Rh_{ij}, RW_{ij} are zero, both PV and storage sizes changes over a sensible range. With Figure 5.17 it is also possible to appreciate the frequencies of different systems configurations. In this case the best system configuration has: 216kW PV array and 864kWh storage capacity.

The same analysis has been performed for the other considered scenario. The resulting best plants are reported in Table 5.7.

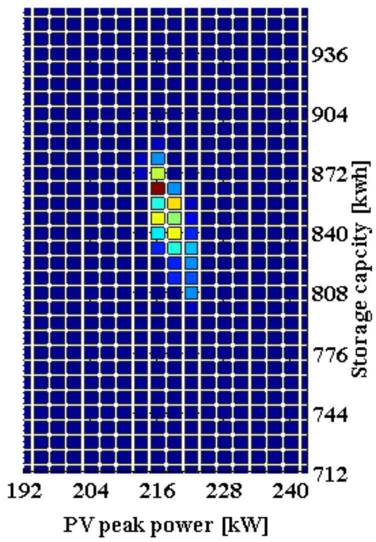

Figure 5.16 Search space and ranges of the resulting optimum PV array and storage sizes for Scenario 1

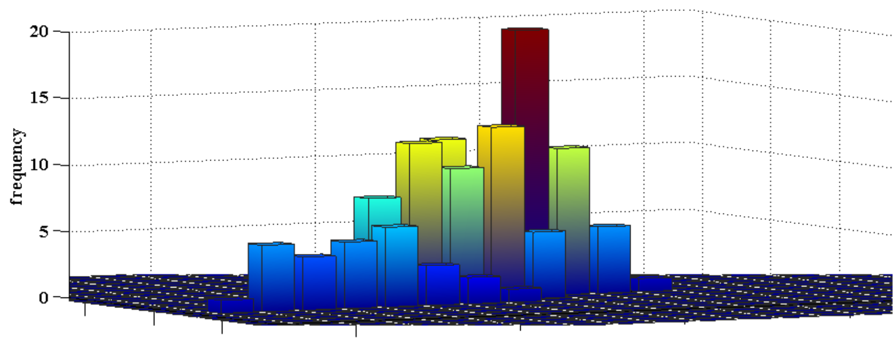

Figure 5.17 Frequency of the different optimum system configuration for Scenario 1

Table 5.7 Resulting best plant configurations

	PV array [kW]	Storage capacity [kWh]
Scenario 1	216	864
Scenario 2	216	848
Scenario 3	216	832
Scenario 4	216	840
Scenario 5	213	856
Scenario 6	213	864
Scenario 7	216	824
Scenario 8	219	824
Scenario 9	222	816
Scenario 10	222	832
Overall	**216**	**848**

Finally, by aggregating the results of each scenario the same analysis can be carried out. Indeed in Figure 5.16 and Figure 5.17 graphical representations for the sizing results of the aggregated scenario are shown, while Table 5.7 also reports the resulting overall best system configuration.

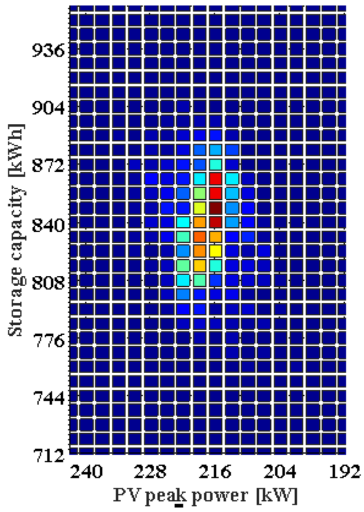

Figure 5.18 Search space and ranges of the resulting optimum PV array and storage sizes by aggregating all the scenarios

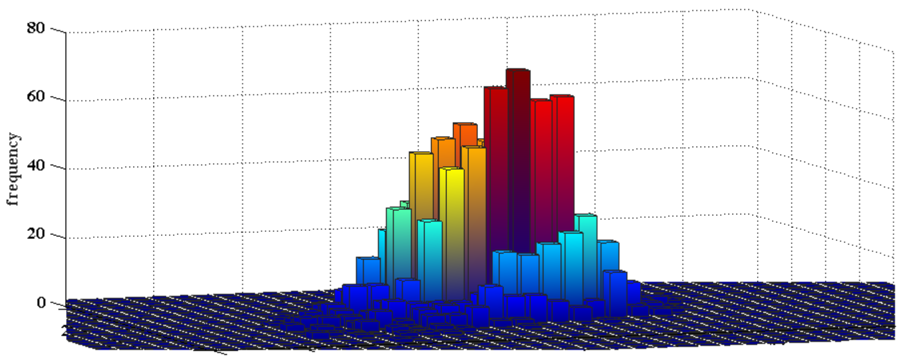

Figure 5.19 Frequency of the different optimum system configuration by aggregating all the scenarios

5.6 Summary

This chapter has addressed the development and implementation of a new procedure to perform load profiles estimates to be employed as input data of the design process for off-grid power systems for rural electrification. The procedure works with the typical input data that are commonly considered in the approach for energy consumption estimates, but it employs stochastic bottom-up approach and specific correlations between main load profiles parameters (i.e. load factor and coincidence factor) in order to build up the coincidence behavior of the electrical appliances considered by the users.

Moreover, the new procedure has been employed in two applications: the first one has shown the capability of the procedure in matching metered daily load profiles of a college in a peri-urban area of Cameroon, the second one has introduced an example of application of the procedure to perform stochastic sizing for an off-grid system.

6 System Capacity Planning of both Off-grid and On-grid Systems

Small-scale generation systems based on renewable energy sources are increasingly gaining importance within power supply services of both developing and developed countries. Indeed, as already debated in Paragraph 4.1, in DCs they can play a pivotal role in the electrification process of rural areas, while in developed ones they are gradually integrating within the main centralized grid in order to reduce the dependence (and its consequences) on fossil fuels.

In addition to the major positive features that brought about this growing interest (Table 4.2), it is worthwhile to mention also the main issues to be addressed when implementing this option. Specifically, these issues stem from the features of renewable energy sources: (i) they are intermittent and seasonal and (ii) short/medium term forecasts are quite difficult due to their high unpredictability. The consequent issues can be organized according to the context of reference (i.e. developing or developed countries).

For DCs, when dealing with rural electrification based on off-grid power systems and mostly with hybrid Micro-Grid, the decision process as regards systems components sizes is not straightforward:

- it means matching a number of renewable sources with an uncertain load demand while providing the most favorable conditions in terms of reliability and cost;
- it often involves to employ a storage systems which has to be sized according to provide proper system reliability, low costs, long life-time, etc. ;
- when a traditional system is employed (i.e. diesel / petrol generators), despite reliability is more easily addressed, further economic (i.e. high O&M costs) and environmental (i.e. emissions) constraints may arise;
- multiple power systems, storage systems, load and energy sources uncertainty require complex control logics and advanced power electronics.

For developed countries, when dealing with the design of Distributed Generation, issues as regards security, power system operating, and economic dispatch strategies have to be tackled (e.g. [112], [121], [157], [268]). Specifically:

- high penetration of Distributed Generation may require managing bidirectional power flows also within the distribution grid;
- Distributed Generation may bring about concerns as regards changes in the voltage profiles (i.e. voltage level increases next to the Distributed Generation thus determining a possible power flow inversion);
- the presence of Distributed Generation contributes in unpredictably changing the load profiles to be supplied with traditional power plants. This led to complicate the economical deals which regulate the unit commitment and power dispatch strategy thus provoking higher costs for the electric market regulating body;
- Distributed Generation does not provide ancillary services, on the contrary they are all supported by traditional power plants which are increasingly difficult to be managed on daily basis.

Within the process of system design, both in case of DCs as well as developed ones, all these issues cannot be tackled at the same step of the analysis. Nevertheless, in both cases, the identification of the main components sizes is preparatory to complete a proper design, implementation and operation of a system within a specific scenario. Indeed, focusing on the scenario of DCs, as already described when introducing the System Design Process addressed in this part of the thesis (Paragraph 1.3, Figure 1.7), once developed the *Context Analysis*, the following step deals with carrying out the identification of the proper mix of energy sources and of the system components sizes. This step has been referred as *System Capacity Planning* and in this chapter a procedure to address it is introduced. Specifically, a particular feature of the presented model relies in the capability to address both off-grid power systems (i.e. application of small-scale generation systems in DCs) and Distributed Generation (i.e. on-grid application in developed countries) planning.

In the following the typical features and scientific literatures analysis of System Capacity Planning approaches is presented, then the features and the general structure of the new procedure are introduced. Procedure steps are also presented through detailed description of the mathematical formulations. Finally the procedure has been applied to two cases: a theoretical off-grid capacity planning for the building B.12, of Bovisa Sud campus of the Politecnico di Milano, and an on-grid capacity planning for the city of Legnano (Italy). The main objective of the applications is to deepen the description of the procedure. In this perspective, mainly data coming from the context of developed countries are employed. Indeed, as already highlighted by the analysis of Ngarenanyuki case, lack of data is a typical in DCs. Therefore, to address the description of this new procedure, estimates or assumed data have been avoided in favor of real metered ones.

6.1 Typical Approaches in System Capacity Planning

As already highlighted, Systems Capacity Planning refers to the identification of the proper mix of energy sources and of the main power system components sizes (i.e. rate powers, storage capacities) (Paragraph 1.3, Figure 1.7). This presumes that at least one energy source (typically renewable one) is locally available, and relating data and end-uses consumptions data are also available or have been properly estimated. Given these information, planning of energy systems generally refers to the solution of the energy balance (i.e. Joule or Watt-hour) between energy sources and consumer loads in order to identify the most suitable system components sizes according to a specific objective function. Different accuracy in the analyses mainly results from the length of the time-step the balance is solved for, the degree of detail in the energy sources data, in the load data, in the mathematical modeling of the system components, and from the approach employed to look for the optimal solution. Usually time-step can vary from monthly- to hour-basis and analyses can be performed throughout a day, a year or several years.

Obviously, in addition to these general features, further ones are present in each specific method or model. In the following a short selection of energy planning approaches available in the scientific literature is presented. The selected papers focus on the scenario of DCs and they refer on papers reviewed in Paragraph 4.4. The objective is to highlights the main general features of available planning methods and models in order to highlights the peculiarities of the new procedure described in this chapter:

- in [198] the capacity planning for a stand-alone PV systems coupled with batteries has been accomplished by employing estimation of daily energy consumption of residential devices and availability of solar radiation. The main components sizing is based on a single daily energy balance, on assumed autonomy days and on simple components modellings;
- in [199] a hybrid Micro-Grid (wind, PV, batteries, diesel) is considered, and different power sources sizes and storage capacity are analyzed by means of energy indicators (i.e. renewable production, diesel production, etc.) in order to identify the best option to supply power to a household. Solar, wind data, and technical features of PV panels, wind turbines and batteries are considered. The energy balance is solved for a year and on monthly basis with simple components modelling;
- in [263] different energy systems options (i.e. traditional systems, off-grid systems, on-grid electrification) are compared according to energy indicators which are computed for different consumption scenarios of a rural village. The analyses within a scenario evolve throughout 15 years and are accomplished with daily energy balances. For each system option, data about the whole supplies chains (i.e. a set of energy systems which describe the different steps of energy conversion from primary sources to final uses) are employed. In this case, optimization of the energy supplies chains (both thermal and electrical power) is performed according to the constraints considered in a scenario (i.e. electrification rates, emission limits, renewables penetrations, etc.). Trends of targeted indicators throughout the considered timespan (i.e. TFC by sources and uses, emissions, etc.) are employed to analyze the different solutions;
- in [269] the optimum sizes of different power sources are identified by minimizing the overall life-time systems cost. Thermal and electrical consumptions are met by local available renewable resources thanks to mathematical constraints which work with yearly energy balances and consider simple components modelling.

These few examples have been considered since they allow identifying further specific features of energy planning approaches which can be summarized as follows:

- the different approaches can be grouped as for: (i) those which particularly address the computation or identification of components sizes in order to properly and precisely match the actual required loads within a *constant* scenario (e.g. [198], [199]), and (ii) those which consider the sizing of the system components as parameters or variables which contribute in analyzing an energy scenario in a global (also evolving) context (e.g. [263], [269]). The former ones better address the sizing issue, the latter ones the planning issue;

- the different approaches can also be grouped as for: (i) those which do not consider economics as main parameters for identifying and computing the system components sizes (e.g. [198], [199], [263]), and (ii) those which consider economic parameters in the process of selection and sizing (e.g. [269]);
- despite the complexity of the issue, in most cases simple modellings are considered for storage systems and for the definition of dispatch strategies within hybrid Micro-Grid (i.e. decision as regards the strategy of operating traditional systems and storage systems).

Also dedicated software tools have been developed to address the issue of Systems Capacity Planning and also in this case they show the same features that have just been recognized for specific methods and models: HOMER Energy [210] employs economic variables to perform life-cycle sizing of systems components within a constant scenario, RETScreen [270] employs economic variables to compare different energy systems solutions within evolving scenarios, MARKAL/TIMES [271] and LEAP [272] allow to analyze the of implementation of energy systems within specific energy/economic-defined scenarios (typically a country, in case of [263] to a village) along several years.

6.2 General Approach and Structure of the New Procedure

Hereafter an introduction of the new procedure for System Capacity Planning is developed according to two sections: (i) the main features of the procedure are introduced in order to highlight the *general approach*, and (ii) the *structure* of the procedure is depicted by a number of sequential steps. Then, in the following paragraph the overall procedure is deeply analyzed by presenting each step through its mathematical formulation.

General approach

The procedure has been developed and implemented in order to permit the *selection* of power sources and the *evaluation* of the sizes of generation and storage systems for small-scale power systems mainly based on renewable sources:

- *selection* refers to the capability, when multiple possible power sources are available, to develop a ranking of the sources in order to identify a preference for one source or for a mix of them;
- *evaluation* refers to the capability, with regards to specific objective functions, to compute the optimum sizes of power generation sources (i.e. Watts) and the capacities (i.e. Watthours) of storage systems.

Further specific features which are addressed by the procedure are also the following:

- the procedure has to be capable to adapt to different kinds of context which have been targeted for the implementation of small-scale power systems: (i) rural electrification interventions in DCs, i.e. off-grid systems planning, (ii) Distributed Generation implementations in developed countries (but in the future also in DCs), i.e. on-grid systems planning, and (iii) interventions in areas with availability of multiple energy sources;
- the procedure addresses only the supply of electricity, no interest is devoted to thermal loads;

- the procedure has to focus on the precise match of the available power sources with the actual required loads within a *constant* scenario. No interest is devoted in analyzing an energy scenario within an evolving context;
- the procedure has not to be developed and implemented as a single mathematical problem which is solved within a black box given input data and boundary constraints. On the contrary, the designer (i.e. the operator of the procedure) should be capable to handle singularly each step of the procedure. The steps should have their own mathematical formulation and the relating outputs;
- in a first step implementation the procedure does not employ economic parameters. Only energetic parameters are employed for the selection and sizes evaluation of system components;
- in addition to renewables the procedure has to be capable to handle also the selection and evaluation of a traditional power sources (diesel/petrol generator) and an electrochemical storage system.

Structure

The procedure is structured according to seven main steps (Figure 6.1):

1. energy maps embracing the yearly data series of consumer loads and generation profiles are collected or computed;
2. according to the targeted context the objective function of the procedure is selected and the energy maps can be processed in order to compute the sizes of the different power sources considered;
3. mathematical-statistical indicators are employed and then aggregated according to a number of methods in order to rank the considered power sources;
4. next to the resulting best power source, the other ones are introduced and a sensitivity analysis is performed in order to evaluate if a mix of the available power sources (i.e. a proper set of different sizes of the available power sources) better fit with the consumer load profile;
5. the integration of a traditional power sources (i.e. a diesel generator) is considered and analyzed;
6. the integration of an electrochemical storage is considered and analyzed;
7. the final planning of the power sources sizes and storage capacity is presented.

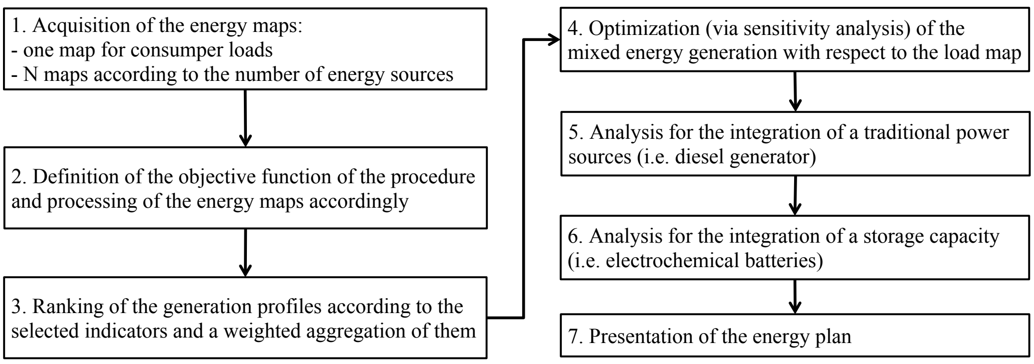

Figure 6.1 Main steps of the procedure for System Energy Planning

6.3 Mathematical Formulation of the New Procedure

In the following the mathematical formulation of each step constituting the procedure (Figure 6.1) is introduced and described. For some steps the formulation differs for off-grid applications and on-grid ones. Nevertheless the descriptions of the two cases run in parallel in order to show how the same procedure structuring permits to handle both cases.

While describing the procedure, the links between inputs and outputs among sequential steps are emphasized in order to highlight the possible actions that the operator can make while applying the procedure. The focus is posed mainly on the steps 1, 2, 3 and 4 which embrace the most innovative features in comparison with the typical System Capacity Planning approaches. An early development and formulation of the steps which address the traditional generator and storage analysis have been carried out and are described. Nevertheless, further improvements are still required.

Step 1: Acquisition of energy maps

The main input data of the procedure refer to the user electric consumption and to the available power supply. These are required in form of time-series of hourly data throughout a year. They can be grouped in two categories:

- load profile: one profile is required representing the hourly energy consumption (i.e. constant average power in a hour) of the considered context;
- generation profiles: *N* profiles can be considered representing the hourly energy production (i.e. constant average power in a hour) of the *N* power sources available in the considered context.

The procedure manages these time series-data in form of matrixes which results in *N+1 energy maps*. These can be described in mathematical form as follows:

$$Y(i,j) = \begin{bmatrix} x_{i,j} & x_{i,j+1} & \cdots & x_{i,J} \\ x_{i+1,j} & x_{i+1,j+1} & & x_{i+1,J} \\ \vdots & & \ddots & \vdots \\ x_{I,j} & x_{I,j+1} & \cdots & x_{I,J} \end{bmatrix} \quad \begin{matrix} i \in [1\,;\,24] \\ j \in [1\,;\,365] \end{matrix} \qquad (6.1)$$

where *Y(i,j)* refers to the overall profiles, *i* refers to the daily hours, *j* refers to the day throughout the year, and hence $x_{i,j}$ represents the single hourly energy data. Accordingly the energy maps can be depicted in graphical form (Figure 6.2).

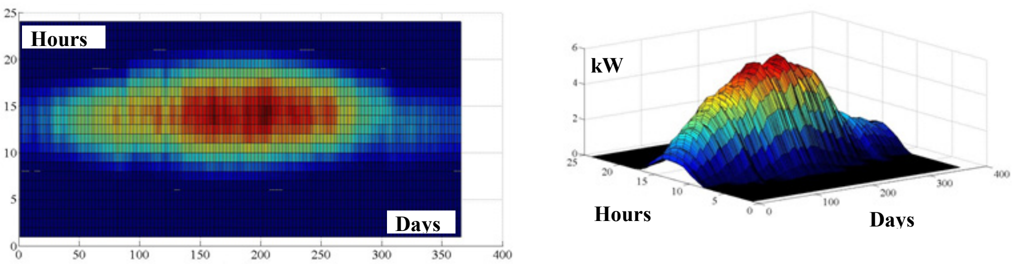

Figure 6.2 Graphical representation (2D and 3D) of the same energy map: the generation profile of a PV system

Matrix form has been selected since it allows analyzing the data (i.e. to compute specific indicators which describe the data) according to different groupings: on daily basis, on seasonal basis, on weekly basis, according to different daily time slot, etc. . *Hours* have been considered as the time step of the procedure since they are a compromise between detailed analysis potential (i.e. the matching between renewable availability and load profile is properly investigated thus leading to the proper analysis of traditional generators and storage sizing and functioning) and computational load.

The load energy maps can be obtained by means of:

- metered consumptions (mostly in case of on-grid applications in developed countries) which need to be processed in order to get average values if several yearly data are available;
- load profiles estimate (mostly in case of off-grid applications in DCs) which can be developed by models as the one described in this thesis (Chapter 5).

The generation energy maps can be obtained by means of:

- metered data of electric productions of real power generation systems, which need to be processed in order to get average values if several yearly data are available;
- mathematical/statistical review of incomplete data;
- system simulation with dedicated softwares.

According with this approach, it may happen that the generation energy maps refer to systems having a defined power size (which most probably is not the best size for the targeted context). As a matter of fact the important feature to be embraced in the procedure does not rely on the magnitude (i.e. the power size) of the profiles, but on the profile shape and its trend throughout the year. This characterizes the profile and determines the degree of "coupling" with the load profile shape. Therefore the generation energy maps will be converted in per unit (pu) reference.

Step 2: Objective function and energy maps processing

This step can be analyzed by considering three main phases:

1. *pre-processing of the generation energy maps* in order to be in the proper form as regards the next phase;
2. *selection and application of the objective function*, i.e. computation of the sizes of each power sources considered;
3. *post-processing of the generation energy maps*: computation of the resulting generation energy maps and computation of the *residual energy map*.

Pre-processing of the generation energy maps

Each generation energy map is converted into pu reference. This is required in order to get the specific features of each power sources without regard to the size of the system. Indeed the size of the system is the targeted variable to be optimized throughout the procedure.

Selection and application of the objective function

Two objective functions have been identified according to the targeted context of intervention:

- in case of off-grid application (i.e. the typical context of rural electrification actions in DCs), the objective function addresses the issue of looking for the size of power source which exactly allows to match the integral of the generation energy map with the integral of the load profile over the whole year (Eq. 6.2);

- in the case of on-grid application (i.e. the typical context of Distributed Generation connected to the grid in developed countries), the objective function addresses the issue of looking for the size of power source which allows the maximum compensation of the load profile while fulfilling the constraint of achieving a numbers of hours of *reverse power flow* which is lower or equal than 5% over a year[11]. *Reverse power flow* refers to the injection of power in the grid by the Distributed Generation (Eq. 6.3).

In this phase the selected objective function is applied to each single generation energy map and the targeted sole load energy map. Accordingly, for each generation energy map a coefficient, which represents the power size of the generation system, is obtained as resulting output of this phase.

The two objective functions are:

$$\sum_{t=1}^{T} P_{L,t} - (\rho^n * \sum_{t=1}^{T} P_{G,t}^{n}) = 0 \qquad off-grid\ case \qquad (6.2)$$

$$P_{L,t} - \sum_{t=1}^{K} (\beta^n * P_{G,t}^{n}) \geq 0, \forall t \in (1, K), K \geq X\%\ of\ T \qquad on-grid\ case \qquad (6.3)$$

where:

- t is the selected time-step, i.e. hour;
- T is the time period considered (year);
- $P_{L,t}$ represents the load energy map;
- $P_{G,t}^{n}$ represents the n-generation pu energy map;
- ρ^n is the coefficient of the n-generation that allows validating Eq. 6.2. It represents the power size to be installed in order to exactly match the energy load during T;
- β^n is the coefficient of the n-generator that allows validating Ineq. 6.3. It represents the power size to be installed in order to not exceed the energy load at least for $X\%$ of T.

ρ^n or β^n value for each available generation energy map is the output of this phase. Focusing on the off-grid case it is worthwhile to mention that, despite the meaning of the objective function refers to the achievement of sizing each generation system in order to completely match the load; the objective is fulfilled considering the overall year. This highlights that in particular hours the resulting generation values energy map are higher(lower) than the required load thus resulting in an excess(lack) of supplied energy. The same occurs in the on-grid case but with limited frequency of higher generation than the required load due to the objective function constraint.

Post-processing of the generation energy maps

In this phase new generation energy maps are computed by multiplying each pu map and the respective resulting sizing parameters (ρ^n or β^n). Then *N residual maps* are computed as follows:

[11] The value refers to the limits suggested by the Italian Standard technical rule CEI 0-16 [482], [483].

$$RP^n(i,j) = P_L(i,j) - (\rho^n * P_G^n(i,j)) \quad \forall(i,j) \qquad off-grid\ case \qquad (6.4)$$

$$RP^n(i,j) = P_L(i,j) - (\beta^n * P_G^n(i,j)) \quad \forall(i,j) \qquad on-grid\ case \qquad (6.5)$$

The residual maps are the energy maps that represents throughout the year the excess(lack) of supplied energy resulting from the superimposition of each obtained generation energy map and the load energy map. The residual maps are employed in the following step to rank the available power sources.

Step 3: Ranking of the available generation profiles

The objective of this step is to rank the available generation profiles from the best one the worst one as regards the capability to better meet the considered load profile. Specifically, at this stage, all the generation profiles are equivalent as regards the selected objective function which has modified them in order to fulfil the same constraint (i.e. the yearly energy integral for the off-grid case and the reverse power flow for the on-grid case). Nevertheless, this is not true when considering the hourly energy maps. In this case, each profile defines its own residual map which stems from the features of the specific power sources of the specific considered context.

The ranking process addresses the issue of assigning a merit to the generation profiles as regards the way they fit with to the load profile by considering the hourly data within the whole residual map. The ranking is computed (i) by applying a selection of 25 mathematical-statistical indicators which have been identified as tools to analyze the residuals map, and (ii) by applying 5 classification methods for these indicators.

In the following, this step of the procedure is described by means of three phases:

1. the list of the identified *residual map indicators* is presented;
2. the *development of the ranking* is described. Specifically this considers: the selection and computation of the indicators for the residual energy maps, and the weighted aggregation of the indicators with the proposed classification methods;
3. further *parameters* are computed for the residual energy maps in order to understand the ideal performances which would be required to a *storage* systems in order to exactly compensate the excess(lack) of supplied energy depicted by the residual maps.

Residual map indicators

The basis of this new energy planning procedure is represented by a set of mathematical-statistical indicators. It was deliberately chosen a statistical approach to characterize the resolution of the energy sources selection in order to employ a rigorous approach.

Given a residual map, the indicators are computed considering the $RP^n(i,j)$ values as a time-series data set. This concept leads to consider that a datum detected at the instant t has a relationship with the one at time $t-1$. The observations consecutive in time are therefore not thought of as a set of random variables, but as part of a stochastic process in which the relationships are given by the degree of connection between the variables that compose it.

The chosen approach for the analysis of the energy profiles is articulated on 25 mathematical-statistical indicators. These express the data characteristics which fall into three main categories: order of magnitude, dispersion and distribution. Moreover indicators can refer to individual hourly values or the interaction between them.

Table 6.1 briefly introduces the 25 indicators, while Appendix B presents a detailed description with mathematical formulations. The selected indicators stem from a first analysis based on the cases examined in the work, but this does not exclude the possibility to refine it thanks to further experience.

In the following, indicators of the residual profile *n* are defined as follows:

$$ind(i)^n \;\; with \;\; i = 1,2,\ldots,25 \tag{6.6}$$

Table 6.1 Mathematical-statistical indicators [273]

I_1	Energy integral
I_2	Hourly average
I_3	Hourly standard deviation
I_4	Maximum hourly value
I_5	Minimum hourly value
I_6	Rate of max/min hourly value
I_7	Range of hourly value
I_8	Quartiles
I_9	InterQuartile range
I_{10}	Mode
I_{11}	Average difference between consecutive values
I_{12}	Standard deviation of difference between consecutive values
I_{13}	Maximum difference between consecutive values
I_{14}	Minimum difference between consecutive values
I_{15}	Allocation of time variations according to the sign
I_{16}	Rate of maximum and minimum difference between consecutive values
I_{17}	Integral of the hourly differences grouped according to the sign
I_{18}	Rate of Average difference between consecutive values and standard deviation
I_{19}	Allocation of the energy integral in 10 classes
I_{20}	Allocation of number of hours in 10 classes
I_{21}	Skewness
I_{22}	Curtosi Index
I_{23}	Coefficient of variation
I_{24}	Average daily energy integral
I_{25}	Autocorrelation

Development of the ranking

In order to obtain the ranking of the generation energy maps the operator has to select the set of indicators which will be employed in the ranking process. The targeted indicators should be selected on the basis of the relevance for the case under analysis and as regards the type of generation considered. Then for each residual map, each indicator within the selected set is computed. Next, the indicators of each residual map have to be aggregated in order to define a value of merit of the generation source and therefore to define the ranking.

Eq. 6.7 represents the equation to compute, by means of the selected and computed indicators, the score (X_n) associated of a residual map *n*:

$$\sum_{i=1}^{25} \alpha_i x_i^n + \alpha_\rho \rho^n = X_n \tag{6.7}$$

where:

- x_i^n is the score associated to the indicator i of the generation profile *n*. This score is defined by comparing with different methods the indicators *i* of the considered generation profiles (the methods which define the score are introduced later on);
- α_i is the weight associated to the indicator *i*;
- ρ^n (or β^n) is the parameter computed with Eq. 6.2 and 6.3, i.e. the power size of the generation *n*;
- α_ρ is the weight associated to the power size parameter.

5 *classification method*s have been developed in order to compare each indicator *i* among each generation profile *n*, and hence to define the scores x_i^n . For each classification method, once all the indicators scores, and the weights as well, have been defined, the final scores X_n associated to each generation profile can be computed by means of Eq. 6.7. Then, the ranking of the generation profiles according to each classification method can be identified. It should be noted that the operator may decide to employ one or more classification methods according to the specific analysis under development.

The 5 classification methods can be described as follows:

1. in the first method, x_i^n are defined by ranking $ind(i)^n$ from the best one to the worst one as regards the residual profiles. That is, the best generation profile is the one resulting in the minimum indicators values of the associated residual map (i.e. the best generation profile is the one with the lowest scattering of values around zero, that is with the lowest excess(lack) of supplied power). The method can be formulated as follows:

$$x_i^n = f(ind(i)^n)\begin{cases} N & if\ ind(i)^n\ is\ the\ best\ one \\ N-1 & if\ ind(i)^n\ is\ the\ second\ best \\ \vdots & \vdots \\ 1 & if\ ind(i)^n\ is\ the\ worst\ one \end{cases} \quad (6.8)$$

   N is the number of considered profiles. In this case $\alpha_i = \alpha_\rho = 1$.

