UNIVERSITÀ DEGLI STUDI DI PAVIA

DOCTORAL THESIS

Models for the Management and the Development of Hybrid Energy Systems: Case Study of Cameroon

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Dedication

I dedicate this work to my late father Pendieu Aloysius Arnold Galako, my source of inspiration, the man who built the person I am.

Abstract

Electrification nowadays of rural areas in various developing countries is around 20%. More than 70% of the population in such countries live in rural areas with a forecasted increase of 6% per year in the near future, with the consequences that these populations live almost without electricity. Nevertheless, these populations have a good potential of common renewable energy resources: hydro, wind, solar energy and biomass. Despite of the great potential (for example, in Cameroon the yearly potential is respectively 3.65 MWh/yr for wind and 5000 TWh/yr for solar energy), the development in the energy sector and the un-electrification have been limited in such rural areas due to (i) the high cost of grid connection, (ii) the large losses associated with the transmission and distribution networks, (iii) the dispersion of the population and the geographical access of the local areas, (iv) the difficult access by road, just to cite a few. This work could be considered as a response of un-electrification, with the objective of electrifying the remote and poor population living in rural and remote areas at the lowest cost. The aim of the research work carried out during the doctoral period covered a feasible study of a model of hybrid microgrid for a remote village in the Far North Cameroon (Salak village). By exploiting the available renewable resources of the local area (solar and wind) in combination with traditional generators (fossil fuel) and a battery bank, would enable to meet the electricity needs with the lowest operation costs and optimized management. The hybrid microgrid is powered by a photovoltaic generator, a wind generator, a battery bank and a diesel generator as its backup. The battery would be charged in case of over-generation from renewables (heuristic approach) but also with diesel generator in case of under-generation from renewables (optization approach). My research begins with a literature review on past and ongoing research studies in the field of hybrid energy systems for remote areas with the objectives of (i) review the different schemes of hybrid energy system in islanding mode for remotes areas; (ii) focus on widely use optimization approaches for design and modeling of hybrid microgrids for electrification in remote areas; (iii) focus on photovoltaic, wind, fuel generator with/without storage; (iv) focus on four specific topologies of hybrid microgrids with or without storage system (PV; Wind; PV+Wind; PV+Wind+Diesel generator); (v) look for the advantages and the disadvantages of each topology of hybrid microgrid. Particle Swarm Optimzation (PSO) Techniques are used to optimize the number of photovoltaic panels , Hybrid Optimization Genetic Algorithm use for minimizing the total cost (minimizing fuel consumption or maximizing efficiency), Mixed Interger Linear Programming (MILP) use also for taking decisions, Hybrid Optimization Model for Renewable Energy (HOMER) use for design and model hybrid micro-grids. The study also reveals the diversify types of hybrid microgrids in the world depending on geographical locations, the variability definitions and applications of microgrids (from W to MW). All these different issues have the main objectives of reducing fuel consumption, performing reliability of the system, preserving environment and providing electricity for remote isolated located populations. The investigation demonstrates the important role played by storage systems in electrification of remote areas. The second step is the acquisition data of solar irradiation and wind speed in all ten regions of Cameroon. The objectives of this study is (i) to have a reliable information about the irradiance and wind speed across the country; (ii) assess the potential of solar and wind energy; (iii) estimate of the hourly output power, the daily and yearly energy production of a solar panel and wind generator; (iv) used solar and wind energy assessment to boost rural electrification in remote villages and contribute to energy supply; (v) use the solar and wind assessment to identify precisely the site where to carry the case study (Salak village). This study concludes that both the Northern regions (Far North, North and Adamawa) have the highest wind potential and moving from the North to the South of the country, the average means wind speed decreases and its shows the quite uniform distribution of solar radiation across the country when moving from North to South. This work finally confirmed that Cameroon has a good potential of solar and wind that could help to electrify remote villages across the country. A further step is the assessment of hydro power plan potential. The objectives of this study is: (i) the identification of rivers that can be hugely exploited for hydroelectricity production; (ii) assess the potential of hydro power plants; (iii) use all the solar and wind potential for electrification and compensate the difference with hydro power plant. The analysis shows that there is a good potential of hydro power. From the potential of solar irradiation, wind speed assessed across the country and the maps of hydroelectric potential assessed from flow rate of some rivers in Cameroon, the mixed of different fluctuating generating sources (solar and wind) could be compensated by hydro power plants existing or could be constructed across the national territory. The study concludes the geographical distribution of different renewable energy sources in Cameroon which is very important because it would help the hydropower just to deliver less energy for fluctuation compensation. The result of this study shows that, according to the energy system distribution structure in Cameroon, the combination of different renewable energy sources with high fluctuations and hydropower could be reliable and cost effective solution for a growing energy demand. Finally the case study of the community of Salak in the Far North Cameroon which aims to propose an optimal design of hybrid energy systems for rural electrification. The objective is (i) to design and implement a model of hybrid energy system for rural electrification of the Salak village community applying a developed heuristic algorithm; (ii) size and design a water production and distribution system; (iii) apply the optimization model and compare the results obtained with the heuristic approach on the Salak village case; (iv) carried out an economic evaluation to determine the cost of any kWh of energy producted either by the only diesel generator or the hybrid generation system. The solar and wind energy are combined with diesel generator and battery storage as backup of the system for supplying the load demand. In this study, the battery would be charged in case of over-generation from renewables (heuristic approach) but also with diesel generator in case of under-generation from renewables (optimization approach). The battery is modelled including its lifetime for economic evaluations using the rainflow counting method. The diesel generator is modelled taking into consideration the value of the maximum load demand. The diesel generator must work inside its best efficient area of operation and a wide research has been done to retrieve such data for small size generators. The heuristic model and the optimization model have been applied and compared. The economic study has been carried out to evaluate the cost of any kWh of energy producted and also the life cycle cost of any configuration. This proposed hybrid energy system would not only start solving the electrification problem of the Salak rural area but could also preserved environment, help improving the quality of life by raising the level of the services.

Preface

This PhD thesis is ultimately based on different written and published papers which contains the results of the research undertaken during this 3 years period of doctorale studies, but some results have not yet been published. The different topics developed in this thesis are all focus and related to feasibility study on hybrid microgrids for both electrical and thermal generation in remote and isolated areas, while combining together renewable generating sources (solar, wind, biomass, water falls, etc.) with fuel generators (diesel generators, coal power plant, etc.) and also storage system (battery bank, capacitor bank, hydro, etc.) for load supply and made a local area o comuninity being autonomous as possible. My research was motivated by the fact that many people living in remote areas and principali in developing countries lack of electricity supply even though they may have an abundance of renewable sources for electrical generation. The research has been focus on hybrid system in which it can be taken in consideration the renewable resources of the site and traditional generation system looking also on cost and technical economic evaluations.

It not has been possible to make a round trip in Cameroon for the installation of an acquisition data station for wind speed, solar energy, and load profile of the selected site for the study. Nevertheless, with the help of some citizens contacted on site, we succeed to have some data with which a feasible study has been carrying out (see Chapter 7).

The most important activities carried out during these three past years include (i) the lectures of *management*, *automation and communication of power systems* (*Gestione*, *Automazione e Comunicazione dei Sistemi Elettrici*) and *management of fotovoltaic systems* (*Gestione dei Sistemi Fotovoltaici*) at the University of Pavia (2014) and *Solar Electric System* at the University of Paderborn (Germany 2015), (ii) several specialized seminars on topics related to the design of microgrids and smart grids, management of microgrids, data acquisition, (iii) the European PhD school of Gaeta on Power Electronics, Electrical Machines, Energy Control and Power Systems (2014), the International Summer School on Hybrid Microgrids of Pavia (2016), (iv) the seminars within the course of *energy management of industrial electrical drives* (*Azionamenti Elettrici Industriali per Energetici*) *and the course of planning of energy transformation* (*Pianificazione delle Trasformazioni Energetiche*) (2014) "Use of Linear Programming and Mixed Integer Linear

Programming for Compressor Room Optimization" at the University of Pavia.

For a visiting period abroad, I have been hosted under the chair of Power Electronics and Electrical Drive Engineering (LEA) held by Prof.Dr.-Ing Joachim Boecker and the research group of Sustainable Energy Concepts (NEK) held by Prof.Dr.-Ing Stefan Krauter at the university of Paderborn (Germany). All my activities carried out in Paderborn was under the Sustainable Energy Concepts (NEK) research.

This three years have been challenging with both ups and downs. It has been relatively too short even though without any social life or spare time, all the initial aiming have not been totally reached. The work here is positioned as a first step towards finding solutions in electrification problems in remote areas and represents anyway a step foward in this field of research. In exception of attending conferences, PhD schools and the Erasmus period abroad financed by the University of Pavia, all the PhD period has not been funded by any institution or organisation but by myself and my family.

Acknowledgments

I would firstly like to express my special thanks to my tutor *Prof.ssa Norma Anglani*, you have been a tremendous mentor for me. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. Your advice on both research as well on my personal growth have been priceless.

Thanks to *Joerg Bendfeld* that gave me the opportunity to work with him and his team at the Sustainable Energy Concepts (NEK) research group held by *Prof.Dr.-Ing Stefan Krauter* and *Prof.Dr.-Ing Joachim Boecker* to have hosted me under the laboratory of Power Electronics and Electrical Drive Engineering (LEA) research group at the university of Paderborn under the Erasmus program flag with a grant of the University of Pavia. A special thanks goes to *Dr.-Ing Noel Djongyang* and the Bachelor students (2015) of the Institut Suprieur du Sahel (ISS-University of Maroua) for the precious informations given to me about the Salak village (for the case study), the solar radiation and wind speed acquisition data and the monitoring of the load demand profile of the Salak rural hospital.

I would like to thank Dr Fabrizio, Edwin, my office partners with who, I have shared together all the stress during these past years. A special thank to my former classmate Dr Liberale for his advices and encouragements.

A special thanks to my family. Words cannot express how grateful I am to my mother, father, brothers and sisters (specially my elder sister *Leutchat Chymène*) for all of the sacrifices that you have made on my behalf. Your prayer for me was what sustained me thus far. I would also like to thank all of my friends who supported me in writing, and incented me to strive towards my goal. At the end I would like express my appreciations to my girl friend Ebegne Thime Winnie Rose Christelle who spent sleepless nights and was always my support in the moments when there was no one to answer my queries.

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Nomenclature

HES	Hybrid Energy System
ASEmax:	maximum average stored energyof battery
SOC0:	State of charge of the battery at the initial time
SOCmax:	State of charge maximum of the battery
SOCmin:	State of charge maximum of the battery
Pbatmax:	Maximum power of the battery
Pbatmin:	Minimum power of the battery
Pdgmax:	Maximun power generated by the diesel generator
Pdmin:	Minimum power generated by the diesel generator
Pre:	Power generated from renewables $(P_{pv} + P_w)$
PL:	Power load demand
VAC:	Volt Alternating Current
DC:	Direct Current
AC:	Alternating Current
F-G:	Fuel Generator
D-G:	Diesel Generator
PV:	Photovoltaic
BSS:	Battery Storage System
PSS:	BPumped Storage System
S-C:	Super Capacitors
Nb-H:	Number of hours
T-Sources:	Traditional Sources

1 Introduction

1.1 Scope of the work

1.1.1 Scope and motivations

My research was motivated by the fact that many people living in remote areas and principali in developing countries lack of electricity supply, even though they may have an abundance of renewable sources for electrical generation. This works tries to bring a part of solution to the current energy crisis facing most developing countries, most African countries, especially those in sub-Saharan Africa and Cameroon in particular. This work focuses in particular to the issue of access to electricity in rural and remote areas. In some countries such as Europe, electricity networks are large and complex structures whose role is to carry electricity from the massive production centers to consumption places, often over long distances. Differently, in many African countries, growth in demand for electricity is not always accompanied by an increase in production and transport capacity, leading to a large gap between supply and demand for electricity. For example, the extension of networks to rural areas and construction of new networks in remote locations face significant economic constraints. This is the case in sub-Saharan Africa, where nearly 70% of the population has no access to electricity (see Table 1.2). With the new policy scenario, if real investments are made by different government in electricity grids, by the year 2030 the access to modern energy will reduced to 50% in rural areas (see Table 1.2). All over the world, it is only in Sub-Saharan Africa countries where the lowest level of rural electricity access are concentrated (see Fig.1.3) [2].

1.1.2 Challenges of rural electrification in developing countries

Challenges to improve access to electricity and energy in various developing countries is very big, more than 70% of the population do not have access to electricity in Sub-Saharan Africa, although the important efforts, the number of the population without access increase with population growth. In Niger for example, a recent survey shows that only 47% of people leaving in cities have access to electricity while, only 0.4% in rural area [17]. This situation is due to many different reasons: low density and dispersion of the population; population far away from the grid; very low income of the population; lack

Region	Population without electricity millions	National electrification rate %	Urban electrification rate %	Rural electrification rate %
Africa	634	45%	71%	28%
Sub-Saharan Africa	632	35%	63%	19%
Angola	16	33%	69%	6%
Benin	7	29%	57%	9%
Botswana	1	53%	69%	32%
Burkina Faso	14	18%	58%	1%
Burundi	10	5%	28%	2%
Cameroon	9	62%	96%	23%
Cabo Verde	0	96%	100%	89%
Central African Republic	5	3%	5%	1%
Chad	13	4%	13%	1%
Comoros	0	69%	89%	62%
Congo	3	42%	56%	16%
Côte d'Ivoire	8	62%	88%	31%
Democratic Republic of Congo	62	18%	42%	0%
Djibouti	1	42%	54%	1%
Equatorial Guinea	0	66%	93%	48%
Eritrea	3	32%	86%	17%
Ethiopia	73	25%	85%	10%
Gabon	0	89%	97%	38%
Gambia	1	45%	66%	13%
Ghana	8	72%	91%	50%
Guinea	9	26%	53%	11%
Guinea-Bissau	1	21%	37%	6%
Kenya	36	20%	60%	7%
Lesotho	2	17%	43%	8%
Liberia	4	10%	8%	11%
Madagascar	21	13%	22%	8%
Malawi	15	12%	46%	5%
Mali	13	26%	53%	9%
Mauritania	3	29%	47%	2%
Mauritius	0	100%	100%	100%
Mozambique	16	40%	67%	27%
Namibia	2	32%	50%	17%
Niger	16	15%	62%	4%
Nigeria	98	45%	55%	36%
Réunion	0	99%	100%	87%
Rwanda	8	27%	72%	9%
Sao Tome and Principe	0	59%	70%	40%
Senegal	6	61%	88%	40%
Seychelles	0	98%	98%	98%
Sierra Leone	5	14%	33%	1%
Somalia	9	15%	33%	4%
South Africa	8	86%	87%	85%
South Sudan	12	1%	4%	0%
Sudan	24	40%	67%	26%
Swaziland	0	65%	84%	60%
Tanzania	36	30%	57%	18%
Togo	5	27%	35%	21%
Uganda	31	19%	52%	12%
Zambia	11	28%	62%	5%
Zimbabwe	7	52%	78%	40%
North Africa	1	99%	100%	99%
Algeria	0	100%	100%	100%
Egypt	1	99%	100%	99%
Libya	0	100%	100%	99%
Morocco	0	99%	100%	97%
Tunisia	0	100%	100%	100%

Figure 1.1: Electricity Access in Africa-2014 [1]

	Without access to electricity			Without access to clean cooking facilities		
	2014	2030	2040	2014	2030	2040
Africa	634	619	489	793	912	849
Sub-Saharan Africa	633	619	489	794	908	844
Developing Asia	512	166	51	1 923	1 600	1 242
China	0	0	0	453	265	200
India	244	56	5	867	763	534
Latin America	22	0	0	75	65	60
Middle East	18	0	0	8	8	8
World	1 186	784	541	2 799	2 585	2 159

Figure 1.2: Energy access projections (million) [1]

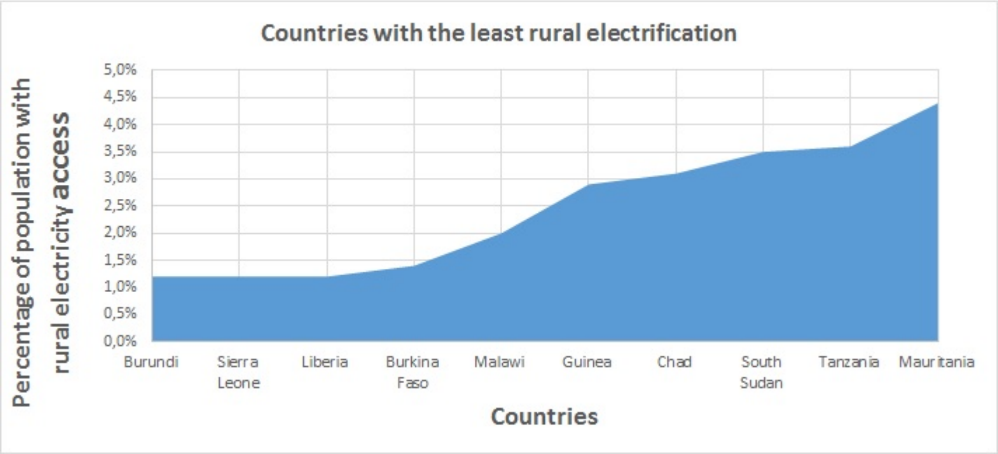

Figure 1.3: Countries with the least rural electrification [2]

of benefit in rural electrification; lack of technical skill of private actors; limited investment capacity from national public states; lack of feasible financing mechanism for rural investment and un-sufficient project capacity; obstacle of credit access for local electricity producers.

1.1.3 Distributed small grid and centralized high power plants for rural electrification in developing countries: what's the best??