2. In the second method, x_i^n are defined as follows:

$$x_i^n = f(ind(i)^n)\begin{cases} 1 & if\ ind(i)^n\ best \\ 0 & if\ ind(i)^n\ not\ best \end{cases} \quad (6.9)$$

   a unitary score is assigned to the generation profile which is the best, while all other generations get the non-scoring. Even in this case the best generation profile is the one resulting in the minimum scattering of values around zero of the associated residual map. In this case, $\alpha_i = \alpha_\rho = 1$. This classification method is more favorable to the best generation.

3. The third classification method is equal to the first one as regards the definition of the values x_i^n which are defined using Eq. 6.8. Nevertheless different values of α_i are considered according to the specific indicators as follows:

$$\alpha_i = f(ind(i))\begin{cases} 3 & if\ ind(i)\ very\ important \\ 2 & if\ ind(i)\ fairly\ important \\ 1 & if\ ind(i)\ not\ much\ important \end{cases} \quad (6.10)$$

These weights are fixed, but the operator is free to set them for selected indicators.

4. The fourth classification method is obtained by defining 10 intervals I_1, I_2 ... I_{10} of equal size. Each indicator is characterized by intervals that are defined by the same width between the maximum and minimum value assumed by that indicator (max $(ind(i)^n)$ and min $(ind(i)^n)$). The values x_i^n are allocated according to the value of the indicators: the closer an indicator is to zero, the higher is the associated score since it falls in the first intervals. This logic can be formulated as follows:

$$x_i^n = f(ind(i)^n)\begin{cases} 10 & if\ ind(i)^n \in [I_1) \\ 9 & if\ ind(i)^n \in [I_2) \\ \vdots & \vdots \\ 1 & if\ ind(i)^n \in [I_{10}] \end{cases} \qquad (6.11)$$

In this case $\alpha_i = \alpha_p = 1$.

5. The fifth classification method involves the analysis of ind(25), i.e. the autocorrelation indicator. For each residual map the autocorrelation values for discretization time up to 1/4 of the amount of data within the considered profiles are calculated. This means that the considered values are: (i) the autocorrelation values of a day (i.e. the first 25, since the former has a step k zero), (ii) the autocorrelation values of one week (i.e. the first 169), (iii) the autocorrelation values of four weeks (i.e. monthly basis, the first 673 values) (iv) the autocorrelation values of a season (i.e. the first 2,017). For each clustering is calculated the average of the absolute values of the autocorrelation. This lead to obtain four average data μ_d^n, μ_w^n, μ_m^n, μ_s^n (daily, weekly, monthly and seasonal). Finally the overall average is calculated and according to this value the scores are assigned as follows:

$$\mu_{tot}^n = \frac{\mu_d^n + \mu_w^n + \mu_m^n + \mu_s^n}{4}$$

$$x_i^n = f(\mu_{tot}^n)\begin{cases} N & if\ \mu_{tot}^n\ best \\ (N-1) & if\ \mu_{tot}^n 2nd\ best \\ \vdots & \vdots \\ 1 & if\ \mu_{tot}^n\ worst \end{cases} \qquad (6.12)$$

The autocorrelation determines a relationship between a datum at time *t* with the one at time *t+1* and it results to be higher when strict relationship occurs in the time-series. Therefore, this indicator is considered the best in inverse form when compared to the previous. Indeed higher scores are given to higher values of autocorrelation.

Some observations can be introduced as regards the classification methods:

- the first two methods are more linear, in fact the score is evaluated without attributing any change in weight to each indicator. They are the most appropriate choice for those operators operator who do not accurately know the characteristics of the generation profiles;
- the third and fourth method are more detailed and evaluate, with different weighting systems, the scores of the indicators. Their use is more significant if further information on the generation profiles are available as well as on the context of intervention. Indeed they allow the operator to better guide the process.

At this stage, having all X_n values is possible to set up a classification synthesis (*final ranking*) based on the results obtained from the five classification methods. The final ranking can be expressed as percentage of compatibility between generation and load profiles. This is computed as the rate between the sum of the ranking position obtained in the 5 methods and the maximum achievable sum.

As already highlighted, the output of this phase is a ranking of the single generation profiles as regards their capability to fit with the load profile.

Storage parameters

Beyond the ranking determination, further constraints that determine the possible insertion of a storage system are calculated. These constraints characterize the residual maps, i.e. the lack / excess of supplied energy which, in perspective, should be managed by a storage system. They are calculated with the aim to support the operator in choosing the best resource. Indeed, they can be used as an *ex-post* verification of the actual effectiveness of the chosen indicators, but also included in the metric analysis.

Three constraints are considered:

- *energy constraints:* represent the minimum and maximum energy as regards the cumulated profile given by the residual profile. They can be formulated as follows for the off-grid case (β^n substitutes ρ^n for the on-grid case):

$$min\left(\sum_{t=1}^{T} P_{L,t} - \rho^n * \sum_{t=1}^{T} P_{G,t}^n\right) \tag{6.13}$$

$$max\left(\sum_{t=1}^{T} P_{L,t} - \rho^n * \sum_{t=1}^{T} P_{G,t}^n\right) \tag{6.14}$$

  Eq. 6.13 expresses the maximum size of the storage system to store all the excess energy produced by the generation *n*. Eq. 6.14 expresses the maximum amount of energy that the storage system should be able to retain to satisfy any demand of the load which is not covered by the generation *n*;

- *power constraints*: represent the minimum and maximum hourly value of the residual profile. They can be formulated as follows for the off-grid case (β^n substitutes ρ^n for the on-grid case):

$$min\left(P_{L,t} - \rho^n * P_{G,t}^n\right) \tag{6.15}$$

$$max\left(P_{L,t} - \rho^n * P_{G,t}^n\right) \tag{6.16}$$

  Eq. 6.15 represents the maximum power flow injected into the storage throughout the yearly hourly time-series. Eq. 6.16 represents the maximum power flow required to the storage in one hour in order to ensure the stability of the system;

- *ramp constraints*: represent the difference between the maximum and minimum values of two consecutive hourly values of the residual map. This parameter is useful for determining the behavior of the storage as regards the capability to cover high rate of change in power flows between one time step and the following one. They can be formulated as follows for the off-grid case (β^n substitutes ρ^n for the on-grid case):

$$min\left[\left(P_L(t) - \rho^n * P_G^n(t)\right) - \left(P_L(t-1) - \rho^n * P_G^n(t-1)\right)\right] \quad (6.17)$$

$$max\left[\left(P_L(t) - \rho^n * P_G^n(t)\right) - \left(P_L(t-1) - \rho^n * P_G^n(t-1)\right)\right] \quad (6.18)$$
$$with = 2, \dots, 8760$$

At the end of this third step the available generation profiles have been ranked from the best one the worst one as regards the capability to better meet the considered load profile. Moreover, a number of parameters to characterize the hypothetical insertion of a storage system are calculated.

Step 4: Optimization of the mixed energy generation

Once the final ranking of the single energy sources has been accomplished, the following step is to evaluate if a mix of the available sources better fit the load profile rather than the resulting best single source. This is performed by a sensitivity analysis which addresses the issue of analyzing if any improvements in the residual maps resulting from a mix of generation energy maps occur. This happens if new generation profiles complementarily integrate the former ones without exacerbating the profile criticalities already present.

This step may require iterative computation of the *step 2* and of the *step 3* already described. Indeed the sensitivity analysis is carried out iteratively in 3 main phases as follows:

- a second generation profile is considered beside the resulting best one according to the ranking, and the *computation of new power sizes* is carried out through modified objective functions;
- a *computation of a new rank* of the generation mix is performed by means of the selected indicators. Then it is verified if the generation mix under analysis leads to any improvement;
- a number of *iteration* of the previous steps is carried out increasing the sizes of the second generation profile and introducing further generation profiles until an optimum solution is recognized by the operator.

Computation of new generators nominal power

The second best generation profile according to the first ranking is considered and its nominal power is computed in order to address the same objective functions. These are modified in order to consider multiple generation profiles. The modified objective functions are formulated as follows:

$$\sum_{t=1}^{T} P_{L,t} - \rho_{1,c} * \sum_{t=1}^{T} P_{G1,t} - \rho_{2,c} * \sum_{t=1}^{T} P_{G2,t} = 0 \qquad off - grid\ case \quad (6.19)$$

$$P_{L,t} - \sum_{t=1}^{K}(\beta_{1,c} * P_{G1,t}) - \sum_{t=1}^{K}(\beta_{2,c} * P_{G2,t}) \geq 0, \quad (6.20)$$
$$\forall t \in (1, K), K \geq X\%\ of\ T \qquad on - grid\ case$$

where:

- t is the selected time-step, i.e. hour;
- T is the time period considered (year);

- $P_{L,t}$ represents the load energy map;
- $P_{G1,t}$ represents the best generation pu energy map according to the first ranking;
- $P_{G2,t}$ represents the second best generation pu energy map according to the first ranking;
- $\rho_{1,c}$ is the coefficient of the best generation energy map which has been reduced by 1% as for the one resulting from Eq. 6.2. It represents the power size of the best generation source to be considered in the new generation mix;
- $\rho_{2,c}$ is the coefficient of the second ranking generation that allows validating Eq. 6.19. It represents the power size to be installed in order to exactly match the energy load during *T* together with the first generation profile;
- $\beta_{1,c}$ is the coefficient of the best generation energy map which has been reduced by 1% as for the one resulting from Ineq. 6.3. It represents the power size of the best generation source to be considered in the new generation mix;
- $\beta_{2,c}$ is the coefficient of the second ranking generation that allows validating Ineq. 6.20. It represents the power size to be installed in order to not exceed the energy load at least for *X%* of *T*.

According to the outputs of the application of the objective functions, new energy maps for the single sources are computed by multiplying each pu map and the respective resulting sizing parameters ($\rho_{1,c}$, $\rho_{2,c}$ or $\beta_{1,c}$, $\beta_{2,c}$). Then a new residual map which refers to the new combination of two generation profiles is computed and is the output of this phase.

Computation of a new rank

At this stage, for the new residual map, all the selected indicators as well as the classification methods for ranking process are computed. Then the decision as regards considering the new mix of generation profiles as the best one proceeds in two steps:

1. the operator can consider the results of the ranking process and discharge the previous best solution if the new one ranks first;
2. the operator can further consider an ex-post evaluation useful to confirm that the new ranking has really provided a new optimum. This can be carried out by looking at the size of the hypothetical storage to be considered within the system. Specifically the new size of the storage is computed as follows for the off-grid case ($\beta_{1,c}$ and $\beta_{2,c}$ substitutes $\rho_{1,c}$ and $\rho_{2,c}$for the on-grid case):

$$min\left(\sum_{t=1}^{T} P_{L,t} - \rho_{1,c} * \sum_{t=1}^{T} P_{G1,t} - \rho_{2,c} * \sum_{t=1}^{T} P_{G2,t}\right) \quad (6.21)$$

$$max\left(\sum_{t=1}^{T} P_{L,t} - \rho_{1,c} * \sum_{t=1}^{T} P_{G1,t} - \rho_{1,c} * \sum_{t=1}^{T} P_{G2,t}\right) \quad (6.22)$$

Eq. 6.21 expresses the maximum size of the storage system to store all the excess energy produced by the generation mix 1 and 2. Eq. 6.22 expresses the maximum amount of energy that the storage system should be able to retain to satisfy any demand of the load which is not covered by the generation mix 1 and 2.

It is expected that the capacity of the energy storage decreases from the previous computation. If this does not happen then the best profile remains the one with a single generation profile.

The output of this phase is to verify if the combination of two generation profiles is better than the single generation profile which has resulted to be the best.

Iteration and identification of the best generation protfolio

If the new mix of generation profiles results to be the best, then a further decrease of the main generation profile can be considered together with a new size of the second one, i.e. Eq. 6.19 and Ineq. 6.20 are considered again with 1% lower values of $\rho_{1,c}$ (or $\beta_{1,c}$) and new values of $\rho_{2,c}$ (or $\beta_{2,c}$) are computed. Accordingly a new ranking is performed together with new size of the storage. Then it is evaluated if the new configuration shows any improvement.

This iterative process can be carried out until any improvement does not occur. Then the third generation profile of the primary ranking can be considered and the whole process can be followed again in order to evaluate if any further improvement occurs by considering a mix with three generation profiles.

Increasing the number of considered generation profiles makes complex the sensitivity analysis. Indeed, with three profiles the local optimal solution can be recognized both by decreasing the first generation profile (while keeping constant the second one) and by decreasing the second profile (while keeping constant the first one). In any case the operator can avoid the sensitivity analysis or stop it once he decides that the result is satisfactory. Actually this search for the optimum configuration follows the approach of the *gradient method*. Nevertheless, the identified solution obviously does not represent the absolute optimum, but it represents an ideal relative optimum. Due to the uncertainty that can be associated to RESs power generation maps and load energy maps, mainly in DCs, a solution associated to a relative optimum has been considered acceptable.

At the end of this forth step the mix of the available energy sources which better fit the load profile has been identified in term of power sizes for each source.

Step 5 / 6: Integration of a traditional power sources (i.e. a diesel generator) and of an electrochemical storage

The evaluation of the optimum sizes of a traditional power source like a diesel generator and of a storage system is not straightforward. Indeed this requires to introduce further constraints and to perform further analyses which stem from the context of applications, i.e. off-grid or on-grid implementations. These result in constraints as regards the reliability of the supply, the fulfilment of technical regulations for grid connection, in analyses for the optimization of dispatch strategies, and in analyses of technical-economical performances, etc. .

As a matter of fact, the analyses of integration of storage and traditional power sources into off-grid power systems provides several rooms for research as it can be recognized in the review reported in Chapter 4. Actually in developing this procedure for System Capacity Planning, the focus has been posed mainly on the steps 1, 2, 3 and 4 which embrace the most innovative features. Nevertheless, an early development and formulation of the steps which address the traditional generator and storage analysis have been carried out.

Integration of a traditional power sources

Both for the off-grid and the on-grid case, to options have been considered in order guide the definition of the size of the traditional generator:

- inserting the generator ex-ante the execution of step 2 and 3. That is, to consider it as a first power source employed to supply the base-load, i.e. to "flatten" the load profile;
- to identify the size of the generator with constraints as regards the number of switching on the total amount of functioning hours. The process to evaluate the size is depicted in Figure 6.3 where the generator is supposed to work only at full capacity once switched on. In this case the operator is free to change the values of the constraints.

Once the size of the traditional generator is identified then the operator can choose whether or not to consider this solution depending on the context and the size of the batteries.

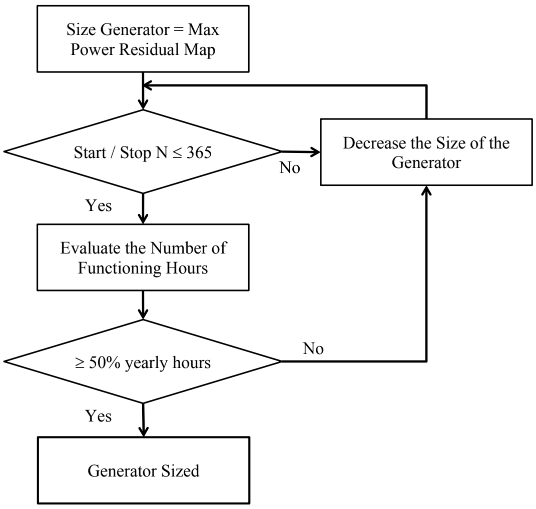

Figure 6.3 Flow chart for evaluation of the traditional generation size

Integration of an electrochemical storage

For the off-grid case the storage has to be sized in order to assure the complete supply of the required load. This is addressed by employing Eq. 6.13 and 6.14 to the residual profile given by the optimum mix of the generation profiles together with the traditional generator one. These equations provide the maximum range of accumulated/discharged energy throughout the year. Accordingly, with this approach the analysis takes place on a seasonal horizon. This leads to consider the worst case and hence it determines an oversizing of the storage system.

For the on-grid case, the need of the battery is related to alleviate some critical functioning conditions for the grid. Indeed, the batteries can absorb energy during the hours in which the generation exceeds the energy demand while avoiding the critical issues of the reversal of flow. In this case, the idea is that the batteries are sized in order to perform the function of peak shaving and the ancillary service (e.g. frequency control). Also in this case, the batteries are dimensioned on a seasonal horizon which leads to an oversizing. Nevertheless, the constraints that must be met to ensure the ancillary services impose that the battery must assure a power ranging from 1.5% to 3% of the nominal total power of the renewable energy technologies installed for 15 minutes (in order to assure the primary frequency regulation). The rest of the energy stored can be dedicated to the function of peak shaving. In the procedure the worst case has been considered and a bond of 3% of the nominal total power of renewables has been considered.

In any case, the choice of the integration of the storage system is always delegated to the operator who evaluates the convenience of such operation according to the results.

Beside the evaluation of the sizes, the storage performances worsen as battery life goes on, and this may deeply affect the overall system performances. Battery life-time, decrease of energy capacity, decrease of power to energy ratio are some of the parameters that change along batteries life-time thus affecting the performances of the overall power system. Several studies have been carried out in order to embrace in the sizing of small-scale power systems this features (e.g. [274]–[276]). In this procedure a simple model has been implemented in order to evaluate, once the batteries have been sized, their performances throughout a year. This model has been employed also in the stand-alone PV system model employed in Chapter 7 and explained in Appendix C.

Step 7: Presentation of the energy plan

The procedure has been implemented as a software tool by using Microsoft Excel and MATLAB. Therefore, the energy maps analysis by means of the set of indicators, the application of the objective functions, the ranking of the generation profiles, the sensitivity analysis and the evaluation as regards the integration of a traditional generator and a storage systems, are automatically performed by the tool. Nevertheless, being the procedure structured in steps, the operator can access the outputs of each step and hence take decisions as regards the following one according to the outputs themselves or according to further elements or preferences.

The final energy plan is a result of the rigorous analysis made by each step of the procedure together with operator judgments.

6.4 Energy Maps Employed in the Applications

As already introduced, in the procedure the energy maps are grouped as follows:

- load profiles representing the hourly energy consumption (i.e. constant average power in a hour) of the considered context;
- generation profiles representing the hourly energy production (i.e. constant average power in a hour) of the power sources available in the considered context.

In this paragraph, the energy maps that are later employed in the applications are introduced and briefly described by means of ind(1), ind(2), ind(4), and ind(5) (Table 6.1). The main objective of the applications is to deepen the description of the new procedure in order to better highlight the specific features in addition to the mathematical formulation. In this perspective, the applications refer, for most of the energy maps, to data coming from the context of developed countries. Indeed, as already highlighted by the analysis of Ngarenanyuki case, lack of data (both in term of energy sources and consumptions) is a typical features of DCs.

Load energy maps

Two load energy maps are considered:

1. the first load energy map refers to one among the primary substation (ps) owned by Enel Distribuzione SpA. A ps is the connection between high to medium voltage grids in the Italian system. In this case data refer to the ps of the city of Legnano

which consists in two MV/LV transformers each one of 25 MVA. Legnano is a city in the northern of Italy in the area of Milan which is one of the most industrialized and densely populated areas of the country. The data were provided by Politecnico di Milano. In particular, the collaboration refers to the Alpstore project which deals with smart-mobility and storage systems within the arena of smart-grid researches [268]. Figure 6.4 shows the graphical representation of the Legnano load energy map and Table 6.2 reports a few features of the map by means of selected indicators.

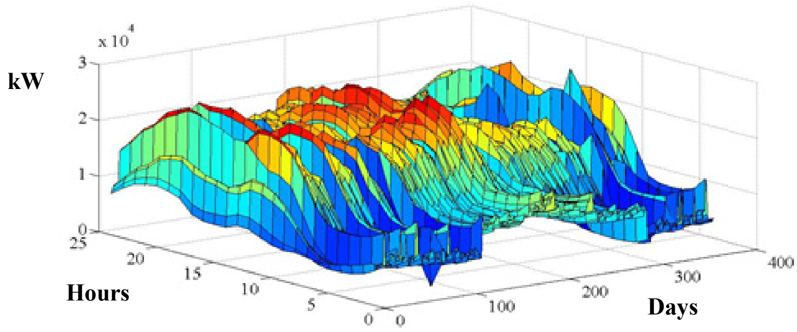

Figure 6.4 Load energy map for the city of Legnano

Table 6.2 Short features overview of Legnano load energy map

Ind(1) - Energy integral	111.1 GWh
Ind(2) - Hourly average	12.7 MW
Ind(4) - Maximum hourly value	27.17 MW
Ind(5) - Minimum hourly value	2.45 MW

2. the second load energy map refers to the consumption of a building within the campus Bovisa of Politecnico di Milano. The data correspond to the energy load of a building located in Via La Masa 34, identified by the number B12. The building hosts primarily classrooms and offices, while in the wind tunnel several labs are located. The data were provided directly by the Politecnico di Milano. Figure 6.5 shows the graphical representation of the Bovisa load energy map and Table 6.3 reports a few features of the map by means of selected indicators.

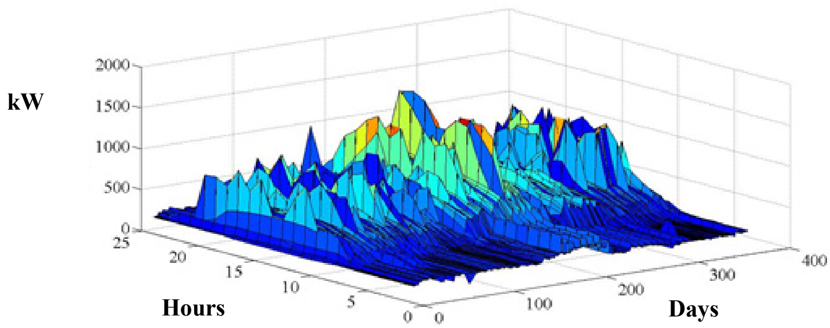

Figure 6.5 Load energy map for building B12 at Politecnico di Milano

Table 6.3 Short features overview of load energy map of building B12 and wind tunnel at Politecnico di Milano

Ind(1) - Energy integral	3.31 GWh
Ind(2) - Hourly average	337.64 kWh
Ind(4) - Maximum hourly value	1.7 MW
Ind(5) - Minimum hourly value	42.46 kW

Generation energy maps

Five generation energy maps are considered:

1. the first generation energy map refers to a PV systems in Italy located in the Lombardia region. Data have been provided by Politecnico di Milano and they are metered data which cover the system supplied power for a whole year. The power size of the system is unknown, but data suggest about 6-7 kW. Basically, this profile represents the typical Distributed Generation which exploit local available energy sources and which is widely spreading in developed countries. Figure 6.6 shows the graphical representation of the PV system generation energy map and Table 6.4 reports a few features of the map by means of selected indicators. The "bell" trend typical of solar energy source can be recognized.

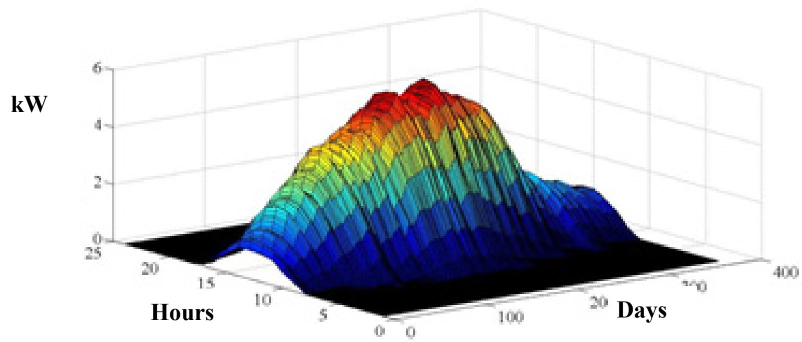

Figure 6.6 Generation energy map for the PV system operating close to the city of Mantova

Table 6.4 Short features overview of generation energy map of the PV system operating close to the city of Mantova

Ind(1) - Energy integral	9.59 MWh
Ind(2) - Hourly average	1.09 kW
Ind(4) - Maximum hourly value	5.83 kW
Ind(5) - Minimum hourly value	0 kW

2. the second generation energy map, adopted for demonstration purposes, refers to the aggregation of all the wind power system connected to the power grid of Belgium, both on-shore and off-shore. Data represent the sum of the power supplied by all the wind systems during the 2012 and they have been collected at the Belgium's electricity transmission system operator webpage [277]. Figure 6.7 shows the graphical representation of the Belgium wind system generation energy map and Table 6.5 reports a few features of the map by means of selected indicators.

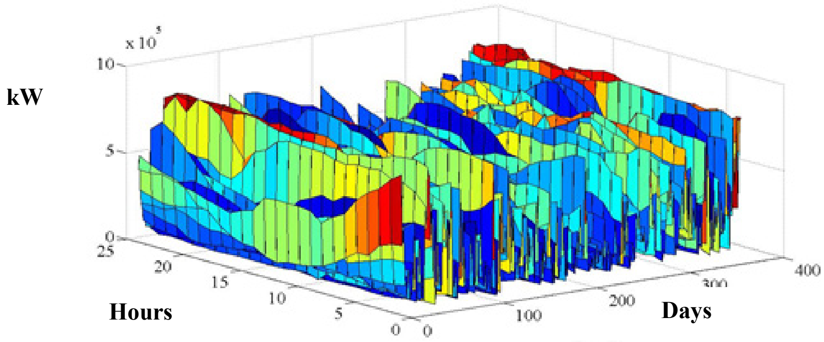

Figure 6.7 Generation energy map for the wind systems connected to the Belgium power grid

Table 6.5 Short features overview of generation energy map for the wind systems connected to the Belgium power grid

Ind(1) - Energy integral	2,327 GWh
Ind(2) - Hourly average	265.63 MW
Ind(4) - Maximum hourly value	879.61 MW
Ind(5) - Minimum hourly value	2 MW

3. the third generation profile refers to a cogeneration system. As opposed to the previous profiles, this set of data does not represent a real plant, but data are simulated. Indeed, the typical behavior of a cogeneration plant is considered. It shows a not-working period during nigh hours and an increasing power generation during the day until the full power supply is reached in the middle of the day. A decreasing power ramp occurs in the evening too, until the cogeneration stops. Moreover, during holidays and week-end days, the system does not work. The system has a nominal power of 300 kW_{el} with the possibility of thermal cogeneration (which is not considered for the sake of this analysis). Basically, it is a small power system which represents a typical Distributed Generation plant for an industrial site. Figure 6.8 shows the graphical representation of the cogenerator generation energy map and Table 6.6 reports a few features of the map by means of selected indicators.

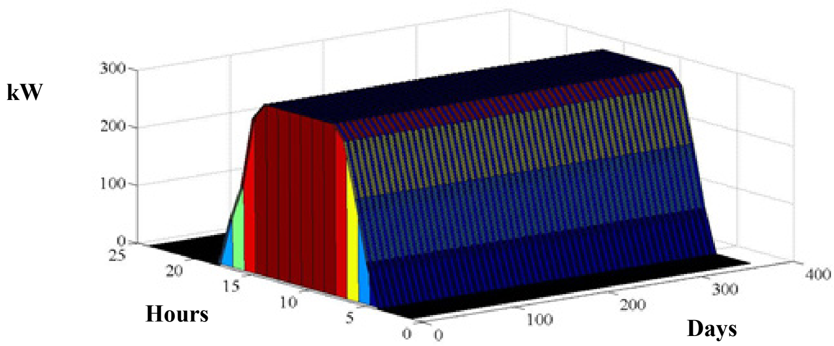

Figure 6.8 Generation energy map for the cogeneration system

Table 6.6 Short features overview of generation energy map for the cogeneration system

Ind(1) - Energy integral	816.7 MWh

Ind(2) - Hourly average	93.2 kW
Ind(4) - Maximum hourly value	300 kW
Ind(5) - Minimum hourly value	0 kW

4. the fourth generation profile refers to a PV system in a sub-Saharan region. Data have been provided by the company Building Energy SpA [278] which operates in the field of renewable energy systems and has also gained experiences in interventions in sub-Saharan countries. The PV system has a power of 10 MW and the profile has been obtained by simulation with a software tool of the company. The software considers a 20% difference between summer and winter production and simulates a mono-axial tracking system for the PV panels. Figure 6.9 shows the graphical representation of the of the PV system generation energy map and Table 6.7 reports a few features of the map by means of selected indicators.

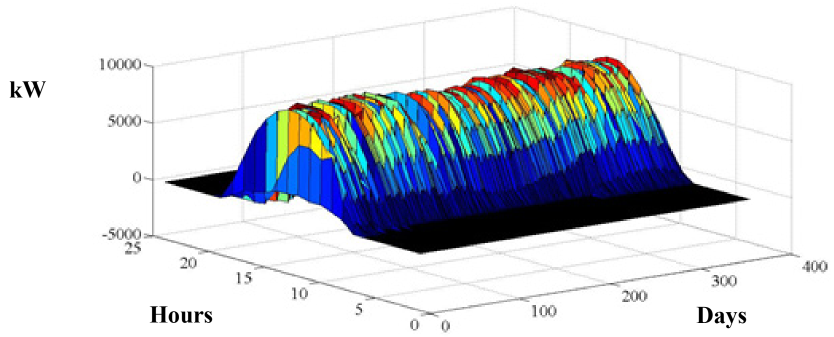

Figure 6.9 Generation energy map for the PV system in sub-Saharan Africa

Table 6.7 Short features overview of generation energy map for the PV system in sub-Saharan Africa

Ind(1) - Energy integral	19.3 GWh
Ind(2) - Hourly average	2.2 MW
Ind(4) - Maximum hourly value	9.45 MW
Ind(5) - Minimum hourly value	0 kW

5. the fifth generation profile refers to the power generation of a 3 MW wind turbine for a whole year. It has been provided by the company Building Energy SpA which has simulated it with a software tool. Figure 6.10 shows the graphical representation of the wind turbine energy map and Table 6.8 reports a few features of the map by means of selected indicators.