The decentralized nature of human settlements in the region implies very high distribution costs for conventional centralized power systems. Contrary to popular belief, many rural Africans reside in individual scattered homesteads and not in concentrated villages. Extending power from centralized generating stations to individual homes is a costly undertaking [18], [19]. In this context, renewables and other decentralized energy options are particularly competitive in delivering modern energy to Africa's rural poor. Decentralization of electricity production can significantly contribute to electrify rural areas in Africa. An opportunity for decentralized sources like photovoltaic has been open up by the finding that it is currently impractical for the centralized grid to meet all of Nigeria's rural electricity demand [20]. Many distributed generation technologies are indeed flexible in several respects: operation, size and expandability. For example, making use of distributed generation allows a flexible reaction to electricity price evolutions. A decentralized power system can function either in the presence of grid, where it can feed the surplus power generated to the grid, or as an independent/stand-alone isolated system exclusively meeting the local demands of remote locations [21]. Energy sector in many developing countries suffer on two fundamental problems: (i) the use of traditional energy sources and the inefficient production and (ii) the un-equal use and distribution of modern energy sources. These two problems can be related to socio-economic and environmental issue and could impacted the quality of life of the population. Renewable energy sources and decentralize power sources are preferable when costless than grid supplies [22]. The extending cost to connect the centralized grid to new structure or remote area depend on many factors, such as the distance from grid to the remote area, the geographical position, the operation and sytem cost and many others more. But what impact significantly the cost of new transmission and distribution line is the line voltage and its capacity [23]. Due to the dispersion of the population, the long distance between the remote area and the grid, the low level of power demand and the power lossess along the transmission lines, build a long power line is costly and cannot be justified [24].

Distributed generation could serve as a substitute for investments in transmission and distribution capacity or as a bypass for transmission and distribution costs. Of course, this is possible only to the extent that alternative primary fuels and renewable sources are locally available in sufficient quantities. In general, the smaller the customer size, the larger the share of transmission and distribution costs in the electricity price (above 40% for households). From the point of view of the system operators, distributed generation units can substitute for investments in transmission and distribution capacity. In some cases, and with a different control, a distributed generation unit can even be used as an alternative to connecting a customer to the grid in a *stand-alone* application. Furthermore, well chosen distributed generation locations (i.e. close to the load) can also contribute to reduced grid losses. There is the increased interest by electricity suppliers in distributed generation because they see it as a tool that can help them to fill in niches in a liberalised market. In such a market, customers will look for the electricity service best suited for them. Different customers attach different weights to features of electricity supply, and distributed generation technologies can help electricity suppliers to supply the type of electricity service they prefer. In short, distributed generation allows players in the electricity sector to respond in a flexible way to changing market conditions. In liberalised markets, it is important to adapt to the changing economic environment in the most flexible way. Distributed generation technologies in many cases provide this flexibility because of their small sizes and the short construction lead times compared to most types of larger central power plants.

Centralized power systems are not nowaday the only option for access of modern energy services where prices of small renewable electricity power systems are decreasing. Developing countries have the opportunity to move easily to new renewable and modern services more quickly because of the less developed centralized electricity infrastructures. Challenges of electrification is different between countries with mature electricity infrastructures and poorly developing countries. Developing countries look for electrification access with a poor population, with limited knowledge of modern energy services and uses. In such countries, eletrification has to be planned in the perspective of rural development due to the poorly electricity load demand. The poorly population needs electricity only for lighting, radio and tv. It is good to mention that access of electricity or modern services would not directly reduce poverty but only a socio-economic development business around the electrified environment can do it [25]. In many developing countries, governmental and non governmental institutions agree that a way of facing the lack of electricity access could be the implementation of renewable energy programmes, the creation of national and regional energy institution network for well diffusion of renewable energy technologies and their benefit to the poorly popultion living in rural and urban zone [26].

1.1.4 Role of government in promoting renewables

Government in developing countries have a major role to play, implementing strategies and policy for long term in promoting renewable energy sources for major access of electricity to their population. To promoting renewable energy sources, the government have to exempt taxes to actors who invest in renewable energy. The government can also support national research and development institutions. With the support of national and international developmental agencies, it could implement a scientific, technological, and industrial development programme. The government may wish to build its own research and manufacturing expertise, so as not to depend solely on expensive imports in the way it does in many other technological areas. It could encourage the promotion of public awareness of the environmental and other benefits of renewables, educating the general public on its advantages. This would extend the current advertising campaigns and renewable energy documentation programmes that reach the people by radio, TV, newspapers. The government could also facilitate an appropriate economic and political climate to attract international investment in the production of renewables systems. The government could ensure a healthy market by restricting monopolies, fostering development of standards and of codes of practice [20]. In the same perspective, the authors discussed about government policy to promote on-grid and off-grid in Nepal as solution for rural electrification areas and socio-economic impact of cooking demand. Where on-grid electrification is developed by government through the Nepal Electricity Authority (NEA) and off-grid hand by another authority under the government who promoted alternative energy technology [27].

In the educational level, training programmes on techno-economic and social-cultural skill have to be put in place in order to have a critical mass of locally trained persons. At the colleges and universities in developing countries, technical and engineering courses and curricula have to be taught so that good technicians and engineers could come out with good skill.

1.1.5 Role of private sector in promoting renewables

In developing countries, private sector can contribute as a good partner in diffusion and development of renewable energy technologies amongs the population. Private sector can be involved in two different levels. The transportation and the distribution lines and services. Due to economical problems facing many developing countries at the beginning of year 1990, privatisation and concession of the energy sector to private foreign companies have been one of the major consequence of the non-investment on electricity infrastructure, the marginalisation of grid extention, electricity access in rural area and urban poor zone. Even though, enormous profit has been made by these companies. In this context, the private local sector has to be the principal actor during the renewal of the concessions and make sure that in the new contract, it can be mentioned and adopted clearly the electrification rural area and the urban poor zone. The local private sector need to be involved in all the process of electrification so that they can contribute significantly.

1.1.6 Funding mechanism for electrification challenges in Sub-saharan countries

Some options and priorities for the future can be: locally, due to economical problem facing developing countries, they have to mobilise all their internal resources for external funding. But to address problem for funding, they need to first mobilise local fund, local loans and national budgets. For external front, many international partners and donors can be mobilised for funding. For example the World Bank's sector syndication approach for electrification projects can make a major contribution, and FEMA (Federal Emergency Management Agency) member ministers will do well to take them up in this regard [28]. The Kyoto Protocol requirement is that countries limit or reduce their greenhouse gas emissions. By setting such targets, emission reductions took on economic value. To help countries meet their emission targets, and to encourage the private sector and developing countries to contribute to emission reduction efforts, negotiators of the protocol included three market-based mechanisms: emissions trading, the clean development mechanism (CDM) and joint implementation (JI). Carbon finance has also tended to by-pass Sub-Saharan Africa and current efforts including those led by the United Nations Environment programme (UNEP) and United Nations Development Programme (UNDP) to assist African countries to gain better access to the clean development mechanism (CDM), could help to improve this situation [29].

There are two registered clean development mechanism project in Cameroon (CDM). Both of them are landfill gas recovery projects: Nkolfoulou and Douala landfill gas recovery and flaring project. In both projects landfill gas is recovered from existing landfills and burned. The gas is not used for energy production. The Ministry of the Environment and Nature Protection is the Designated National Authority for CDM. The two projects are registered to sell carbon credits via the U.N.'s clean development mechanism (CDM), but the price of CDM offsets has slumped, blunting prospects for the landfill improvement scheme, according to officials with the state-owned hygiene and sanitation company Cameroon (HYSACAM). The two power plants have been built for around 10 million euros (around 13.6 million USD). Priority of united nations development programme (UNDP) works in Cameroon is for democratic governance, energy and the environment and fight against poverty.

The world bank had 25 active projects in Cameroon in April 2012. One of the projects is the environmental and social capacity building for the energy sector project aimed at improving the management of and the accountability for environmental and social issues related to large infrastructure investments.

In Ghana, the promotion of solar photovoltaic implementation with the aim of expanding the rural electrification has been support by many international and development agencies such as the canadian international development agency (CIDA), danish international development agency (DANIDA), german technical cooperation (GTZ), the united nations development programme/global environment facility (UNDP/GEF), world bank and the spanish government [30]. Still in Ghana, a national energy fund has been successfully used to finance renewable energy projects and energy efficiency activities on a sustainable basis. An important challenge is the building of discrete renewable energy projects into large programmes which can be financed by major bilateral and multilateral donor and financing agencies [26]. In the Comoros, a small island nation in the indian ocean, the world bank energy sector management assistance programme (UNDP/ESMAP) assisted the government to identify an international consortium through a tender to locally developed the market for solar equipment. The consortium has been granted a three year exemption of taxes and duties and the promotion campaign for the use of solar energy has been launched by the government [31]. The intelligent energy europe (IEE) which is the european community support program of energy and transport works to increase renewable sources and efficiency by overcoming the non-technological barriers (legal, financial, institutional, cultural, social, etc.). Microgrid project has been carried out in the frame of *coopener project* of the IEE with the objective of promotion and dissemination of the use of micro-grid with high content of renewable energy sources (RES) for the far away villages electrification in Senegal with the package contains of:(i) project coordinator, (ii) training in renewable energy sources and microgrids, (iii) analysis of local needs for the electrification of rural areas, (iv) definition of a kit for the electrification of rural villages, (v) specific dissemination activities, (vi) common dissemination activities [32]. A co-financed project called $ELSA$ (Electricite pour le Sahel)by the european union commission and the state of Burkina Faso aims to improve access of energetic services for 30 localities. This action taken is the continuity of the co-financed program call $Facilite\ Energie\ ACP-UE$ (African, Caribbean, and Pacific Group of States) and $DANIDA$ (Danish International Development Agency) 2007-2009, which have permit to establish the program of access of energetic services in the horizon 2025 for any 13 regions of the country. The realization of the project is ensured by the FDE (Fond de Developpement de l'Electricite) and the company IED-France (Innovation Energy Development) which is the realization delegate of the project. The choice of the region is because of the socio-economic situation, region where poverty, dry season, worst repartition of rain season, the mortality of animals and the inundations are permanent. The second element is the fact that, over 586 localities compose the region, only five localities have been electrified till today covering only 9.2% of the population, for an access of electricity less than 2%. The world bank has accepted financial aid through FDE to extend the regional grid (MV). The *ELSA project* will deeply consolidated realization through: (i) the improvement (densification) of the existing grid; (ii) hybridization of the fuel system (photovoltaic+diesel generators); (iii) connect the nearest localities from the production site [33]. The so call *Energies durables dans les regions d′Agadez et Tillaberi* which was the first project *Facilite Energie* financed and signed by the european union with an amount of 3.25 million of euros with Niger. 420 million of euros have been financed for 140 projects such as: (i) the interconnection and big project of electrical generation; (ii) the fund for energetic regional centres; (iii) the fund for regulation agencies; (iv) the Global Energy Efficiency and Renewable Energy Fund (GEEREF) which supplies the capital risk for private actors who invests in renewable energy and in energy efficiency. The objective of the fund is to help the population of the 77 countries of ACP, signatories of the Cotonou (Benin) agreement include Niger to accesses on basic energetic services and re-enforce the states capacity in energy field. It concerns in particular: (i) the increasing access to modern sustainable energetic services at a reasonable price to the poor population in rural and urban zone, (ii) the improvement of the governance and the practice in energy sector at the regional, national and local level, promoting the renewable energy and energy efficiency in particular [17].

1.1.7 Socio-economic benefits of renewable energy foe electrification in rural areas in developing countries

There are socio-economic benefits to use renewable energy by the population. Renewable energy apply in rural area in developing countries could create jobs, and motivate the creation of small industries. It could also improve the quality of life and provide other social-economic benefits that are difficult to quantify. It is clear that renewable energy will receive widespread acceptance in the rural areas, because of the inadequate conventional electricity supply there [20]. There is some anecdotal evidence that the relatively successful dissemination of solar photovoltaic systems in rural areas of Kenya is linked to growing wealth of high income rural farmers. The ongoing liberalization of cash crop marketing in Sub-Saharan African countries is expected to increase the income of rural farmers, which in turn should lead to increased demand for modern energy services [34]. Recently, international energy agency (IEA) has been focusing on the poverty reduction through the improvement of energy situation in developing countries, and devoted a chapter to explain roles of energy for the development in its World Energy Outlook 2002 (IEA, 2002). Access to credit and cumbersome subsidy delivery mechanism have been perceived as the major factors affecting the expansion of rural electrification by the stakeholders, requiring innovations in these areas so that a large rural population can have access to electrification [27]. Photovoltaic is identified as the most economical decentralized source to contribute to rural development. The current low level of photovoltaic utilisation in many countries have been identified as being chiefly due to lack of awareness among potential buyers and energy planners of its large-scale applicability. Energy availability improves the standard of living. Lack of energy, on the other hand, can bring down food shortages, a reduced life expectancy, and an increase in illiteracy and infant mortality. Thus to achieve an acceptable and sustainable standard of living, a certain level of energy availability is necessary, and this must be obtained in an environmentally friendly way [20]. Some benefits of rural electrification in developing countries can be listed as follow: (i) Socio-economic benefits (improvement of economic productivity in industry and agriculture through deployment of modern and efficient processes (e.g., cooling and ventilation); stimulus to economic activity in the service sector, including small-scale enterprises), (ii) Socio-political benefits (improvement of living conditions including education, health care, and gender equality; improved accessibility through telecommunication facilities, stimulus for entrepreneurs and middle class to stay in area; enhanced societal stability), (iii) Environmental and Health benefits (fuel switch for lighting: safer and often cheaper).

1.1.8 Which type of electrical architecture for rural electrification in developing countries

Many studies have been carried out to estimate the electricity demand load needs of the population in developing countries. In this context, Mandelli et al. have carried out a study on load profile estimation for off-grid rural areas. The study indentifies two different approaches (literature approach based on three key parameters: the load factor, the daily energy consumption and the peak power demand; and the new mathematical procedure base on stochastic method) [35]. Another study have been made on effective approach of modelling rural energy needs and an innovative stochastic method which formulates different possible realistic daily load profiles for un-electrified rural areas in Soroti in Uganda [36]. A typical rural household load profile in Cameroon is composed by three persons living in two rooms appartment, the load is composed by two incadescent lamps in two rooms, a fluoriscent lamp outdoor for security and a radio [37]. The study concludes that the load profile for a household in Cameroon and in rural area is very low. Following the same goal, [38] realise a survey on household energy consumption in Cameroon. The results of the survey which categorized the load demand profile in three classes have been used as input of the stochastic study to determine the energy load demand profile. [25] found that population living in developing countries have a poorly electricity load demand and their electricity needs is only for lighting, radio and tv. Electrification planning in various developing countries have been done without taking into account the needs of the population, when we know that the needs increase with the time. The objective was only electricity access for lighting. At the beginning, the population need electricity only for lighting, radio and tv. But when there is already light, they need refrigerators, washing machine, grounding machine, etc and their electricity needs increase and their consumption also. This is why it is important to carry out a good study on social behaviour of the population before and after electricity availability, to understand their way of being/living, their needs in terms of electrical appliances. So that different types of categorized loads could be identified. This sociological study would help to precisely predict the load demand profile of the electrified population and well defined the best configuration of hybrid energy system, the good energy management strategy and ensure the best continuous electricity supply. The hybrid system could also be over-sized or sized such that in the future, it could be easily integrated new generating and storage systems to the existing one to well faced the new demand load. According to climate conditions and the geographical position of the area, we can have different kind of renewable resources (solar, wind, hydro, biomass, biogas) and mineral (petrol, gas) resources that can be assessed. The potential of different resources can be determined using different methods. The assessment of renewable resources can be made using satellite meteorological station [5], [39] or local meteorological station for more precision. The assessment can be made during a certain period (days, weeks, months, years, etc...) with a different measurement time steps (seconds, minutes and hours) [40], [41], [6]. The assessment of data is made by different type of instruments and the data can be recorded [42]. The data recorded can be re-elaborated and used as input in mathematical models or in software to determine the potential of energy sources of a define area [43]. Being in possession of the available potential of energy sources of the local area, we can built different kind of configuration of hybrid stand-alone systems, combining differents generation and storage sources in a proper and optimize way. Many types of optimization approaches, mathematical model algorithm and software tools for design, size, modeling and simulation of hybrid energy systems for remote areas can be used to determine the best configuration [44] and a good management strategy methods [45] could be implemented such a way that the system could be optimized and at the lowest cost.

1.2 Outline

The thesis is organized as follows: in Chapter2, investigation on different schemes of hybrid energy systems (HES) in islanding mode for remote areas with a focus on solutions for remote electrification which are basically composed by one or a mixed of different energy sources and storage systems. This work analysis the widely used mathematical approaches for optimization, sizing and modeling of hybrid energy systems for remote and isolated electrification areas including the role of storage system and also analysis the advantages and disadvantages of different solutions proposed. In Chapter3, an investigation on assessment of solar and wind potential across the ten regions in Cameroon has been carried out. The scope of the work was: (i) focused on assessment of two different energy resources (solar and wind), (ii) understanded how to determine the potential of solar irradiation and wind energy across the country, (iii) determined which region is good enough to conduct a case study, (iv) determined the daily output power of solar and wind energy and the daily and yearly energy production by soalr and wind energy. NASA (surface meteorological and solar energy) database is used for the assessment by introducing the geographical coordinate of any regions and obtaining the daily solar radiation and the average means wind speed for every month of the year. This particular study concluded that (i) not only the Northern regions of Cameroon have the highest wind potential, but also the North West and some towns in the other regions; (ii) the fact of having enormous potential of solar energy can contributed to electrify remote villages across the country and contribute to better life and prosperity. While these results reflect the general trend, it is important to conduct field studies in substantial number of places in order to further estimate with accuracy the potentials of wind energy in Cameroon. Chapter4, as Cameroon possesses the second largest hydro power potential in Central Africa, electricity is distributed all over the country by three separate transmission grids, isolated one to another without any possibility of electricity exchange between them. The aim of the work is: (i) identified river that can be hugely exploited for hydroelectricity production and (ii) to see how hydropower can contribute for fluctuation compensation in case of unavailability of wind or solar energy. A draft of solar and wind potential profile has been estimated, with the difficulty of having a good smooth profile of wind and solar energy potential for a whole year. Finally, in Chapter5, the work carried out is a feasible study of a hybrid energy system (HES) for rural electrification in Cameroon and particularly in the village of Salak in the Far North region. The hybrid energy system is composed by two renewable sources (solar and wind), a traditional generator (diesel generator) and a battery bank for storage. The work (i) reviews some hybrid energy systems (HES), (ii) describes the proposed hybrid energy system, (iii) shows how the different components of the Salak rural hybrid energy system can be modeled, optimized and simulated. The load is composed by a rural hospital, a nursery school, a primary school, a secondary school and 150 houses for up to 500 inhabitants. A heuristic algorithm is developed to manage the hybrid energy system in an optimized way such, the daily fuel consumption could be minimized. An optimized method using dynamic programming is applied and compare with the heuristic method algorithm. An economic analysis is carried out to determine the life cycle cost of different systems and the cost of any kWh of energy producted by any configuration. This study demonstrates how the Salak rural comunity even though isolated from grid, but with great potential of renewable sources could be electrified and be autonomous during all the year while minimizing the system operation cost.

2 Hybrid Energy System for Remote Areas and the Role of Storage:An Overview

This chapter provides an overview on different mathematical approaches for sizing, designing, modeling and simulating hybrid energy systems for remote areas. It also sheeds light on ongoing studies helping to choose the best configuration of hybrid energy system for the Salak case study that should be carried-out.

2.1 Introduction

Electrification nowadays of rural areas in various developing countries is around 20% [46]. More than 70% of the population in such developing countries live in rural areas with a forecasted increase of 6% per year in the near future. It means that more than 70% of the population live almost in total darkness. Progress in grid extension is slower than population growing. The common renewable energy resources are: hydro, wind, solar energy and biomass (i.e. wood chips, coffee/cocoa chips, pellets). Despite of the great potential, the development in the energy sector has been limited in such countries. The non electrification of rural areas is due to the high cost of grid connection, the large losses associated with the transmission and distribution networks, the dispersion of the population, the difficult access by road, the geographical access of the local areas just to cite a few. A solution to this problem can be the decentralization of the electrical production and the choice of *hybrid microgrids* with the objectives of making local areas be autonomous.

According to climate conditions and the geographical position of the area, we can have different kind of schemes for hybrid microgrids. For many authors [47], [48], [49], the concept of *"Microgrids"* can be defined as a group of interconected loads and distributed generation sources within a clearly defined boundary that can be operated in parallel with the utility grid or as an electrical island. The concept of *"Hybrid Microgrid"* means that the microgrid includes renewable energy sources or integrates renewable technologies.

In this chapter, a review of different schemes for such microgrids are proposed. With the aims of (i) review different schemes of hybrid energy system in islanding mode for remotes areas, (ii) focus on widely use optimization approaches, mathematical model algorithm and software tools for design, size, modeling and simulation of hybrid energy system for remote areas electrification; (iii) give the pros and cons of different types of widely used hybrid schemes in terms of power balance, voltage and frequency fluctuation control and reliability.

The analysis focus on a review of different types of hybrid micro-grids for electrification of isolated areas with the main objectives of making the local area being more reliable and reduced the fluctuation of voltage, frequency and power balance. All these analysis are proposed in the following sections.

This chapter is organized as follows: Section 2.2, a state of art of hybrid energy system for remote areas will be done; section 2.3, an overview on different issues of modeling of hybrid micro-grids with its main features such as sizing, optimization and energy management system methods is given: a critical observations are made; section 2.4, a focus on photovoltaic, wind and fossil fuel generators with or without storage systems are discussed: advantages and disadvantages of each schemes are investigated; section 2.5 result obtained will be exposed and in section 2.6, conclusions are drawn.

2.2 State of art of some hybrid systems

Many studies have been carried out in this issue, [50] study an off grid for powering base transceiver station using combining renewable energies (wind and solar) with diesel generator and three different types of batteries. The diesel generator works only when there is not energy from renewables and the batteries are all empty but also plays the role of battery charger. [51] study electrication of a stand-alone customer in Iran combining two mains renewable sources (wind and solar) with diesel generator woring as backup and battery bank used for storage. The diesel generator works only when there is not energy from renewables and the batteries are all empty but also plays the role of battery charger. In [52] the author analysis an integrated methodology, investigates the possibility of creating a combined electricity generation system based on the exploitation of wind and solar potential of the numerous islands of the Aegean Archipelagos as well as on the utilization of an appropriate energy storage configuration. The proposed electrification solution can replace the existing thermal power stations based on imported oil with considerable production cost reduction. In this context, the main parameters of the combined renewable energy system (RES) and energy storage system (ESS) based installation are calculated first and accordingly used in order to prove the economic viability of the proposed solution. In [53] the authors present an economic analysis of the feasibility of utilizing a hybrid energy system consisting of solar, wind and diesel generators for application in remote areas of southern Ghana using levelized cost of electricity (LCOE) and net present cost of the system. In [54] the authors focus their study on development of optimal sizing model based on an iterative approach to optimize the capacity sizes of various stand-alone photovoltaic/wind/diesel/battery hybrid system components for zero load energy deficit. The optimization results show that a photovoltaic/wind/diesel/battery option is more economically viable compared to photovoltaic/wind/battery system or diesel generator only. In [44] the authors present modeling and optimization of a photovoltaic/wind/diesel/battery-based hybrid system for electrification to an off-grid remote area located in Rafsanjan, Iran. Different generation systems (PV/wind/diesel/battery, wind/diesel/battery, PV/diesel/battery, and diesel alone) are studied where, from the case study, it is found that using wind/diesel/battery is the most cost-effective system. In [55] the authors demonstrate the feasibility of an hybrid renewable energy system, his relatively cost-effective solution in areas where the national utility grid is expensive, and thus is suitable for power applications in remote areas. The authors introduced two hybridizing techniques for integrating PV, wind and hydro power into one mini grid where one of the technique was implemented to connect a hybrid PVwind system to hydro dominant system via mini-grid connecting the Thingan and Kolkhop villages in Makawanpur District of Nepal. In [56] the authors study how to determine the optimum dimensions of a stand-alone PV-diesel system, under the restriction of minimum long-term electricity generation cost, and accordingly obtain a comparison with diesel-only systems. For this purpose, the developed methodology is applied to a representative Greek island, with results obtained being rather encouraging for the implementation of the proposed solution. In [57] the authors investigate in this particular context, to estimate the appropriate size of a wind-solar-diesel system, so as to meet the energy demand of typical remote consumers under the criterion of minimum first installation cost. The representative case studies of the Greek territory with different quality of wind and solar potential are currently investigated, with the results obtained designating the advantages of the proposed solution, especially for locations of low wind potential.

2.3 Modeling of hybrid microgrids systems

Due to many different reasons, autonomous hybrid energy systems (HES) have different types of configuration schemes, different types of applications, different types of motivations and different types of solutions solved. In what follows, the sizing and the optimization of different Hybrid Energy Systems are dated below while, energy management system considerations will be discussed further below.

2.3.1 Design, Sizing and Modeling of different Hybrid Energy Systems

This subsection describes the different methods and tools used for the design, size modeling and simulation of hybrid energy systems in stand-alone mode. This subsection investigates on important aspect dealing with feasible issues of hybrid stand-alone systems. Data used for solar radiation and wind can be obtained using a short or long term monitoring data acquisition system of the site or using external means such as NASA climate instruments or Wind atlas [58]. Hybrid Optimization Method for Renewable Energy (HOMER) is one of the most common computer model for the design of the hybrid micro-grids [59]. For instance, Particle Swarm Optimization (PSO) and Hybrid Optimization Genetic Algorithm (iHOGA) have been used together with HOMER. But other different methods are used such as Mixed Integer Linear Programming (MILP). Sizing and optimization methods are also use for technical and economical aspect of hybrid energy systems [60].

In [61] the authors report their achievement with respect to the case study of two islands. An actual configuration composed by a small thermal power generator and a small wind park, supplied two islands (Karpathos and Kasos). Because of several malfunctions of the normal operation of the utility network due to the non-interconnection of the two islands, system instability, etc..., the proposed configuration is based on a new wind park (WP) sized for annual average velocity of 11.5 m/s and a total sized power of 4.5 MW and a pumped storage system (PSS) with a total power of 4.48 MW and a reservoir capacity of 465.062 m^3. This configuration uses renewable energy and at the same time solve the system instability, improve the dynamic security of the non-interconnected power system through the combined WP-PSS. In [62] the authors investigate the performance evaluation of a stand-alone photovoltaic system for an isolated island in Honkong (China). The local island was originally supplied by 3 Diesel power generators and the fossil fuel for diesel generator was transported by sea. Power was supplied for only a limited number of hours every days owing to an extremely cost of energy supply. Data acquisition for the whole year 2011 with a 5 min interval horizon temporal was implemented and it also provides useful reference information for future photovoltaic system design and operation. The battery storage system (BSS) in this case has two main objectives: stabilizing frequency fluctuation and power balance during day and night. In [63] the authors study a stand alone photovoltaic system (38 kWh/day) which supplies electricity to a determined load and an electrolyzer (32 kWh/day). The electrolyzer produces hydrogen for storage system and the hydrogen will be used in a fuel cell to produce electrical energy. Result of the study shows that the micro hydro stand alone or solar photovoltaic/battery stand alone are more competitive than conventional diesel generator system. In [64] the author evaluates an optimal photovoltaic hybrid system for remote villages in Far North Cameroon using interactive optimization method based on desired annual working hours of diesel generators and the Net Present value technique. At the end of the study, the system composed by photovoltaic/diesel is the optimal option for constant energy demand if the photovoltaic module cost is at most 2.25 euros/Wp with the fuel escalation rate is 20% and the remote fuel cost is 1.12 euros/l and the hybrid energy system composed by photovoltaic/diesel/battery is the optimal option for variable energy demand for all the selected value of sensitivity. The authors proposed an optimal design of photovoltaic-wind-diesel-battery hybrid system for remote electrification in Ghana. The optimum is obtained through a developed iterative optimization techniques which minimize lost power supply and the annualized cost of of system [65]. An iterative algorithm approach based for techno-economic optimization size, of various combined type of hybrid stand-alone system (PV/Wind/Diesel/Battery) in Algeria have been carried. This algorithm take into consideration the total net present cost and the enrgy cost and models all configurations giving the rate of 0% of total energy deficit. The optimal configuration is predicted on the basis of the minimum cost [54]. An iterative algorithm is used for optimization size of a hybrid generation system using battery bank. The optimization model takes into account the deficiency of power supply probability and the levelized unit electricity cost [66]. In [67] the authors study the optimal sizing of a hybrid renewable system composed by wind turbine, photovoltaic panel and diesel power generator (16 kW) located in the area of Dakar (Senegal) with a storage system composed by battery. Deterministic algorithm is used for optimal sizing and system cost minimization. The study shows that, when the power produced by the renewable sources is greater than the demanded power and the battery bank is completely charged, the the oversizing of the energy can be used for the pumping of water. In [68] the authors study how to increase access to electricity to two remote communities in Cape Verde using mathematical modeling based on mixed integer linear programming (MILP). Due to the badly geographical and dispersed nature of villages, the frequent incidence of blackouts, the high cost of diesel fuel, the pollution problem, the non electrification of the community of Santiago island, three types of configurations (C1, C2, C3) design has been studied to solved this problem. At the end of the study, the best configuration has been defined as wind-photovoltaic-Batteries. In the same context, discrete harmony search algorithm has been applied as optimize size model for rural electrification in Iran. The optmimal photovoltaic/wind/diesel/battery hybrid system has been compare with a diesel generation alone in terms of total annual cost and environmental emissions. The discrete harmony search algorithm is compare with simulated annealing algorithm to determine the best configuration and it is found that the pv/wind/diesel/battery is the best configuration found and the most cost-effectiuve system [44]. In [69], the authors implemente a heuristic technique to model a hybrid energy system composed by photovoltaic, diesel generator and battery for remote consummers in South Africa. Two different days of two different seasons (winter and easter) of the year have been analysed. The optimization of the hybrid system for low fuel consumption has been performed with the quadratic programming toolbox of matlab. The hybrid system reached up to 73% and 77% and 80.5% and 82% fuel saving respectivelly in winter and summer. A techno-economic study of a photovoltaic/wind/diesel/battery hybrid system for rural electrification in Algeria has been carried out. The optimization reveals that the best hybrid configuration in all the six sites of the investigation is the pv/wind/diesel/battery instead of wind or photovoltaic hybrid system alone [70]. The feasibility of photovoltaic-wind-diesel hybrid system for rural electrification in Saudi Arabia has been carried out. The previous system was composed by eight diesel generators of 1.12 kW each. The new hybrid system permittes to reduce the fuel consumption using HOMER software for optimization tool [71]. In [72] the authors for this analysis, use average daily global solar radiation data on horizontal surfaces for Jos (Nigeria) obtained from NASA Surface meteorology and solar energy website (NASA) to study the possibility of using hybrid energy system (HES) for electricity generation in rural and semi-urban areas in the northern part of Nigeria. A technical and economical analysis of the system based on photovoltaic, diesel generator (with/without battery) was carried out and simulated for a peak load demand of 236 kW using HOMER software. In [73] the authors study an optimal design and planning of a renewable energy micro-grid on the sites of Waterloo, Ontario in Canada. Because of the higher price of diesel fuel, the cost of the transmission line and the losses during transmission of energy, a study has been carried out to evaluate an optimal configuration. This case study shows the dual use of HOMER and PSO for (i) optimization design, (ii) for the connection of the thermal load and (iii) for the possibility of connecting an external grid for a maximum distance of 153 km. In [74] the authors discussed on integration of hybrid energy system (HES) with conventional diesel generator in the town of Randhunibari in Bangladesh. The hybrid scheme proposed is composed by: a photovoltaic array, a small hydro power, the battery and the conventional diesel generator for the backup. The HOMER sofware is used for system cost optimization. A techno-economic study has been carried out on wind/diesel hybrid system for remote village electrification in Algeria using HOMER software. The optimization is obtained evaluating the energy production, the lifecycle cost and the greenhouse gases emission reduction [75]. Also an economic analysis has been carried out on photovoltaic hybrid system in different climatic zones in South Africa for rural electrification using HOMER software. The hybrid system is composed by pv/battery/diesel [76]. The authors use the techno-economic analysis aspect to compare two different solar and wind hybrid system for a remote communication station in Nigeria. The HOMER software has been used for optimal modeling and simulation. The photovoltaic-diesel-battery hybrid system is the best configuration and the most economically feasible [77]. A techno-economic analysis of three different configurations (diesel only, wind-diesel-battery and pv-wind-diesel-battery) has been caried out for rural electrification in Iran. HOMER software has been used for optimization purpose. The study concludes tha the photovoltaic-wind-diesel-battery is the best configuration [78]. A feasible study has been carried out on solare-wind hybrid system for remote community of 200 families in Ethiopia using HOMER optimization software. The optimization is achieved with the lowest net present cost. The study also analysis the influence of wind penetration, photovoltaic cost and diesel price for the optimum solutions [79]. The authors [80] also investigate on feasibility of a small-scale hydro/photovoltaic/wind/diesel/battery hybrid system for rural community in Ethiopia using HOMER software for optimal and sensitive analysis with the objective of reducing the net present cost of the entire system. The simulation of a photovoltaic-wind hybrid system and hydrogen storage for rural electrification in Morocco has been conducted using HOMER software. The study compares two different configurations (AC-DC). The optimization is obtained well managing the hybrid system at the lowest cost [81]. A feasible study of solar-wind-diesel hybrid system implementation in four rural localities in Algeria has been carried out. The HOMER software has been used as the optimization tool for cost reduction [82]. The authors analysis the assessment of solar radiation and its integration in a photovoltaic-diesel-battery hybrid system for rural electrification in Saudi Arabie. The optimization is obtained by HOMER software. Different configurations of hybrid system are investigated and the photovoltaic-diesel-battery beeing the best configuration which offered the high degree of flexibility, the maximization of the diesel efficiency and the minimization of operation and maintenance cost [83]. In [84] the authors work on energy management system, study the dynamic simulation and performed the hybrid energy system compose on wind/photovoltaic/micro-turbine/baterry by using Matlab/Simulink, but also study the optimal sizing of the energy system and carried out the economical analysis using a genetic algorithms for minimizing the annualized cost of the system. In [85] the authors propose a methodology of optmimal size of a stand-alone photovoltaic/wind/diesel/battery hybrid system in Senegal. The optimization is based on minimize levelized cost of energy and the reduction Co_2 gases using genetic algorithm. The reduction of generation cost of hybridation of an off-grid remote area in Tanzania has been implemented and the optimization obtained by the levelized cost of electricity [86]. An optimal design of a photovoltaic-wind-battery hybrid system in remote area in North Western coast of Senegal. The optimization is obtained by minimizing the annualized cost of the system and the cost power supply probability by using multiobjective genetic algorithm [87]. In [88] a study has been carried out for the electrification of a village in Malaysia *Kampung Opar* based on renewable hybrid energy system only. The village of Kampung Opar has been selected because some people in this area do not have access of electricity. The accurate hybrid optimization genetic algorithm (HOGA) is used for this study. The control strategy, which is important in hybrid system with more than one power sources, is used to check availability and connection of sources to the system and state of charge of the battery.

2.3.2 Energy management system method in different hybrid energy systems

This subsection describes energy management system and control of hybrid energy systems.