Table 6.8 Short features overview of generation energy map for the wind turbine

Ind(1) - Energy integral	12.9 GWh
Ind(2) - Hourly average	1.47 MW
Ind(4) - Maximum hourly value	3.12 MW
Ind(5) - Minimum hourly value	0 kW

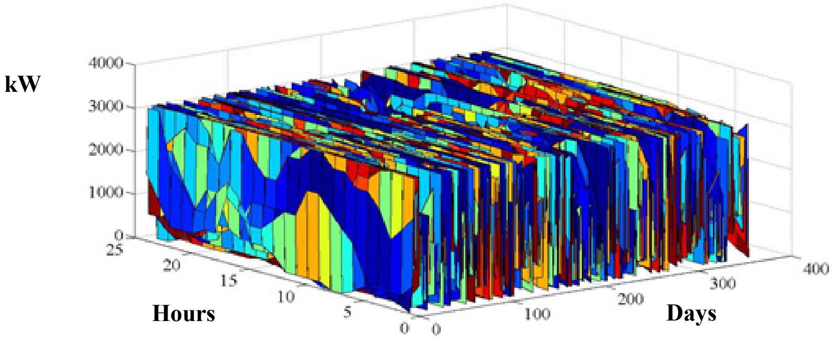

Figure 6.10 Generation energy map for the wind turbine

6.5 Application 1: Off-grid System Capacity Planning

The planning of the system capacity for the off-grid case has been applied to the building B12 at Politecnico di Milano (Figure 6.5). It has been selected for the off-grid case since it shows the lowest energy requirement, the lowest peak power and the lowest average hourly energy supply, thus being the most proper for a small-scale power system.

As regards the generation profiles, all the five generation energy maps previously described have been considered for the analysis.

Looking at the selection of the statistical-mathematical indicators for the ranking process, among the 25 defined indicators, those which better adapt to the considered analysis have been selected. They are 11 and are briefly introduced in the following:

- the parameter ρ^n, i.e. the generations power size according to the objective function (Eq. 6.2);
- the indicators addressing the analysis of data scattering: from ind(3) to ind(9);
- the features of the hourly trend has been considered by computing the indicators from ind(11) to ind(14);
- the relationships among data within the series has been analyzed by ind(25).

These indicators have been computed for the residual maps resulting from Eq. 6.4 as regards the five single generation profiles. Table 6.9,

Table 6.10 and Table 6.11 show results as regards indicators computations for the five residual maps.

Table 6.9 Computed indicators for the single generation profiles in the off-grid case

	Profile 1	**Profile 2**	**Profile 3**	**Profile 4**	**Profile 5**
ρ [kW]	2,010.75	1,250.55	1,215.24	1,619.21	798.24
ind (3) [kWh]	444.46	352.96	524.00	463.75	360.24
ind (4) [kWh]	1,174.58	1,616.54	1,589.28	1,543.00	1,613.16
ind (5) [kWh]	-1,631.88	-1,033.63	-1,215.24	-1,461.91	-798.27
ind (8) [kWh]	*	*	*	*	*
ind (9) [kWh]	432.12	412.80	803.45	510.71	534.02
ind (11) [kWh]	0.0037	0.0005	0.0037	0.0037	-0.0865
ind (12) [kWh]	152.12	98.34	175.57	194.04	159.97
ind (13) [kWh]	755.41	722.44	1,050.98	1,006.82	908.08
ind (14) [kWh]	-759.00	-778.54	-759.00	-1,179.00	-843.14
ind (25)	◦	◦	◦	◦	◦

Table 6.10 Details for ind(8) off-grid case

Quartile *	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5
25%	-174.28	-205.67	-491.05	-242.30	-295.68
50%	212.52	38.22	226.38	217.36	21.57
75%	257.84	207.13	312.40	268.40	238.34

Table 6.11 Details for ind(25) off-grid case

Autocorrelation	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5
I° value	0.9414	0.9604	0.9439	0.9125	0.9013
II° value	0.8095	0.9093	0.8302	0.7417	0.7877
III° value	0.6268	0.8501	0.6877	0.5278	0.6768

Given the values of the 11 selected indicators, the rank of the generation profiles has been carried out by applying the five developed classification methods. The ranking results for the five methods are depicted in the following by radar graphs: (i) each colored line represents a coupling between the load energy map and one generation energy map, (ii) the concentric polygons depict the possible score of the indicators, (iii) these scores are defined on the segments which pass through the center.

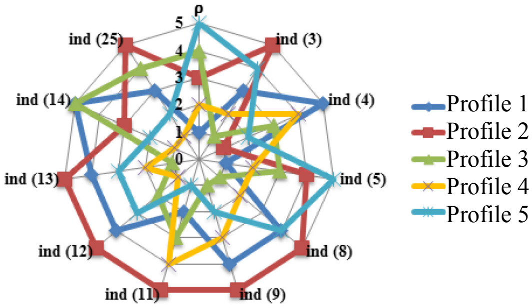

Figure 6.11 Graphical representation for the first classification method, off-grid case

Figure 6.11 shows the ranking results for the first classification method (Eq. 6.8): the best coupling is reported by the generation energy map 2, indeed it shows 7 indicators with best results, the second best profile is the generation energy map 1 (2 best indicators), then the generation energy map 5.

Similarly, Figure 6.12, Figure 6.13 and Figure 6.14 shows generation profile ranking according to classification method 2, 3 and 4 respectively.

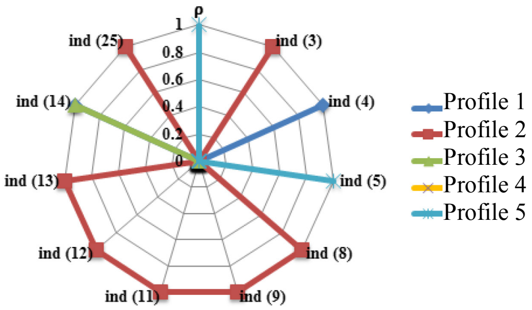

Figure 6.12 Graphical representation for the second classification method, off-grid case

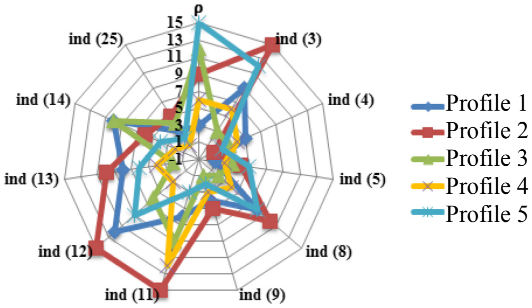

Figure 6.13 Graphical representation for the third classification method, off-grid case

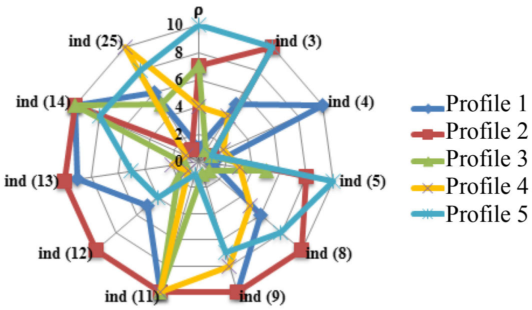

Figure 6.14 Graphical representation for the fourth classification method, off-grid case

The aggregation of the results of the five classification methods, which provides the final ranking of the generation energy maps, is reported in Table 6.12. The best profile refers to the generation energy map 2 which reports a probability to fit with the load energy map of 99.02%, the generation energy map 1 follows reporting 80.49%, finally the generation energy map 5 is the third one with 63.90%.

Table 6.12 Synthesis of the five classification methods and final ranking for the off-grid case

	Profile 1	**Profile 2**	**Profile 3**	**Profile 4**	**Profile 5**
Rank 1	4	5	2	1	3
Rank 2	4	5	2	1	4
Rank 3	4	5	2	1	3
Rank 4	4	5	1	2	3
Rank 5	0.5	0.3	0.2	0.4	0.1
Ranking in %	80.49	99.02	35.12	26.34	63.90

Considering the three best profiles (i.e. profiles 2, 1, 5) the sensitivity analysis has been performed. This analyzes the integration of multiple profiles in order to get a better match with the load energy map. At this stage the reference parameter to recognize the optimum solution is the size of the storage systems. The sensitivity analysis has been carried out in four steps: (i) adding up profile 1 and performing the optimization with two generation profiles, (ii) adding up also profile 5 and performing the optimization by reducing profile 2 and keeping constant profile 1 (3 generations, Case I), (iii) adding up also profile 5 and performing the optimization by reducing profile 1 and keeping constant profile 2 (3 generations, Case II), (iv) starting from optimum got at point (ii) and decreasing also profile 1 (3 generations, Case III). Results are shown in Table 6.13. The green cell highlights the best case as regards the objective function (i.e. minimum storage size), while the red cell highlights the worst one. This is associated to the single generation profile. It is clear how adding further generation reduces the storage sizes. The optimum result is given for three generation profiles which allow reducing by more than 70% the size of the storage when compared to the best single generation profile.

Table 6.13 Sensitivity analyses results, off-grid case

	Case	Storage [kWh]	Profile 2 [kW]	Profile 1 [kW]	Profile 5 [kW]	Total Power [kW]
1	1 generation	512,615	1,250.55	0.00	0.00	1250.55
2	2 generations	134,855	725.32	844.51	0.00	1569.83
3	3 generations Case I	133,194	616.52	844.51	69.45	1530.48
4	3 generations Case II	133,844	725.32	836.07	3.35	1564.74
5	**3 generations Case III**	**133,104**	**616.52**	**836.07**	**72.80**	**1525.39**

In order to complete the analysis in Table 6.14, Table 6.15 and Table 6.16 are shown the values associated for the 11 targeted indicators with reference to the five accomplished sensitivity analyses. The green cells highlight the best results (which are most reported by the last case), while the red cells highlight the worst results (which are most reported by the single generation source). This result confirms the optimization which has been performed by looking at the storage size.

Table 6.14 Computed indicators for the sensitivity analyses in the off-grid case

	1 generation	2 generations	3 generations Case I	3 generations Case II	3 generations Case III
ρ1 [kW]	1,250.55	725.32	616.52	725.32	616.52
ρ2 [kW]	0	844.51	844.51	836.07	836.07
ρ 3[kW]	0	0	69.45	3.35	72.80
ind (3) [kWh]	352.96	246.01	233.69	245.24	232.99
ind (4) [kWh]	1,616.54	1,117.52	1,078.53	1,120.17	1,081.18
ind (5) [kWh]	-1,033.6	-1,065.3	-972.1	-1,058.8	-965.5
ind (8) [kWh]	*	*	*	*	*
ind (9) [kWh]	412.80	305.06	278.14	304.41	277.39
ind (11) [kWh]	0.0005	0.0019	-0.0057	0.0015	-0.006
ind (12) [kWh]	98.34	93.69	93.22	93.42	93.03
ind (13) [kWh]	722.44	721.79	721.99	721.56	721.76
ind (14) [kW]	-778.54	-770.33	-747.75	-769.32	-746.74
ind (25)	°	°	°	°	°

Table 6.15 Details for ind(8) for the sensitivity analyses of off-grid case

Quartile*	1 generation	2 generations	3 generations Case I	3 generations Case II	3 generations Case III
25%	-205.67	-143.41	-131.25	-143.50	-131.31
50%	38.22	37.28	32.31	37.05	31.99
75%	207.13	161.65	146.90	160.90	146.08

Table 6.16 Details for ind(25) for the sensitivity analyses of off-grid case

Autocorrelation	**1 generation**	**2 generations**	**3 generations Case I**	**3 generations Case II**	**3 generations Case III**
I° value	0.960	0.927	0.920	0.927	0.920
II° value	0.909	0.831	0.815	0.831	0.815
III° value	0.850	0.722	0.696	0.723	0.698

The integration of a traditional generator has been applied with the following approach: (i) an ex-ante analysis has been performed in order to evaluate the size of the generator which would flatten the load profile without considering the available generation energy map, then (ii) a rank and a sensitivity analysis has been performed considering the five single generation profiles and looking at the best (i.e. minimum) size of the storage.

The size of the traditional generator has been computed by considering the larger power rate which has not shown a number of starts-and-stops higher than 365 per year. Table 6.17 shows data about the considered traditional generator. Accordingly a residual map results from the contribution of the generator to the load profile (Figure 6.15). The available five generation profiles have to address the supply of this profile.

Table 6.17 Data about the traditional generator for the off-grid case

Power rate	197.98	[kW]
Required energy by the load out of the generator	1,635	[MWh]
Supplied energy from the generator	1,673	[MWh]
Functioning hours per year	8,450	[h/year]

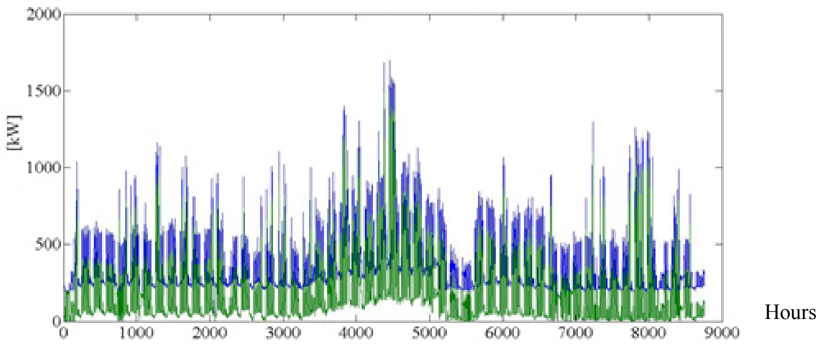

Figure 6.15 Yearly load profile (blue), resulting yearly load profile out of the contribution of the traditional generator (green)

At this stage, according to the 11 selected indicators, a new rank of the five generation energy maps has been developed in order to identify the best profiles as regards the residual profile resulting from the implementation of the traditional generator. Figure 6.16 summarizes the applications of the classification methods and it shows Profile 1 as the best one.

Then a sensitivity analysis has been performed in order to identify the best mix of the generation energy maps capable to minimize the size of the storage. Table 6.18 shows the results of the sensitivity analysis: the best mix refers to two generations profiles (1 and 2) which allow reducing by about 49% the storage size when compared to the best single profile. Three profiles do not allow further improvements of the storage size. It is worthwhile to mention that the resulting storage capacities are quite high if compared with real implementations.

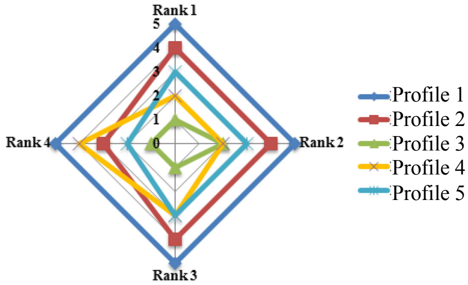

Figure 6.16 Graphical representation of the ranking results for the case with traditional generation for the off-grid case

Table 6.18 Sensitivity analyses results for the case with traditional generation, off-grid case

	Case	Storage [kWh]	Profile 1 [kW]	Profile 2 [kW]	Profile 4 [kW]	Total Power [kW]
1	1 generation	267,083	993.91	0.00	0.00	993.91
2	**2 generations**	**130,171**	**626.16**	**228.71**	**0.00**	**854.87**
3	3 generations Case I	130,922	619.90	228.71	2.49	851.10
4	3 generations Case II	130,239	626.16	226.43	1.46	854.05
5	3 generations Case III	130,937	619.90	226.43	3.94	850.27

6.6 Application 2: On-grid System Capacity Planning

The planning of the system capacity for the on-grid case has been applied to the primary substation of the city of Legnano (Figure 6.4). For the on-grid case the objective function addresses the of looking for the size of power source which allows the maximum compensation of the load profile while fulfilling the constraint of achieving a numbers of hours of *reverse power flow* which is lower or equal than 5% over a year.

As regards the generation profiles, all the five generation energy maps previously described have been considered for the analysis.

Looking at the selection of the statistical-mathematical indicators for the ranking process, among the 25 defined indicators 11 have been selected:

- the parameter β^n, i.e. the generations power size according to the objective function (Eq. 6.3);
- the indicators addressing the analysis of data scattering: ind(1), ind(2), ind(3), ind(9) and ind(20);
- the features of the hourly trend has been considered by computing the indicators from ind(11) to ind(14);
- the relationships among data within the series has been analyzed by ind(25).

These indicators have been computed for the residual maps resulting from Eq. 6.5 as regards the five single generation profiles. Table 6.19, Table 6.20 and Table 6.21 show results as regards indicators computations.

Table 6.19 Computed indicators for the single generation profiles in the on-grid case

	Profile 1	**Profile 2**	**Profile 3**	**Profile 4**	**Profile 5**
β [MW]	19.14	10.68	8.76	14.91	7.27
ind (1) [GWh]	79.58	82.82	87.22	80.61	80.92
ind (2) [MWh]	9.08	9.45	9.95	9.20	9.23
ind (3) [MWh]	5.30	5.47	6.00	5.44	5.60
ind (9) [MWh]	7.238	7.93	9.36	7.78	8.22
ind (11) [kWh]	-0.02	-0.04	-0.02	-0.02	-0.84
ind (12) [MWh]	1.91	1.64	1.90	2.02	2.01
ind (13) [MWh]	8.87	8.77	8.88	9.21	10.27
ind (14) [MWh]	-7.67	-7.66	-7.78	-10.72	-10.07
ind (20)	*	**	***	****	*****
ind (25)	◦	◦	◦	◦	◦

Table 6.20 Details for ind(20) on-grid case

*	829	1250	1261	1767	1599	1024	637	328	45	20
**	1001	953	1161	1492	1420	1247	963	413	92	18
***	1077	1136	1156	1364	1265	1116	992	476	147	31
****	826	1327	1271	1601	1441	1034	724	430	81	25
*****	1142	1086	1223	1524	1417	1081	794	369	102	22

Table 6.21 Details for ind(25) on-grid case

Autocorrelation	**Profile 1**	**Profile 2**	**Profile 3**	**Profile 4**	**Profile 5**
I° value	0.935	0.954	0.949	0.930	0.935
II° value	0.782	0.856	0.840	0.789	0.820
III° value	0.578	0.729	0.704	0.607	0.680

Given the values of the 11 selected indicators, the rank of the generation profiles has been carried out by applying the five developed classification methods. The ranking results for the five methods are depicted in the following by radar graphs: (i) each colored line represents a coupling between the load energy map and one generation energy map, (ii) the concentric polygons depict the possible score of the indicators, (iii) these scores are defined on the segments which pass through the center.

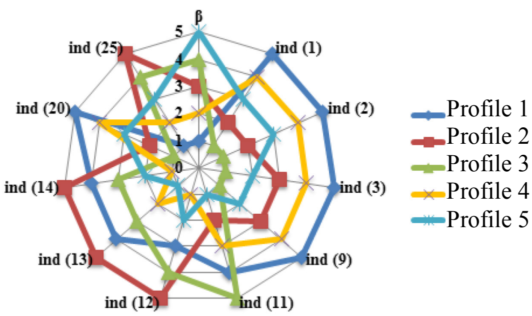

Figure 6.17 Graphical representation for the first classification method, on-grid case

Figure 6.17 shows the ranking results for the first classification method (Eq. 6.8): the best coupling is reported by the generation energy map 1, indeed it shows 5 indicators with best results, the second best profile is the generation energy map 2 (4 best indicators), then the generation energy map 4.

Similarly, Figure 6.18, Figure 6.19 and Figure 6.20 shows generation profile ranking according to classification method 2, 3 and 4 respectively.

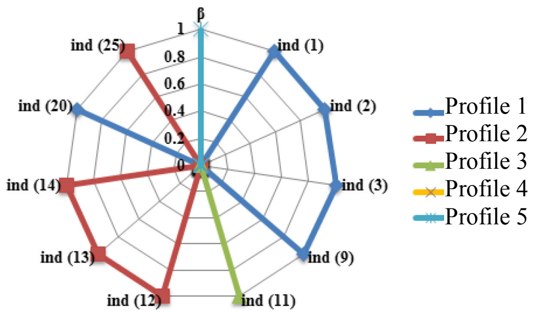

Figure 6.18 Graphical representation for the second classification method, on-grid case

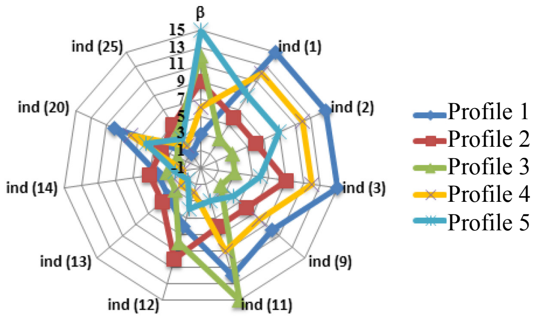

Figure 6.19 Graphical representation for the third classification method, on-grid case

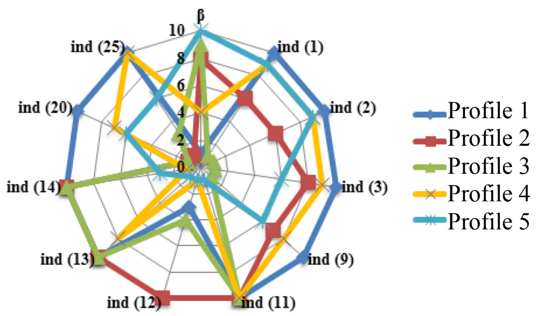

Figure 6.20 Graphical representation for the fourth classification method, on-grid case

The aggregation of the results of the five classification methods, which provides the final ranking of the generation energy maps, is reported in Table 6.22. The best profile refers to the generation energy map 1 which reports a probability to fit with the load energy map of 99.02%, the generation energy map 2 follows reporting 75.12%, finally the generation energy map 4 is the third one with 54.15%.

Table 6.22 Synthesis of the five classification methods and final ranking for the on-grid case

	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5
Rank 1	5	4	2	3	1
Rank 2	5	4	3	1	3
Rank 3	5	3	1	4	2
Rank 4	5	4	1	3	2
Rank 5	0.3	0.4	0.5	0.1	0.2
Ranking in %	**99.02**	**75.12**	**36.59**	**54.15**	**40.00**

Considering the three best profiles (i.e. profiles 1, 2, 4) the sensitivity analysis has been performed. This analyzes the integration of multiple profiles in order to get a better match with the load energy map. At this stage the reference parameter to recognize the optimum solution is the energy requested to the grid which has to be minimized. The sensitivity analysis has been carried out in four steps: (i) adding up profile 2 and performing the optimization with two generation profiles, (ii) adding up also profile 4 and performing the optimization by reducing profile 1 and keeping constant profile 2 (3 generations, Case I), (iii) adding up also profile 5 and performing the optimization by reducing profile 2 and keeping constant profile 1 (3 generations, Case II), (iv) starting from optimum got at point (ii) and decreasing also profile 2 (3 generations, Case III). Results are shown in Table 6.23. The green cell highlights the best case as regards the objective function (i.e. minimum energy requested to the grid), while the red cell highlights the worst one. This is associated to the single generation profile. It is clear how adding further generation reduces the energy requested from the grid. The optimum results for three generation profiles which allow reducing by about 14% the amount of energy requested from the grid when compared to the best single generation profile.

Table 6.23 Sensitivity analyses results, on-grid case

	Case	Grid Energy [GWh]	Profile 1 [MW]	Profile 2 [MW]	Profile 4 [MW]	Total Power [MW]
1	1 generation	79.58	19.14	0.00	0.00	19.14
2	2 generations	69.23	13.40	7.48	0.00	20.88
3	**3 generations** Case I	**68.70**	**10.18**	**7.48**	**2.84**	**20.51**
4	3 generations Case II	69.16	13.40	6.51	1.29	21.20
5	3 generations Case III	68.71	10.18	7.40	2.94	20.53

In order to complete the analysis in Table 6.24, Table 6.25 and Table 6.26 are shown the values associated for the 11 targeted indicators with reference to the five accomplished sensitivity analyses. The green cells highlight the best results (which are most reported by the Case I with three Generation), while the red cells highlight the worst results (which are most reported by the single generation source). This result confirms the optimization which has been performed by looking at the storage size.

Table 6.24 Computed indicators for the sensitivity analyses in the on-grid case

	1 generation	2 generations	3 generations Case I	3 generations Case II	3 generations Case III
β1 [MW]	19.14	13.40	10.18	13.40	10.18
β2 [MW]	0.00	7.48	7.48	6.51	7.40
β4 [MW]	0.00	0.00	2.84	1.29	2.94
ind (1) [GWh]	79.58	69.23	68.70	69.16	68.71
ind (2) [MWh]	9.08	7.90	7.84	7.89	7.84
ind (3) [MWh]	5.30	4.83	4.79	4.86	4.79
ind (9) [MWh]	7.22	6.84	6.78	6.77	6.79
ind (11) [kWh]	-0.017	-0.036	-0.036	-0.033	-0.036
ind (12) [MWh]	1.91	1.71	1.68	1.73	1.68
ind (13) [MWh]	8.87	8.80	8.44	8.65	8.43
ind (14) [MWh]	-7.67	-7.62	-7.70	-7.66	-7.71
ind (20)	*	**	***	****	*****
ind (25)	°	°	°	°	°

Table 6.25 Details for ind(20) for the sensitivity analyses of on-grid case

*	829	1250	1261	1767	1599	1024	637	328	45	20
**	1243	1229	1454	1794	1448	922	498	141	21	10
***	1246	1248	1450	1777	1427	922	509	156	16	9
****	1236	1246	1453	1802	1431	888	516	156	23	9
*****	1246	1245	1456	1775	1422	922	513	156	16	9

Table 6.26 Details for ind(25) for the sensitivity analyses of on-grid case

Autocorrelation	1 generation	2 generations	3 generations Case I	3 generations Case II	3 generations Case III
I° value	0.935	0.936	0.938	0.935	0.937
II° value	0.782	0.796	0.802	0.792	0.802
III° value	0.578	0.615	0.626	0.604	0.625

Finally, in order to highlight the different contributions in matching the load energy map, Figure 6.21, Figure 6.22 show respectively: the load energy map of the primary substation of the city of Legnano (i.e. the targeted load) and the load energy map for the city of Legnano out of the contributions of the best generation profile mix.

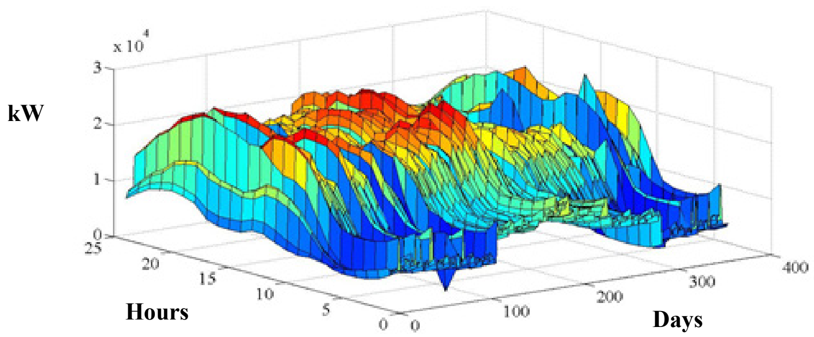

Figure 6.21 Load energy map for the city of Legnano

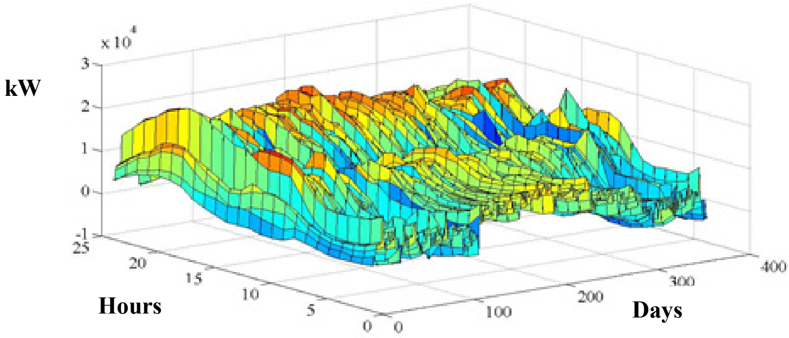

Figure 6.22 Load energy map for the city of Legnano out of the contributions of the best generation profile mix

6.7 Summary

This chapter has addressed the macro-step of Strategy Selection and System Sizing within the System Desing Process, and specifically it has described a first step development and implementaion of a new procedure to perform System Capacity Planning (Paragraph 1.3, Figure 1.7). Despite at the moment, the new procedure allow performing the identification of the proper mix of energy sources and of the system components sizes as other approaches and software tools do, it has been developed with a structure which embraces elements of originality.

Firstly it embraces the capability to address both off-grid power systems and Distributed Generation planning. Moreover it is capable to adapt to any kind of context which has been targeted for the implementation of small-scale power systems (i.e. multiple renewable energy sources implementation, integration of storage systems and traditional diesel generators) and it has been structured in a sequence of steps which have their specific mathematical formulations and which can be handle singularly be the designer in order to adapt the process to particular features of the targeted context or to specific design judgments. A particular feature is also the use of statistical-mathematical indicators to analyze and rank the available energy sources to be employed in the system planning.

The specific capabilities of the new procedure have been also highlighted by means of two application cases which have addressed the planning of an off-grid and an on-grid power system respectively.

7 Appropriate Techno-Economic System Sizing for Rural Areas

In the previous chapter System Capacity Planning has been employed to select and size the main system components for an off-grid rural electrification intervention. At this stage input data only refer to energy consumption patterns and energy resources availability. Moreover selection and components sizing have been performed by means of indicators and performances parameters which only refer to energy quantities. Nevertheless, more often Strategy Selection and System Sizing approaches also employ economic parameters. In this case, these approaches, which can be identified as *Techno-Economic System Sizing*, can work as further analyses following and refining System Capacity Planning or they can perform Strategy Selection and System Sizing starting from primary data of Context Analysis (Paragraph 1.3, Figure 1.7).

A quite common tool which exemplifies Techno-Economic System Sizing is the software HOMER Energy [210]. It performs steady-state energy simulations throughout a year of all the possible system configurations considered by the designer. Beside energy models of the system components, it also embraces capital and O&M costs. These two aspects lead to perform Strategy Selection and System Sizing by minimizing the life-time cost given targeted energy performances.

Minimization of life-time costs is often employed as objective function for system sizing since it leads also to minimize the cost of electricity. This is quite appropriate for rural electrification actions. Nevertheless the typical Techno-Economic System Sizing approaches for off-grid power systems follow a design process which can be considered inappropriate as regards the features of the rural areas.

In this regards, this chapter introduces an appropriate Techno-Economic System Sizing for off-grid power systems. Specifically it describes a novel sizing methodology which requires only data coming from the context of intervention and employs a new objective function which addresses the minimization of overall energy costs of the rural consumers.

The chapter is structured as follows. Firstly it introduces the typical techno-economic sizing techniques for off-grid PV systems. These are described in order to highlight the limits as regards the capability to address appropriate Techno-Economic System Sizing process for rural electrification. PV systems have been considered as targeted technology since it is the one which will contribute the most to rural electrification in the near future. Indeed, the methodology can be applied to any off-grid systems, but it has been exemplified for the off-grid PV systems case. Then the novel sizing methodology is described together with the new definitions of the Value of Lost Load (i.e. a new input datum) and the Levelized Cost of Supplied and Lost Energy (i.e. the new objective function). A simple approach to compute the Value of Lost Load in rural areas is introduced and the overall sizing process is depicted. Finally the novel methodology is applied to a case study for a PV Micro-Grid in a rural area of Uganda.