In [89] a configuration currently based on an offshore wind turbine (375 kW), tidal turbine (175 kW) and a diesel generator system (290 kW) is used for powering an oil platform. Because of the low flexibility to respond to the demand changes, the high pollution, noise and the low efficiency of the diesel generator, a micro-turbine and battery (3.27 kAh) has been suggested as a back up and an appropriate supervisory controller is designed to manage the whole system. In [90] the authors proposed an energy management system (EMS), based on power electronics system to reduce fuel consumption into the Forward Operating Base (FOB). The objective of the study is to introduce an Energy Management System (EMS) into the FOB power system in order to make more efficient the used generators and reduce overall fuel consumption. The EMS provides an interface between power sources, loads, and energy storage elements to form a micro-grids. The power electronics system plays the role of interface between the two diesel generators, the battery energy System and the load, according to the set priorities. Following the same goal, an energy management system based on power electronics has been implemented to optimize the use of energy sources and storage sources in Forward Operating Base (FOB). This power electronics energy management system plays a role of interface within the generation sources, storage and different types of loads and works in an intelligent manner to supply only the critical load in case of insufficient power generated [91] Energy management strategy is applied for optimal management and control of Pv/wind/diesel/battery hybrid system for power supply system in South Africa. The optimization here is applied such to minimize the cost operation and maximize the use of renewable energy sources while considering battery life improvement. Here two approaches of the model predictive control techniques (MPC) have been applied and compare (open and close loop). Result shows that, the best is made with the close loop approach [92]. A management strategy also has been implemented using mathematical models for hybrid stand-alone in Algeria. HOMER software is used in this study for the optimization process maximixing the use of renewable electricity and fuel saving. The hybrid system is formed by Pv/wind/diesel/battery and in conclusion the study shows that the use of renewable sources reduce drastically the fuel cost [93]. An optimal energy management strategy has been proposed by [94] for autonomous hybrid system in Morocco using linear programming method. The hybrid system is formed by photovoltaic/wind/diesel/battery. In [95] an optimal operating strategy and cost optimization have been implemented as well as the emissions reduction for a microgrid. Multiobjective optimisation has been applied for the environmental and economical problem, minimizing the cost function of the pv/wind/Fuel cell/micro turbine/diesel hybrid system. An operation planning and energy management strategy is implemented to provide flexible distribution and prediction of photovoltaic generation integration in the microgrid. In this study, two differents energy management strategies ars used: (i) the central energy management of the whole microgrid and (ii) the local energy management strategy at the customer side. This deterministic operating planning and energy management performed the day-ahead power scheduling for the conventional photovoltaic power prediction and load forecasting [45].

2.4 Focus on photovoltaic, wind, fuel generators with o without storage system

2.4.1 Photovoltaic system with or without storage system

In remote areas far away from grid, where solar energy is available, a stand alone photovoltaic system can be employed to generate electricity to the local remote population. The electricity can be supplied directly when the solar radiation is available during the day time or by the use of different storage systems which can ensured the supply during day time and night.

Stand alone photovoltaic system with storage system

Electrical production system composed by photovoltaic panels and storage system, can produce electricity during night and day time. The sized and the modeling of the photovoltaic system can be done taking into account the load profile of the local area and the solar radiation profile during the day. The deficit of power during the day time and the night can be quantified and used for sizing the battery bank. The load can also be divided into two categories (critical load and non critical load), in this way the whole system can be well managed. Depending on load requirement, during the day time, in case of low load demand or high power production, the battery can be charged. During night time when photovoltaic system is not producing, the battery can be discharged to supply the load demand.

The voltage can be maintained at the desired value through the inverter DC link of the photovoltaic system and the voltage fluctuation can be avoided. The frequency can be maintained injecting in the grid, energy from the battery bank and avoiding frequency fluctuation.

This system is seen reliable in terms of power balance, frequency and voltage fluctuation and enable to supply electricity all the time in the local area. In [96] the authors evaluate the optimal option for the supply of two days autonomy energy demands of thirty three transceiver stations in Cameroon with a photovoltaic hybrid systems. The photovoltaic hybrid system is computed using the solar resource modules of HOMER and the geographical coordinates for all the sites with the specific hourly load data and the hourly monthly radiation. three hourly temperature data available on the website of the NASA is used to generate average monthly temperatures needed in the calculation of the output of solar modules. The energy costs and breakeven grid distances for the possible power options is computed using the Net Present Value Technique and financial data for selected power system components. In [97] the authors analysis a new generalized sizing method for photovoltaic hybrid system (PVHS) based on desired annual generator hours has been proposed and tested with varying monthly energy demands (M1) and a constant daily profile of 72.6 kWh/d (M2). The results obtained showed that the PV array sizes computed with M1 were higher that those computed with M2 at renewable energy. In [98] the author study how to maximize the photovoltaic solar energy penetration using storage system. The author in this paper focus on the effects of distributed energy resources, advantages of grid connected photovoltaic, the role of energy storage technology and the possibility of combining solar energy production with battery and super capacitor as storage system. It is carried out that the power systems are designed to operate at a sinusoidal voltage of a given voltage and frequency which contribute for power quality for both customer and utility point of view. In [99] the authors analyze and simulate a Pico-hydro and a photovoltaic hybrid systems, incorporating a bio-gas generator for the electrification of remote villages in Cameroon for the supply of a hostel which has an energy demand of 73 kWh/day and 8.3 kWp. The results show that off-grid options based on renewable energy resources could be a suitable alternative for rural electrification in the low power range (10-50 kW) in Cameroon. In [37] the authors modeled a Solar/diesel/battery hybrid power systems for the electrification of typical rural households and schools in remote areas in the far north province of Cameroon. These results show that there is a possibility to increase the access rate to electricity in the far north without relying to grid extension or more thermal plants in the northern grid or more independent diesel plants supplying power to remote areas of the province. In [100] the authors propose an optimum sizing methodology able to define the basic parameters of a combined photovoltaic and energy storage systems (pumped hydro, battery, flywheel, fuel cells, compressed air, super capacitor) electricity generation configuration. In [101] the authors analyze a seawater pumped hydro-power plant and study the pumping system, powered by solar energy through a photovoltaic field in two different configurations:two constant speed pumps of different size and two variable speed pumps of the same size. Annual simulations of the systems were carried out by a TRNSYS model examining different sizes of photovoltaic field and storage volume. The results confirm that PV pumping with variable speed pump operation can effectively decrease the load on the transmission grid, realizing on the whole year-off-grid operation. In [102] the authors investigate and study the pumped storage for a standalone micro-grid photovoltaic system, based on the developed mathematical models and operational principle. The propose power generation and pumped storage system for a remote island in Hong Kong was designed, simulated, and finally optimized using the single-objective and double-objective Genetic Algorithm technique to maximize power supply reliability and minimize system life cycle cost.

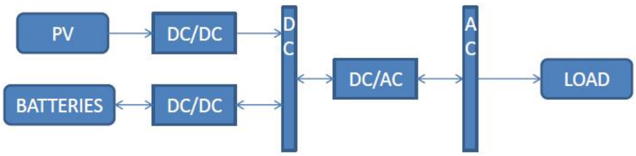

Figure 2.1: Proposed stand-alone based only on photovoltaic system with or without storage system.

Wind power system with or without storage system

In some remote local areas where wind energy is permanent and available during the day, electricity can be produced directly from the wind generator or from the storage system in case of low or non-availability wind energy to supply the load demand. In [103] the authors study the introduction of pump storage system in a wind farm electricity production system in the Greek island of Lesbos. Despite of the potential of wind energy availability in several Greek islands, the limitations of energy distribution infrastructure make the cost of electricity very high. To avoid these limitations, the proposed hybrid system system works as follow: the surplus of the wind generation system supplies the water pump station system, the water pumped system carries water from the lower to the upper reservoir, the hydro electric power plant is used in case of peak demand in the network. In case the upper reservoir is full and there is still wind energy surplus, the residual will be forwarded to the low priority load. The wind generating system and the storage system will play a dual role, supply electricity to covered load demand and guarantee the power balance, voltage and frequency regulation.

Stand alone wind power system with storage system

Wind power production system when combined with storage system can provided electricity to a local area during day and night period.

The total load profile of the local area known can be divided into different types of load. The measurement of the energy deficit of power supply during the day and night time for almost a whole year will be useful to sized and model the combined system.

The voltage control can be realized using the DC link of the inverter of the wind generator which maintains the value of the voltage at the desired value of the grid or either with the DC/DC converter of the battery.

The frequency control can be realized by increasing the rotation speed of the rotor machine of the wind generator in case of low frequency in the grid or by decreasing the rotation speed of the rotor machine of the wind generator in case of high frequency in the grid or either injecting in the grid the energy stored.

This system composed by wind power and battery bank seen to be more reliable in terms of power balance control, voltage and frequency fluctuation control. In [104] the authors investigate the effects of introducing a Wind Powered Pumped Storage System (WP-PSS) in isolated electricity systems assuming unfavourable conditions such as low onshore wind potential and low PSS head height. The WP-PSS investigated, examined under the most unfavourable conditions, proved to be technically and financially feasible. In [11] the authors simulate an off-grid generation options for remote villages in Cameroon using a load of 110 kWh/day and 12 kWp. The energy costs of proposed options were simulated using HOMER, a typical village load profile, the solar resource of Garoua and the flow of river Mungo. The results of this simulation showed that for a fuel cost of 1 euro a 14 kW micro-hydro plant with a 15 kW diesel generator and 36 kWh battery storage produced electricity at a cost of 0.296 euro/kWh for remote communities. In [105] the authors analyze how a Pumped hydro storage (PHS) systems which are located at isolated regions and are able to exploit the rejected wind energy amounts produced by local wind farms, seem to gain interest worldwide and to become essential in regard to higher shares of renewable generated electricity. In [106] the authors investigate on the optimum sizing for a hybrid power station (HPS) operating in an island system. The analysis addresses the sizing of the main HPS components (hydro turbines, pumps, wind farm, reservoirs), adopting either the investors perspective, where the objective is to maximize the return on the HPS investment, or a system perspective, where the optimization target is the maximization of renewable energy sources penetration, along with maintaining the lowest possible generation cost in the system. Genetic Algorithms (GAs) are applied for the optimization and a real isolated island power system is used as a study case. In [107] the authors investigate the benefit of optimally integrating wind power in Kenya with pumped hydro storage. The approach includes development of an optimal control strategy to deploy paired wind and pumped hydro storage resources, for the Lake Turkana Wind Power project.

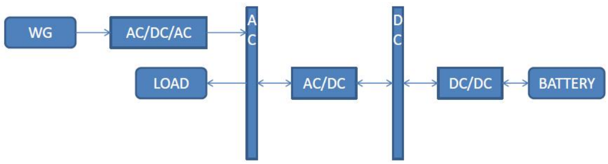

Figure 2.2: Proposed stand-alone based only on wind power system with or without storage system

2.4.2 Photovoltaic, wind power with or without storage system

In a particular local area where wind and solar energy are available, their dual use for electrical production can be more useful. Because of the intermittency of the wind and solar energy during the whole day, the supply of electricity cannot be permanent. That is why storage system can be more important, not only for supplying electricity during the day time and night, but also by improving the reliability of the entire system in terms of power balance, voltage and frequency regulation.

Photovoltaic, wind power without storage system

In a remote local area where wind and solar energy are available, the combination of wind and photovoltaic production system can be used to supply electricity. Having informations about the total load demand of the local area, it is possible sized and modeled the photovoltaic production system and the wind production system. The load profile can be separated into different types of loads.

Due to the intermittency of wind and solar energy, the electrical production depends only on the local wheather. The electrical production and electricity supply will not be surely permanent during all the day and night time. Concerning the voltage control, it can be made either, by the DC link of the inverter of the photovoltaic system or the DC link of the inverter of the wind generator system.

The frequency control can be maintained using the variable speed synchronous machine of the wind generator. In case of low frequency in the grid, the speed of the rotor of the synchronous machine increases and also the inertia, consequently the frequency increases till the value desired of the grid. In case of high frequency in the grid, the speed of the rotor reduces, the inertia also and consequently the frequency decreases till the desired value of the grid.

In this combined system, the control of voltage can be made by the wind production system and the photovoltaic production system and the frequency control by the wind generator system.

In [108] the author proposes a study which introduces a hybrid renewable energy conversion system in detail. The solar and wind energy sources are modeled separately and collected together to build a distributed generation system and graphically presented in simulink model. In [109] the authors analysis and carried out a study on hybrid energy system containing two subsystems with two scenarios. While in the first scenario, these subsystems are connected to allow power flow between them, in the second scenario there is no connection between the two subsystems. Each subsystem contains a power typical demand for a household or a small factory or store and receives power from photovoltaic (PV) arrays, a small-scale wind turbine and the electric grid.

Photovoltaic, wind power system with storage system

A stand alone composed by photovoltaic panels, wind power system and storage system (as battery can be) can supply electricity to a remote local area during day time and night. The total load demand of the local area determined for the the whole year can be used to divide loads in two categories: critical and non critical.

It can be installed a measurement instruments for wind power system and the photovoltaic system to calculate the deficit of electrical production and sized the battery and contribute to well optimized the whole system.

The voltage control can be made by the DC link of the inverter of the wind generator and the DC link of the inverter of the photovoltaic system.

The frequency control can be maintained using the variable speed synchronous machine of the wind generator. In case of low frequency in the grid, the speed of the rotor of the synchronous machine will increase and also the inertia, consequently the frequency will increase till the desired value of the grid.

In case of high frequency in the grid, the speed of the rotor will reduce, the inertia also and consequently the frequency will decrease till the desired value of the grid. Frequency control can also been avoided by injecting in the grid energy from the battery bank by discharging it.

In [110] the authors propose a study based on a pumped hydro storage serving for off-grid hybrid renewable energy systems using mathematical model and simulation program. The complementary characteristics between solar and wind energy output were presented in this study, which can reduce the storage capacity. The results reveal that the PV has a relatively higher share of energy production than that of the wind turbines since the solar energy resource matches better with the load pattern. In [111] the authors present a study on heuristic procedure to design rural community off-grid electrification projects based on wind and solar energies considering micro-scale resource variations, generation close or far from demand points and a combination of independent generation points and micro-grids.

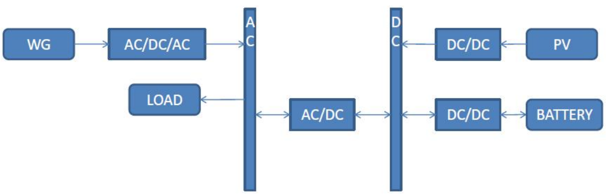

Figure 2.3: Proposed stand-alone based on photovoltaic, wind power system with/without storage system.

2.4.3 Fuel generator, photovoltaic and wind power system with or without storage system

Local areas far from the network where solar and wind energy are available, electricity can be produced. The electricity can be supplied only when the solar radiation and wind energy are available. If a traditional generator (as diesel generator can be) is associated with a photovoltaic and wind generation system, (i) the supply of electricity can be done during the whole day without interruption, (ii) the entire system can be well sized, modeled and optimized, (iii) the diesel generator can be used as backup of the system during the unavailability of renewable energy, (iv) the hybrid system can be more reliable in terms of power balance, voltage and frequency regulation. If in addition of the hybrid system, there is a storage system, a part of the advantages specified above, the storage system will contribute to reduce the overall fuel consumption of the diesel generator.

Fuel generator, photovoltaic, wind power system without storage system

In a specific local area where solar energy and wind energy are available, the combination with a fuel generator can enable the hybrid micro-grids to supply electricity during day time and night to the local population. The traditional generator plays the role of backup of energy and supplies the load demand in case of unavailability of the renewable energies or in case of insufficiency of solar or wind energy.

The voltage control can be made by the DC link of the inverter for wind generator and the DC link of the inverter of the photovoltaic system. The DC link maintains the output value voltage of the inverter at the requested value of the grid. Concerning the frequency control, it can be maintained using both the variable speed synchronous machine of the wind generator and the traditional generator. In case of low frequency in the grid, the speed of the rotor of the synchronous machine will increase and also the inertia, consequently the frequency will increase till the value desired by the grid. In case of high frequency in the grid, the speed of the rotor will reduce, the inertia also and consequently the frequency will decrease till the desired value of the grid.

For this hybrid combined system, the control of voltage can be made by the wind production system and the photovoltaic production system while, the frequency control can be made either by the wind generator system or by the fuel generator system. This combined system is seen more reliable in terms of power balance, voltage and frequency regulation.

Fuel generator, photovoltaic, wind power system with storage system

In a local area where renewable sources such as solar energy and wind energy are available, their combination with fuel generator and a storage system can be seen more appropriate to supply electricity all the time during day and night all over the year.

The voltage regulation control can be made through the DC link of the wind generator inverter, the DC link of the photovoltaic inverter and the DC link of the fuel generator. The voltage value of the DC bus and AC bus of the grid will be maintained at the desired value of the user.

The frequency fluctuation control can be made through the use of the wind variable speed generation system, the fuel generator variable speed and the storage system (such as the battery for example). In this case when the frequency of the grid decreases, the rotor speed of one or both the wind generator or fuel generator increase and the storage system (battery) can inject energy into the grid and respectively the frequency will increase. While, when the frequency of the grid increases, the rotor speed of one or both the wind generator or fuel generator decrease and the storage system (battery) is turn off, the wind generator inject energy into the grid and respectively the frequency decrease. In this stand alone hybrid system, it is easier to notice that the use of different generating sources and the storage system can contribute to optimized the system when supplying the electricity all the time, day and night to the local population.