The physical model of the Micro-Grid as well as the numerical technique employed to optimize the components sizes for the case study are quite similar to others available in the literature; they have been implemented in MATLAB and they are briefly described in Appendix D. All numerical examples as well as graphs that are presented refer to the mentioned physical model, the numerical technique and to the Ugandan case. Finally in **Error! Reference source not found.**E a detail of the figures adopted for the study is reported. Input data for the case study are the results of activities carried out during a two-months mission in Uganda.

7.1 Sizing Techniques for Off-grid PV Systems

In the context of RESs, off-grid PV systems are those which probably will contribute the most to rural electrification in the near future. Indeed, solar energy is the most available RES in DCs [279] and, as expected, PV systems are becoming more and more popular in rural areas thanks to a growing market that benefits from an appreciable decreasing of components costs, from the integration of PV technology in rural electrification programs, and from an increasing commitment of Multinational Corporations due to the huge potential market [280]–[283].

Sizing techniques are a main research topic when addressing off-grid PV. In fact, sizing off-grid PV systems is not straightforward since it means matching an unpredictable energy source with an uncertain load demand while providing the most favorable conditions in terms of system reliability and cost. Sizing techniques are based on the solving of the balance between solar radiation and load demand, taking into consideration the features of the system components. Differences mainly result from the length of the time-step the balance is solved for, and from the methods employed to look for an optimal solution: a short time-step and a great complexity of the solver are accompanied by a high degree of detail in the solar and load data and in the mathematical modeling of the system components.

Khatib et al. [175] have recently reviewed Techno-Economic System Sizing techniques for off-grid PV systems. In accord with this review it can be state that, except for the simple intuitive sizing methods, whatever techniques are employed, they ultimately search for an optimal combination of system reliability and cost. In fact, system reliability is proportional to system cost, and hence the greater the reliability the higher will be the cost and vice versa (Figure 7.1 and Figure 7.2). Therefore, any technique aims at optimizing the system by analyzing the relationship between reliability and cost in order to find the best trade-off [284].

System reliability can be identified with the Loss of Load Probability (LLP) (Eq. 7.1), which is the share of the electricity demand (E_D) not fulfilled by the power system over a certain period (T) [201], [285]:

$$LLP = \frac{\sum_{t=1}^{T} LL(t)}{E_{D,T}} \qquad (7.1)$$

where *LL(t)* is the *Loss of Load* (i.e. the demand load not fulfilled) at the time-step (*t*).

System cost is commonly identified by means of the Net Present Cost (NPC) (Eq. 7.2), which is defined as the present value of the sum of discounted costs that a system incurs over its lifetime (*LT*) [286]:

$$NPC = \sum_{y=1}^{LT} \frac{Inv(y) + O\&M(y)}{(1+r)^y} \quad [€] \qquad (7.2)$$

where, for each year (*y*): *Inv(y)* considers the investment and replacement costs of the system components, *O&M(y)* are the operation and maintenance costs, and $(1+r)^y$ is the discount factor.

A further consideration resulting from the review is that, except for the intuitive methods, whatever techniques are employed, as input datum they all require a target level of reliability, i.e. a maximum value of LLP that is tolerated by the consumers. Then, the optimization process generally consists in searching for the combination of the system components sizes (i.e. PV array size and battery bank size), which have the minimum NPC while fulfilling the LLP condition. This approach can be graphically described and it is depicted in Figure 7.3: once given the loads demand, the solar source availability, and the techno-economic features of system components, it is found that different size combinations of PV arrays and battery banks have the same LLP and NPC values, and hence they define a set of iso-LLP and iso-NPC lines respectively. Therefore the optimum system is represented by the size of the PV array and the capacity of the battery bank which identify the point of tangency between the targeted iso-LLP line and an iso-NPC line, that indeed is the minimum NPC value for the chosen LLP value [201].

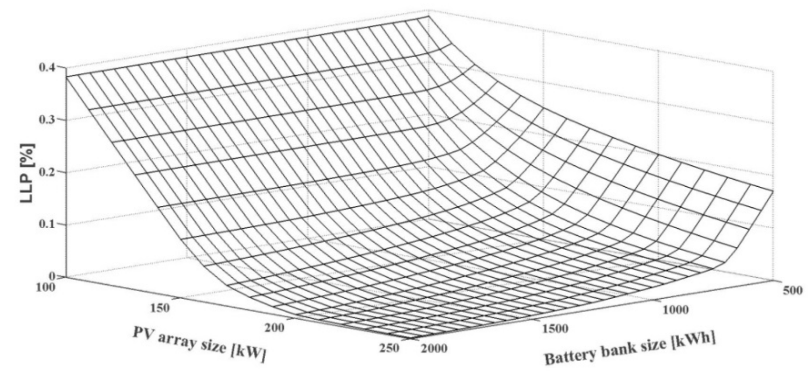

Figure 7.1 LLP values for different size combinations of solar array and battery

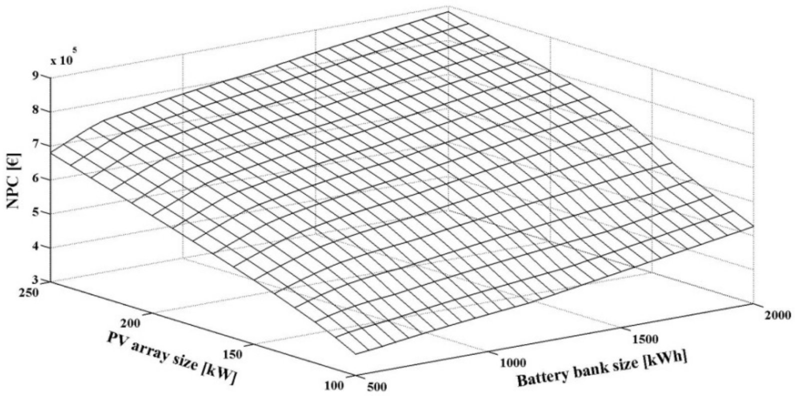

Figure 7.2 NPC values for different size combinations of solar array and battery

Particularly when applied to system sizing for electrification action in rural areas of DCs, this optimization approach has an important defect. Indeed, for the conditions that occur in these contexts, neither system designers nor customers have any specific reference which can lead to set a context-appropriate LLP target value. In fact, for off-grid applications in developed countries, the reliability of the existing electric supply service can be a benchmark for designers and, in any case, also customers have sufficient experience with the electric service to understand and contribute to defining the targeted LLP since they are aware of the relation with costs. On the contrary, in rural areas of DCs neither designers nor customers have any frame of reference about reliability, indeed: (i) it is unreasonable to consider the national centralized grid due to the frequent outages (Table 3.5), (ii) rural people not reached by the grid do not have any experience with a supply service, and (iii) even people who have access to electricity (e.g. typically in the case of small autonomous diesel generators and rechargeable batteries), decide to consume it according to the importance of the need, the cost, and the energy source availability, i.e. the Loss of Load concept is meaningless in this case.

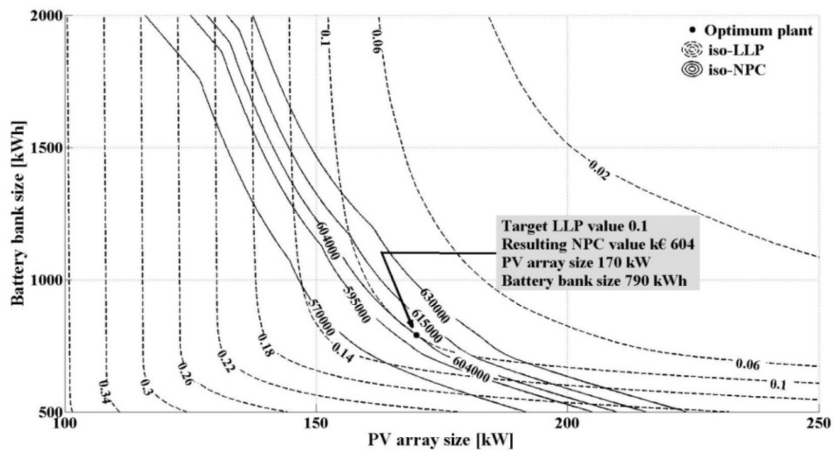

Figure 7.3 Graphical representation of system size optimization design

Actually, the definition of correct reliability levels within the scientific literature is still an open issue [287]. Indeed, while Wenham et al. [288] generally suggest that the type of loads should determine the system reliability; on the contrary, in a number of papers no procedures or considerations about the features of the users' conditions are employed in setting the target LLP (e.g. [201], [284], [289]–[293]). System reliability mostly results in the range of 0.95 to 1 and it appears as a *researchers' recommendation*. Therefore, it can be stated that this optimization process, but also the resulting sizing outputs are inappropriate to rural areas of DCs.

7.2 Novel Sizing Methodology Designed for Rural Areas

In developing the new sizing methodology the main aim was to have a design optimization process and the relating results which are appropriate as regards the context of rural areas of DCs. This objective has been addressed by considering two elements:

- both the process and the results have to be linked to the features of the local context, and hence the parameters and assumptions which drive the system optimization cannot be defined externally. Specifically this means that the LLP of the plant has to be considered with a different approach compared with the traditional techniques. Nevertheless, systems which are more reliable must be favored over those which are less reliable, hence the sizing process cannot prescind from embracing the Loss of Load parameter;
- the electricity cost should be as low as possible. Indeed from the final users' perspective and particularly in poor rural contexts, services must be as affordable as possible.

In order to meet the first point a further cash flow which accounts for an economic value of the energy not supplied has been introduced in the computation of the NPC. The idea is that a new off-grid PV system will provide a power supply service which will substitute the traditional systems: e.g. kerosene lamps, batteries, small diesel generators, etc. . Nevertheless, when the new system incurs in a Loss of Load, it can be assumed that the consumers might go back to the traditional systems in order to fulfil the assumed energy needs. This results in them going to further energy expenses.

The modified NPC is defined as follows:

$$NPC^{*} = \sum_{y=1}^{LT} \frac{Inv(y) + O\&M(y) + \sum_{t=1}^{T} LL(t) * VOLL}{(1+r)^{y}} \quad [€] \qquad (7.3)$$

where VOLL is the economic Value of Lost Load in the targeted context [€/kWh_{LL}].

This definition contributes to favor the most reliable systems because a cost associated with the Loss of Load, which has a trend equal to the LLP, has been *internalized* into the NPC (Figure 7.1). Indeed, it has been added to the NPC a term which contributes with higher values for less reliable and cheaper systems, and with smaller values for more reliable and more expensive systems. With this approach the problem relating to the definition of the LLP is shifted to the necessity to estimate the VOLL.

In order to meet the second point a modified definition of the Levelized Cost of Energy (LCoE) has been employed as the objective function of the proposed methodology. The LCoE is defined as the price for electricity that would equalize the present value of the sum of discounted costs (i.e. the NPC) and the present value of the sum of discounted revenues (Eq. (7.4)). The LCoE is a convenient tool for comparing the unit costs of different technologies over their economic life, and it is closer to the investment costs for electricity production in monopoly markets with regulated prices rather than to the investment costs in competitive markets with variable prices [294]. Monopoly markets are the common situation in DCs where, in addition, incentive schemes for off-grid renewables are seldom implemented [295]. Therefore the LCoE can be considered a reference value for the electricity cost that rural consumers would face. Moreover, it has also been employed as objective function in a number of analyses that deal with renewable-based off-grid systems (e.g. [173], [296], [297]). The LCoE definition is:

$$\sum_{y=1}^{LT} \frac{E(y) * LCoE}{(1+r)^y} = \sum_{y=1}^{LT} \frac{Inv(y) + O\&M(y)}{(1+r)^y} = NPC \quad (7.4)$$

where $E(y)$ is the electricity served each year to the consumers by the system. The traditional definition of the LCoE has been modified by considering the internalization of the VOLL-related costs. Therefore, the new definition refers to the NPC* and it has been named *Levelized Cost of Supplied and Lost Energy* (LCoSLE):

$$\sum_{y=1}^{LT} \frac{E(y) * LCoSLE}{(1+r)^y} = \sum_{y=1}^{LT} \frac{Inv(y) + O\&M(y) + \sum_{t=1}^{T} LL(t) * VOLL}{(1+r)^y} = NPC^* \quad (7.5)$$

Given the loads demand, the solar source availability, the techno-economic features of system components, and the VOLL, the LCoSLE function (Eq. (7.6)) identifies a single combination of PV array and battery bank size which supplies electricity at the cheapest cost (Figure 7.4). Moreover, an NPC* value and an LLP value are output parameters of the optimum plant.

$$LCoSLE^* = f(PV_{size}, B_{size}) = \frac{r * (1+r)^{LT}}{(1+r)^{LT} - 1} * \frac{NPC^*}{E(y)} \quad [€/kWh] \quad (7.6)$$

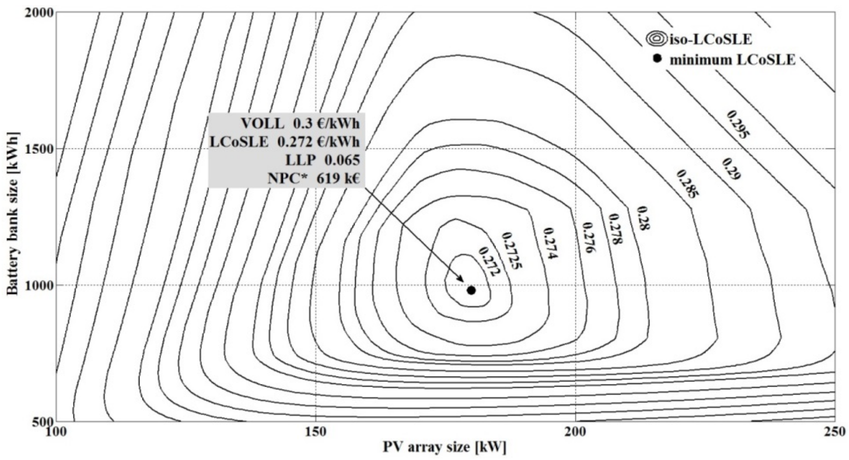

Figure 7.4 LCoSLE function trend and minimum

A number of considerations show that the LCoSLE is an appropriate parameter in sizing off-grid PV systems for rural electrification. In fact,(i) it is based on the estimate of the VOLL which can be related to the local context features, (ii) it does not require an LLP input datum, (iii) it identifies the optimum system univocally once the VOLL is set, and (iv) it identifies an optimum system which is tailored to the local conditions. Indeed, if the VOLL increases, the optimization process looks for a trade-off between investment costs and Loss of Load-related costs (i.e. traditional energy expenses), and it returns a system with larger components sizes, higher NPC, but lower LLP thus limiting the traditional energy expenses (Figure 7.5). The opposite occurs when VOLL decreases.

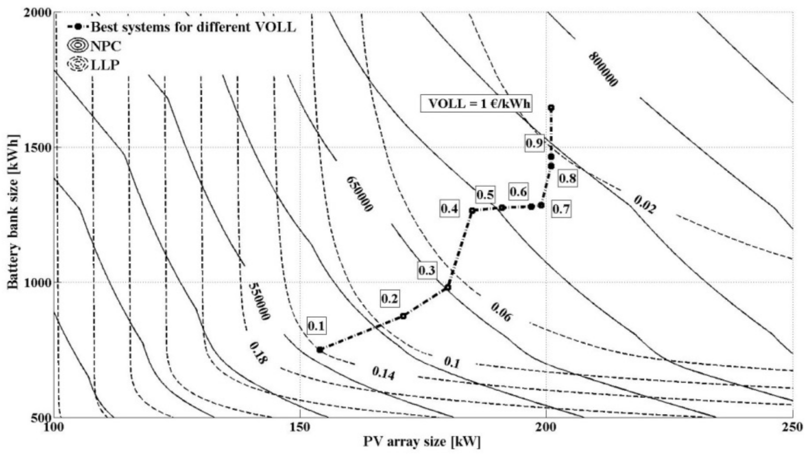

Figure 7.5 Best systems combinations for different values of VOLL

Additional considerations can be made by comparing the proposed sizing methodology and the traditional one in order to further stress the features that make the new methodology appropriate and to show the differences in the results. The comparison is carried out with reference to Figure 7.6, which shows the relation between Life Cycle Cost (LCC) and LLP for optimum off-grid PV systems when the novel and the traditional sizing processes are employed. Specifically:

- the *x-axis* reports the Life Cycle Cost of the systems, i.e. the NPC* in case of the new methodology and the NPC in case of the traditional one; the *y-axis* reports the LLP;
- the solid line shows the trend in the LLP and the LCC that are associated to optimum systems using the proposed methodology and once the VOLL is set. E.g. given the VOLL equal to 0.28 €/kWh$_{LL}$, the optimum system has 0.07 LLP, and about 695 k€ LCC (*Cost 2*);
- the dotted line shows the trend in the LLP and the LCC that are associated with optimum systems using the traditional approach and once the LLP is set. E.g. given the LLP equal to 0.07, the optimum system has a LCC of about 645 k€ (*Cost 1*).

At least three statements can be made:

1. in the proposed methodology the initial datum for the sizing process is the VOLL while the LLP is an output of the system optimization and its value is related to the context. Indeed, given a VOLL, there is an optimum LLP which refers to certain PV and battery sizes, and which brings about an amount of PV system cost and traditional energy expenses thus leading to the minimum cost of energy. This is the optimum and most appropriate system for that context;
2. comparing the results for the same LLP value (e.g. LLP 1) – that is: the VOLL corresponds to about 0.28 €/kWhLL – the LCC is Cost 1 for the traditional

approach, and Cost 2 for the new one. The difference between the two values (A) refers to Loss of Load-related costs that are not considered in the traditional approach. Indeed, the new methodology embraces all the expenses relating to the consumers' needs: the PV system cost (Cost 1) and the traditional energy expenses (A);

3. comparing the results for the same LLC value (e.g. Cost 2) – that is: the consumers have a limited budget assigned for the electric energy needs – the traditional approach suggests a system with LLP 2, which has larger components and smaller LLP than the system suggested by the new one (LLP 1 in case of VOLL 0.28 €/kWhLL). As a consequence, while with the new approach the designer has complied with the consumer limit since the budget will cover both PV system cost and traditional energy expenses, with the traditional one the budget will be overrun since further expenses will occur due to the Lost Load (B). In this case the LLC will finally be Cost 3: about 725 k€ with VOLL 0.28 €/kWhLL.

As final remarks, it can be state that the main peculiarity of the new sizing methodology is the capability, given an economic value of the electric energy unit at local level, to optimize the off-grid PV system in order to minimize to overall expenditure that targeted consumers face in meeting the electric energy needs. This comprises the cost associated with the PV system, but also those associated with compensating the Loss of Load with traditional energy systems.

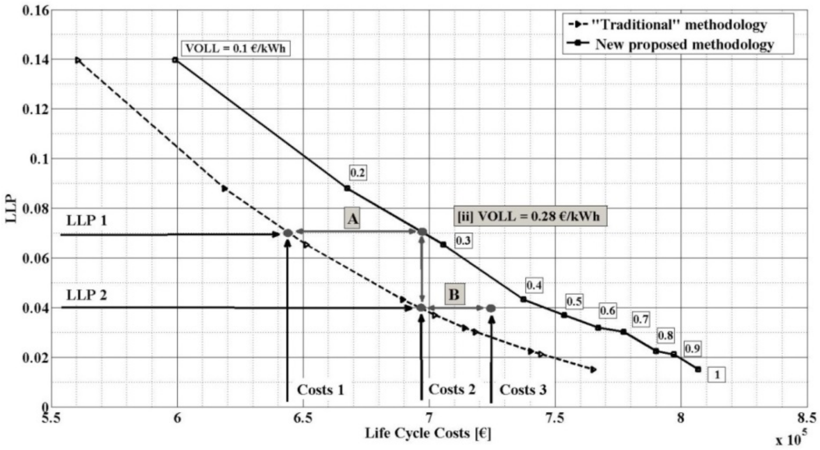

Figure 7.6 Comparison between the proposed sizing methodology and the traditional one

7.3 An Approach to Estimate the Value of Lost Load

The key parameter of the proposed sizing methodology is the Value of Lost Load (VOLL) which can be computed as regard the specific features of the targeted context. In the scientific literature, a field of research deals with the VOLL which is considered as a monetary expression for the costs associated with interruptions of electricity supply (e.g. [298], [299]). In this framework, VOLL is considered a useful parameter that contributes to the quantification of the electric supply security of a country or a region as regards system failures in production, transmission or distribution. Van der Welle et al. [300] define VOLL as the total economic damage caused by undelivered electric energy divided by the amount of undelivered electric energy, and they propose values for VOLL in the range of 4–40 \$/kWh for developed countries and 1–10 \$/kWh for

DCs. Moreover, from their review some considerations can be made about the VOLL concept:

- it has arisen in the context of developed countries, hence where electric systems are fully developed;
- it has arisen from analyses about security of the supply in economies which deeply rely on electric energy, hence where electricity is supposed to be always available;
- it is linked to the concept of the local electric market and is determined by its characteristics;
- the estimated value is determined by the causes, the features, and the consequences of supply interruptions;
- there are a number of methodologies to compute the VOLL (e.g. revealed preferences, stated preferences, proxy methods, case studies).

Based on this overview, it can be stated that the concept of an economic value associated with the Loss of Load has been already employed, there are several methodologies, and it undoubtedly depends on the features of the reference context. Nevertheless, in the author's opinion, the methodologies available in the literature are heavily oriented towards electrical systems of developed countries or, in any case, to centralized systems, and they can hardly be used for rural areas of DCs. Therefore, a simple procedure has been developed, which may fall within proxy methods, and which estimates the VOLL on the basis of two assumptions:

- when losses of load occur the consumers fall back on traditional energy systems to meet the expected energy needs;
- the VOLL relates to the cost associated with the use of traditional energy systems.

These assumptions presume that in the targeted context there is no electric supply service, thus the concept of interruption does not apply, and all the consumers still have a back-up system (i.e. the traditional energy systems). Therefore, as a first approximation, there is no economic damage due to losses of load, except for the traditional fuel costs.

The proposed procedure consists of five steps:

1. employing the same load demand data required for the PV system simulation, it is necessary to compute: (i) the daily electricity consumption associated with each device available within each consumer class, and (ii) the daily electricity consumption of each class;
2. for each device it is necessary to identify the traditional energy system that consumer would use once losses of load occur. To this purpose, two classes of rural consumers are considered: (i) those who already have electricity via small diesel generators, and hence they use such generators to supply power to all the devices in the case of losses of load, and (ii) those who do not have electricity and who employ the PV system electricity to substitute kerosene for lighting purposes and to recharge autonomously mobile phones batteries;
3. for each traditional energy system it is necessary to estimate the VOLL. It has been considered (i) small-scale diesel generators, (ii) kerosene lamps and (iii) recharging mobile service.

   For case (i) VOLL relates to the cost of diesel required to produce one kWh as follows:

$$VOLL_{diesel} = \frac{c_{diesel}}{\eta_{gen} * LHV * v} \quad [€/kWh_{LL}] \qquad (7.7)$$

where c_{diesel} [€/lit] is the local cost of diesel, η_{gen} is the efficiency of the generator, LHV [kWh/kg] is diesel low heating value, and v is diesel specific volume [kg/lit]. No electrical distribution losses are considered.

For case (ii) VOLL is computed considering the equivalence between electricity and traditional systems in terms of time the light is needed, rather than considering the equivalence in terms of energy. Assuming an average rate power of electric lights ($P_{el,light}$), the associated hours of light related with 1 kWh_{LL} can be computed:

$$h_{light,LL} = \frac{1}{P_{el\ light}} \quad [h/kWh_{LL}] \tag{7.8}$$

then VOLL results:

$$VOLL_{ker\ lamp} = c_{ker\ lamp,h} * h_{light,LL} \quad [€/kWh_{LL}] \tag{7.9}$$

where $c_{ker\ lamp,h}$ [€/h] is the cost relating to the consumed kerosene during one hour of lamp functioning. $c_{ker\ lamp,h}$ can be computed by means of households average data about monthly kerosene consumption, daily lamp functioning hours, and kerosene cost.

For case (iii), the traditional solution is to charge mobile phones at kiosks or market places that provide charging services. Considering the battery capacity ($C_{B,mobile}$), the charging voltage ($V_{B,mobile}$), and the price for the charging service ($c_{recharge,mobile}$), VOLL can be calculated as follows:

$$VOLL_{mobile} = \frac{c_{recharge\ mobile}}{C_{B,mobile} * V_{B,mobile}} \quad [€/kWh_{LL}] \tag{7.10}$$

4. for those consumer classes who employ different traditional energy systems it is necessary to compute a *class-VOLL* by weighing each VOLL value with the share of the relating energy needs as regards the overall class energy requirement;
5. finally, the *overall-VOLL* for the targeted context is calculated by weighing each class-VOLL value with the shares of the relative consumers energy needs as regards the overall amount of needed energy.

7.4 Overall Structure of the Novel Sizing Methodology

Both the computation of the VOLL and the LCoSLE-based objective function are elements of a sizing process that include several steps. Indeed, in Figure 7.7 the overall structure of the novel Techno-Economic System Sizing methodology is shown. This structure refers to the complete process that has been implemented in MATLAB in order to apply the novel sizing methodology to a real case study. It includes: (i) three main building blocks which process the main input data, (ii) the optimization process, (iii) a further set of sizing settings, and (iv) the sizing results.

The building blocks elaborate the *primary input* data in order to obtain a set of proper *outputs* for the optimization process. The optimization process implements a *physical model* of the system which comprises three components (PV array, battery bank, and inverter), moreover it accomplish the optimization by means of a numerical technique. This technique performs lifecycle *simulations* of all the combinations of PV array and battery bank within user-defined size ranges and it computes the LCoSLE. Then the components combination which results to have the minimum LCoSLE is *detected* as the optimum system. Furthermore, system components techno-economic *settings* as well as optimization settings are required by the optimization process.

In the previous sections the VOLL building block as well as the LCoSLE-based objective function for the optimization process has been described, while in the following the *Solar Resource* and the *Load Demand* building blocks are detailed since they have specific peculiarities as regards rural areas of DCs. On the other hand, both the physical model of the system as well as the numerical technique are quite similar to others available in the literature, and hence the main implemented features are reported in at paragraph "Main features of the system physical model" while a description of the core equations is reported in Appendix D.

Solar resource data

Usually in rural remote areas of DCs no weather stations are available, therefore a general approach to obtain solar resource data for these contexts consists in three steps: (i) mean daily solar irradiations and ambient temperatures can be obtained from the Surface meteorology and Solar Energy website of the NASA [301], (ii) the synthetic hourly solar radiation incident on the surface of the PV array can be computed by means of the method developed by Graham et al. [235], [236], (iii) given the incident radiation and the ambient temperature, the PV cell temperature can be calculated by means of the procedure shown by Duffie et al. [302]. Hourly time series of incident radiation and cell temperature are employed within the physical model of the system to compute the power production profile of the PV array throughout the year.

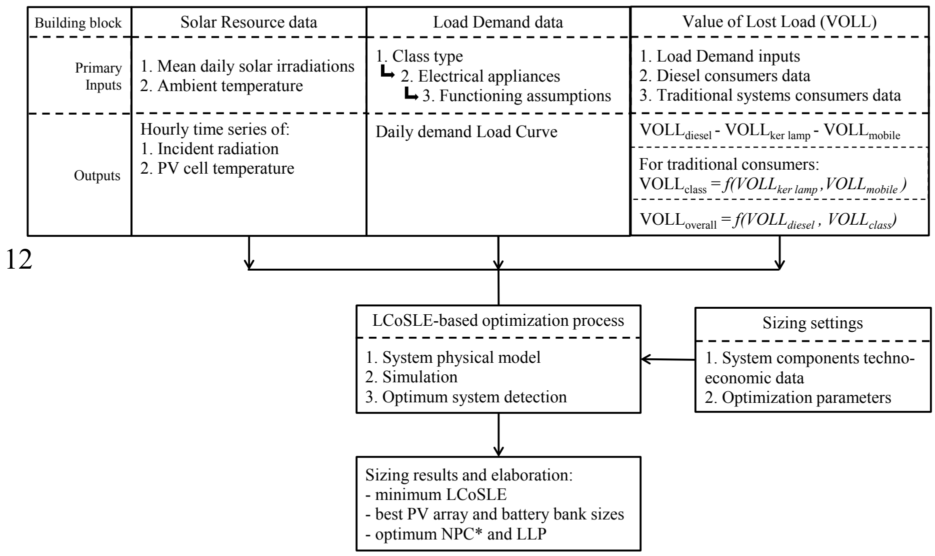

Figure 7.7 Overall structure of the novel sizing methodology

Demand load data

The daily demand load profile is required as input datum for the simulation of the system. On the basis of the observed socio-economic features of the targeted context a single load profile, as representative of each day of the year, is adequate to perform the system sizing. In this case a simple procedure similar to the second approach described in Paragraph 5.2 has been employed to build up the load profile:

1. a number of user classes (*Class Type*) has been identified and the number of users within each class (N_{US}) has been defined;
2. type (*App Name*), rate power (P_{App}), and number (N_{App}) of electrical appliances available for each user of each class have been defined;
3. for each electrical appliance, the functioning hours (h_{funct}) and the possible functioning windows ($W_{f,n}$) have been assumed, i.e. the space of hours when an appliance can work:

$$Tot_w = \sum_{n=1}^{Num\,Win} W_{f,n} \quad [h] \tag{7.11}$$

$$h_{funct} \leq Tot_w \quad [h] \tag{7.12}$$

Table 7.1 shows an example of the estimated load data for a user class.

4. the contribution of each appliance to the load profile is given by the equivalent constant power ($P_{eq,App}$) throughout the functioning windows which would equalize the required energy:

$$P_{eq,App} * Tot_W = P_{App} * h_{funct} * N_{App} \quad [kWh] \tag{7.13}$$

5. the daily demand load profile was finally computed by adding together the contribution of each and every appliance considering the number of users within each class.

Table 7.1 Example of assumed load demand data for a user class

Class Type	N_{US}	App Name	P_{App} [W]	N_{App}	h_{funct}	$W_{f,1}$ h_{start}	$W_{f,1}$ h_{stop}	$W_{f,2}$		$W_{f,3}$	
Family_1	50	Lights	3	4	6	0	2	17	24	-	-
		Phone Charger	5	2	3	0	9	13	15	17	24
		Security Lights	5	1	12	0	7	17	24	-	-

Main features of the system physical model

Main features of the mathematical modeling of the implemented components and simulation approach can be summarized as follows:

- the effect of the cell's temperature on PV array power output was applied;
- a minimum State of Charge of the battery bank (SOC_{min}) was considered;
- a battery bank power-to-energy ratio $(P/E)_R$ was considered in order to introduce a constraint to the maximum power output of the battery bank as regards the rated capacity;
- the lifetime of the battery bank was considered by using the *rainflow* cycle counting method [274], [303];
- the inverter size was defined as regards the power peak occurring within the load profile and considering the inverter efficiency;
- simulations are based on hourly time-steps.

7.5 Sizing PV Micro-Grid Main Components for a Rural Area in Uganda

Hereafter the application of the proposed methodology for the sizing of the main components of a PV Micro-Grid located in a rural area of Uganda is described. All the assumptions and input data are the results of activities carried out during a two-months mission in Uganda.

The specific location of the Micro-Grid is Soroti, which is a small but expanding town in the central-east district of Uganda (1.72N / 33.6E). In Soroti the electric grid reaches only few business activities and houses in the city center, while part of the population use small diesel generators to power domestic appliances and working equipment. Moreover, there are large residential areas where households live without electricity and make use of traditional systems to satisfy their basic needs. The typical conditions of the peripheral areas of Soroti were surveyed and a hypothetical Micro-Grid which addresses the energy needs of 100 households and usual relating activities (e.g. micro and small enterprises, kiosks, market place, school, etc.) is considered.

Solar Resource and Load Demand data

Primary inputs of *Solar Resource* are reported in Table 7.2 and they show that solar energy potential of the region is interesting for PV applications due to high values of irradiation.

As regards primary inputs of *Load Demand*, it is assumed that in the area reached by the Micro-Grid dwell 100 households which can be divided into six user classes according to the income levels. Moreover, 11 user classes which comprise business activities and local services are also considered. In the baseline situation, the households falling within class *Family_1* have the lowest income and rely on traditional energy systems for their energy needs (Table 7.1), on the contrary all the other household-related classes as well as the business activities and services have small-scale diesel generators. Table 7.3 reports a summary of the user class energy consumptions resulting from the context-based assumptions and considering 8 persons per households [304]. The details of each user class are listed in Appendix E. The resulting demand load profile is shown in Figure 7.8.

Table 7.2 Solar resource and temperature data for Soroti

Month	Mean daily irradiation [kWh/m^2/day]	Ambient Temperature [°C]
January	6.22	21.9
February	6.56	22.5
March	6.36	21.9
April	5.99	21.1
May	5.72	20.7
June	5.39	20.7
July	5.29	20.8
August	5.67	21.1
September	6.22	20.8
October	6.01	20.5
November	5.83	20.6
December	6.07	21.2

Table 7.3 Summary of energy consumptions for the defined user classes

	Class Type	N_{US}	$E_{class,day}$ [kWh/day]	$E_{user,day}$ [kWh/day]	$E_{pc,year}$ [kWh/year/pc]
1	Family_1	50	8.1	0.16	7.4
2	Family_2	15	10.2	0.68	31.1
3	Family_3	15	31.0	2.07	94.2
4	Family_4	10	31.4	3.14	143.3
5	Family_5	5	30.7	6.14	280.0
6	Family_6	5	41.4	8.28	377.9
7	Enterprise_1	15	98.7	6.58	-
8	Enterprise_2	5	130.8	26.16	-
9	Mobile Money	5	2.0	0.40	-
10	Kiosk	10	67.6	6.76	-
11	Barber	2	4.6	2.30	-
12	Tailor	3	2.6	0.87	-
13	Market Place	1	25.5	25.50	-
14	Club	3	91.1	30.37	-
15	Street Lights	1	69.0	69.0	-
16	Primary School	1	1.8	1.80	-
17	Pharmacy	1	16.9	16.90	-
	Total Load		663.4		

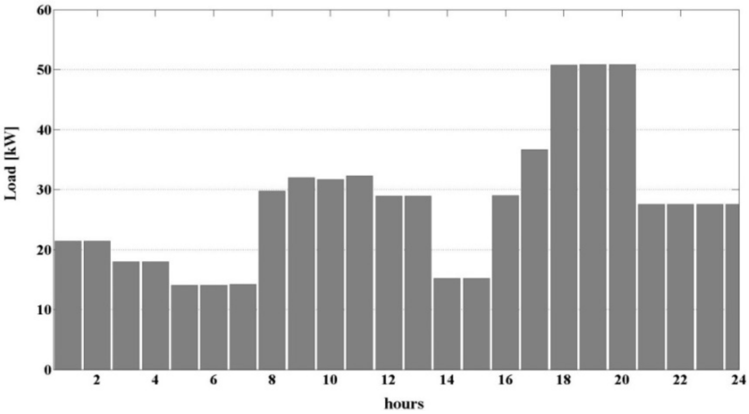

Figure 7.8 Daily load profile for the targeted area

Computation of the Value of Lost Load

As mentioned before, in the rural context under consideration a number of households and activities use small diesel generators. However, there are residential areas where families live without electricity and they rely on traditional solutions to satisfy their basic energy needs. In these circumstances, the calculation of the VOLL needs to take into account the dichotomy between users who did not have electricity before the installation of the PV Micro-Grid and those who had electricity via diesel generators.

Following Eqs. (7.7)(7.9)(7.10) and on the basis of context based techno-economic information (Table 7.4), the VOLL values for the traditional energy systems considered are computed (Table 7.5).

Table 7.4 Techno-economic data for VOLL computation

Diesel generator efficiency	η_{gen}	35	%
Diesel LHV	LHV	12.33	kWh/kg

Diesel specific volume	V	0.825	kg/l
Diesel cost	c_{diesel}	3000	UGX/l
Mobile battery capacity	$C_{B,mobile}$	1000	mAh
Mobile battery voltage	$V_{B,mobile}$	5	V
Recharging phone cost	$c_{recharge\ mobile}$	300	UGX/charge
Household lighting expenditure in kerosene		30,000	UGX/month
UGX-€ Exchange		3500	UGX/€

Table 7.5 Resulting VOLL values [€/kWh$_{LL}$]

$VOLL_{diesel}$	0.24
$VOLL_{ker\ lamp}$	3.97
$VOLL_{mobile}$	17.14
$VOLL_{Family\_1}$	7.92
$\boldsymbol{VOLL_{overall}}$	**0.33**

To calculate the VOLL for user class *Family_1* the relative weights of the two traditional systems need to be considered. Considering that lighting load is 70% of the total needs and mobile-phone charging the remaining 30%, the final VOLL results:

$$VOLL_{Family\_1} = VOLL_{\ker lamp} * 0.7 + VOLL_{mobile} * 0.3 = 7.92 \quad [€/kWh_{LL}] \qquad (7.14)$$

Finally, to calculate the overall VOLL the relative weights of the two main user classes (i.e. those who have diesel generators and those who do not) need to be considered. Table 7.3 shows that diesel-based users account for 98.8% of the total day load, while traditional users account for the remaining 1.2%:

$$VOLL_{overall} = VOLL_{Family\_1} * 0.012 + VOLL_{diesel} * 0.988 = 0.33 \quad [€/kWh_{LL}] \qquad (7.15)$$

Sizing settings

Technical parameters of the components are reported in Table 7.6. Component costs input data and the parameters for the economic analysis are shown in Table 7.7. Information about PV modules and batteries are the result of a survey among Ugandan local suppliers, while inverter cost as well as O&M and other investment costs have been estimated on the basis of Politecnico di Milano Department of Energy experience. Simulations were performed ranging PV array size from 150 to 300 kW with 1 kW step and battery bank size from 500 kWh to 1500 kWh with 5 kWh step.

Table 7.6 Physical model assumptions

Balance of system efficiency	η_{BOS}	85	%
Minimum battery State of Charge	SOC_{min}	40	%
Battery power-to-energy ratio	$(P/E)_R$	50	%
Battery charge efficiency	η_{CH}	85	%
Battery discharge efficiency	η_{DISCH}	90	%
Inverter efficiency	η_{Inv}	90	%

Table 7.7 Cost and economic parameters assumptions

	Note	Cost	
PV modules	Monocrystalline	1000	€/kW

Battery	Lead-Acid (sealed)	140	€/kWh
Inverter		500	€/kW
Other investment costs	% on main component costs	20	%
O&M		50	€/kW/year
Plant Life Cycle	*LT*	20	Years
Discout rate	*R*	6	%

Sizing results

For the targeted context and following the proposed sizing methodology, the optimum plant has LCoSLE equal to 0.382 €/kWh with a PV array of 214 kW and a battery bank of 790 kWh. This system will cost 1 M€ over the lifecycle (NPC*) and will guarantee an LLP of 5.8% (Table 7.8).

The cost of energy results higher (+0.14 €/kWh) for those consumers who already have power supply via small diesel generator, nevertheless it is much lower (-7.54 €/kWh) for the poorest share of the population (half of the total) who rely on traditional energy systems and who gain access to the electric supply service. As expected, the LCoSLE is also higher than the cost of the electricity provided by the Ugandan distribution company (UMEME) via the centralized system which is about 0.19 €/kWh for domestic consumers and about 0.14 €/kWh for commercial consumers [305]. On the other hand it is in line with cost assessments for off-grid systems [306].

It is emphasized that the new sizing methodology, which is founded only on data characterizing the local situation, leads to an appropriate off-grid PV system design. Indeed the results show that by means of the simple approach for the VOLL computation, the new methodology identifies a system design which is reliable and supplies electricity with a fair cost while minimizing the energy bill of the consumers.

Table 7.8 Sizing results Micro-Grid Soroti

PV array size	214	kW
Battery bank size	790	kWh
Inverter size	57	kW
Minimum LCoSLE	0.382	€/kWh
NPC modified	1000	k€
NPC	947	k€
LLP	5.8	%

The economic analysis is obviously affected by a number of simplifications in the Micro-Grid model as well as in the assumptions about the actual energy sistuation: e.g. the electric and control system configurations of the Micro-Grid, and the investment and O&M cost for small scale diesel generators were not considered. In order to cope with with this model uncertainty, a final sensitivity analysis may bring to a better sizing process. Moreover, the optimization process identifies the single optimum combination of PV array and battery bank, these component sizes would hardly be those adopted. Indeed components availability, electric system configuration, consumer geographical distribution, etc. can affect the final requirements of PV array and battery bank sizes. In this case, it can be useful to understand the effects of non-excessive variations in the components sizes on the system performance parameters. Therefore, for the Soroti case, Figure 7.9 shows the optimum plant and the area which comprises all the components combinations with LCoSLE at the most 1% bigger than the optimum LCoSLE. The optimum plants as regards different VOLL values (i.e. 0.15 and 0.60 €/kWh_{LL}) it is also shown in order to highlight the effect of the VOLL on the optimization process. It results that system combinations which fall within 1% of the LCoSLE range from 0.04 to 0.1 LLP and from 1 M€ to 900 k€ NPC, while the same range contains the optimum systems with VOLL between 0.15 to 0.6 €/kWh.

7.6 Summary

This chapter has addressed the macro-step of Strategy Selection and System Sizing within the System Desing Process, and specifically it has described a new Techno-Economic System Sizing methodology (Paragraph 1.3, Figure 1.7). The main objective of the novel methodology relies in having a design optimization process and the relating results which are appropriate as regards the context of rural areas of DCs. Indeed, the traditional sizing techniques require as input datum the Loss of Load Probability parameter which, for the conditions that occur in rural areas, is difficult to set. As a consequence the System Design Process may result in under or over sizing thus leading to poor performances or unaffordable electricity cost respectively. On the contrary, the novel methodologies employs: (i) as input datum the Value of Lost Load, which can be related to the feature of the targeted context, and (ii) the Levelized Cost of Supplied and Lost Energy as objective function, which embrace the overall energy costs of a rural consumers.

Hence, the main peculiarity of the new sizing methodology is the capability, given an economic value of the electric energy unit at local level, to perform Techno-Economic System Sizing by minimizing the overall expenditure that targeted consumers face in meeting the electric energy needs. This comprises the cost associated with the power system, but also those associated with compensating the Loss of Load with traditional energy systems.

Despite the novel methodology can be applied to any type of off-grid power systems, it has been exemplified for the off-grid PV systems case. Specifically it has been employed to size a PV Micro-Grid in the city of Soroti (Uganda).

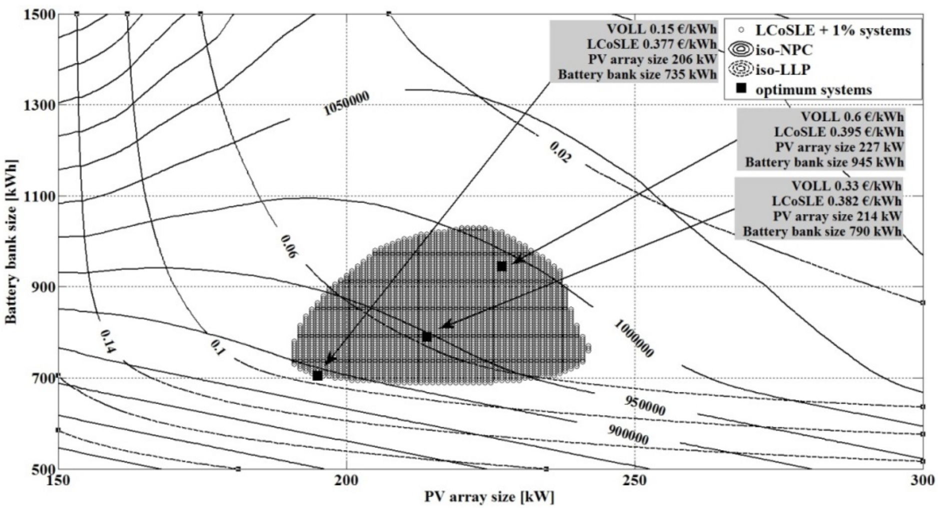

Figure 7.9 Area comprising the systems with LCoSLE at the most 1% bigger than optimum LCoSLE for VOLL 0.33 €/kWh, and optimum systems for VOLL o.15 and 0.6 €/kWh

8 Electro-Mechanical Analysis for Off-grid Systems

In Chapter 6 and Chapter 7 of this thesis, a procedure for System Capacity Planning and a new methodology to carry out an appropriate Techno-Economic System Sizing for applications in rural areas have been presented. Both of them contribute, with different objectives, to the issue of Strategy Selection and System Sizing which refers to the identification of the proper off-grid power system type and of the main power system components sizes (Paragraph 1.3, Figure 1.7).

Once selected the energy sources and determined the components sizes, the System Design Process should address the optimization of the system functioning. This refers to analyses coping with the real interactions of all the system components (i.e. power sources, storage systems, power electronics, control systems, etc.) during the system working. Specifically, the issue of *System Functioning Optimization* has been structured in this thesis according to two building blocks: *Dispatch Strategy Optimization* and *Real Time Power Control* (Figure 1.7). The former performs the optimization of the power flows among the system components throughout a day or in particular conditions according to specific objectives functions, the latter focuses on the analysis of the trends of electrical parameters (typically frequency and voltage) in order to verify the correct interactions among all the systems components during system functioning.

When applying the results of these analyses to real system functioning, they both involve and affect the design of the system control. Indeed, both power flows optimum management, and frequency and voltage control depend on how the system components interact and are operated according to the different functioning conditions. Nevertheless, quite different mathematical models and hence different approaches are employed to study the two topics. Therefore, System Functioning Optimization is often partially addressed depending on the specific targets of the research/analysis.

In order to address this issue, in this Chapter a new approach to system modelling is introduced. The approach aims at providing analyses in order to balance the limits and integrate the results of the already available approaches for Dispatch Strategy Optimization and Real Time Power Control. Specifically, the objective of the new approach is to address a first step analysis of off-grid power systems functioning with simplified electro-mechanical models capable to allow studying both dispatch strategies as well as frequency and voltage trends.

In the following this chapter briefly reviews the typical configurations of Micro-Grids for off-grid applications. The specific architecture of the hybrid Micro-Grid that will be implemented by the project Energy4Growing in Ngarenanyuki is also introduced in order to point out those aspects that have worked as motivations in developing the new approach. Then, a short overview of the typical methods and analyses carried out within the scientific literature to address Dispatch Strategy Optimization and Real Time Power Control are presented. Next, the new approach and the description of the development of the mathematical models of the main Micro-Grids components are reported. Finally the implementation in MATLAB Simulink of the actual power system at Ngarenanyuki school (i.e. MHP plant coupled with dump loads) is described and the results of a number of simulations are presented in order to highlight the features of the new modelling approach.

It is worthwhile to mention that this chapter collects the results of the research developments carried out in the final part of the PhD activities. Specifically, the addressed topic allows opening this thesis also to electrical engineering aspects for off-grid power systems which are pivotal when moving from Strategy Selection and System Sizing to real implementations. In the author's opinion, the proposed approach and relating models still require further developments and analyses in order to be fully recognized as a novel approach which can deeply contributes to improve the design process of off-grid systems. Nevertheless the early results obtained are worth to be presented since they are quite promising. The contents of this chapter has been developed also by means of collaboration with prof. M. Molinas and prof. E. Tedeschi at NTNU (Trondheim).

8.1 Micro-Grids Layouts

In Paragraph 4.3, coupling an energy system perspective with a local context perspective, Micro-Grids have been considered as systems: (i) composed by autonomous units where conversion and distribution have no interaction with other units, (ii) often based on local energy sources (i.e. renewables), (iii) sized for specific local energy needs of several consumers, and (iv) embracing a distribution system. Moreover, Hybrid Micro-Grids have been considered as systems: (i) composed by several conversion units, (ii) based on several different energy sources, (iii) often embracing energy storage systems, and (iv) supplying electricity to several consumers. Nevertheless, considering an electric perspective the following general features can be also associated to Micro-Grid:

- they are an aggregation of power generation systems which are locally controlled;
- they operate with a local low (≤ 1kV) or medium voltage distribution network;
- from outside they result to be autonomous systems;
- when connected to a main grid (i.e. developed countries electric power system) they are capable to switch to islanding functioning in case of main grid breakdowns or if the functioning parameters of the Micro-Grids themselves are inadequate for parallel operation with the main grid.

Within the same perspective, further features of Micro-Grids for developed and DCs (i.e. respectively grid-connected and off-grid), can be also highlighted considering the layout of the Micro-Grid developed within the CERTS project (Figure 8.1), which has been one among the first and breakthrough project about Micro-Grids [307].

In developed countries applications:

- different power sources based on both renewable and traditional energy sources are employed;
- the Micro-Grid is connected to the main grid via the Point of Common Coupling (PCC) which provides the reference signal for the frequency to the power sources within the Micro-Grid;
- the EMS defines the set-point of active and reactive power for the different power sources in order to properly set the dispatchment strategy and to perform voltage regulation. In this case the EMS has to evaluate/estimate loads as well as renewable generation profiles. Further capabilities of the EMS refer to safety management, islanding functioning, black-starts, and power flow management with the main grid via the PCC.

In DCs applications:

- different power sources based on both renewable and traditional energy sources are employed;
- the Micro-Grid is not connected to the main grid and typically the distribution system works at low voltage. In this case, the reference signal of the frequency must be provided by one power source among those available within the Micro-Grid. This generator works in *grid-forming* mode, while all the other work in *grid-following* (i.e. they inject power at the frequency they "read" on the grid);
- the EMS defines the set-point of active and reactive power for the different power sources in order to match the load profile, properly set the dispatch strategy, and to perform voltage regulation. In this case the EMS has to evaluate/estimate the available power and accordingly could connect or disconnect the loads.

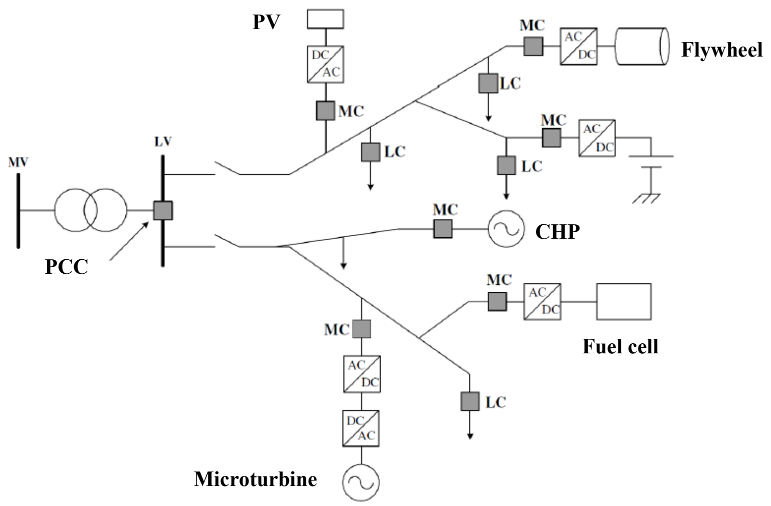

Figure 8.1 Layout of the Micro-Grid developed by the CERTS project

Focusing on applications in DCs, according to the users connections, the type of loads, and the way the Micro-Grid is operated, three main system layouts can be identified: (i) systems with functioning in series, (ii) systems with functioning in parallel, (iii) systems with commutator functioning.

Figure 8.2 shows the typical configuration of systems functioning in series. This configuration requires that all generators, including all the rotating machines (i.e.

traditional generators, hydro-turbines, etc.), are connected in parallel via a DC bus which is further connected also to the storage system. This approach allows simple management logics, but integrating several power sources (mainly in case of multiple rotating machines) brings about complexity as regards power electronics interfaces and the DC bus. Indeed, the AC network is generated by means of a *grid-forming* inverter while rectifiers are needed to interface the power sources with the DC bus. This requires a data bus to integrate the rectifiers and define the active and reactive power set points of each power sources in order to control the DC voltage. This also results in difficulties in connecting *ex-post* further sources, thus limiting the Micro-Grid expansion.

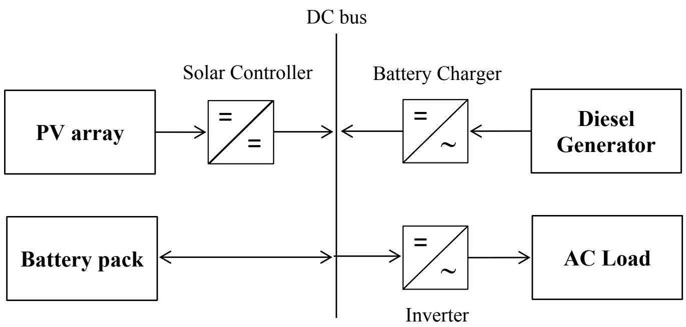

Figure 8.2 Hybrid Micro-Grid with functioning in series

In order to increase the reliability and the efficiency of the previous configuration, the commutator functioning can be employed (Figure 8.3). In this case all generators are still connected in parallel through a DC bus. Nevertheless a rotating machine (typically a traditional generator) can also directly supply power to the AC loads by the change-over switch. This allows supplying power to the load even in case of inverter failure with higher conversion efficiency. However, complexity in integrating several power sources and expanding the Micro-Grid remain.

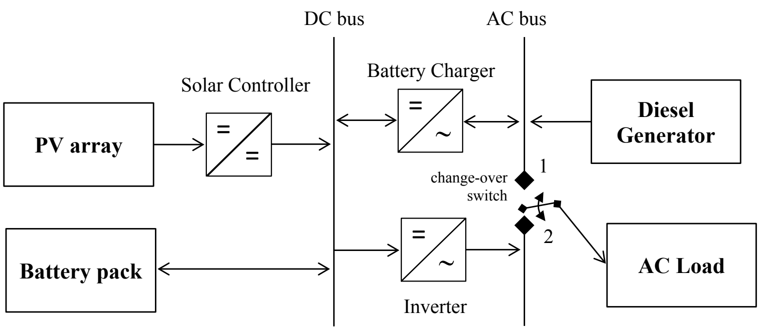

Figure 8.3 Hybrid Micro-Grid with commutator functioning

A different approach is employed for the functioning in parallel (Figure 8.4). This configuration provides that the generators can be connected in parallel via the DC bus (which is also connected to the accumulation system) or by means of the AC bus. Typically the rotating machines (i.e. traditional generators, hydro turbines, etc.) are connected to the AC bus, while PV, wind turbine, and storage are connected to the DC bus. The AC grid can be generated by means of a rotating machines connected to the AC bus, thus leading the other power sources and the bi-directional inverter to work in *grid-following* mode. Besides, the bi-directional inverter can also be operated in *grid-forming* mode if failures or unavailability of energy resources occur for the rotating machines.

In this case, the frequency on the AC bus works as reference signal to set the power injections of the bi-directional inverter. Moreover, on the AC side, if several generators are available they can be managed according to the typical control approaches of meshed grids. This allows avoiding the data bus and results in easier integration of further power sources thus expanding the Micro-Grid. On the contrary, more adequate management logics (e.g. to share the power among several different power sources, to control frequency and voltage) are required as well as more sophisticated inverters.

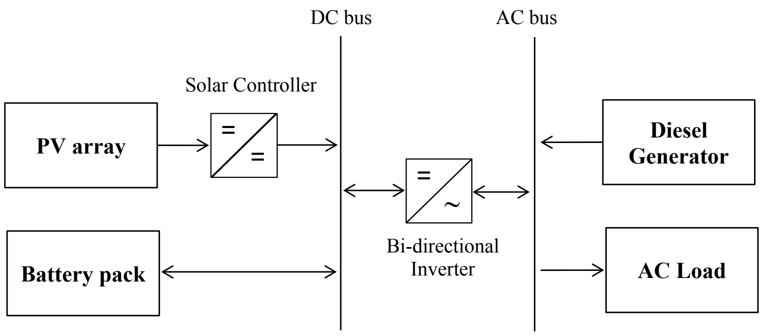

Figure 8.4 Hybrid Micro-Grid with functioning in parallel

Considering the Energy4Growing project and the current system available at Ngarenanyuki school (Paragraph 1.2), the configuration chosen for the new implementation of the Hybrid Micro-Grid is the one with functioning in parallel. Indeed, at the moment in the school the Banki turbine coupled with the synchronous generator and the dump load is the system that can allow providing AC power at 50Hz. Hence it can be considered as the power source capable to generate the AC grid. In addition, new implementations of PV array and electrochemical batteries can be connected to a DC bus and then to the AC one thanks to a bi-directional inverter. Finally, this configuration can easily allow integrating further power sources on the AC grid, i.e. a petrol generator is already available at the school and clearly the required energy is expected to grow in the future.

The detailed layout of the Hybrid Micro-Grid to be implemented in Ngarenanyuki is shown in Figure 8.5:

- Q1 is the DC/AC control board which connects the PV and the batteries to a double AC busbars system via the bi-directional Interface Converters (IC). The IC permits two different operation modes: (i) PV and battery pack in parallel with the MHP plant or the petrol generator (grid following mode), (ii) PV and battery pack in stand-alone functioning (grid forming mode). The double busbars configuration will allow a future easy connection to the national centralized grid;
- Q2 is the AC board which comprises: (i) the devices to monitor the status of the Micro-Grid, (ii) the PLC equipped with specific logics to manage the energy flows, (iii) the Human Machine Interface.

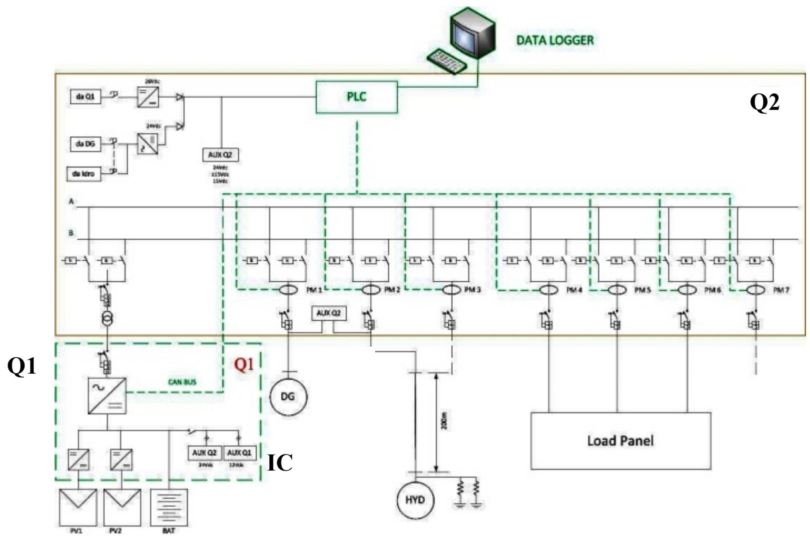

Figure 8.5 Hybrid Micro-Grid architecture for Ngarenanyuki site

Considering the current system employed at Ngarenanyuki (i.e. the MHP plant with the dump loads) and the proposed Micro-Grid development some issues as regards Dispatch Strategy Optimization and Real Time Power Control occur. In the following, they are briefly presented in order to point out those aspects that have worked as motivations in developing the new approach presented in this chapter.

Currently, during the system functioning, the dump loads keep the balance between the generation and the consumption sides while assuring the stability at 50Hz of the power supply. On the other hand, the stability is preserved to the detriment of dissipated energy on air by the dump loads.

The proposed architecture of the hybrid Micro-Grid provides for the parallel functioning of (i) the turbine/synchronous generator/dump load group and (ii) the PV/battery pack apparatus. This solution can limit the dissipated energy; nevertheless, it brings about issues as regards the control of the system as well as the life-time performances of the battery pack. Indeed the battery pack can be operated in order to absorb part of the power on the dump load thus minimizing the dissipated energy and increasing the system efficiency. On the other hand this may increase the charge/discharge cycles of the battery pack (probably with shallower but more frequent cycles) thus decreasing its lifetime. Therefore it is necessary to analyse the functioning conditions of the battery pack, as regards the energy flows, in order to optimize the system control logics aiming at the longest life-time (i.e. to perform Dispatch Strategy Optimization).

Nonetheless, the control logics that coordinate the operations between the battery pack and the dump loads can compromise the system real time control. Indeed dealing with the energy flows in order to optimize the battery pack/dump loads functioning can come into conflict with the energy flows control for the proper system frequency regulation. Therefore it is necessary to analyse the control logics with regard to the system components reaction times, the rates of change in the power flows that can occur during the system functioning, the system inertia, etc. (i.e. Real Time Power Control).