This hybrid system is seen to be more reliable in terms of power balance, voltage and frequency fluctuation control. In [52] the author analysis an integrated methodology, investigates the possibility of creating a combined electricity generation system based on the exploitation of wind and solar potential of the numerous islands of the Aegean Archipelagos as well as on the utilization of an appropriate energy storage configuration. The proposed electrification solution can replace the existing thermal power stations based on imported oil with considerable production cost reduction. In this context, the main parameters of the combined renewable energy system (RES) and energy storage system (ESS) based installation are calculated first and accordingly used in order to prove the economic viability of the proposed solution. In [53] the authors present an economic analysis of the feasibility of utilizing a hybrid energy system consisting of solar, wind and diesel generators for application in remote areas of southern Ghana using levelized cost of electricity (LCOE) and net present cost of the system. In [54] the authors focus their study on development of optimal sizing model based on an iterative approach to optimize the capacity sizes of various stand-alone PV/wind/diesel/battery hybrid system components for zero load energy deficit. The optimization results show that a PV/wind/diesel/battery option is more economically viable compared to PV/wind/battery system or diesel generator only. In [44] the authors present modeling and optimization of a PV/wind/diesel/battery-based hybrid system for electrification to an off-grid remote area located in Rafsanjan, Iran. Different generation systems (PV/wind/diesel/battery, wind/diesel/battery, PV/diesel/battery, and diesel alone) are studied where, from the case study, it is found that using wind/diesel/battery is the most cost-effective system. In [55] the authors demonstrate the feasibility of an hybrid renewable energy system, his relatively cost-effective solution in areas where the national utility grid is expensive, and thus is suitable for power applications in remote areas. The authors introduced two hybridizing techniques for integrating PV, wind and hydro power into one mini grid where one of the technique was implemented to connect a hybrid PVwind system to hydro dominant system via mini-grid connecting the Thingan and Kolkhop villages in Makawanpur District of Nepal. In [56] the authors study how to determine the optimum dimensions of a stand-alone PV-diesel system, under the restriction of minimum long-term electricity generation cost, and accordingly obtain a comparison with diesel-only systems. For this purpose, the developed methodology is applied to a representative Greek island, with results obtained being rather encouraging for the implementation of the proposed solution. In [57] the authors investigate in this particular context, to estimate the appropriate size of a wind-solar-diesel system, so as to meet the energy demand of typical remote consumers under the criterion of minimum first installation cost. The representative case studies of the Greek territory with different quality of wind and solar potential are currently investigated, with the results obtained designating the advantages of the proposed solution, especially for locations of low wind potential.

2.5 Results of the investigation

From the investigation result shows in Table 2.1, it can be clearly noticed the important role of storage systems in remote electrification areas. The diversity of type of generating system combined with storage system depend on the geographical location. This investigation shows that relevant works in this past years are mostly feasible and techno-economic studies. There are lack of concrete implemented and functional hybrid energy system in remote areas. Differents approaches listed in this investigation study can be classified in two categories: (i) software models use for optimal design, size, management and simulation of hybrid energy systems by minimizing the total system cost (Hybrid Optimization Model for Electrical Renewable (HOMER) and Hybrid Optimization Genetic Algorithm (iHOGA));(ii) mathematical optimize algorithm such as iterative algorithm use for techno-economic evaluation in hybrid system, heuristic and harmony search algorithm use for feasible and techno-economic evaluation, Genetic Algorithm (GA) use for minimization cost of the hybrid system, Mixed Interger Linear Programming (MILP) use also for optimization and management in multi-source generation and storage in a hybrid system. In Africa, in America and in Middle East and in asia, the generating system is mostly based on fossil fuel generator integrated with renewable energy such as photovoltaic, wind, hydro and the storage system is mostly based on battery. While in Europa, the generating system is mostly based on fossil fuel generator integrated by renewable energy such as wind and hydro with the storage system mostly based on battery and pumped storage system.

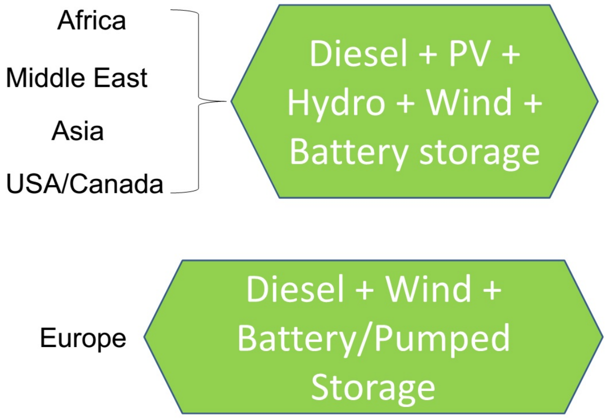

Figure 2.4: Hybrid system configurations summary of the investigation

2.6 Conclusion

The different methods of optimization and different approaches for design, size management and simulation of different types of renewable hybrid energy systems have been discussed above. It has been identified that control strategies achieved good voltage, frequency regulation and power sharing. It can also be noticed that the configuration scheme with a coupled AC and DC bus is widely used, has a high energy efficiency, low cost of the control system, possibility of adding future different generating systems (traditional and renewable sources) or different loads (AC or DC) but the control and the management strategy of the whole system can be more complicated. It is clear to note the extremely variability of the definition and the applications of microgrids including a simple island area, a remote village, a city or a town, a Forward Operating Base (FOB) to an oil platform just to cite these examples. The important role of storage system in electrification of remote areas has been clearly noticed for the constant electricity supply. It has emerged that Cameroon, the country situated in Central Africa could have as best configuration for hybrid energy system for remote areas PV/Wind/Diesel/Battery system. All these different issues have the main objectives of reducing fuel consumption, performing reliability of the system, preserving environment while, providing electricity for remote isolated located populations.

Table 2.1: Result of the Investigation

Authors	Countries	T-Sources	Renewable Sources	Storage System	Type of Study
[64]	Cameroon	D-G	PV	BSS	Economical
[72]	Nigeria	D-G	PV	BSS	Feasibility
[67]	Senegal	D-G	PV/Wind	BSS	Feasibility
[68]	Cape Verde	.	PV/Wind	BSS	Feasibility
[96]	Cameroon	D-G	PV	BSS	Feasibility
[112]	Cameroon	D-G	PV	BSS	Economical
[99]	Cameroon	.	PV/hydro	BSS	Feasibility
			Bio-gas		
[37]	Cameroon	D-G	PV	BSS	Feasibility
[11]	Cameroon	D-G	PV	BSS	Feasibility
[113]	Kenya	.	Wind/Hydro	PSS	Feasibility
[111]	Cape Verde	.	PV/Wind	BSS	Feasibility
[54]	Algeria	D-G	PV/Wind	BSS	Economical
[73]	Canada	D-G	Wind/PV	BSS	Feasibility
			Hydro		
[90]	USA	D-G	.	BSS	Feasibility
[62]	China	.	PV	BSS	Feasibility
[114]	Indonesia	.	PV	BSS	Feasibility
[74]	Bangladesh	D-G	Hydro	BSS	Feasibility
[88]	Malaysia	.	PV/Wind	BSS	Feasibility
[98]	Australia	.	PV	BSS	Feasibility
				Super Capacitor	
[102]	China	.	PV	PSS	Economical
[110]	China	.	PV/Wind	PSS	Feasibility
[55]	Nepal	.	PV/Wind	BSS	Feasibility
			Hydro		
[115]	Greece	D-G	Wind	PSS	Stability
[63]	Germany	.	PV	BSS	Electricity
			Fuel Cells	Electrolyser	
[100]	Greece	D-G	PV/Hydro	BSS	Feasibility
				Super Capacitor	
			Fuel Cells	Flywheels	
[103]	Greece	.	Wind	PSS	Feasibility
[104]	Greece	D-G	Wind	PSS	Feasibility
[116]	Greece	.	Wind	PSS	Economical
[105]	Greece	.	Wind/Hydro	PSS	Economical
[106]	Greece	D-G	Wind/Hydro	PSS	Economical
[109]	Spain	.	PV/Wind	.	Feasibility
[52]	Greece	.	PV/Wind	BSS/PSS	Feasibility
			Hydro/Fuel Cells	S-C/Flywheels	
[56]	Greece	D-G	PV	BSS	Feasibility
[57]	Greece	.	PV/Wind	BSS	Feasibility
[71]	Saudi Arabia	D-G	PV/Wind	.	Feasibility
[84]	Iran	F-G	PV/Wind	BSS	Feasibility
[89]	Iran	F-G	Wind/Tidal	BSS	Feasibility
[108]	Turkey	.	PV/Wind	.	Feasibility
[44]	Iran	F-G	PV/Wind	BSS	Feasibility

2.7 Published papers:

1. M.K. Pendieu, N. Anglani. Hybrid Energy System for Remote Areas and the Role of Storage IEEE International Conference on Industrial Technology (ICIT) 2015, Sevilla, Spain. Pages: 1031-1038.

3 Assessment and potential of solar and wind energy resources in Cameroon

This chapter presents an assessment of solar radiation and wind speed in Cameroon and the evaluation of the potential of solar and wind energy sources within the ten regions of the country. Therefore, this work will helped to have a better understanding on the panorama of solar and wind energy potential and to choose where can be the better place to carry out the case study.

3.1 Introduction

Cameroon is a Sub-Saharan African country, situated in central Africa (see Fig.3.1). The neighbooring countries of Cameroon are: Chad in the North East, Nigeria in the West, Central Africa Republic in the East, Equatorial Guinea and Gabon in the South, Republic of Congo in the South East. The total superficie is 475.440 km^2 and it is located at latitude 6°00 N and longitude 12°00 E. The country has actually an estimation population of roughly 20.3 millions [117] compared to only 4.5 millions in 1950, with a forecasted increase of 2% each year. For the US Central intelligence agency, the Cameroon estimation population on July 2014 is 23.130.708 millions with 2.6% population growth rate per year. From the total population of Cameroon, 52.1% live in urban areas and the annual urbanisation of 3.23% between 2010 and 2015 [118]. The country is divided on ten regions with 13 principal towns: Yaounde, Douala, Garoua, Maroua, Ngaoundere, Bafoussam, Bamenda, Bertoua, Kribi, Ebolowa, Buea, Edea and Nkongsamba. About 20% of the population live in two major cities: Douala (economical capital) and Yaounde (political capital). Electrification nowadays of rural areas in various developing countries is around 20%. More than 70% of the population in such developing countries (include Cameroon) live in rural areas with a forecasted increase of 6% per year in the near future [117]. It means that more than 70% of the population live almost in total darkness. National access to electricity in Cameroon increased from 37% in 1996 to 46% in 2002 and to 48% in 2007, above the average for Africa resource rich countries. According to different estimations, between 65% and 88% of the urban population has access to electricity. Only about 14% of rural population has access to electricity [119]. Over 13.000 localities that count Cameroon, only about 3.000 localities are electrified.

Electricity supply is unevenly distributed within the country. There are three separate grids: the Northern Interconnected Grid (NIG) supplies the three Northern provinces (Ngaoundere, Garoua, and Maroua), the Eastern Isolated Grid (EIG) supplies the eastern provinces (Bertoua, Abong-Mbang and Batouri) and the Southern Interconnected Grid (SIG) covers the south-west regions (Yaounde, Douala, Bafoussam and Bamenda) [3] (see Fig.3.2). Transmission grids are completely isolated from one to another and no exchange of available surpluses can be made between the grids. Together with the Government, the Bank and other sector donors are all considering the best technical solution for interconnecting the three grids. Progress in grid extension is slower than population growth. Many strategies are now taking by the government of Cameroon. The government policy seeks to get the country out of under-development, through the implementation of the long-term Energy Sector Development Plan (PDSE 2030) and the Poverty Reduction Strategy Paper (PRSP) [118]. Development of the energy sector is seen as a factor for attracting investment and strengthening growth.

Moreover, Cameroon development objectives under the Vision 2035 envisage significant investments in the energy sector, with the inclusion of renewable energies. The policy goals of the government are to ensure energy independence through increased production and delivery of electricity, of oil and gas (petroleum resources) and to ensure their contribution to economic development [118].

According to climate conditions and the geographical position of the area, we can have different kind of schemes for hybrid micro-grids. The word hybrid means that the micro-grid can include different generating technologies both traditional such as a diesel generator, renewable sources and storage. This chapter is organized as follows: In section 3.2, the status of different assessment methods are investigated. Section 3.3, an overview of weather specification in all the 10 regions is described and explained the diversity and the variability of solar energy and wind energy across the country. Section 3.4 describes the methodology of assessment used and the calculation of hourly ouput power, daily and yearly energy production of solar irradiation and wind speed. Section 3.6 shows the results obtained after the assessment of solar irradiation and wind speed. In section 3.7, conclusions are drawn.

Figure 3.1: Geographic situation of Cameroon

3.2 State of art

In [96] the authors evaluate the optimal option for the supply of two days autonomy energy demands of 33 transceiver stations in Cameroon with a photovoltaic hybrid systems. The photovoltaic hybrid system is computed using the solar resource modules of HOMER and the geographical coordinates for all the sites with the specific hourly load data and the hourly monthly radiation. For the sizing of the hybrid system, the frequency of temperature acquisition has been recorded in each three hours using the NASA database. The Net Present Value Technique and financial data for the selected power system components have been used for the breakeven grid distances calculation.

In [40] the authors evaluate the economical assessment of photovoltaic systems of four types of ptotovoltaic technology; crystalline silicon (c-Si), amorphous silicon (a-Si) and cupper indium selenide (CIS) photovoltaic modules in different locations in Cameroon. A long term data acquisition for the study was carried out using satellite derived solar radiation. Photovoltaic software was used to evaluate the energy generated by the photovoltaic systems with optimally inclined photovoltaic modules. The economic assessment revealed that a payback period of 5.6 years and the levelized cost of electricity genera-

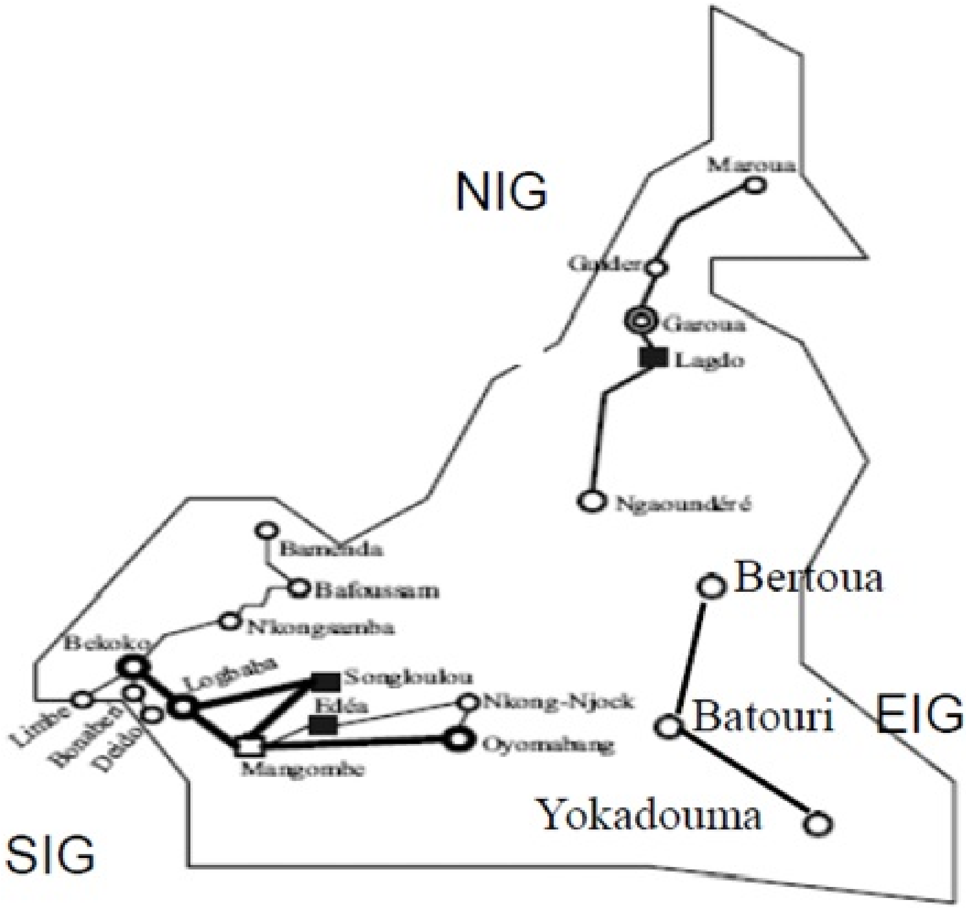

Figure 3.2: The three transmission lines in Cameroun (NIG and SIG from Ref. [3]) with the third Eastern Isolated Grid added

tion can be achieved in these different locations. The authors in [120] study the potential of solar energy for rooftop in Ontario. The solar data acqisition has been assess by Canadian Geographic Information Systems database (GIS). In [121] the authors assessed the solar energy from the estimation of solar irradiance from satellite images. The Malaysian Meteorology database has been used to extract from daily global solar radiation, the means hourly data and then used it to assess monthly solar radiation in three sites Malaysia. Many models have been tested and evaluated in many cities with good results [122]. Solar energy has been assessed in Saudi Arabia for solar energy power plants deployment. The solar radiation has been collected in thirty meteorological stations in all the country for a period of one year, with a data measurement frequency of one minute [123]. In Algeria, an assessment of solar energy has been done in four different regions using the meteorological wind hourly acquisition database for five years period. The result of the investigation shows that, two of the five regions selected for the study have a good wind energy potential and a yearly wind speed average of 5.8 m/s and 5.7 m/s at the height above the ground of seventeen meters. This two potential wind production farms will also help to provide drinking water to the remote community [124]. The mean average monthly wind speed data of two sites in North-East Nigeria has been recorded for twenty one years years by the meteorological department at the height of ten meters. The two sites revealed a good wind energy potential for stand alone and medium scale wind power generation [125]. Wind energy potential of four different sites in Ethiopia have been assessed. The data from wind speed has been obtained from the National Meteorological Services Agency (NMSA). The data has been taken to the height of ten meters for three consucutive years [58]. The study carried out on potential of wind energy in various cities in Ethiopia using twenty one meteorological stations reveal the available potential of wind energy [126]. In turkey, the wind energy potential has been investigated in various regions and the hourly wind speed of a period of one year have been assessed. The study reveals the abundance of wind energy potential in the northern parts and the north-western parts, at locations along the Aegean Sea and Marmara sea coast [127]. Assessment of wind energy in various regions in Iran has been investigated and the wind speed data have been aquisited for a period of one year with an interval of ten minute at heights of ten, thirty and fourty meters above the ground level. For the feability study, the geographical information system (GIS) maps have been used [128]. The authors analysed and identified the potential sites for high wind enrgy potential in Oman. The hourly data from wind speed have been assessed for five years period in twenty-nine meteorological weather stations [129]. Wind energy potential and economic analysis for rural electrification in Vietnam, have been assessed using respectively the WAsP 10.0 and the RETScreen International software at the height of eighty meters above the ground level with a mean wind speed of 7.2 m/s. The collected daily wind speed data for 5 years period has been used for the purpose [130]. A ten years wind speed daily data has been collected by the meteorological station in the city of Batna in Algeria. The daily wind speed data has been assessed with a time period of three hours at the height ten meters above the ground level. Four types of wind turbines of different manufacturer have been used to estimate the output power [131].