8.2 System Functioning Optimization

In the scientific literature two main types of analyses are typically carried out in order to address the issues of Dispatch Strategy Optimization and Real Time Power Control:

- optimum dispatch is typically carried out by means of analyses which deals with the flows of energy within the system (e.g. [308]–[311]). The objective is to identify the best regulation algorithm for the interaction among various system components. The regulation strategy determines the energy flows from the various power sources, towards the user loads, and dump loads, including the charging and discharging of the energy storage systems, in such a way as to optimize system performance according to targeted objective functions (i.e. operating cost, battery life-time, etc.). Dispatch analyses are typically based on the steady-state solution of the energy balance (i.e. Joule or Watt-hour) between energy sources, storage, and consumer loads and employing mathematical modelling of the system components. Different accuracy in the analyses mainly results from the length of the time-step the balance is solved for the degree of detail in the load/energy source data, in the mathematical modeling of the system components, and from the approach employed to look for the optimal solution. Usually time-step can vary from day-to-day to one-minute and analyses are performed throughout a year, a week, a day of for particular functioning conditions. Also system sizing methodologies often embrace dispatch strategies to perform system simulation and hence sizing the components. Nevertheless in these cases dispatch strategies are defined before the analysis and hence they are not optimized for the specific case. Typically *cycle charging* and *load following* strategies are considered (i.e. [173], [267], [312]). Recently, also in dispatch strategy optimization, multi-objective optimizations have been employed in order to embrace also environmental parameters in the system control [202], [313];
- real time power control analyses (e.g. [314]–[317]) take into account that a power supply system is a highly nonlinear system that operates in a constantly changing environment (i.e. when considering Micro-Grids, loads and generators outputs can change continually). They address the study of frequency and electrical quantities control (e.g. current and voltage) and their main objective is to analyze the continuance of intact system operation following a disturbance. Specifically they can focus on observing the trend of system variables during a disturbance, on the size of the disturbance, and on the time span that must be taken into consideration in order to restore stability. These analyses are based on circuit models of the components and on the solving of the related equations within the continuous time-domain. They are typically carried out for short intervals (from few to tens of seconds) in order to study the development of frequency and voltage.

In this framework, and at the light of the example of the hybrid Micro-Grid under study for Nagrenanyuki school, it is important to address some important aspects of the design process of off-grid systems that which are not appropriately addressed both by optimum dispatch strategy and real time power control analyses:

- concerning dispatch strategy analyses: (i) even when electrical quantities are employed in system components modelling, systems are studied with steady-state numerical simulations and hence trends of V and f are never analyzed, (ii) typically the dispatch algorithm focuses on the energy balance without considering the consequences it has on system control and hence on V and f.

These aspects can affect the size as well as the life-time of the components, especially when systems include rotating machines together with RE generators, power converters and electrochemical storage;

- concerning power stability analyses, they do not provide elements to optimize the flows of energy among the main system components and they are too heavy when addressing issues that occur over longer periods (i.e. battery charge/discharge cycle, computation of Loss of Load, Excess Energy, etc.).

8.3 An Approach for Electro-Mechanical Analyses

In order to address the above mentioned issues, hereafter a new approach to system modelling is introduced. It aims at providing analyses in order to balance the limits and integrate the results of the already available approaches for dispatch strategy optimization and real time power control. The approach adopts classical mathematical models for generators and load representation; nevertheless, the adoption of such models for an off-grid power supply system design instead of classical energy variable models is an innovative content.

The objective of the new approach is to develop off-grid power supply system simulation models capable of:

- working over medium term period (i.e. days) with typical time-steps of real time power control analyses;
- embracing simplified electrical models of power sources and power electronics in order to address at least V and f trends analysis;
- embracing simplified models of system control units in order to address the analysis of different control strategies and their consequence on V and f trends;
- considering the effects of the previously-mentioned aspects on the performances of particular components such as battery pack or dump loads.

Actually, the goal could be summarized in the development of a model library useful to simulate the electro-mechanical operation and dynamic behaviour within an off-grid system (based on both static converter interfaced and rotating machines), with respect to perturbation in the power injections from load and generators.

In the following, looking at the parallel functioning architecture at Ngarenanyuki (Figure 8.5), the developments of the models for a synchronous generator, for the dump load, the user load and the static machines (i.e. PV panels and electrochemical batteries) are described. Specifically, main focus is given to the synchronous generator and the dump loads. They compose the actual configuration of the Nagrenanyuki power system which has been addressed by the first step implementation of the new approach. Indeed, modelling and analysing the interactions between the MHPplant and the dump loads is the first step towards the study of integrating the electrochemical batteries.

2-poles synchronous generator model

The dynamic behaviour of a 2-poles synchronous generator can be exhaustively analysed by the 7th order model in the Park variables which is made up of the following equations (with reference to Figure 8.6):

$$p \cdot \varphi_d = V \cdot \sin(\delta) - R \cdot i_d + \omega_m \cdot \varphi_q \qquad (8.1)$$

$$p \cdot \varphi_q = V \cdot cos(\delta) - R \cdot i_q + \omega_m \cdot \varphi_d \qquad (8.2)$$

$$p \cdot \varphi_F = V_F - R_F \cdot i_F \quad (8.3)$$
$$p \cdot \varphi_D = -R_D \cdot i_D \quad (8.4)$$
$$p \cdot \varphi_Q = -R_Q \cdot i_Q \quad (8.5)$$
$$p \cdot \omega_m = \frac{C_e - C_r}{J} \quad (8.6)$$
$$p \cdot \delta = \omega_m - \omega \quad (8.7)$$

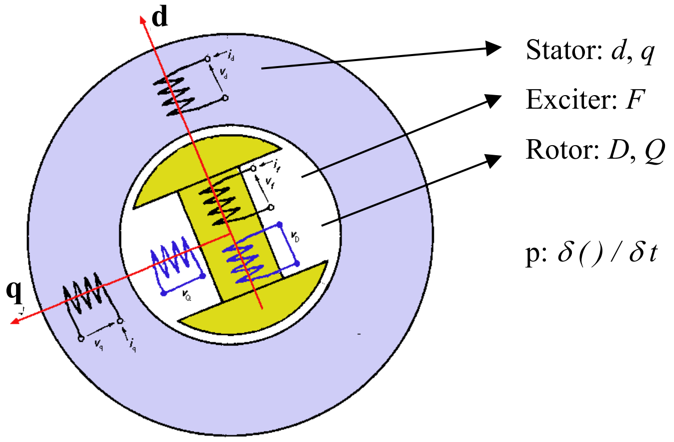

Figure 8.6 Synchronous generator model w.r.t. Park transformation

where:

- p represents the derivative as regards time;
- ϕ represents the concatenated electromagnetic flux;
- C represents the torque;
- J represents the inertia;
- ω represents the angular velocity;
- δ represents the load angle.

In accord with the previously mentioned targeted features of the new approach the 7th order model is simplified by considering electro-magnetic dynamics faster than mechanical ones, hence electro-magnetic variables are supposed with steady-state behavior. Consequently the differential equations from (8.1) to (8.5) become algebraic equations since the time derivative of the magnetic flux (i.e. $p{\cdot}\phi$) are assumed non-existent. Therefore the simplified electro-mechanical model of the synchronous generator is based on equations (8.6) and (8.7) (i.e. the swing equation) that account for the change in the angular velocity ($p{\cdot}\omega_m$) of the generator given the engine and load torques ($C_e - C_r$) and according to the system inertia (J). Moreover, according to the new approach, the synchronous generator can be modelled as an ideal voltage source (supposing the voltage regulator able to maintain the given set-point) driven by the swing equation and hence accounting for changes in power injections from load and power source that results in change in angular velocity (i.e. system frequency).

Dump loads model

In an off-grid power supply system the frequency can be maintained constant by eliminating the unbalance between generations and load consumptions. Acting on the generation side means to use conventional speed governors which use electronics to sense changes in speed in order to control the resource exploitation (e.g. water flow in case of hydropower). Nevertheless, the generation control mechanism is typically not used in rural electrification interventions when the power ratings of off-grid systems are less than 100kW. Indeed in these cases, the cost of such a governor usually exceed the cost of the generator itself [318]–[320]. For this reason uncontrollable prime movers are preferred. These act on the load side so that the generator output power is held constant despite variations of the users' loads. The different strategies which can be adopted in this direction are: dump load control, priority switched-load control, flywheel, superconducting magnetic energy storage systems, and battery energy-storage systems [321]–[323].

Over the last two decades, especially dump loads in the form of electronic load controllers (ELC) have spread. The ELC functioning is based on the measure of the prime mover speed and on the compensation for variation in the main load by automatically varying the amount of power dissipated in a resistive load, thus keeping the total load just right to attain the correct speed and generate stable frequency. There are several advantages of ELC: the use of simpler and cheaper prime mover with less moving part, less expensive than equivalent flow control governor, high reliability and low maintenance, and they can be fitted at any point in electrical system.

The two most commonly employed techniques used for ELC are [324]:

- the phase delay action: where the dump load comprises a permanently connected single resistive load. As a result of the detection of a change in the user load, a power electronic switching device adjusts the average voltage applied to the dump load, and hence the power dissipated. This technique introduces harmonics causing overheating of electrical equipment connected to the system.
- the binary load action: where the dump load is made up from a switched combination of separate resistive loads. In response to a change in the consumer load, a switching selection is made to connect the appropriate combination of load steps. During transitions, full system voltage is applied to the new fraction of the dump load and hence harmonics are not produced at all.

At the Ngarenanyuki school, a pair of 2kW binary ELC dump loads is installed and each of them has 15 regulating steps of 133W [325]. This ELC are fitted with PID μp-controlled frequency system. As a result, the plant frequency changes affect the feedback in function of the entity, duration and speed.

Accordingly, modeling binary dump loads can be based on a series of resistors each one of regulating power P_{dump_step}. Each of them are connected or disconnected by a PID controller that keeps the system frequency at 50Hz. In numbers, the PID output represents the electrical power to be dissipated by the dump loads P_{dump}. An array of Boolean variables (R_{dump_status}) represents the on-off status of each resistor. Hence, after having identified the positional number i of the last activated resistance, a decision about the control action is made by comparing the current dumped electrical power with P_{dump} and then by connecting or disconnecting a further resistance (Table 8.1).

Table 8.1 Binary dump loads control algorithm for frequency stability

If	$P_{dump\ step} \cdot i < P_{dump}$
	$R_{dump,status}(i + 1) = 1$
Else	$R_{dump,status}(i) = 0$

User load model

Electric loads can be modeled by means of simple approaches (i.e. current sources or impedances) or advanced approaches which consider change in absorbed active and reactive power according to the imposed voltage (i.e. dynamic loads). In this first step development of the new modelling approach, the attention is devoted to the analysis of frequency trends during system functioning (i.e. the models of the synchronous generator as well as the dump loads clearly consider only active power flows). Therefore, an ideal current source which injects power at the grid frequency imposed by the synchronous machine is employed as the user load mode with a constant PQ behaviorl. Still, this model is consistent as for considering that the electro-magnetic dynamics are faster than the mechanical dynamics, and hence the related variables evolve according to a steady-state behavior.

Static machines models

Having reference to the parallel functioning layouts for this first step development of the new modelling approach, the static power sources (as PV panels) and the storage systems (as electrochemical batteries) are connected to the AC grid by means of power electronic systems operating in grid following mode. Therefore, they can be modelled by means of ideal current source which injects power at the grid frequency imposed by the synchronous machine. Still, this model is consistent as for considering that the electro-magnetic dynamics are faster than the mechanical dynamics, and hence the related variables evolve according to a steady-state behavior.

8.4 Electro-Mechanical Model for a Micro Hydropower Plant

The new approach and related models have been applied to the case of Ngarenanyuki school. As already highlighted, a main issue to tackle as regards the development of the hybrid Micro-Grid is to study the integration of the battery bank with the already existing dump loads. Indeed the batteries can be managed in order to reduce the dissipating power on the dump loads, but this must not compromise the stability of the Banki turbine-synchronous generator block which generate the AC grid at 50Hz.

Therefore, as a first step in applying the new approach, a model of the MHP plant composed by the synchronous generator, the dump loads and the user loads has been developed in order to start analyzing the issue of battery bank integration. In addition, as already observed when introducing the components modellings, at the moment the model is capable to simulate only the dynamic behaviour as regards the active power flows among the system components and to show the frequency trend during the functioning as well.

Micro hydropower plant modelling

The model of the actual configuration of the MHP plant at Ngarenanyuki according to the new approach has been implemented in MATLAB SimPowerSystem. Specifically it considers (1) the synchronous generator, (2) the dump loads and (3) the user loads (Figure 8.7) which have been implemented according to the previously described models:

1. an ideal controlled voltage source represents the synchronous generator. The input signal which drives the generated voltage is given by Eq. 8.8 where the angular velocity ω results from the swing equation (Eq. 8.9):

$$V = 230 \cdot \sqrt{2} \cdot \sin(\omega t) \quad (8.8)$$

$$J \cdot \omega \cdot p\omega = P_{gen} - P_{load} - P_{dump} \quad (8.9)$$

2. an ideal controlled current source represents the user loads. The input signal which drives the generated current is given in Eq. 8.10 where the RMS current value (I_{load}) is given by Eq. 8.11 and the angular velocity ω results from the swing equation:

$$I = I_{load} \cdot \sqrt{2} \cdot \sin(\omega t) \quad (8.10)$$

$$P_{load} = 230 \cdot I_{load} \cdot \cos(\varphi) \quad (8.11)$$

3. the dump loads model has been implemented according to the description provided in Paragraph 8.3. Specifically, 30 resistors each of 133W are managed by a PID controller that keeps the system frequency at 50Hz. Indeed no frequency regulators have been modeled for the MHP plant.

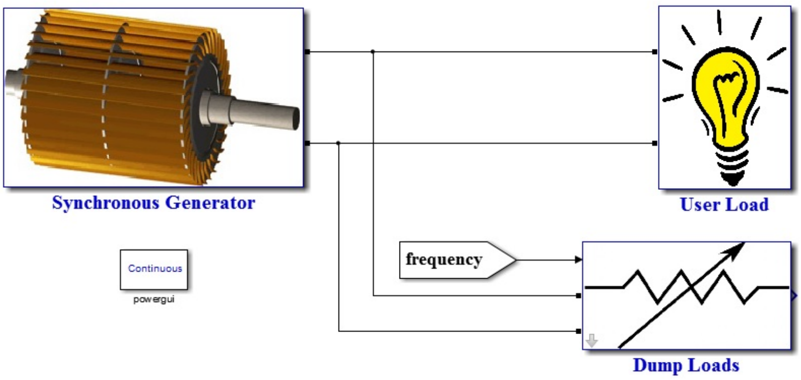

Figure 8.7 SimPowerSystem building blocks for MHP plant at Ngarenanyuki

Model validation

In the following a number of results relating to early simulations of the MHP plant model are presented in order to mainly highlight the capabilities of the new approach.

In all the graphs the active power flow from the synchronous generator is depicted by the blue line, the required active power of the users load is depicted by a red line, the dissipated active power by the dump loads is depicted by a green line, the frequency trends is depicted by the black line.

Figure 8.8 and Figure 8.9 show the behaviour of the dump loads which dissipate the excess power injected by the generator according to the power required by the user load. Moreover when change in user loads occurs, the intervention of the dump loads managed by the PID results in small energy unbalances within the grid which affect the value of the frequency. Specifically, Figure 8.8 refers to a simulation with a simple load profile with two power steps, while Figure 8.9 refers to a more realistic generator and user load profiles that have a number of power steps and ramps. In both cases, the dump loads operate in such a way as compensate for the excess energy. Moreover, when positive (negative) power steps occur in the user loads, the generator reacts providing (absorbing) power thus decreasing (increasing) the frequency. This can be recognized by means of the frequency trends that also highlight the intervention of the dump loads according to the PID control in order to restore the nominal frequency.

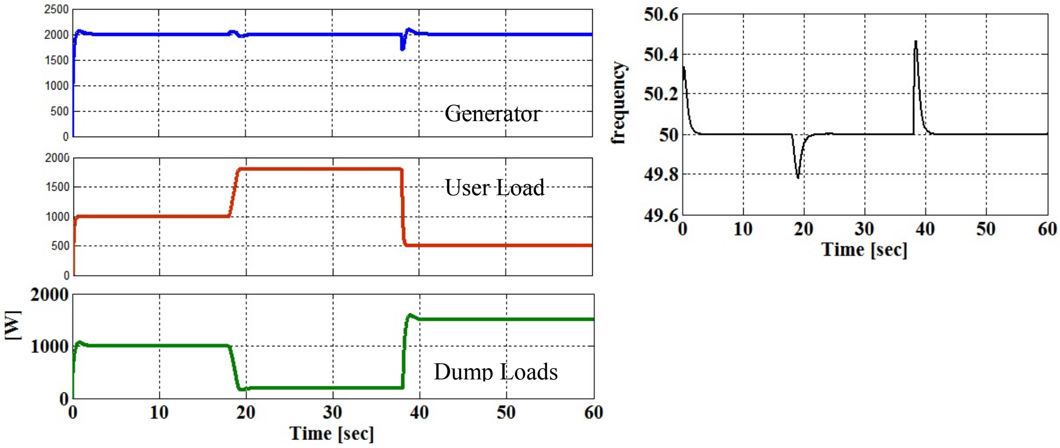

Figure 8.8 Model outputs for "steps load profile": active power profiles (left), frequency trend (right)

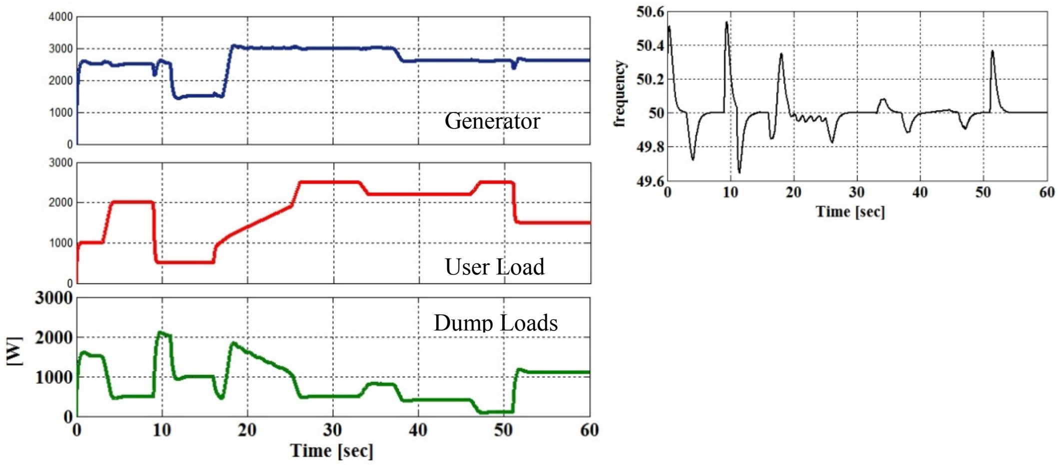

Figure 8.9 Model outputs for "realistic load profile": active power profiles (left), frequency trend (right)

An early validation of the model based on the on-site metering for October 22, 2014 of the functioning system has also been carried out.

In Figure 8.10 the metered power flows with 1 minutes average data storing for the synchronous generator, user loads and dump loads are reported, while Figure 8.11 shows the metered frequency with the same sampling and for the same period. Looking at the three frequency drops that have occurred during the period under study, it can be stated that most probably they have been caused by decreases of the available water flow (i.e. a decrease of the power output from the turbine) which have not been followed by manual disconnection of user loads (i.e. the operator did not recognize the issue and did not switched off any electrical devices). Nevertheless the metered power flow absorbed by the loads decreases since the loads “adapted” to the new conditions occurring in the system.

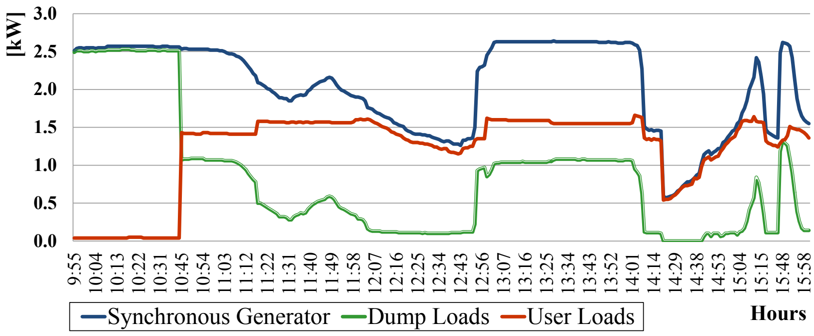

Figure 8.10 Metered power flows of October 22, 2014 for the actual power supply system of the school

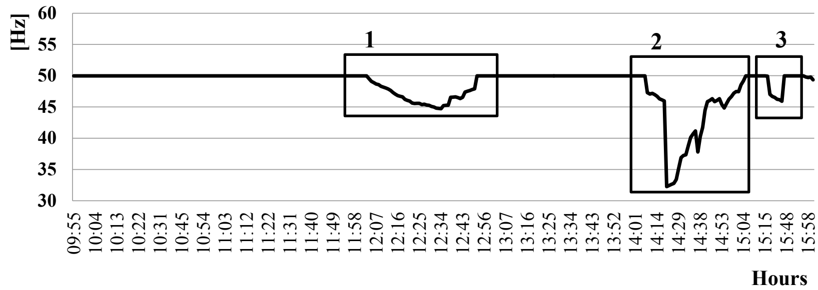

Figure 8.11 Metered frequency of October 22, 2014

According to the observation that has just been made and employing metered data, a simulation of the MHP plant functioning has been carried out with in order to assess the capabilities of the model.

Specifically, Figure 8.12 shows the power profiles considered as input data for the simulation: the active power flow from the synchronous generator (i.e. blue line) exactly follows the metered values (cfr. Figure 8.10), on the contrary the active power requested by the user load exactly follows the metered values (cfr. Figure 8.10) apart in the periods where the frequency drops and it has been supposed the load would have been remained constant if the water flow did not have decreased. As a consequence during the simulated period, three times the user load exceeds the generation power, and hence it is expected that the model reacts with frequency decreases.

The simulation results are shown in Figure 8.13 and Figure 8.14 which report the resulting active power profiles and the resulting frequency profile respectively.

Looking at the active power profiles, it can be noticed that the dissipated power on the dump loads exactly compensates the excess power generated via the Banki turbine according with the load profile. Moreover it can be notices that the model exactly develops the user load profile according to the available power from the turbine. Indeed, in the periods where the input generated power was lower than the input required one (Figure 8.12), the simulation compute a load profile that decreases since it adapts to the generation profiles. Finally, it can be state that the power profiles resulting from the system functioning simulation match the metered one thus showing the proper development of the model.

Looking at the frequency profile, it can be noticed that according to the lack of power generation, the frequency drops, while the stability at 50 Hz is properly restored and well maintained when power generation exceed the required load. This highlights the proper operation of the dump loads model which compensates the excess load in order to balance the active power flow while operating to keep the stability. Nevertheless, the model does not properly model the situation of unbalance. Indeed, comparing the frequency values within out-of-stability conditions (i.e. when the frequency drops due to power generation lacks) computed by the model and the metered ones, it can be noticed that the simulation results are lower than the real ones (i.e. minimum values of about 20 Hz and about 32 Hz respectively). Reasons lie in:

- the lack of voltage trend modelling (i.e. to consider also reactive power analysis and relating proper components models) which would allow to implement dynamic load models (i.e. loads that change their absorbed active and reactive power according to the system conditions). Indeed, with the current models, even if the injected power drops below the required one, this latter is not affected;
- the inaccurate value of the synchronous generator and Banki turbine inertia which affects the output value of the frequency according to the swing equation (Eq. 8.9). In this case, despite constructor manuals have been considered, the correct value can be obtained only by calculating the value with local test on the system.

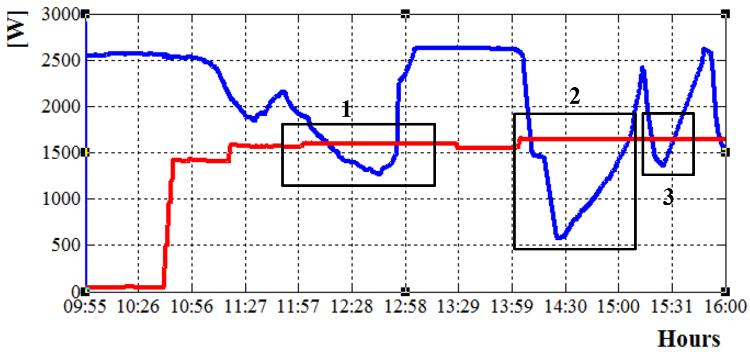

Figure 8.12 Considered power profiles for the synchronous generator and user load for simulating the behavior of the MHP plant on October 22, 2014

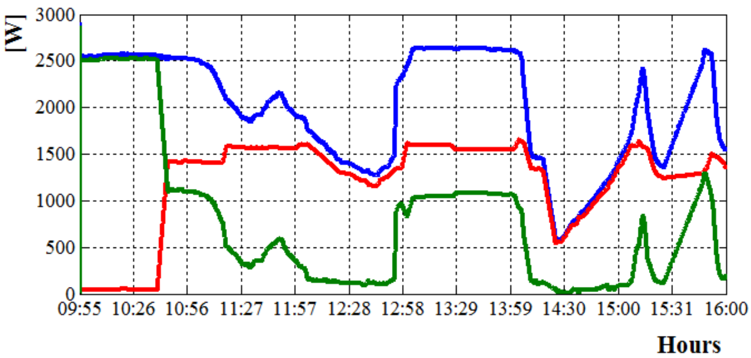

Figure 8.13 Power profiles resulting from the system functioning simulation

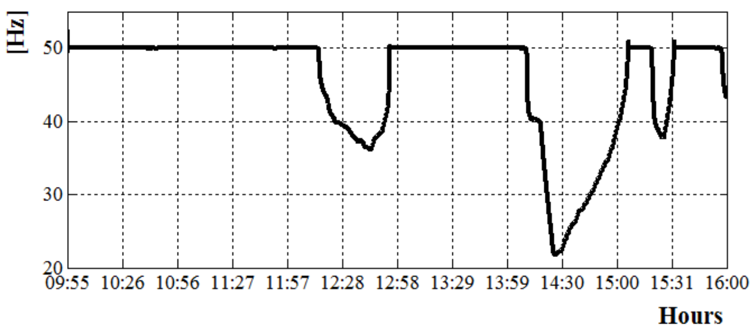

Figure 8.14 Frequency resulting from the system functioning simulation

8.5 Summary

This chapter has addressed the macro-step of System Functioning Optimization within the System Desing Process, and specifically it has described a first step development of a new approach for electro-mechanical dynamic analysis of off-grid systems (Paragraph 1.3, Figure 1.7). The main objective of the new approach is to allow developing simplified integrated analyses of dispatch strategies and real time power control. This aim arises from the observation that dispatch strategy optimization and real time power control are performed by different approaches and hence different mathematical models. Nevertheless, both analyses may affect the desing of the system control. An example of this issue has been presented by the case of the Energy4Growing project where the current system made up by Banki turbine-synchronous generator block has to be integrated with a PV and battery bank system. In this case, optimum energy flows management (i.e. dispatch strategy) have to be implemented while assuring system stability in the different functioning conditions.

In this frame a new approach capable to simulate off-grid system functioning, working over medium term period (i.e. days) with typical time-steps of power stability analyses, and embracing simplified electrical models of system components in order to address dispatch strategy together with V and f trends analyses has been devised.

A first step development of system components modellings which address active power flows together with frequency analyses has been described. Specifically the mathematical models of a 2-phase synchronous generator, of dump loads ELC and user loads have been described and they have been employed to model the actual configuration of the MHP plant at Ngarenanyuki school. Comparisons between metered power flows data for 6 hours of October 22, 2014 at the school and early simulations, show promising results. Indeed the model correctly represents the active power flows among the synchronous generator, the users load and the dump load while considering also the frequency trend. Despite further refinements are required in order to better model the stability feature of the system (i.e. frequency development during unbalances does not correctly match the metered data), the results show that the approach deserves further developments in order to be employed to study the integration of the battery bank and the PV system within the actual power system of the school.

9 Conclusions and Future Works

This doctoral thesis is part of the research topic related to "energy for sustainable development in developing countries." In general terms this theme refers to the analysis of specific problems of the energy sectors of DCs and the resulting consequences on the sustainable development of these countries. Looking at the energy sector of DCs, a "problem of energy" is typically mentioned. This basically consists in the strong energy dependence on traditional biomass (firewood and charcoal) and low rates of electrification and low per capita consumption of electricity. From these two aspects derive a series of negative consequences that hinder the development process at local, but also at country level. In particular, the population of rural areas of DCs is one that most suffer the consequences of the problem of access to energy. In fact, these areas are often not reached by the electricity grid and the only energy source is traditional biomass. In particular the absence of electricity supply severely limits the ability to improve the capability to meet basic services both at home and community level. In many rural areas, however, strong technical and economic feasibility constraints limit the provision of electricity supply via the traditional paradigm of the centralized system. In these cases, off-grid systems based on RESs are the only viable solution. Nevertheless, the process leading to the identification of the best technical off-grid solution within a specific application context is not trivial, and there are many research topics open in this regard.

In this context, this thesis mainly focuses on the problem of access to electricity in DCs and on the analysis of off-grid systems for electrification of rural areas. The thesis is organized into two parts which deal, through different chapters, with two specific topics respectively.

- the first part offers an in-depth analysis and capitalization of the issue of access to energy in DCs with particular attention to the problem of rural electrification,
- the second part introduces some methods and models that have been developed to respond specifically to some particular issues related to the process of designing small-scale power systems for off-grid implementations in rural areas of DCs.

Both subjects have been elaborated by means of some among the specific topics which were indeed recognized as main issues occurring in rural electrification actions based on off-grid small-scale power systems (Table 9.1). These topics have been identified by referring to the project Energy4Growing, which the research activities of this thesis partially contributed to and which cope with the development and implementation of a Hybrid Micro-Grid in a school of rural Tanzania.

Table 9.1 Main issues as regards rural electrification actions based on off-grid small-scale power systems

1	Analysis of the access to energy scenario in DCs
2	Analysis of the energy framework where the electrification action takes place
3	Analysis of rural areas of DCs: typical energy needs and technology solutions for rural electrification
4	Analysis and estimate of energy resources availability and electric consumption patterns
5	System selection and sizing
6	Optimization of the dispatch strategies and the real time power control of the system
7	Monitoring and evaluation of the rural electrification intervention

Figure 9.1 has showed a schematic structuring of these topics and has highlighted the specific contributions of the thesis. Part I constituted the framework of reference of the thesis and it was based on the review and analysis of the scientific literature. Part II described four specific methods and models which addressed some steps of the design process for off-grid power systems for rural electrification.

A brief summary of the thesis contributions and possible future research directions are discussed below.

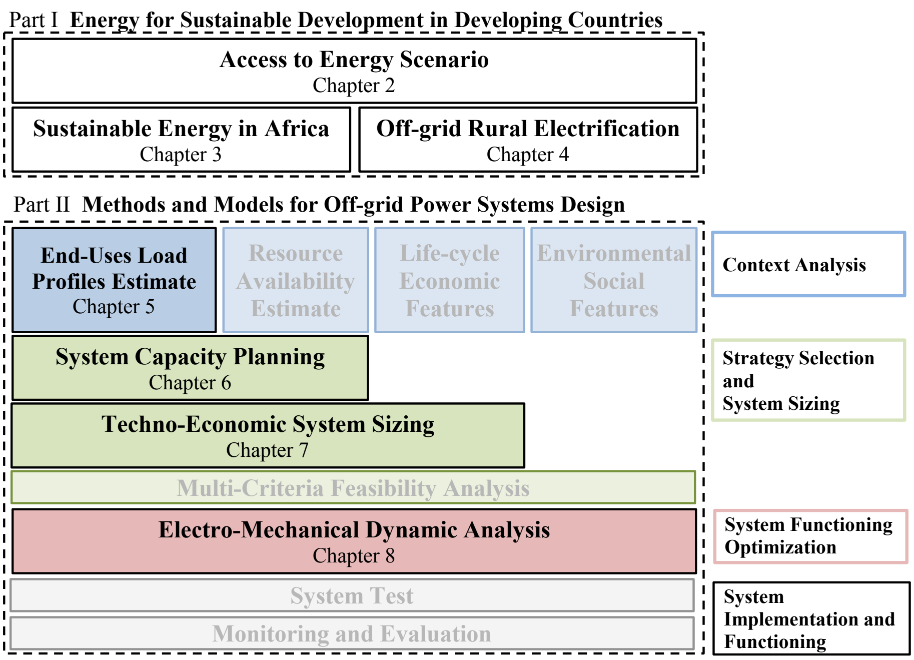

Figure 9.1 Summary of the thesis' contributions

9.1 Conclusions

Part I Energy for Sustainable Development in Developing Countries

Global Dimension of Access to Sustainable Energy: in chapter 2 the link energy – development has been analyzed with the particular focus on the features of DCs. For this context a detailed analysis has been presented in order to assess the specific issues as regards energy and sustainable development. This has emphasized the burden of traditional biomass dependence and lack of access to electricity which both highly contribute in hindering the process of development.

Sustainable Energy in Africa: Current Situation and Main Issues: in chapter 3 the energy situation of Africa has been assessed by combining data about final energy consumptions, electric power system sector and energy resources, with an analysis based on the Energy Indicators for Sustainable Development. Moreover, an overview of the energy-related action plans developed by different local players has been carried out. The main output is the development of an energy situation framework highlighting the cause–effect linkages between the analyzed EISD and the energy-related action plans.

Review of Off-grid Systems for Rural Electrification: in chapter 4 a detailed description of rural areas of DCs and a detailed analysis of off-grid power systems has been carried out. Specifically typical general features and typical energy need occurring in rural areas have been described and classified. This introduced the frame to develop the Off-grid Systems Matrix which depicted a taxonomy for off-grid power systems for rural electrification. According to the matrix a wide review of the scientific literature has been carried out. The review has been the basis which supports the development of the specific methods and models which are described in the second part of this thesis.

Part II Methods and Models for Off-grid Power System Design

Load Profile Estimate with Stochastic Procedure: in chapter 5 the development and implementation of a new procedure to perform load profiles estimates has been described. The procedure is a tool in supporting the computation of input data of the design process for off-grid power systems for rural electrification. This allows overcoming the lack in the scientific literature of rigorous approaches about energy consumption modelling in DCs. The procedure works with the input data that can be reasonable collected or assumed in DCs and it employs a stochastic bottom-up approach with specific correlations between main load profiles parameters (i.e. load factor and coincidence factor) in order to build up the coincidence behavior of the electrical appliances considered by the users. Moreover, the new procedure has been employed in two applications: the first one has shown the capability of the procedure in matching metered daily load profiles of a college in a peri-urban area of Cameroon, the second one has introduced an example of application of the procedure to perform stochastic sizing for an off-grid system.

System Capacity Planning of both Off-grid and On-grid Systems: in chapter 6 a first step development and implementaion of a new procedure to perform System Capacity Planning has been described. A number of elements of originality can be recognized. It can address both off-grid power systems and Distributed Generation planning. It is capable to adapt to different kind of contexts which have been targeted for the implementation of small-scale power systems (i.e. multiple energy sources, integration of storage systems and traditional diesel generators). It has been structured in a sequence of steps which can be handle singularly be the designer in order to adapt the particular case under study. Finally a particular feature is also the use of statistical-mathematical indicators to analyze and rank the available energy sources to be employed in the system planning. Two application cases have been presented to show the planning of an off-grid and an on-grid power system respectively.

Appropriate Techno-Economic System Sizing for Rural Areas: in chapter 7 a new Techno-Economic System Sizing methodology has been described. It overcomes the limits, given by the use of the Loss of Load input datum, of the typical sizing techniques. On the contrary, the novel methodology employs the concept of Value of Lost Load and the Levelized Cost of Supplied and Lost Energy as new objective function. The main peculiarity is the capability, given an economic value of the electric energy unit at local level, to perform Techno-Economic System Sizing by minimizing the overall expenditure that targeted consumers face in meeting the electric energy needs. This comprises the cost associated with the power system, but also those associated with compensating the Loss of Load with traditional energy systems. The new methodology has been applied to off-grid PV system sizing and particularly to a case study of a Micro-Grid sizing in rural Uganda.

Electro-Mechanical Analysis for Off-grid Systems: in chapter 8 a first step development and implementation of a new approach that addressed System Functioning Optimization has been introduced. The new approach allows developing simplified integrated analyses of dispatch strategies and real time power control analyses. Indeed it works over medium term period (i.e. days) with typical time-steps of power stability analyses, and embraces simplified electrical models of system components in order to address dispatch strategy together with V and f trends analyses. A first step development of system components modellings which address active power flows together with frequency analyses has been described. Specifically the mathematical models of a 2-phase synchronous generator, of dump loads ELC and user loads have been described and they have been employed to model the actual configuration of the MHP plant at Ngarenanyuki school (Energy4Growing project site).

9.2 Future Works

There are several research directions on methods and models for sizing and analysis of off-grid power systems to explore extending the work presented in this thesis. In this section, some of them are discussed.

Stochastic off-grid system sizing: this thesis has introduced a first step application of the stochastic procedure for load profile estimate to the sizing of off-grid systems. The objective of this application is to consider in the design system process the uncertainty associated to load profiles in rural areas. While the thesis has identified the best sizing of the system components as the one which occurs the most within a number of given scenario, a rigorous stochastic sizing should lead to the development of a probability distribution of system sizes according to all the possible range of input data scenario in a given context.

Multi-objective multi-criteria system capacity planning: this thesis considers a procedure for system capacity planning which is based on energy data of available resources and consumer needs and employs statistical-mathematical indicators to identify the best source matching the needs. The proposed structure is clearly preparatory to further developments and advancements: (i) also economic data can be considered and objective functions can embrace system costs in addition to energy performance targets, (ii) the approach based on indicators can be further developed in order to introduce also indicators which refer to environmental and social aspects. In general, the possible developments are oriented towards a multi-objective (i.e. the optimum planning can be based on both energy and economic objective functions and mathematical programming), multi-criteria (i.e. the selection of the best technical options or the best mix of resources can be based on a number of criteria which embraces also aspects different from energy or economic indicators) system capacity planning.

Advanced system components mathematical modelling: this thesis has employed mathematical modellings of specific off-grid system components to address the system design process. One of the most difficult components to be modelled are electrochemical batteries. Specifically despite several energy models of electrochemical batteries are available, any of them appropriately address the issue of modelling the component performance throughout system life-time. Indeed this aspect may deeply affect the system sizing when life-cycle techno-economic analyses are performed. Comparisons of different models already available and monitoring of real system functioning (i.e. the hybrid Micro-Gird of the Energy4Growing project) may improve the modelling of this component.

Dispatch strategy optimization in steady-state analyses: this thesis has not considered particular dispatch strategies in analyzing the integration of traditional power systems (i.e. diesel generator) in off-grid systems. Indeed, when studying dispatch strategy in life-cycle steady-state analyses, typically cycle-charging and load-following dispatch strategies are implemented. Nevertheless, different dispatch strategies may optimize the system functioning according to the system configurations and energy sources and consumer load data. Developing a methodology to recognize the best dispatch strategy given typical system configuration, consumer energy loads and energy sources availability will contribute in optimizing the sizing of power source and storage systems in off-grid applications.

Voltage and Frequency analysis via Electro-Mechanical modellings of off-grid systems: this thesis has presented a first step development and implementation of a model to integrate the study of dispatch strategy and real time power control with the aim to study the control system of an off-grid power system. The presented mathematical modellings of the systems components require further investigation as regards the capability to exactly depict the trends of the frequency by considering the sole active power flows. Moreover, a further development step is the advancement in the system components modellings in order to embrace also reactive power flows analysis and hence address the study of the trends of the voltage.

Appendix A

Rationale and methodology of literature review for off-grid systems

The main objective of the review introduced in Chapter 4 is to provide an analytical overview of the present situation as regards the 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, the review has focused on journals belonging to the Elsevier group, and among these journals a selection according to the relevance of the scope of each journal and the objectives of the review has been carried out. Selected journals are given in Table A1.

Table A1 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

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 the key-words, a selection has been carried out and has been based on the following rules:

- papers must deal with off-grid systems for rural electrification;
- reference context of the papers must be related to DCs;
- publication date must be in the range from years 2000 to 2013.

Selected paper have been then grouped according to the five topic categories and assigning each single paper to a maximum of three of them.

In the following a detailed analysis of the selected papers is reported. For each paper, 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 are reported.

Analysis of the research trends and most addressed topics

Figure A1 shows the trend over the years of the publications considered in this thesis. 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 36, 41, and 54 respectively in 2011, 2012, and 2013. 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 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 A2 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.

Feasibility studies is the most populated sub-category, including a total of 95 papers, distributed as it follows: 20 papers addressing Stand-alone systems, 27 addressing Micro-Grid systems, and 48 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.

Models and methods for simulation and sizing, and *Case studies*, occupy the second position in the ranking, with a total of 49 and 48 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 category 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 *Policies*, 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.

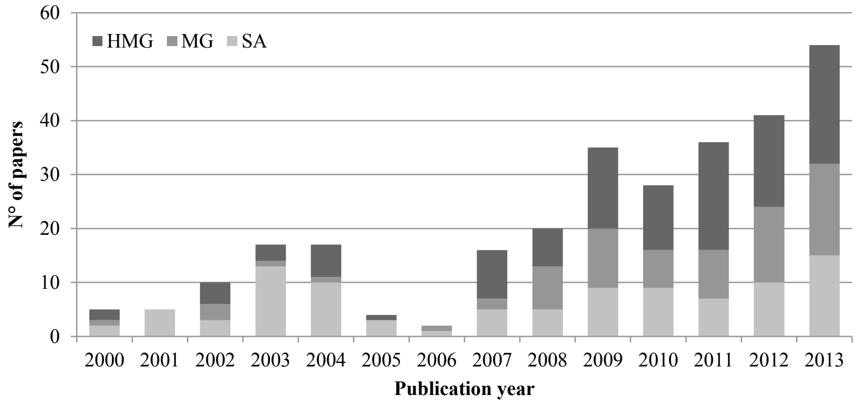

Figure A1 Trend of publications over the years

Table A2 Distribution of papers among *topic* and *system categories*

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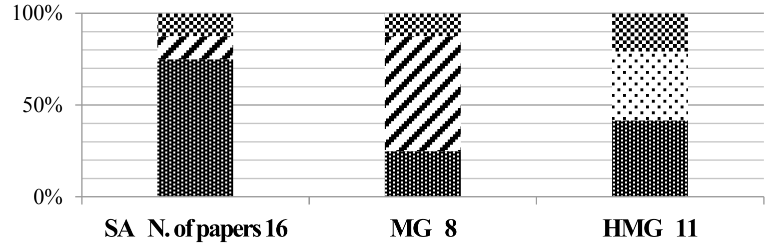
Paper N. 35</td><td>
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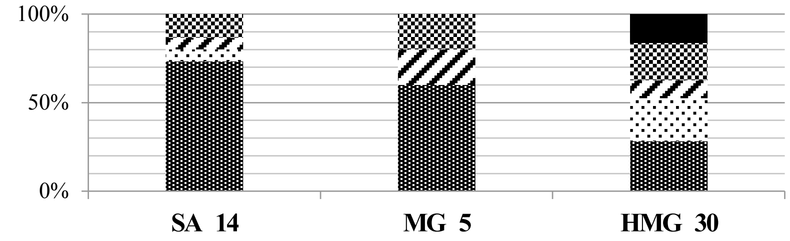
Paper N. 49</td><td>
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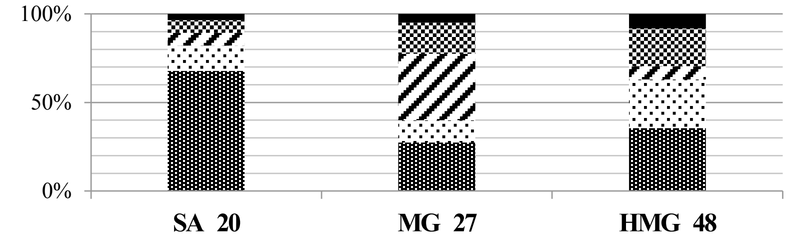
Paper N. 95</td><td>
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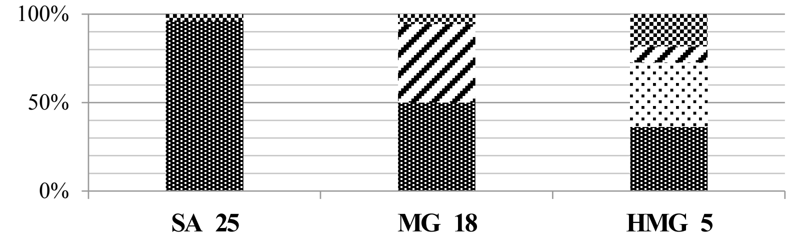
Paper N. 48</td><td>
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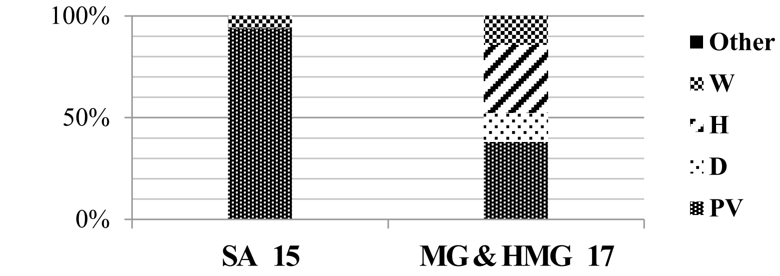
<tr><td>Policies
Paper N. 32</td><td>
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</table>

Detailed review of the selected papers

Table A3 Layout and components: Stand-alone systems

Publication	Location	Technology	Size [kW]	Description
[326]	Saudi Arabia	PV, B	-	Design and usage of a PV system for automated irrigation
[184], [193], [327]	Bangladesh, Algeria	PV, B	0.2-10	Components, layout and performance analysis of different PV pumping systems
[183], [328]–[330]	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
[186]	Nepal	W	-	Results of mechanical testing and choice of timber for wind blades, testing of different coatings and blades, and installation
[331]	Thailand	W, B	0.002	Development of roof-ventilator-based power generator
[185], [194]	Malaysia, Bangladesh	PV, B	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 Pump-as-Turbine (PAT)
[182], [332]	Bangladesh, Ethiopia	PV, B	0.001-0.05	Components, layout and performance analysis of different micro utility systems such as lanterns and multifunctional devices
[333]	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
[334]	Algeria	PV, B	-	Performance analysis of a DC-DC converter assisted by MPPT control in comparison with other approaches

Note: H (Hydro), PV (Photovoltaic), W (Wind), B (Battery), D (Diesel), BG (Biogas), BM (Biomass), DCs (Developing Countries)

Table A4 Layout and components: Micro-Grid

Publication	Location	Technology	Size [kW]	Description
[335], [336]	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
[207], [337]–[339]	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
[187]	-	W	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
[188]	Indonesia	Solar thermal	10	Development of small scale concentrated solar power plant with Organic Rankine Cycle for remote areas

Table A5 Layout and components: Hybrid Micro-Grid

Publication	Location	Technology	Size [kW]	Description
[340]	Cameroon	W, D, B	5.6	Modeling of wind-diesel-battery hybrid power systems for electrification of rural areas
[191], [341]	Bangladesh, Senegal	PV, W, 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
[189], [196], [342], [343]	Jordan, Argentina, Bangladesh	PV, D, B	1.5-41	Design, layout, energy productivity and fuel consumption of different PV-diesel-battery hybrid plants
[344], [345]	Burkina Faso	PV, D	12-55	Design and performances of a new PV-diesel-battery hybrid system without storage
[346]	DCs	PV, W, B	-	Design of a new series-parallel resonant high frequency inverter for Stand-alone PV-wind systems
[190]	Malaysia	PV, W, 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

Table A6 Models and methods for simulation and sizing: Stand-alone

Publication	Location	Technology	Size [kW]	Description
[192]	India	W	-	Modelling and simulation of wind-driven roto-dynamic pumps to compute instantaneous and integrated performances
[198]	Bangladesh	PV, B	~ 0.3	Intuitive sizing technique for PV-battery systems
[193], [347]–[349]	Sahara	PV	-	Optimal operation and sizing of PV pumping systems with optimization of the induction motor efficiency
[350]	Algeria	PV	-	Model for current-voltage curves of PV modules and Loss of Load Probability computation for PV pumping systems
[351]		PV, D, B		Development of sizing curves for PV-battery and Diesel-battery systems via simulations
[352]	Turkey	PV	3	Analyses of power output errors due to use of solar radiation correlations in PV pumping sizing
[353]	Iran	W	85	Simulation and sizing of wind turbine considering instantaneous wind speed variations
[200], [354]	Algeria	PV	-	Numerical sizing technique for solar pumping systems optimization
[194]	Malaysia	H	2.85	Matlab-Simulink model for simulation of real PHP plant in university campus
[333]	Iraq	PV, B	~ 3	Visual Basic tool to design PV-battery systems based on an intuitive sizing technique

Table A7 Models and methods for simulation and sizing: Micro-Grid

Publication	Location	Technology	Size [kW]	Description
[355]	India	H	1000-10,000	Analytical approach to determine the correlations for the cost of different components of SHP schemes
[203]	India	PV, B	1-700	Design space approach for the optimum sizing of PV-battery systems incorporating solar resource

				uncertainty
[201]	Malaysia	PV, B	< 1	Numerical sizing technique for PV-battery system
[262]	Algeria	PV, B	~ 1	Matlab-Simulink PV-battery model for optimal sizing with energy management of load
[356]	Tunisia	W, B	13-16	Integrated Optimal Design for selection and sizing of the system components of wind turbine and batteries

Table A8 Models and methods for simulation and sizing: Hybrid Micro-Grid

Publication	Location	Technology	Size [kW]	Description
[199], [357]–[361]	Saudi Arabia	W, 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
[195]	India	W, PV, H, D, B	25	Mathematical modelling development, dispatch strategy analysis and simulation for system sizes optimization (non-linear constrain) via cost minimization
[260], [261], [362], [363]	India	W, PV, H, BG, BM	~ 100	Optimization model for decentralized energy planning based on simple technology modelling, reliability and economic parameters. Application to rural area comprising several villages
[340]	Cameroon	W, D, B	5.5	Wind availability characterization and intuitive monthly-based sizing technique, economic analysis
[364]	Algeria	W, PV, D, B	~ 10	Matlab-Simulink model of the system, and techno-economic optimization for 6 rural sites
[196]	Bangladesh	PV, D, B	~ 3	Genetic algorithm to perform simulation and optimum sizing (minimization of costs), HOGA tool used
[365]	Senegal	W, PV, B	~ 40	Multi-objective optimization (LCoE, reliability) with genetic algorithm. Analysis of load profile influence
[204]–[206], [366]	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
[367]	Senegal	W, PV, D, B		Mathematical modelling development, dispatch strategy analysis and simulation for system sizes optimization via cost minimization using Dividing RECTangles optimization algorithm
[368]	Algeria	PV, D, B	~ 200	System simulation based on electrical models of components and economic feasibility analysis
[264]	Laos	PV, H, D, B	~ 10	System modelling and optimization via genetic algorithm based on LCoE, given a target reliability
[369]	Iran	W, D	~ 300	New control strategy for wind turbines coupled with diesel generator, simulation of the system
[370]	Palestine	W, PV, D,B	~ 15	Numerical technique for system simulation and optimization based on Cost of Energy and autonomous days
[371], [372]	Senegal	PV, W, D, B	~ 50	Multi-objective optimization (LCoE, CO2) with genetic algorithm, analysis of the influence of load

				profile
[373]	Perù	W, PV	-	Geographical and technology configuration optimization for rural electrification planning based on heuristic indicators assessment
[309]	Philippines	PV, D, B	~ 10	Sizes and dispatch strategy optimization via system simulations: linear programming with Matlab
[197]	Sri Lanka	W, PV, D, B	~ 10	Multi-objective optimization with evolutionary algorithm based on economic and environmental parameters, analysis of different dispatch strategies
[342]	India	PV, D, B	~ 40	Multi-objective optimization with economic and environmental parameters, analysis of different dispatch strategies

Table A9 Feasibility study: Stand-alone

Publication	Location	Technology	Size [kW]	Description
[374]	Nigeria	PV	0.06	Assessment of the domestic load demand in small villages sited in rural areas. Data collection of domestic load via questionnaire
[375]	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
[376]	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
[377]	Vietnam	PV, W, B	0.1-0.15	Economic feasibility study of RE technologies (wind turbine and PV) for households needs in remote and rural areas
[378]	India	PV, W, BG	~1	Comparative study for economic evaluation of PV, windmill, biogas and gas-driven dual fuel engine for water pumping and irrigation
[189], [379]–[381]	Cameroon, Egypt, Bangladesh, Jordan	PV, D, B	2-8	Feasibility analysis of a PV plant: comparison with diesel generator and grid extension costs for the whole energy demand
[208], [382], [383]	India, Iran, Kenya	PV, B	0.01-0.07	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
[207]	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
[184], [200], [354], [384], [385]	Algeria, Zambia	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

[183], [386]	Senegal, Tanzania	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

Table A10 Feasibility study: Micro-Grid

Publication	Location	Technology	Size [kW]	Description
[387], [388]	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
[389], [390]	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
[391]	India	PV, H, BM, W	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
[211]	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
[237]	Argentina, Chile	W, D	Up to 5	Simulation and measurement systems for wind and hybrid (wind-diesel) systems in south Patagonia. Wind resource measurements via loggers to validate simulation results
[355], [392]		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
[393], [394]	India, Malaysia	W	3.2-50	Assessment for wind energy potential in Penang Island. Techno-economic evaluation of small wind plants already implemented or under implementation in India.
[201], [262], [395]	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
[396]	Senegal, Africa	PV, W	130-150	Feasibility study via LCC: LCoE computed considering environmental externalities costs
[212]	Iran	H	50-200	Method sites selection for MHP plants in remote areas based on natural resources and electricity situation basing on different techno-environmental-social-economic parameters
[397]	Thailand	H	320-6000	Potential MHP sites in Thailand for both reservoir and run-of-the-river schemes
[398]	India	H	Up to 25,000	Analysis of SHP systems sustainable development in India
[399]	Nigeria	H	1000-6000	Assessment of potential of SHP in Nigeria evaluating capital, operating and maintenance costs and government initiatives
[213]	Laos	H	Up to 5	Feasibility study for suitable communities

				where install PHP systems basing on social, environmental and technical aspects
[148]		PV, BM	25	Model for choosing among off-grid PV, biomass gasifier and conventional grid extension using Economical Distance Limit from the existing grid access, based on LCC analysis
[400]	India	H	400-900	Methodology approach for feasibility of MHP run-off-river scheme
[356]	Tunisia	W, B	2-16	Systemic optimization approach for the design of wind turbine plant coupled with storage for rural area electrification
[401]	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
[402]	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
[136]	Afganistan Nepal	PV, H, W, D	20-400	Comparison among different RE systems for electrification of rural areas. LCoE to evaluate the cost effectiveness of present electrification processes
[228]	Africa	H, PV, D	15	Spatial-economic analysis to identify least cost electrification options in sub-Saharan Africa

Table A11 Feasibility study: Hybrid Micro-Grid

Publication	Location	Technology	Size [kW]	Description
[199], [357], [359]	Saudi Arabia	W, 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
[362]	India	PV, W, BM	100	Model for hybrid system optimization using LINDO software. Results of the model are compared and tested using TORA and HOMER tools
[403]	Saudi Arabia	W, D	4000	Pre-feasibility analyst to evaluate the wind potential instead of a diesel generator for a village
[404]	Cameroon	PV, D, B	5-180	Modeling of a typical rural community load supplied by a PV-diesel system with storage
[405]	Cameroon	PV, H, D	12	Techno-economic feasibility study for a typical rural village load profile
[391]	India	H, BM, W, PV	5-100	Preliminary assessment to identify potential areas for hybrid RE system installation in India. Economic feasibility analyses carried out
[237]	Argentina, Chile	W, D	> 1	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
[360], [361], [406]–[408]	Saudi Arabia	PV, D, B	> 10	Evaluation of potential of RE technologies for typical residential and commercial building loads. Techno-economic feasibility study for PV-diesel hybrid systems with storage
[195], [267]	Ethiopia, India	PV, H, W	>6	Design, sizing and optimization studies for basic needs in rural villages. Application to selected villages loads
[409]	Iran	W, FC, BG	1	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
[410]	Senegal	PV, W, 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
[230]	Ecuador	PV, D	20-30	Techno-economic model for the introduction of PV-diesel hybrid systems in rural areas. Sensitivity analysis of fuel cost
[266]	Cameroon	PV, H, BG	~8	Hybrid system composed by PHP plant, PV, and biogas. Subsystems simulation considering the load profile of a hostel
[366]		PV, H, BM, BG, D, B	> 10	Techno-economic feasibility study with mixed integer linear programming model
[411]	Indonesia	PV, H, FC, D	> 500	Feasibility study for supplying energy to an ICT center comparing PV-hydro, PV-hydro-fuel cell, PV Stand-alone and diesel systems
[343], [376], [400], [412], [413]	Argentina, Chile, Palestine, Saudi Arabia	PV, D, B	0.84-800	Feasibility study of PV system coupled with diesel generator and storage. COE and Present Value of Cost evaluation. Long-term performance of PV-diesel-battery system in rural areas
[260], [363]	India	H, BM, BG, PV, W, B	1-100	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
[365]	Senegal	PV, W, B	2-16	Method based on a multi-objective genetic algorithm for PV-Wind system with storage sizing and optimization. Minimization of the annualized cost system and LPSP
[404], [414]	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
[368], [415], [416]	Algeria, Bangladesh	PV, W, 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
[417]	Algeria	PV, W, D	< 1	Optimization method for PV-Wind system.