3.3 Specificities and weather in different regions

According to geographical position, each region has it own specificity in terms of weather. The Far North has two seasons: one dry, and one wet. These are further broken down based on average temperatures, yielding four distinct periods in the Sudan area: dry and relatively cool from November to January as the region experiences a shade of winter from climes further north, dry and hot from January to April, torrential rain from April to June, and cool and sporadically wet from June to November. In the Sahel zone, the wet periods are shorter, lasting only five to seven months in the south but shortening toward Lake Chad. Temperatures reach their highest levels from January to May. Beginning at about 11° N, the region only experiences about 25 to 30 rainy days each year from the Benoue depression south, the North experiences tropical climate of the Sudan type. Average rainfall is between 900-1500 mm per year, decreasing from south to north due to elevation. Garoua, the major city, thus receives between 500-1000 mm per year. Rainfall in the Benoue depression is unpredictable, though it rarely drops to less than 1000 mm in any one year. North of the Benoue depression, a Sahel climate prevails. Here, the dry season lasts longer, and temperatures reach even higher levels. Regional temperatures average 24°C in the south along the plateau. In the depression, they rise to 26°C. North of the reservoir, temperatures climb as high as 28°C. Seasons follow a wet/dry pattern, with rough divisions in November (dry) and April (wet). The year begins under the influence of the harmattan winds in the dry season. In this period, temperatures are at their highest and rainfall is virtually nonexistent. This period of stifling heat continues until April, which brings with it torrential rains and lower temperatures. Rains sease up in June, though temperatures remain lower and humidity relatively high. Then in November, the region becomes drier and temperatures cool as a shadow of winter sets in. The Adamawa region's has a high elevation and relatively a cool climate average between 22 and 25°C. However, specific conditions vary between the South Cameroon and Adamawa Plateaus. The former experiences an equatorial climate of the Guinea type with four seasons: a long, dry period from December to May, a short, wet period from May to June, a short, dry season from July to October, and finally a long, wet season from October to November. The climate of the Adamawa Plateau is classified as tropical of the Sudan type. It has only two seasons; November begins the dry period, and April the wet. Rainfall here averages 900 to 1500 mm per year and decreases further north. May and June are the wettest, with occasional tornadoes, August with a rainfall peak. In addition, temperatures decrease from November to January, as conditions similar to those that cause winter in temperate climates take at least a tentative hold. Temperatures rise due to the harmattan beginning in January, reaching a high in April. Torrential rains in May and June bring temperatures down once again. This region experiences an equatorial climate of the Cameroon type. Rainfall is within 1500 to 2000 mm with a long dry period followed by a long wet period. The Centre falls completely within a Type A or Guinea type climate. This gives the region high humidity and precipitation, with rainfall averaging 1000-2000 mm each year. Precipitation is highest in the southern most portions and reduces toward the north. Temperatures are fairly steady, averaging 24°C for the entire region except for the Northwestern portions of Mbam division, where they fall to 23°C. The Centre also experiences equatorial seasons, alternating between rainy and dry periods. The long dry season begins the year, running from December to May. After this comes the short rainy season, which lasts from May to June. The short dry season comes next, from July to October. The year ends in the long rainy season from October to November. Douala features a tropical monsoon climate (Koppen climate classification) with relatively constant temperatures throughout the course of the year. The city typically features warm and humid conditions with an average annual temperature of 27°C and an average humidity of 85%. Douala sees plentiful rainfall during the course of the year, experiencing on average roughly of 3600 millimetres precipitation of rainfall per year. Its driest month is December where on average 28 millimetres of precipitation falls while its wettest month is August when on average nearly 700 millimetres of rain falls. The climate of the South region is Type A or Guinea type climate. Humidity is high, and precipitation averages 1500-2000 mm per year in the interior and 2000-3000 mm per year in the coastal region. The coast from the north of Kribi south to Ebodje gets as much as 4000 mm of rain per year. Temperatures are relatively high as well, averaging 24°C and 26°C from Kribi north along the coast. Instead of traditional seasons, the Guinea type climate affords alternating dry and wet periods. The year begins in a long dry season that lasts from December to May. This is followed by a light wet season from May to June and a short dry season from July to October. A heavy wet season begins around October and lasts through November. The East has a Type A wet equatorial climate (also known as a Guinea type climate), meaning that it experiences high temperatures (24°C on average) and a lack of traditional seasons. Instead, there is a long dry season from December to May, a light wet season from May to June, a short dry season from July to October, and a heavy wet season from October to November. Humidity and cloud cover are relatively high, and precipitation averages 1500-2000 mm per year except in the extreme eastern and northern portions, where it is slightly less. High elevations and moderate to high humidity give the West region of Cameroon more pleasant climates. Temperatures average a cool 22°C, and rainfall is moderate. Except for the Southeastern most portions, the West experiences two major seasons instead of the traditional four: the year begins in a long, dry period of little rain, which runs until May, then, the rains begin in May or June and last until October or November. Though the transition is gradual, the Southeastern reaches of the region are part of the South West Cameroon Plateau and thus have four seasons: the long dry season from December to March, the short rainy season from March to June, the short dry season from June to August, and the long rainy season from September to December. The climate is equatorial of the Cameroon subvariety in the Northwestern third and equatorial of the Guinea type in the Southeastern two-thirds. Rainfall, moderated by the mountains, averages 1000-2000 mm per year throughout, it is highest at the area of the Bamendjing reservoir. Because of its location at the foot of Mount Cameroon, the climate in Buea tends to be humid, with the neighbourhoods at higher elevations enjoying cooler temperatures while the lower neighbourhoods experience a hotter climate. Extended periods of rainfall, characterized by incessant drizzle, which can last for weeks, are common during the rainy season as are damp fogs, rolling off the mountain into the town below. Its proximity to the equator which is consistently hot and humid, gives Debundscha a long rainy season and a short dry season in a year. Debundscha's coastal location with the giant Mount Cameroon behind it, a giant mountain massive rising from the coast of the South Atlantic ocean to a height of about 4095 metres and blocking rain forming clouds from passing it results in abundant rainfall for Debundscha during the year. The major rainfall falls on the ocean-facing south-western slope of Mount Cameroon and on Debundscha, at the foot of this slope.

3.4 Methodology used for the assessment of solar and wind energy

Here is explained the methodology used to assess solar radiation and wind speed across the country. Up to 73 cities have been considered for solar energy and only 20 cities for wind potential.

3.4.1 Solar energy

Taking into consideration some works of many authors, Cameroon has an abundance of solar energy resources. The solar energy intensity can be grouped into two categories across the country. The Northern regions and Southern regions has the highest solar energy intensity with an estimation of 5.8 and 4 kWh/m^2/day respectively [132]. Recent estimates are quite encouraging with the values of 4.9 kWh/m^2/day in the Southern regions [133]. As argued by [133], the conditions for the exploitation of Cameroon's solar energy resources are ideal. Infact, according to [133], the whole country possesses great solar energy potentials with some regions far above the required average to generate useful energy.

Do not relaying on meteorological stations for collecting weather data in a precise way in different sites in Cameroon, the NASA (surface meteorological and solar energy) and RETScreen International [5], [39] have been used for this work. The geographical coordinate of the ten regions that count Cameroon and all the departments of all the 10 regions have been found. The geographical coordinates in terms of latitude and longitude have been introduced in the NASA software database as input data. The daily solar radiation for a period of 22 years (July 1983-December 2005) has been assessed as output data at the elevation height of 902 meters. Then, after the elaboration of the twenty two years daily data recorded, the means average monthly and yearly solar radiation has been calculated. The cities of the departments have been selected from the North to the South, the centre and from the East to West. All the departements of the regions have been selected to be sure to have all the entire particularity of the regions (Table 3.4). Fig.3.3 illustrates the distribution of solar irradiation in Cameroon taken from solar GIS (geographical information system) software [4] Fig.3.4 illustrates the daily solar irradiation of the city of Mora in the Far North region for a six months period of the year 2005. This figure shows how abundant is the solar radiation in the region.

3.4.2 Wind energy

Wind energy resources have never received any considerable attention in Cameroon. Attempts have been made by [134], [135] in assessing the wind potential in

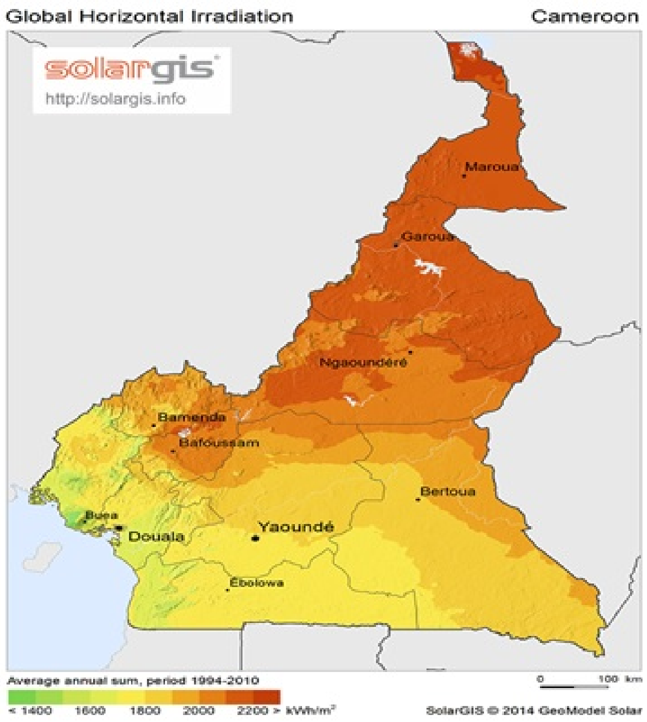

Figure 3.3: Global Horizontal Solar irradiation in Cameroon [4]

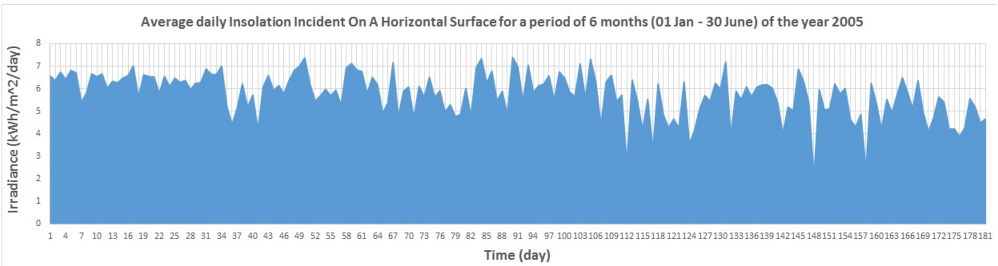

Figure 3.4: Daily solar irradiance for a period of 6 months of the year 2005 in Cameroon [5]

Cameroon. These studies were based on meteorological data from the National Meteorological Department located in the Adamawa and Northern regions of Cameroon. Although the studies focused only on the Northern regions of the country, their outcome clearly indicated that these parts of the country are endowed with enormous wind potentials. This deficiency in studies about wind energy in Cameroon has been related in the recently completed Masters study in the Brandenburg Technical University Cottbus, Germany to further provide an insight into the potential of wind energy towards sustainable economic development as a whole [133].

As explained before in the case of solar energy assessment, the NASA (surface meteorological and solar energy) and RETScreen software database have been used for the wind speed assessment. The geographical coordinates (in terms of latitude and longitude) of the ten regions and all their departments have been found and used as input data in the NASA software. As output, the average monthly and yearly wind speed is assessed at 50 m above the surface of the earth. The cities of the departments have been selected from the North to the South, the centre and from the East to West for all the regions for been sure to have selected all the entire particularity of the regions (Table 3.6). This potential decreases towards the Southern regions, where wind speeds decreases. This conclusion is quite similar to the studies carried out by Refs. [134], [135]. Fig.3.6 shows the maps of global wind speed distribution in Cameroon taken from wind atlas software [6].

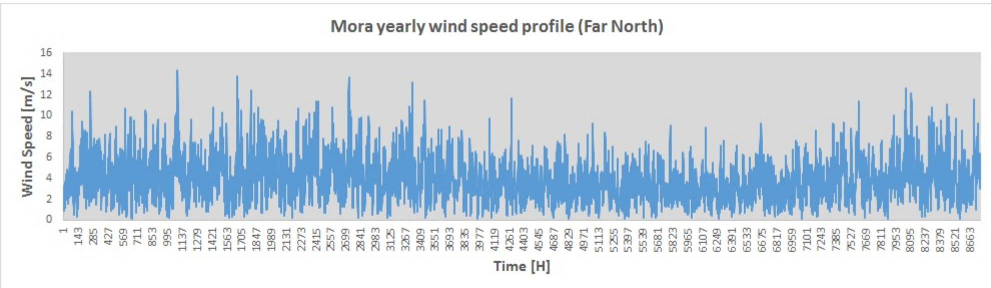

Figure 3.5: Yearly wind speed profile of Mora Cameroun 2005 [5]

Fig.3.5 illustrates the hourly wind speed profile of the city of Mora in the Far North region for a yearly period. This figure shows how interesting is the wind speed in the region for a good potential.

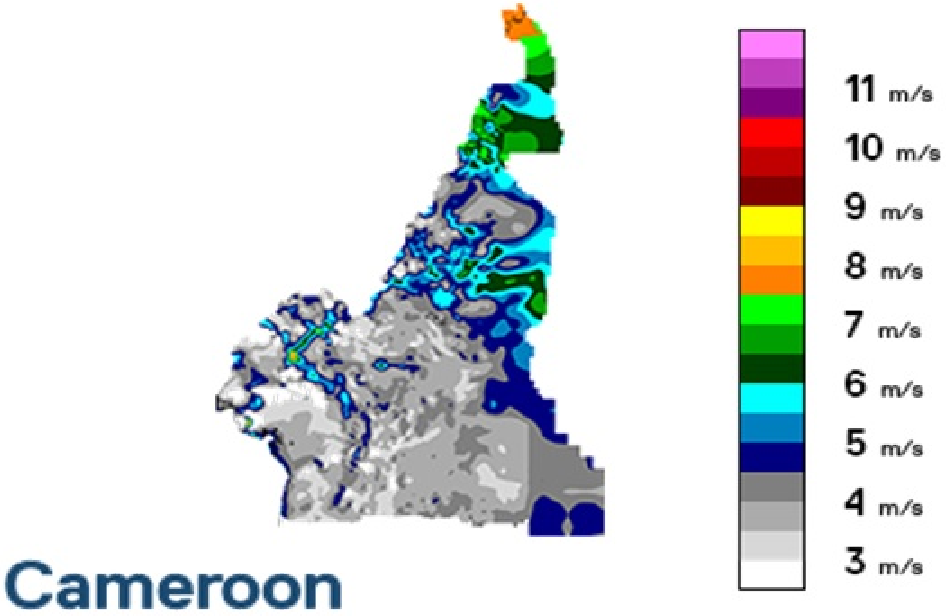

Figure 3.6: Global Wind Speed maps in Cameroon [6]

3.4.3 Combined measurements and modeling program

Uneven heating of the Earth's surface by the sun causes the wind. The warmer air in some places rises. The resulting low pressure area draws in cooler air. The resulting wind flow is affected by many influences like the Coriolis force, the terrain, the obstacles, buildings and woods. The energy in the wind is proportional to the cubic of the wind speed; this means if the wind speed doubles the energy goes up by a factor of eight. For a reliable Wind power prognosis the knowledge of the local wind potential is crucial. For this reason a reliable measurement should be taken into an account. The standard height of wind instruments is 10 m above the ground, but this a mainly because of historical reasons. Many meteorological institutions use this height for their weather forecasts and for agricultural issues. The better way is to measure the wind speed and direction at hub height of the planned wind turbine. The hub heights vary between 10 m for very small turbines of 5 kW up to 150 m for very large turbines of 6000 kW. Because of the given infrastructure and the lack of really big cranes the focus should be on turbines with hub heights around 30 to 50 m. For this reason the measuring height should be at the same height levels. While shorter towers have cost advantages, their lower accuracy is less attractive. Wind speed almost always rises with altitude, so the average wind speed at 60 meters is usually higher than the 30 meter data. The right coefficient can scale the data up. But every site needs a different coefficient. The best location for a good measurement is open terrain, which is defined as an area where the distance between the instrument and any obstruction is at least ten times the height of that obstruction. Even the slope of the terrain in the vicinity of the site should be taken into account. An obstruction may be a building or a hill, a tree or woods. The height, the location and the density of the obstructions should be documented. On locations where a large influence of these obstructions on the wind speed can't be avoided the measuring height should be raised. Those obstructions can be:

- Buildings: Aerodynamic effects due to buildings should be avoided to the extent possible in the siting of wind sensors; such effects are significant, not only in the vicinity of the structures themselves, but at considerable distances downwind.

- Trees: Seasonal effects should also be considered for sites near trees. For dense, continuous forests where an open exposure cannot be obtained, measurements should be taken at least 10 m above the height of the maximum height.

The sensors mounted on towers should collect wind speed measurements at more than one height. To avoid the influence of the structure itself, closed towers and similar solid structures should not be used. Open-lattice towers or a tilt-up tower (tall pipe with lots of guy wires (Fig.3.7) are preferred. Towers should be located at or close to plant elevation in an open area representative of the area of interest. At least two identical conventional and reliable cup anemometers should be arranged on booms. The anemometers measure the wind speed at two different height levels. The lowest level should be 15 m below the top anemometer. This approach allows the calculation of the vertical wind profile. The registration of the wind direction is conducted by a conventional wind vane. Data concerning atmospheric humidity, air temperature and air pressure and temperature difference can complete these figures. Wind instruments should be mounted on booms at a distance of at least twice the diameter/diagonal of the tower (from the nearest point on the tower) into the prevailing wind direction. Where the wind distribution is strongly bimodal (very strong seasonal change of wind direction) the booms should be at right angles to the predominant wind directions.

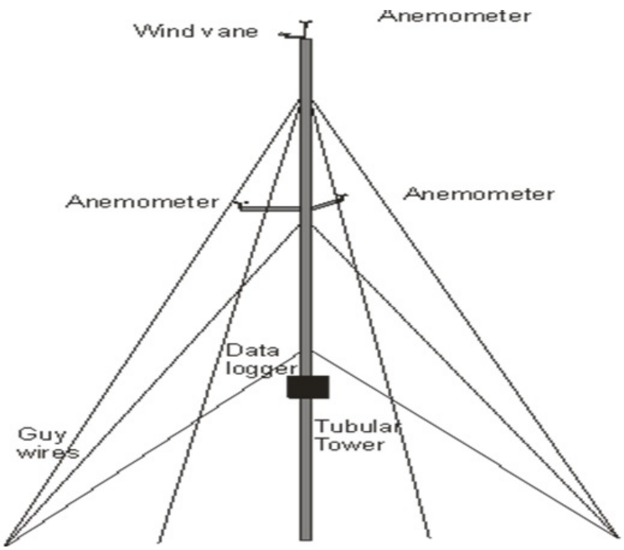

Figure 3.7: Tower with anchors for landbased observation [6]

The surface roughness over a given area reflects man-made and natural obstructions, and general surface features. Differences in the surface roughness over the area of interest can create differences in the wind scheme. A method of estimating surface roughness length, zo, is presented in European wind atlas [41]. A single well-located measurement site can be used to provide representative wind measurements for non-coastal, flat terrain, rural situations.

The base data for a field study as a combined measurement and modeling

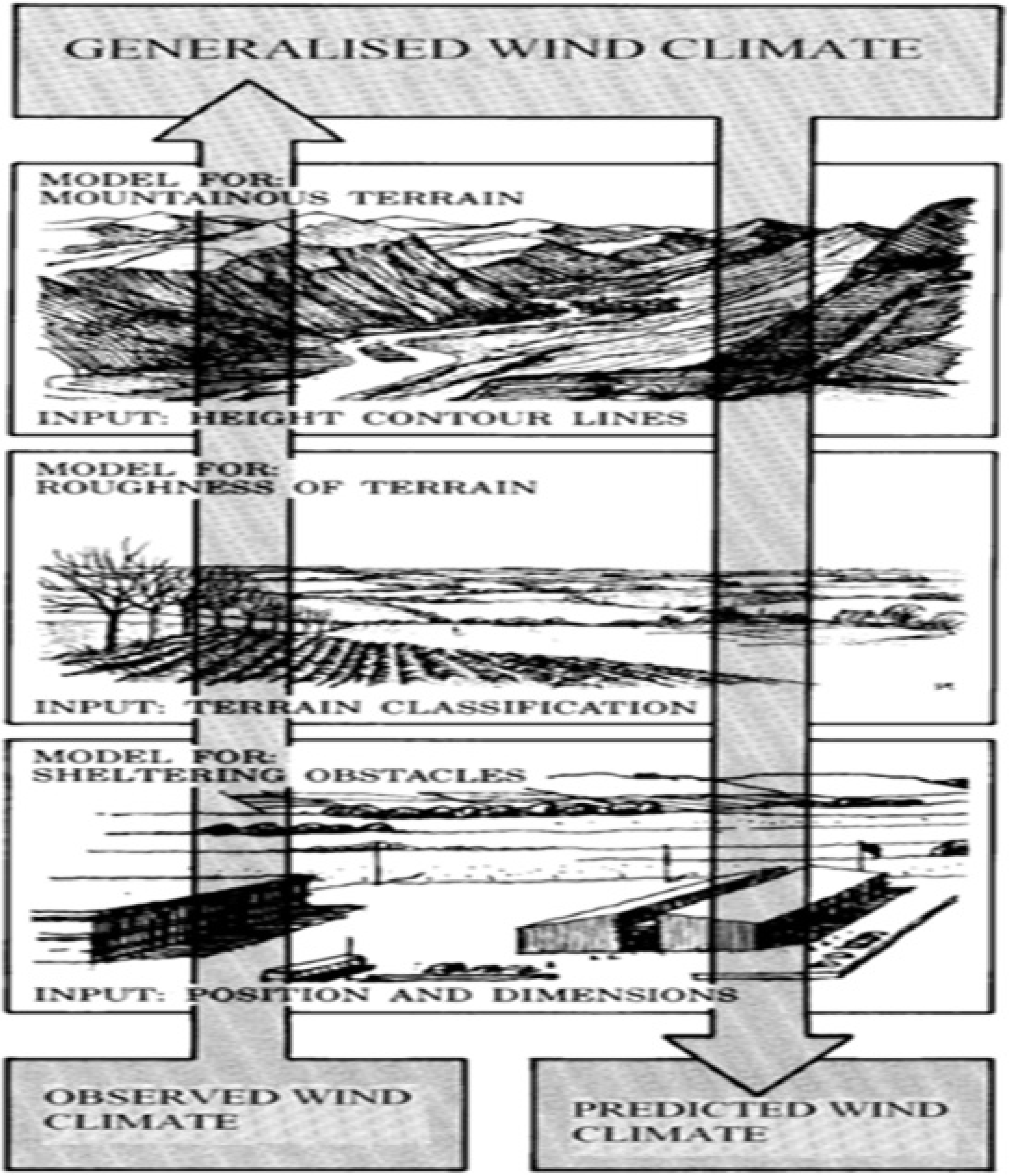

Figure 3.8: Methodology of data handling [7]

program are the measured climatological data and on the other hand the data for the obstacles around the measuring point, data to classifies the surface roughness and elevation data. The data for the obstacles has to be gathered while erecting the measuring mast, the roughness data can be collected out of terrain maps or satellite pictures and the SRTM (Shuttle Radar Topography Mission) data are the base for the elevation data. The combination of all this data allows generating a generalized wind climate (Fig.3.8) [42]. This generalized wind climate is the base data for various calculations. By using this procedure wind potential predictions for a certain region can be carried out. To predict the wind potential for a country several measuring masts have to be installed and should deliver data for at least one year. The modeling is used for a vertical extrapolation, the correction for climatological variations and to spatially prediction of the wind potential.

3.5 Potential evaluation of solar and wind energy

The mathematical formulations used to evaluate the energy potential of solar and wind sources are drawn below. From the hourly solar radiation assessed, it has been caculated the power production capacity per square meter. Then, it has been calculated the yearly production capacity using the total number of hours of availability of solar radiation per year. Finally, knowing the density of the population and the total area used, the yearly energy potential of any city have been assessed.

3.5.1 Solare energy calculations

The Photovoltaic panel output power has been modeled using the manufacturer datasheet. The data provided by the manifacturers (I_{sc}, V_{mp}, I_{mp}, V_{oc}, α, β, I_{st}, T_{st}, η_{re}) are respectively short circuit current (8.95 A), voltage at maximum power (24.91 V), current at maximum power (8.23 A), open circuit voltage (29.55 V), current coefficient temperature(0.07 A/°C), voltage coefficient temprature (-0.38 V/C), irradiation in standard condition (1000 W/m^2), standard temperature (25°C) and the reference module efficiency (15.57). The monocrystalline photovoltaic panels have a nominal power of 205 W. There are two kind of photovoltaic output calculation technique in the literature. These techniques are known as electrical parameter based techniques and efficiency based technique. In this study, the electrical parameter based technique would be used. The hourly output power (P_{pv}) of the photovoltaic generator panel is calculated as

$$P_{pv}(t) = \eta_{pv}(t) A_{pv} G_{pv}(t) \tag{3.1}$$

where η_{pv} is the photovoltaic generator efficiency, A_{pv} (m^2) is the area of the photovoltaic module, G_{pv} (W/m^2) is the hourly insolation and P_{pv} (W) the hourly output power of the photovoltaic generatore module.

The efficiency of the photovoltaic module is calculated as

$$\eta_{pv} = \eta_{re}\eta_{pc}[1 - \beta(T_c - T_{ref})] \tag{3.2}$$

here η_{re} represents the reference module efficiency (assumed here as 15.57%), η_{pc} is the power conditioning efficiency (assumed to be 86%), T_c the actual cell temperature and T_{re} the reference cell temperature. T_c should be calculated from equation 3.3 and replaced in equation 3.2. β is the voltage temperature coefficient for module efficiency (assumed here to be -0.38 V/°C).

Module efficiency is a function of its nominal efficiency, η_{re} which is measured at a reference temperature T_{re} assumed to be 20°C.

$$T_c(t) = T_a(t) + [(NOCT - 20)/800]G_{pv}(t) \tag{3.3}$$

where $T_a(t)$ is the instantaneous ambient temperature, NOCT is the nominal operating cell temperature defined as the temperature reached by open circuited cells in a module (assumed to be 33°C) and 800 is the irradiance on cell surface (W/m^2).

The daily DE_{pv} [Wh/day] and yearly solar energy production YE_{pv} [kWh/year] by the photovoltaic module is calaculated as

$$DE_{pv} = \sum_{t=1}^{24} P_{pv}(t) \tag{3.4}$$

here the 12 represents the total number of hours of insolation per day and 8760 represents the yearly total number of hours.

$$YE_{pv} = \sum_{t=1}^{8760} P_{pv}(t) \tag{3.5}$$

The data taken from the NASA software has been elaborated and shown in Table 3.1.

Data elaboration continues from Table 3.1.

3.5.2 Wind energy calculations

For the potential of wind energy, only 20 cities with a minimum wind speed of 3 m/s have been considered. For the assessment, the yearly wind profile has been taken into account and the minimum and maximum wind speed value. Various wind turbine with different wind curve and annual energy production have been considered and the best with good performaces have been chosen.

Table 3.1: Hourly, daily and yearly solar output power production

Regions	Cities	H_{pv} [kWh/m^2/day]	G_{pv} [kW/m^2]	$[Area]$ [km^2]	P_{pv} [GW]	Nb-H [Hrs/yr]	YE_{pv} [TWh/yr]
Far North	Maroua	5.02	0.431	4665	2010	4822	9695
	Kousserie	5.33	0.436	1900	828	4822	3992.6
	Blangoua	5.01	0.416	2500	1040	4822	5014.88
	Yagoua	4.88	0.436	950	414	4822	1997.27
	Kalfou	4.79	0.431	615	265	4822	1278.14
	Mora	5.12	0.4405	1735	764	4822	6434.4
	Mokolo	5.75	0.434	1650	716	4822	3452.55
North	Garoua	5.75	0.434	644	279	4822	1345.33
	Poli	5.75	0.435	10000	4350	4822	20975.7
	Tchollire	5.75	0.428	9810	198	4822	20242.75
	Touboro	5.72	0.432	490	211	4822	1020.72
	Pitoa	5.75	0.435	812	353	4822	1702.16
Adamawa	Ngaoundere	5.66	0.427	2177	929	4822	4479.6
	Belel	5.6	0.423	4000	1690	4822	8149.18
	Ngaoundal	5.61	0.424	8000	3392	4822	16356.22
	Tibati	5.65	0.426	8000	3408	4822	16433.37
	Tignere	5.6	0.423	5000	2225	4822	10198.53
	Banyo	5.44	0.411	8520	3501	4822	16881.82
	Meiganga	5.56	0.42	2653	1114	4822	5371.7
Centre	Yaounde	4.67	0.334	297	104	4822	501.48
	Bot-Makak	4.43	0.334	2500	835	4822	4026.37
	Nanga-Eboko	5.05	0.364	7000	2548	4822	12286.45
	Obala	5.01	0.372	475	176	4822	848.67
	Makenene	4.69	0.355	885	314	4822	1514.108
	Ntui	5.01	0.77	1650	622	4822	2999.28
	Yoko	5.36	0.401	15000	6015	4822	29004.3
	Mfou	4.67	0.358	3338	1195	4822	5762.29
	Nkolmetet	4.43	0.334	532	177	4822	853.49
	Akonolinga	4.83	0.364	6172	2246	4822	10830.31
Littoral	Douala	4.28	0.323	923	0.298	4822	1437
	Edea	4.43	0.341	180	166	61	294.142
	Ngambe	5.06	0.382	470	179	4822	863.1382
	Mouanko	4.41	0.333	1378	458	4822	2208.47
	Nkongsamba	4.28	0.323	280	90	4822	433.98
	Melong	4.76	0.357	497	177	4822	853.49
	Yabassi	4.28	.323	3080	994	4822	4793
	Yimgui	4.69	0.353	2000	706	4822	3404.33
South	Ebolowa	4.64	0.35	8697	3.043	4822	14673.34
	Ngoulemakong	4.67	0.346	700	242	4822	1167
	Djoum	4.7	0.35	8000	2800	4822	13501.6
	Sangmelima	4.64	0.35	2155	754	4822	3635.78
	Zoetele	4.67	0.353	1644	580	4822	2796.76
	Kribi	4.57	0.345	8697	3000	4822	14466
	Lolodorf	4.43	0.335	1200	402	4822	1938.44
	Ambam	4.64	0.351	2798	982	4822	4735.2
	Ma'an	4.35	0.328	2436	799	4822	3852.77

Table 3.2: it continues from Table 3.1

Regions	Cities	H_{pv} [kWh/m^2/day]	G_{pv} [kW/m^2]	$[Area]$ [km^2]	P_{pv} [GW]	Nb-H [Hrs/yr]	YE_{pv} [TWh/yr]
East	Bertoua	5.02	0.379	100	37.9	4822	182.75
	Ngaroua-Boulai	5.33	0.397	2125	843.62	4822	4065
	Yokadouma	5.01	0.379	9533	3613	4822	17422
	Moloundou	4.88	0.368	15000	5520	4822	26617.4
	Abong-Mbang	4.79	0.361	11340	4093	4822	19736.4
	Batouri	5.12	0.387	5786	2239	4822	10796.4
	Ouli	5.33	0.403	2548	1026.8	4822	4951.2
West	Bafoussam	4.97	0.375	91	34.125	4822	164.55
	Santchou	4.76	0.359	95	34.105	4822	164.45
	Bagangte	4.97	0.375	800	300	4822	1446.6
	Tonga	4.69	0.355	360	127.8	4822	616.25
	Foumban	4.97	0.375	418	156.75	4822	755.85
	Magba	5.46	0.412	579	258.54	4822	1246.68
S-West	Buea	4.28	0.323	7000	2261	4822	10902.54
	Bangem	5.01	0.379	1500	568.5	4822	2741.3
	Tombel	4.28	0.323	1007	325.26	4822	1568.4
	Menji	4.97	0.375	106	39.75	4822	191.67
	Manfe	5.07	0.358	7000	2513	4822	12117.68
	Akwaya	4.76	0.383	488	186.904	4822	901.23
	Kumba	4.28	0.323	3105	1003	4822	4836.46
	Mundemba	4.28	0.323	1557	503	4822	2425.46
N-West	Bamenda	4.97	0.375	1747	655.12	4822	3159
	Fundong	5.25	0.397	7000	2779	4822	13400
	Benakuma	5.07	0.383	1050	402.15	4822	1939.16
	Mbengwi	5.25	0.397	1792	711.42	4822	3430.46
	Njikwa	5.07	0.383	685	262.35	4822	1265.05
	Ndop	5.25	0.397	1126	447	4822	2155.43

The power production capacity and the output power production has been calculated for ogni square meter for all the cities. Knowing the number of hours of availability of wind speed per year, it has been calculated the annual energy capacity and the annual energy production. The basics power stages of wind conversion system are shown in Fig.3.9. The hourly output wind power P_w (W) available in a cross sectional area A perpendicular to a wind stream moving at a speed of v (m/s) having air density ρ (kg/m^3) is expressed as

$$P_w(t) = \frac{1}{2}\rho.Av^3(t) \tag{3.6}$$

This instantaneous wind power is converted to mechanical power P_m (W) through the wind turbine, which is given by

$$P_m = C_p P_w \tag{3.7}$$

where, C_p is the power coefficient of the wind turbine (%).

This mechanical power is then transformed to transmission power P_t (W) system (gear, etc) given by

$$P_t = \eta_m P_m \tag{3.8}$$

where, η_m is the transmission efficiency [%].

This transmission power is converted to electrical power P_e [W] through the generator given by

$$P_e = \eta_g P_t \tag{3.9}$$

where, η_g is the generator efficiency [%].