				Sensitivity analysis for 4 different locations
[418]	Iraq	PV, D	4	Design of a hybrid power supply system for a Reverse Osmosis desalination plant. HybridRO software for optimization
[261]	India	PV, H, BM, W	> 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
[209]	Saudi Arabia	PV, W, D	> 10	Feasibility analysis of hybrid systems including PV and Wind technologies for supplying typical commercial building loads
[370], [419]	Buthan, Palestine	PV, W	>5	Sizing and optimization models for hybrid systems. Minimization of the total cost installation, dump load and CO2 emissions
[367], [371], [372], [420], [421]	Egypt, Ethiopia, Senegal	PV, W, D	10-15, >100	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
[422]	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
[265], [423]	RD Congo, Cameroon	PV, W, D	~1	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
[424], [425]	Indonesia, Taiwan	PV, W	1-100	Techno-economic feasibility and optimization studies for hybrid systems and Micro-Grids via HOMER and GAMS/PATH software
[309], [342]	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
[401]	Indonesia	PV, H	>10	PV and MHP systems evaluation via LCoE in comparison with traditional diesel systems
[312]	Iran	PV, D	>10	Techno-economic feasibility analysis for PV-diesel system potential in rural areas of Iran
[426]	Algeria	PV, W, D	0.1-1	Feasibility analysis and comparison of different hybrid systems based on PV, diesel and wind

Table A12 Case studies: Stand-alone systems

Publication	Location	Technology	Size [kW]	Description
[427]	Kenya	W	-	Case studies of wind pump projects: local manufacturing and installation, benefits, and challenges to be faced for the dissemination in Africa
[385], [428]	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

[429]–[431]	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
[214], [432], [433]	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
[219], [376]	Botswana, Palestine	PV, B	0.05-0.4	Analysis of different factors acting as barriers for the application and diffusion of SHS
[434], [435]	Bangladesh, Thailand	PV, B	0.02-1	Economic and financial sustainability of SHS and charging stations: techno-economic determinant factors
[225], [436]–[438]	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 telecommunications network
[439]	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
[440]	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
[216], [217], [332], [441]	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
[215], [442]–[444]	Morocco, Jordan	PV, B	0.04-0.13	Analysis of different large-scale SHS programs in rural areas: implementation, costs results, and feedback from users
[445]	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

Table A13 Case studies: Micro-Grid

Publication	Location	Technology	Size [kW]	Description
[218]	India	PV, B	25	Feasibility of a PV system, compared to other conventional systems, considering the socio-economic and environmental perspective
[446]–[448]	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
[449]–[451]	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
[229]	Rwanda	H	100-	Aspects such as the institution arrangement,

			500	local people participation, and private-financial sector collaboration are discussed by comparing four MHP plants based case studies
[452]	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
[453]	Bolivia	H	15-100	Performance analysis of a set of rural MHP plants and considerations on their implementing organization, also regarding the management perspective
[231]	India	PV, B	-	A comparative evaluation of household preferences among PV Stand-alone and Micro-Grid systems
[454]	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
[395], [455], [456]	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
[187]	DCs	W, 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)
[445]	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
[457]	Malaysia	H	7.5-35	Techno-economic and social aspects of two MHP projects are compared in order to find out the main barriers to sustainability

Table A14 Case studies: Hybrid Micro-Grid

Publication	Location	Technology	Size [kW]	Description
[196], [458]	Bangladesh, Thailand	PV, D, B	4-180	Analysis of PV-diesel-battery systems' performances in a techno-economic and social perspective
[237]	Argentina	W, D, B	4-10	Results of experience with measurement systems applied to wind-diesel-battery systems in south Patagonia.
[459]	Nepal	H, PV	0.5	Analysis of the benefits for remote villages in Nepal due to hybrid systems electrification
[418]	Iraq	PV, W, 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

Table A15 Policy: Stand-alone

Publication	Location	Technology	Size [kW]	Description
[220]	Indonesia	PV	-	Description and evaluation of governmental SHS rural electrification program
[222]	-	PV	0.05	Qualitative analysis of impacts of SHS in GHG emission reduction in a rural context
[221]	-	PV	-	Analysis of social issue relating to solar pumping, proposal for a new type of pump
[460]	Nepal	PV	0.04	Status, programs and experiences of SHS distribution in Nepal
[461]	Bangladesh	PV	-	Qualitative description of a business model to promote sustainable rural development via PV systems
[462]	Sri Lanka	PV	0.025	Analysis of socio-economic impacts of SHS within monitored households
[463]	Sri Lanka	PV	-	Quantitative analysis and discussion of factors contributing in changing the perception of PV technology for rural electrification
[216]	Ghana	PV	-	Survey and impact evaluation of SHS system on indoor air pollution, recommended policy
[219]	Botswana	PV	-	Comparison and evaluation of SHS distribution project for 3 villages, recommendations for further projects
[464]	India	PV	0.02-0.07	Estimate of CO2 mitigation potential due to SHS implementation under Clean Development Mechanism
[442], [443], [465]–[467]	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
[468]	Mongolia	PV, W	-	Status of electricity in Mongolia, history, development, challenges and benefits analysis of Rural Electricity Access Project
[328]	East Timor	PV	0.01-0.08	Comparison of benefits between 3 sizes of SHS for rural areas, policy implications
[223]	Kenya	PV	-	Modeling and analysis of energy transition to SHS for lighting needs in rural areas of Kenya
[232]	Asia, Africa	PV	0.02-0.15	Overview of LED SHS: technology, aid and programs in the world, models and best practices of financing

Table A16 Policy: Micro-Grid, Hybrid Micro-Grid and miscellaneous analyses

Publication	Location	Technology	Size [kW]	Description
[140]	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
[225]	Nigeria	PV	-	Rural electrification with PV in Nigeria: potential, situation, benefits and policy issues
[128]	India	-	-	Rural electrification status in Rajasthan region, qualitative analyses of electrification options and proposal for a sequential Distributed Generation-based approach for electrification

[229]	Rwanda	H	100-500	History, analyses, project results and considerations about a program for MHP plants implementations in Rwanda
[230]	Ecuador	PV, D	110	Description of innovative feed-in incentive system for hybrid system promotion. RE Premium Tariff. Use of HOMER tool.
[231]	India	PV	-	Econometric analysis to compare SHS and Micro-Grid PV systems within specific rural village population (Sundarban)
[226]	Nepal	H, PV	-	As for rural electrification in Nepal: review of financing approaches for MHP and SHS, survey and analysis of RE market development.
[129]	Senegal	PV, W	-	RE Premium Tariff to boost RE systems. Econometric model developed, policy implications analysed
[398], [469]	Tanzania India	H	10-5000	As for rural electrification with S/MHP plants in Tanzania and India: situation, expectations, challenges and policy recommendations
[450]	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
[187]	Perù, Nicaragua, Mongolia	W	0.185-1	Analysis of appropriateness of locally manufactured wind turbine: 3 case studies description and evaluation
[224]	Nepal	-	-	Review of rural electrification in Nepal with RE as regards: status of technology development, policy interventions and incentives, impediments
[233]	Mali	D	~ 7	History, benefits, challenges, and lessons learned about a program of multi-functional platforms implementations in Mali
[228]	Africa	PV, H, D	-	Mapping best economic solution for rural electrification over the African continent, policy and financial implications
[227]	Malaysia	PV, W, H	-	Rural electrification in Malaysia: potential of and barriers to RE, policies and issues
[470]	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

Appendix B

Load data assumptions for the Cameroon Presbyterian College in Bali

Class Type	N_{US}	App Name	P [W]	N_{App}	min_{funct}	$W_{f,1}$		$W_{f,2}$		$W_{f,3}$	
						h_{start}	h_{stop}				
Family_1	18	TV	80	1	360	16:00	22:30	-	-	-	-
		Stereo SET	36	1	420	5:30	7:30	14:00	20:00	-	-
		Ph. chargers	5	3	240	0:00	6:00	22:00	24:00	-	-
		Indoor bulb	26	5	300	5:00	7:00	18:00	22:00	-	-
		Outdoor lights	26	1	120	18:00	22:00	-	-	-	-
		Security light	5	1	720	0:00	6:00	18:00	24:00	-	-
		Fridge	40	1	1440	0:00	24:00	-	-	-	-
		PC	50	1	120	17:00	21:00	-	-	-	-
		Iron	800	1	6	5:30	6:00	19:05	20:25	-	-
		DVD	15	1	360	16:00	22:30	-	-	-	-
		Flask	700	1	30	5:00	5:30	-	-	-	-
		Blender	350	1	45	11:00	11:20	13:00	14:00	-	-
Family_2	14	TV	80	1	300	6:00	7:00	16:00	23:00	-	-
		TV overnight	80	1	360	0:00	5:00	23:00	24:00	-	-
		Radio	5	1	240	5:00	6:30	17:00	22:00	-	-
		Stereo SET	50	1	90	20:00	22:00	-	-	-	-
		Ph. charger	5	2	240	0:00	6:00	22:00	24:00	-	-
		Indoor bulb	26	4	300	5:00	8:00	17:30	23:30	-	-
		Outdoor bulb	26	1	240	18:00	22:00	-	-	-	-
		Security Light	26	1	720	0:00	6:00	18:00	24:00	-	-
		Iron	800	1	6	5:30	6:30	19:30	21:00	-	-
		DVD	15	1	300	6:00	7:00	16:00	23:00	-	-
Family_3	11	Ph. charger	5	2	180	0:00	6:00	22:00	24:00	-	-
		TV	85	1	240	16:00	22:30	-	-	-	-
		Indoor bulb	26	3	300	5:00	6:30	18:00	22:30	-	-
		Iron	800	1	15	19:00	20:00	-	-	-	-
Dormitories	1	Lights	26	32	120	5:00	6:30	18:00	19:00	-	-
		Tubes	36	31	120	5:00	6:30	18:00	19:00	-	-
		Safety lights	26	21	720	0:00	6:00	18:00	24:00	-	-
Classrooms	1	Bulbs	26	49	300	5:00	7:00	18:30	21:30	-	-
		Tubes	36	8	300	5:00	7:00	18:30	21:30	-	-
		Safety bulbs	30	14	720	0:00	6:00	18:00	24:00	-	-
		Safety tubes	40	2	720	0:00	6:00	18:00	24:00	-	-
Kitchen	1	Lights	26	6	690	5:30	11:00	12:00	15:00	17:00	20:00
		Radio	5	1	690	5:30	11:00	12:00	15:00	17:00	20:00
		Sharpener	50	1	1	5:30	11:00	-	-	-	-
		Fridge	53	2	1440	0:00	24:00	-	-	-	-
Bakery	1	Lights	26	4	600	6:00	16:00	-	-	-	-
Refactory	1	Bulbs	26	5	90	18:30	19:30	-	-	-	-
		Tubes	36	9	90	18:30	19:30	-	-	-	-
Canteen	1	Bulbs	26	1	270	8:00	9:00	14:00	15:00	17:00	19:30
		Tubes	10	1	270	8:00	9:00	14:00	15:00	17:00	19:30
		Bulb	40	1	270	8:00	9:00	14:00	15:00	17:00	19:30
		Fridge	40	1	1440	0:00	24:00	-	-	-	-
Workshop	1	Lights	26	1	1440	0:00	24:00	-	-	-	-
		Radio	5	1	1440	0:00	24:00	-	-	-	-
Dispensary	1	Bulbs	26	1	390	8:00	12:00	16:00	18:00	19:00	21:30
		Tubes	36	1	390	8:00	12:00	16:00	18:00	19:00	21:30
Church	1	Bulbs	26	8	210	6:00	7:00	19:00	21:30	-	-
		Tubes	36	8	210	6:00	7:00	19:00	21:30	-	-
Ad. office	1	Bulbs	26	4	540	7:30	16:30	-	-	-	-
		Tubes	40	7	540	7:30	16:30	-	-	-	-

		Minitube	18	1	420	7:30	14:30	-	-	-	-
		Electronics	32	19	402	7:30	14:30	-	-	-	-
Library	1	Tubes	40	1 2	420	7:00	14:00	-	-	-	-
		Photocopier	32	1	420	7:00	14:00	-	-	-	-
CCU	1	Bulbs	26	4	480	8:00	16:00	-	-	-	-
		Tubes	36	11	480	8:00	16:00	-	-	-	-
		Laptop	55	18	480	8:00	16:00	-	-	-	-
		Printer_1	550	4	10	8:00	16:00	-	-	-	-
		Printer_2	510	1	30	8:00	16:00	-	-	-	-
		Photocopy1	1280	1	10	8:00	16:00	-	-	-	-
		Photocopy2	1300	2	5	8:00	16:00	-	-	-	-
		Standby	35	1	480	8:00	16:00	-	-	-	-

Appendix C

The chosen approach for the analysis of the energy profiles presented in Chapter 6 is articulated on 25 mathematical-statistical indicators. These express the data characteristics which fall into three main categories: order of magnitude, dispersion and distribution. Moreover indicators can refer to individual hourly values or the interaction between them.

In the following each indicator is introduced with its mathematical formulations. The reference targets of the indicators are the energy maps as defined in Paragraph 6.3. Hereafter the formulation of the indicators does not refer to the definition of the energy maps in terms of matrixes ($x_{i,j}$, where i refers to the daily hours, and j refers to the days throughout the year), but it refers to the energy maps in terms of hourly time series throughout the year (x_i, where i refers to the yearly hours [1, N], N = 8760).

1. **Energy integral:** is the integral value of the load demand or generation of an entire year. It is a fundamental datum for the analysis since it determines physical information such as the amount of the energy consumed or produced in a year, and hence it defines the order of magnitude of the analyzed profile.

$$I_1 = \sum_{i=1}^{N} x_i \qquad [Wh] \tag{C1}$$

2. **Hourly average:** the average is a single value that briefly describes the set of considered data. Indeed it expresses the magnitude or the central tendency of the set of data collected. Although it is useful, it does not provide any information as regards the data set variability.

$$I_2 = \frac{\sum_{i=1}^{N} x_i}{N} \qquad [Wh] \tag{C2}$$

3. **Hourly standard deviation:** in our application, it returns the variation as regards the average in energy consumption or generation.

$$I_3 = \sqrt{\frac{\sum_{i=1}^{N} (x_i - I_2)^2}{N}} \qquad [Wh] \tag{C3}$$

4. **Maximum hourly value:** in our application, it provides an idea of the maximum hourly load to be met or the maximum power available in an hour.

$$I_4 = max(x_i) \ with \quad i = 1,2, \dots, N \qquad [Wh] \tag{C4}$$

5. **Minimum hourly value:** in our application, it provides an idea of the minimum hourly load to be met or the maximum power available in an hour.

$$I_5 = min(x_i) \;\; with \;\;\; i = 1,2,\dots,N \quad [Wh] \tag{C5}$$

6. **Rate of max/min hourly value:** is the ratio between I_4 and I_5. It describes the order of magnitude of the minimum value as regards the maximum one. The more this ratio is close to the unity, the more the order of magnitude is similar and the two data are equidistant from I_2.

$$I_6 = \frac{I_4}{I_5} \tag{C6}$$

7. **Range of hourly value:** is the simplest variability index and is given by the difference between the measured maximum and minimum data.

$$I_7 = I_4 - I_5 \tag{C7}$$

8. **Quartiles [0.25, 0.5, 0.75]**
9. **InterQuartile range (IQR):** is the difference between the third and first quartiles, i.e. the amplitude of the range that contains the "middle half" of the observed data.

$$I_9 = q_3 - q_1 \tag{C8}$$

10. **Mode**
11. **Average difference between consecutive values:** represents the average value of time variations of the energy required or generated. It is useful to define the order of magnitude of the ramp that characterizes the profile. This provides information for the aggregation of multiple energy sources and the insertion of a possible accumulation system.

$$I_{11} = \frac{\sum_{i=2}^{N}(x_i - x_{i-1})}{N - 1} \tag{C9}$$

12. **Standard deviation of difference between consecutive values:** provides the information relating to the dispersion of the difference between the hours.

$$I_{12} = \sqrt{\frac{\sum_{i=2}^{N}\left((x_i - x_{i-1}) - I_{11}\right)^2}{N - 1}} \tag{C10}$$

13. **Maximum difference between consecutive values:** indicates the maximum value that the ramp can assume.

$$I_{13} = \max(x_i - x_{i-1}) \;\; with \;\; i = 2,3,\dots,N \tag{C11}$$

14. **Minimum difference between consecutive values:** indicates the minimum value that the ramp can assume.

$$I_{14} = \min(x_i - x_{i-1}) \;\; with \;\; i = 2,3, \dots, N \qquad (C12)$$

15. **Allocation of time variations according to the sign:** the differences between consecutive hourly values can be negative, positive or zero. This allocation is designed to quantitatively define the hourly power flows with a possible storage.
16. **Rate of maximum and minimum difference between consecutive values:** is the relationship between I_{13} and I_{14}. As in the previous case is additional information for the sizing of a possible accumulation system.

$$I_{16} = \frac{I_{13}}{I_{14}} \qquad (C13)$$

17. **Integral of the hourly differences grouped according to the sign:** represents the sum of the energy difference between one hour and the previous one. The sum is carried out between the classes defined by the indicator I_{15}. It means that all the hourly differences with the same sign are aggregated.
18. **Rate of Average difference between consecutive values and standard deviation:** is the relationship between I_{11} and I_3. It defines the order of magnitude of the difference between consecutive hours compared to the difference of the hourly value with the average. If this ratio tends to zero then the difference between hourly data is less significant than the dispersion of the data.

$$I_{18} = \frac{I_{11}}{I_3} \qquad (C14)$$

19. **Allocation of the energy integral in 10 classes:** in each of the 10 classes the hourly values which fall within the limits imposed by the respective interval are summed. Each interval is established by dividing the distance of the maximum hourly value, expressed by I_4, with respect to zero (equivalent to a zero energy demand and to a zero generation) in 10 of the same classes. Therefore the hourly values in the first class will fall within 10% of I_4, in the second those comprised between 10% and 20% of I_4 and so until the completion of the last class.
20. **Allocation of number of hours in 10 classes:** the allocation of the number of hours is carried out in a similar way to the previous case. The energy value for the hour under examination is not added, but the counter of the number of hours is considered.
21. **Skewness:** the index of asymmetry of a distribution is a value that seeks to provide a measure of its lack of symmetry about the mean. If it assumes a negative value, data are "shifted" to the left of the average, if it assumes a positive value data are "shifted" to the right of the average. If it assumes zero it is a necessary but not sufficient condition to define a symmetric distribution.

$$I_{21} = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - I_2)^3}{{I_3}^3} \qquad (C15)$$

22. **Curtosi Index:** indicates the difference from a normal distribution. If it is less than 3 indicates a distribution more flattened than a normal (also called platykurtic distribution), vice versa assuming a value greater than 3 defines a more elongated one than a normal (also called leptokurtic distribution); Finally, if the index assumes the value of 3 it defines a normal distribution. It is an indicator used to establish the importance of the "tails" of the distribution

$$I_{21} = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - I_2)^3}{{I_3}^3} \qquad (\text{C16})$$

23. **Coefficient of variation:** is a further dispersion index. It is calculated as the ratio between the standard deviation and the absolute value of the average.

$$I_{23} = \frac{I_3}{|I_2|} \qquad (\text{C17})$$

24. **Average daily energy integral:** is the average of the values of the integral of hourly values within the time interval corresponding to one day (24 hours). It has the same function of the indicator I_2 not at hourly, but at daily level.
25. **Autocorrelation:** defines the degree of dependence between the values of a data series. It is used to provide indication of the fact that an information x_i can be considered dependent to some extent from information at a previous time step x_{i-k}. Where k is the discretization step of time and it is considered up to a value of N/4, with N representing the number of data in the series.

Appendix D

Mathematical models and numerical optimization adopted

Numerical methods for off-grid PV system sizing are quite common in the literature (e.g. [201], [274], [284], [289], [290], [292], [471]–[476]). These methods are based on energy steady state simulation, i.e. different combinations of PV array and batteries are simulated on a yearly basis and one or more criteria are used to choose the best combination that addresses the load. A simulation consists in solving the energy balance of the system and of the change in the battery state of charge (SOC) for each time-step considered, usually an hour. During and/or at the end of the simulation the decision variables are also computed, and once all the possible system combinations have been simulated, these variables lead to identifying the optimum system.

Numerical methods are preferred when accurate results are required in order to optimize the energy and economic cost of the system. Moreover, different degree of complexity in the mathematical modeling of the system components can be easily adapted according to the type of analyses to be carried out. Drawbacks of this technique are the long calculation time required and the need of long and accurate input data series.

In Chapter 7 a numerical method has been employed for the simulation and optimization of the PV Micro-Grid which is based on the model shown in [201]. The physical modeling and the numerical technique have been implemented in MATLAB which was employed to perform the optimization process. In the following we report the main equations that define the mathematical models of the system components and the technical parameters which have not been described in the paper text.

The simulation of the system and the optimization method consists in three steps. The first step involves the estimation of PV energy output for each time-step of the simulation (t):

$$E_{PV}(t) = PV_{size} * \left(1 - \rho_T * \left(T_{Cell}(t) - T_{Rif}\right)\right) * \frac{\mathrm{H}_\beta(t)}{h} * \eta_{BOS} \quad [kWh] \qquad (\text{D1})$$

where:

- $H_\beta(t)$ is the specific solar irradiation on tilted surface for the chosen time-step;
- PV_{size} is the rated power of the panels under simulation at an irradiance h of 1 kW/m^2, an ambient temperature of 25°C and an air mass value of 1,5;
- ρ_T is the temperature coefficient of power respect to solar cell temperature provided by the manufacturer (normally 0.35÷0.45 %/°C);
- η_{BOS} is the balance of system efficiency which embraces all the losses not directly related to the sun energy conversion process.

Eq. (D1) also considers the effect of the solar cell temperature (T_{Cell}) on the output of the PV modules. The solar cell temperature at each time-step of the simulation can be calculated by means of the procedure shown by [302].

The second step describes the battery bank behavior by estimating the amount of energy that flows through the battery and the change in the battery state of charge. For each time-step the difference between PV array output ($E_{PV}(t)$) and load required by the user ($E_D(t)$) after inverter efficiency (η_{Inv}) is calculated:

$$\Delta E = E_{PV}(t) - \frac{E_D(t)}{\eta_{Inv}} \quad [kWh] \qquad \text{(D2)}$$

If the difference is positive the battery will be under charge, on the contrary a discharge will occur. Moreover the energy stored in the battery (i.e. the battery State of Charge, SOC) needs to be updated based on the amount previously stored ($E_{Bat}(t-1)$):

$$E_{Bat}(t) = \begin{cases} E_{Bat}(t-1) + \Delta E * \eta_{CH} \;, & \Delta E > 0 \\ E_{Bat}(t-1) + \dfrac{\Delta E}{\eta_{DISCH}} \;, & \Delta E < 0 \end{cases} \quad [kWh] \qquad \text{(D3)}$$

where η_{CH} and η_{DISCH} are respectively the battery charge and discharge efficiencies. Then, the SOC needs to be updated based on the previously value:

$$SOC(t) = SOC(t-1) \pm \frac{E_{Bat}(t)}{B_{size}} \qquad \text{(D4)}$$

Furthermore, the energy stored in the battery is subjected to the following constraints:

- to respect a minimum and maximum level of the state of charge (SOC_{min} – SOC_{max});
- to respect the power-to-energy ratio ($(P/E)_R$) of the battery. As a matter of a battery of capacity B_{size} cannot accept or provide every amount of inflow or outflow power. In order to model these features, we consider the power-to-energy ration so that, if for example the $(P/E)_R$ is 0.5 and the B_{size} is 1 kWh, the battery can provide or accept a maximum of 500W for an hour.

The battery lifetime approach used is the *rainflow* cycles counting method, based on Downing's algorithm [303]. This method is based on counting the charge/discharge cycles Z_i corresponding to each range of the Depth of Discharge (split in m intervals) for a year. For each interval there is a number of Cycles to Failure (CF_i) obtained from Figure D1. Battery duration can be calculated as follows:

$$Life_{Bat} = \frac{1}{\sum_{i=1}^{m} \frac{Z_i}{CF_i}} \quad [year] \qquad \text{(D5)}$$

The third and final step is the computation of the techno-economical parameters that are employed to look for the optimum system. Here we report the equations to compute the Loss of Load, while for the Loss of Load Probability, the new proposed Net Present Cost, the VOLL, and others the reader should refer to the paper text.

The Loss of Load (*LL*) indicator represents the amount of energy required by the load that remains unsatisfied because the system is unable to supply enough power. LL is computed during the discharge phase of the battery ($\Delta E < 0$) when one between two conditions occurs:

$$\mathrm{LL}(t) = \begin{cases} (SOC_{min} - SOC(t)) * \eta_{DISCH} * \ \eta_{INV} * \ B_{size} & SOC(t) < SOC_{min} \\ (\Delta E - (\mathrm{P}/E)_R * \ \mathrm{B}_{size} * \ \Delta t) * \ \eta_{INV} & \dfrac{\Delta E}{\Delta t} \geq (\mathrm{P}/E)_R * B_{size} \end{cases} \quad [kWh] \qquad (\text{D6})$$

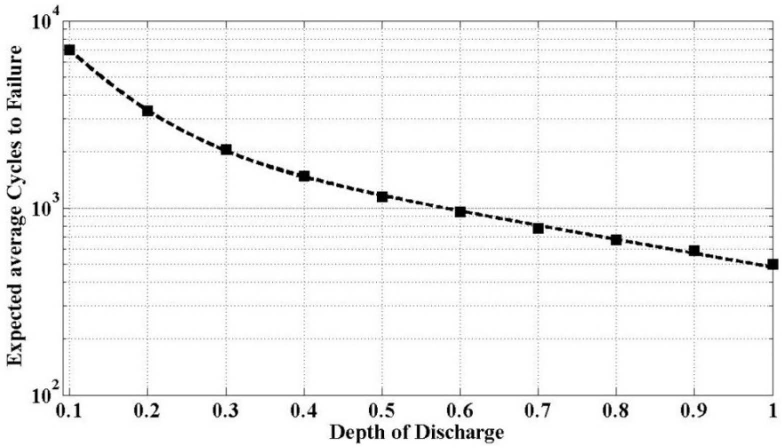

Figure D1 Cycles to Failure vs Depth of Discharge for lead acid battery

Appendix E

Load data assumptions for the Micro-Grid area in Soroti

Class Type	N_{US}	App Name	P [W]	N_{App}	h_{funct}	$W_{f,1}$ h_{start}	h_{stop}	$W_{f,2}$		$W_{f,3}$		Tot_W
Family_1	50	Lights	3	4	6	0	2	17	24	-	-	9
		Phone Charger	5	2	3	0	9	13	15	17	24	18
		Security Light	5	1	12	0	7	17	24	-	-	14
Family_2	15	Lights	3	4	6	0	2	17	24	-	-	9
		Phone Charger	5	2	3	0	9	13	15	17	24	18
		Security Light	5	1	12	0	7	17	24	-	-	14
		Radio	5	1	4	6	9	17	24	-	-	10
		AC-TV (small)	100	1	5	11	15	17	24	-	-	11
Family_3	15	Lights	3	8	6	0	2	17	24	-	-	9
		Phone Charger	5	2	3	0	9	13	15	17	24	18
		Radio	5	1	4	6	9	17	24	-	-	10
		Security Light	5	2	12	0	7	17	24	-	-	14
		AC-TV (small)	100	1	5	11	15	17	24	-	-	11
		Fridge (small)	250	1	5	0	24	-	-	-	-	24
Family_4	10	Lights	3	12	6	0	2	17	24	-	-	9
		Phone Charger	5	4	3	0	9	13	15	17	24	18
		Radio	5	1	4	6	9	17	24	-	-	10
		Security Light	5	4	12	0	7	17	24	-	-	14
		AC-TV (small)	100	1	5	11	15	17	24	-	-	11
		Standing Fan	55	1	6	8	24	-	-	-	-	16
		Decoder	15	1	5	11	15	17	24	-	-	11
		Fridge (small)	250	1	5	0	24	-	-	-	-	24
		Internet Router	20	1	6	0	24	-	-	-	-	24
		Laptop (small)	55	1	6	0	2	11	15	17	24	13
Family_5	5	Lights	3	16	6	0	2	17	24	-	-	9
		Phone Charger	5	4	3	0	9	13	15	17	24	18
		Radio	5	2	4	6	9	17	24	-	-	10
		Security Light	5	6	12	0	7	17	24	-	-	14
		AC-TV (big)	200	1	6	11	15	17	24	-	-	11
		Standing Fan	55	2	6	8	24	-	-	-	-	16
		Decoder	15	1	6	11	15	17	24	-	-	11
		Fridge (big)	400	1	5	0	24	-	-	-	-	24
		Internet Router	20	1	8	0	24	-	-	-	-	24
		Laptop (big)	80	2	8	0	2	11	15	17	24	13
Family_6	5	Lights	3	16	6	0	2	17	24	-	-	9
		Phone Charger	5	4	3	0	9	13	15	17	24	18
		Radio	5	2	4	6	9	17	24	-	-	10
		Security Light	5	6	12	0	7	17	24	-	-	14
		AC-TV (big)	200	1	6	11	15	17	24	-	-	11
		Standing Fan	55	2	6	8	24	-	-	-	-	16
		Decoder	15	1	6	11	15	17	24	-	-	11
		Fridge (big)	400	1	5	0	24	-	-	-	-	24
		Internet Router	20	1	8	0	24	-	-	-	-	24
		Laptop (big)	80	2	8	0	2	11	15	17	24	13
		Hair Dryer	1000	1	0.5	17	24	-	-	-	-	7
		Printer	50	1	0.5	17	24	-	-	-	-	7
		Stereo	100	1	3	17	24	-	-	-	-	7
		Water Heater	660	1	2	0	2	18	24	-	-	8
Enterprise_1	15	Fluor. Tube (small)	36	10	6	7	11	16	20	-	-	8
		Phone Charger	5	4	3	7	13	15	20	-	-	11
		Security Light	5	4	12	0	7	17	24	-	-	14
		Internet Router	20	1	10	7	20	-	-	-	-	13

		Laptop (big)	80	1	8	7	13	15	20	-	-	11
		Laptop (small)	55	5	8	7	13	15	20	-	-	11
		Printer	50	2	2	7	13	15	20	-	-	11
		Standing Fan	55	2	8	7	13	15	20	-	-	11
		Fluor. Tube (big)	47	20	6	7	11	16	20	-	-	8
		Phone Charger	5	15	3	7	13	15	20	-	-	11
		Security Light	5	10	12	0	7	17	24	-	-	14
		Internet Router	20	1	10	7	20	-	-	-	-	13
		Laptop (big)	80	5	8	7	13	15	20	-	-	11
Enterprise_2	5	Laptop (small)	55	10	8	7	13	15	20	-	-	11
		Standing Fan	55	5	8	7	13	15	20	-	-	11
		Water dispenser	550	1	3	7	13	15	20	-	-	11
		Photocopier	750	1	1	7	13	15	20	-	-	11
		Ceiling Fan	75	5	8	7	13	15	20	-	-	11
		PC	400	1	10	7	20	-	-	-	-	13
		Lights	3	2	3	8	11	16	20	-	-	7
Mobile Money	5	Phone Charger	5	3	3	8	18	-	-	-	-	10
		Standing Fan	55	1	6	10	18	-	-	-	-	8
		Lights	3	2	3	8	11	16	20	-	-	7
		Phone Charger	5	1	3	8	18	-	-	-	-	10
Kiosk	10	Standing Fan	55	1	6	10	18	-	-	-	-	8
		Fridge (small)	300	1	8	0	24	-	-	-	-	24
		Fridge (big)	500	1	8	0	24	-	-	-	-	24
		Lights	3	5	8	8	13	15	20	-	-	10
Barber	2	12V shaver	10	5	6	8	13	15	20	-	-	10
		Ceiling Fan	75	3	8	8	13	15	20	-	-	10
		UV sterylizer	50	1	2	8	13	15	20	-	-	10
		Lights	5	3	8	8	13	15	20	-	-	10
Tailor	3	Sewing machine	50	1	3	8	13	15	20	-	-	10
		Ceiling Fan	75	1	8	8	13	15	20	-	-	10
		Lights	3	25	3	8	11	16	20	-	-	7
		Security Light	5	25	12	0	7	17	24	-	-	14
Market Place	1	Fridge (small)	300	3	8	0	24	-	-	-	-	24
		Fridge (big)	500	3	8	0	24	-	-	-	-	24
		Standing Fan	55	10	8	8	13	15	20	-	-	10
		Radio	5	10	4	10	13	15	18	-	-	6
		Fluor. Tube (small)	36	10	8	0	4	17	24	-	-	11
		Fluor. Tube (big)	47	5	8	0	4	17	24	-	-	11
		Security Light	5	5	12	0	7	17	24	-	-	14
		Phone charger	5	10	8	15	24	-	-	-	-	9
		AC-TV (small)	130	2	9	0	4	15	24	-	-	13
		AC-TV (big)	200	1	9	0	4	15	24	-	-	13
		PC	400	1	9	0	4	15	24	-	-	13
Club	3	Laptop (big)	80	10	6	15	24	-	-	-	-	9
		Printer	50	1	1	15	20	-	-	-	-	5
		PicoProjector	18	1	4	0	2	20	24	-	-	6
		Amplyfier	6	1	4	0	2	20	24	-	-	6
		Ceiling Fan	75	3	8	0	4	15	24	-	-	13
		Music System	178	1	8	0	4	15	24	-	-	13
		Internet Router	20	1	9	0	4	15	24	-	-	13
		Fridge (small)	300	2	8	0	24	-	-	-	-	24
		Fridge (big)	500	1	8	0	24	-	-	-	-	24
Street Lights	1	Lights (Street)	50	100	12	0	7	17	24	-	-	14
		Led strips	8	100	12	0	7	17	24	-	-	14
		Fluor.Tube (small)	36	10	4	8	17	-	-	-	-	9
Primary School	1	Phone Charger	5	7	3	8	17	-	-	-	-	9
		Security Light	5	4	12	0	7	17	24	-	-	14
		Lights	3	10	3	8	11	16	20	-	-	7
		Security Light	5	4	12	0	7	17	24	-	-	14
Pharmacy	1	Fridge (small)	300	3	8	0	24	-	-	-	-	24
		Fridge (big)	500	2	8	0	24	-	-	-	-	24
		Standing Fan	55	3	8	8	13	15	20	-	-	10

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