Figure 3.9: Basic power stages of wind energy conversion system

For the present work, the power output from wind has been calculated by the follwing formulas

$$P_{wind}(t) = \frac{1}{2}\rho Av^3(t) \tag{3.10}$$

Here P_{wind} (W) is the hourly output wind power, A (m^2) is the area section of the rotor of the wind turbine, v (m/s) the wind speed of the air and ρ (kg/m^3) the air density. The swept area of the wind turbine and the air density considered for the output power calculation are respectively 1 m^2 and 1.225 kg/m^3.

The daily wind energy production DE_{wind}(Wh/day) is

$$DE_{wind} = \sum_{t=1}^{24} P_{wind}(t) \tag{3.11}$$

here, 24 represents the total number of hour per day. But in this particular case, 8 hours is the number of hours of wind speed disposition in Cameroon [136]

The yearly wind energy production YE_{wind}(Wh/year) is

$$YE_{wind} = \sum_{t=1}^{8760} P_{wind}(t) \tag{3.12}$$

here, 8760 represents the total number of hours per year.

The data has been assessed by the ISS Maroua Cameroon and has been elaborated and shown in Table 3.3.

Table 3.3: Hourly power production, yearly wind output power production and potential

Regions	Cities	$Speed$ [m/s]	P_{wind} [W/m^2]	P_{Output} [W]	$Nb-H$ [Hrs/yr]	YE_{wind} [kWh/m^2/yr]	AEP [MWh/yr]
Far North	Maroua	5	75.6	514.4	5293	537.4	3.65
	Kousserie	5.3	89.6	609.6	5830	721.2	4.9
	Blangoua	5.2	84.2	572.2	5685	652	4.43
	Yagoua	5.01	77	523.8	5373	558	3.79
	Kalfou	5	75.6	514.4	5293	537.4	3.65
	Mora	5.1	80.8	549.2	5484	604.3	4.1
	Mokolo	4.9	72.2	490	5160	496.6	3.37
North	Garoua	4.8	67	455	4916	429.3	2.92
	Poli	4.63	60.8	413.4	4647	363.6	2.46
	Tchollire	4.7	62.4	424.2	4711	379	2.57
	Touboro	4.6	58.8	400.1	4513	336	2.28
	Pitoa	4.8	70	455	4916	336	2.92
Adamawa	Ngaoundere	4.54	57.3	389.7	4444	321.4	2.18
	Belel	4.6	58.5	397.5	4495	332.5	2.26
	Ngaoundal	4.6	58.5	397.5	4366	322.6	2.19
	Tibati	4.56	58.1	395	4349	318.6	2.16
	Tignere	4.53	57	387.2	4401	314.1	2.13
	Banyo	4.24	46.7	317.5	3471	194.3	1.32
	Meiganga	4.6	58.5	397.5	4366	322.6	2.19
Littoral	Ngambe	4.6	59.6	405.4	4493	343.5	2.33

The data shown in Table 3.4, has been assessed from NASA sotware and been elaborated . The data shown in Table 3.6, have been received from the ISS Maroua Cameroon and hves been elaborated .

3.6 Results obtained and discussions

It can be noticed that moving from the North to the South of the country, the average means wind speed decreases while, the average means daily solar radiation is seen to be uniform across the country (see Fig.3.3). In Table 3.4, it has been represented the monthly means average of solar radiation, while in Table 3.6, the monthly means average wind speed of all the specified sites. It can be noticed that in the Far North region, all the cities have an average means wind speed which varies from 4 to 4.8 m/s from December to May which corresponds with the dry season, from June to November, the average means wind speed varies from 2.8 to 4 m/s which corresponds to rainy season. In the North region, from November to June, the average means wind speed varies from 3.2 to 4.3 m/s While, it's varies from 2.6 to 3 m/s from July to October. In the Adamawa region, the average means wind speed from November to June varies from 3 to 3.9 m/s while, from July to October varies from 2.4 to 3 m/s. In the Centre region, from January to March and from June to September, the average means wind speed varies from 1.7 to 3.8 m/s while, varies from 1.3 to 1.6 m/s from October to December and from April to May. In the Littoral region, the average means wind speed varies from 1.8 to 3.4 m/s from January to March and from 1.5 to 2.7 m/s from April to June. While, from July to September and from October to December, varies respectively from 1.8 to 1.6 m/s and from 1.4 to 3.1 m/s. In the South region, from January to March and from April to July, the average means wind speed varies respectively from 1.4 to 1.9 m/s and from 1.2 to 1.8 m/s while, varies from 1.6 to 2.5 m/s from August to September and from 1.2 to 1.3 m/s from October to December. In the East region, the average means wind speed from January to April varies from 2.2 to 3.1 m/s while, from May to December varies from 1.4 to 2.8 m/s. In the West region, from January to August, the average means wind speed varies from 1.7 to 2.5 m/s while, varies from 1.4 to 2.3 m/s from September to December. In the South West region, the average means wind speed varies from 1.8 to 2.4 m/s and from 1.6 to 2.2 m/s respectively from January to March and from April to May while, from June to September and from October to December, varies respectively from 1.8 to 2.9 m/s and from 1.4 to 1.9 m/s. In the North West region, from January to September, the average means wind speed in all the cities varies from 1.9 to 2.6 m/s while, varies from 1.6 to 2.3 m/s from October to December. It can be observed that, the wind speeds are higher during the dry season as supposed to be and low wind speeds during the rain season. These monthly and annual solar radiation values fall within the range 3-6 kWh/m^2/d which have been used in the implementation of photovoltaic systems in most remote applications around the world [137]. From elaborations and calculations made on solar radiation, the hourly means output power capacity are 440.5 W/^{2}, 435 W/^{2}, 424/^{2} W, 377 W/^{2}, 357 W/^{2}, 353 W/^{2}, 379 W/^{2}, 375 W/^{2}, 377 W/^{2}, 383 W/^{2} and the yearly means energy production are 2124 kWhm/^{2}/yr, 2098 kWh/m^2/yr, 2044 kWh/m^2/yr, 1818 kWh/^{2}/yr, 1721 kWh/^{2}/yr, 1702 kWh/^{2}/yr, 1827 kWh/^{2}/yr, 1808 kWh/^{2}/yr, 1818 kWh/^{2}/yr, and 1846 kWh/^{2}/yr respectively for Far North, North, Adamawa, Centre, Littoral, South, East, West, South West and Nord West regions (see Table 3.8). Following the same goal, from wind speed, the means power production per square meter is 79.3 W/^{2}, 63.8 W/^{2}, 56.37/^{2} W, 59.6 W/^{2} and the yearly means energy production is 440.115 kWh/^{2}/yr, 303.05 kWh/^{2}/yr, 250.84 kWh/^{2}/yr, 267.78 kWh/^{2}/yr respectively for Far North, North, Adamawa, Littoral regions (see Table 3.8). The power and the energy output from wind generator is not seen to be small because we considered in this study a 1 m^2 swept area of the wind turbine. It would increased considerably if all the swept area of the wind turbine increases. The daily and yearly power production by square meter assessed in the cities with the example of Maroua shown in Fig.3.10, 3.11 demonstrates the complementarity between solar and wind.

Table 3.4: Monthly means solar radiation in Cameroon [kWh/m^2/day]

Cities	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Maroua	5.61	6.24	6.56	6.31	5.96	5.5	5.03	4.85	5.34	5.7	5.85	5.56
Kousserie	5.25	5.92	6.67	6.73	6.54	6.19	5.54	5.31	5.54	5.52	5.24	4.87
Blangoua	5.15	5.46	5.85	6.19	6.2	5.77	5.77	5.03	5.27	5.29	5.17	4.87
Yagoua	5.71	6.3	6.62	6.33	6.03	5.58	5.04	4.87	5.35	5.79	5.91	5.65
Kalfou	5.61	6.24	6.56	6.31	5.96	5.5	5.03	4.85	5.34	5.7	5.85	5.56
Mora	5.59	6.29	6.67	6.56	6.29	5.86	5.27	4.98	5.52	5.77	5.74	5.35
Mokolo	5.94	6.36	6.55	6.24	5.87	5.42	4.98	4.75	5.23	5.71	6.09	5.82
Garoua	6.07	6.36	6.5	6.24	5.78	5.37	4.94	4.83	5.16	5.7	6.17	5.93
Poli	6.28	6.54	6.51	6.1	5.65	5.3	4.89	4.78	5.09	5.66	6.21	6
Tchollire	6.23	6.54	6.51	6.16	5.67	5.26	4.92	4.81	5.12	5.6	5.17	5.99
Touboro	6.45	6.78	6.54	5.91	5.5	5.12	4.75	4.68	5.06	5.4	6.19	6.27
Pitoa	6.07	6.36	6.5	6.24	5.78	5.37	4.94	4.83	5.16	5.7	6.17	5.93
Ngaoundere	6.48	6.74	6.53	5.83	5.42	5.02	4.67	4.66	4.85	5.25	6.16	6.27
Belel	6.44	6.75	6.5	5.69	5.33	4.95	4.56	4.54	4.86	5.19	6.16	6.26
Ngaoundal	6.44	6.67	6.35	5.79	5.39	5.07	4.64	4.76	4.96	5.05	5.95	6.29
Tibati	6.45	6.64	6.32	5.75	5.51	5.13	4.71	4.79	5.04	5.19	5.96	6.26
Tignere	6.42	6.65	6.41	5.75	5.4	4.98	4.63	4.6	4.82	5.18	6.09	6.23
Banyo	6.43	6.57	6.05	5.51	5.29	4.87	4.43	4.47	4.71	4.96	5.85	6.17
Meiganga	6.5	6.76	6.33	5.67	5.25	4.89	4.59	4.63	4.9	4.93	5.93	6.31
Yaounde	5.43	5.49	5.2	4.97	4.65	4.26	4	3.98	4.27	4.14	4.56	5.12
Bot-Makak	5.31	5.36	5.07	4.88	4.58	4.01	3.53	3.35	3.69	3.86	4.46	5.04
Nanga-Eboko	5.81	5.95	5.55	5.19	4.82	4.48	4.38	4.5	4.75	4.6	5.02	5.5
Obala	5.73	5.86	5.45	5.19	4.94	4.61	4.33	4.37	4.63	4.55	4.97	4.46
Makenene	5.6	5.6	5.18	4.95	4.75	4.35	3.91	3.74	4.1	4.18	4.67	5.28
Ntui	5.73	5.86	5.45	5.19	4.94	4.61	4.33	4.37	4.63	4.55	4.97	5.46
Yoko	6.25	6.39	5.91	5.46	5.16	4.75	4.53	4.66	4.84	4.9	5.54	5.98
Mfou	5.43	5.49	5.2	4.97	4.65	4.26	4	3.98	4.27	4.14	4.56	5.12
Nkolmetet	5.31	5.36	5.07	4.88	4.58	4.01	3.53	3.35	3.69	3.86	4.46	5.04
Akonolinga	5.5	5.64	5.33	5.11	4.71	4.4	4.28	4.26	4.48	4.4	4.68	5.16
Douala	5.41	5.36	4.88	4.55	4.37	3.91	3.41	3.04	3.44	3.7	4.3	5.05
Edea	5.31	5.36	5.07	4.88	5.58	4.01	3.53	3.35	3.69	3.89	4.46	5.04
Ngambe	5.84	6.01	5.67	5.4	4.62	3.78	3.93	4.66	4.53	5	5.58	5.65
Mouanko	5.41	5.49	4.99	4.81	4.5	3.81	3.48	3.45	3.61	3.79	4.44	5.12
Nkongsamba	5.41	5.36	4.88	4.55	4.37	3.91	3.41	3.04	3.44	3.7	4.3	5.05
Melong	5.81	5.77	5.35	4.99	4.68	4.32	3.86	3.58	4.09	4.32	4.88	5.48
Yabassi	5.41	5.36	4.88	4.55	4.37	3.91	3.41	3.04	3.44	3.7	4.3	5.05
Yimgui	5.6	5.6	5.18	4.95	4.75	4.35	3.91	3.74	4.1	4.18	4.67	5.28
Ebolowa	5.3	5.36	5.19	4.94	4.61	4.25	4.16	4.04	4.27	4.18	4.39	4.97
Ngoulemakong	5.43	5.49	5.2	4.97	4.65	4.26	4	3.98	4.27	4.14	4.56	4.12
Djoum	5.3	5.45	5.21	4.99	4.6	4.29	4.24	4.18	4.48	4.33	4.42	4.94
Sangmelima	5.3	5.36	5.19	4.94	4.61	4.25	4.16	4.04	4.27	4.18	4.39	4.97
Zoetele	5.43	5.49	5.2	4.97	4.65	4.26	4	3.98	4.27	4.14	4.56	5.12
Kribi	5.41	5.57	5.2	4.92	4.51	3.9	3.94	3.98	3.82	3.82	4.7	5.11
Lolodorf	5.31	5.36	5.07	4.88	4.58	4.01	3.53	3.35	3.69	3.89	4.46	5.04
Ambam	5.3	5.6	5.19	4.94	4.61	4.25	4.16	4.04	4.27	4.18	4.39	4.97
Ma'an	5.12	5.13	4.92	4.65	4.34	4	3.91	3.71	3.77	3.71	4.14	4.78

Table 3.5: it continues from Table 3.4

Cities	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Bertoua	5.86	6.01	5.6	5.29	4.83	4.36	4.2	4.35	4.62	4.56	5.04	5.54
Garoua-Boulai	6.34	6.42	5.89	5.5	5.07	4.69	4.39	4.5	4.78	4.8	4.58	6.06
Yokadouma	5.87	5.86	5.51	5.32	4.9	4.5	4.34	4.25	4.56	4.54	4.92	5.59
Moloundou	5.62	5.62	5.37	5.27	4.84	4.43	4.36	4.24	4.45	4.4	4.62	5.29
Abong-Mbang	5.49	5.64	5.3	5.16	4.69	4.25	4.19	4.22	4.46	4.35	4.61	5.1
Batouri	6.03	6.1	5.65	5.45	4.94	4.53	4.24	4.33	4.66	4.66	5.15	5.72
Ouli	6.34	6.42	5.89	5.5	5.07	4.69	4.39	4.5	4.78	4.8	5.58	6.06
Bafoussam	6.14	6.19	5.5	5.01	4.83	4.42	4.02	3.92	4.21	4.39	5.21	5.76
Santchou	5.81	5.77	5.35	4.99	4.68	4.32	3.86	3.58	4.09	4.32	4.88	5.48
Bagangte	6.14	6.19	5.5	5.01	4.83	4.42	4.02	3.92	4.21	4.39	5.21	5.79
Tonga	5.6	5.6	5.18	4.95	4.75	4.35	3.91	3.74	4.1	4.18	4.67	5.28
Foumban	6.14	6.19	5.5	5.01	4.83	4.42	4.02	3.92	4.21	4.39	5.21	5.79
Magba	6.26	6.4	5.98	5.59	5.31	4.98	4.74	4.77	4.94	4.94	5.65	5.96
Buea	5.41	5.36	4.88	4.55	4.37	3.91	3.41	3.04	3.44	3.7	4.3	5.05
Bangem	5.87	5.86	5.51	5.32	4.9	4.5	4.34	4.25	4.56	4.54	4.92	5.59
Tombel	5.41	5.36	4.88	4.55	4.37	3.91	3.41	3.04	3.44	3.7	4.3	5.05
Menji	6.14	6.19	5.5	5.01	4.83	4.42	4.02	3.92	4.21	4.39	5.21	5.79
Manfe	5.81	5.77	5.35	4.99	4.68	4.32	3.86	3.58	4.09	4.32	4.88	5.48
Akwaya	5.98	6.04	5.7	5.31	4.97	4.57	4.19	4.01	4.37	4.7	5.24	5.74
Kumba	5.41	5.36	4.88	4.55	4.37	3.91	3.41	3.04	3.44	3.7	4.3	5.05
Mundemba	5.5	5.7	4.97	4.62	4.32	3.6	3.19	3.11	3.26	3.63	4.29	5.14
Bamenda	6.14	6.19	5.5	5.01	4.83	4.42	4.02	3.92	4.21	4.39	5.21	5.79
Fundong	6.3	6.35	5.83	5.34	5.07	4.62	4.29	4.27	4.48	4.74	5.65	6.08
Benakuma	5.98	6.04	5.7	5.31	4.97	4.57	4.19	4.01	4.37	4.7	5.24	5.74
Mbengwi	6.3	6.35	5.83	5.34	5.07	4.62	4.29	4.27	4.48	4.74	5.65	6.08
Njikwa	5.98	6.04	5.7	5.31	4.97	4.57	4.19	4.01	4.37	4.7	5.24	5.74
Ndop	6.3	6.35	5.83	5.34	5.07	4.62	4.29	4.27	4.48	4.74	5.65	6.08

Table 3.6: Monthly means wind speed in Cameroon [m/s]

Cities	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Maroua	4.1	4	4.4	4.6	4.2	3.5	3.2	3.1	2.8	3.2	3.8	4.3
Kousserie	4.7	4.7	4.8	4.8	4.4	3.9	3.7	3.4	3.3	3.6	4	4.6
Blangoua	4.6	4.5	4.6	4.6	4.3	3.8	3.6	3.3	3.2	3.5	3.9	4.5
Yagoua	4.2	4.1	4.4	4.7	4.3	3.6	3.3	3.1	2.9	3.3	3.9	4
Kalfou	4.1	4	4.4	4.6	4.2	3.5	3.2	3.1	2.8	3.2	3.8	4.3
Mora	4.3	4.3	4.6	4.7	4.3	3.6	3.3	3.2	2.9	3.3	3.9	4.5
Mokolo	4	3.9	4.3	4.5	4.1	3.4	3.2	3	2.8	3.1	3.7	4.2
Garoua	3.8	3.8	4.1	4.3	3.9	3.3	3	2.9	2.7	3	3.5	4
Poli	3.6	3.6	3.9	4	3.7	3.2	2.9	2.8	2.6	2.9	3.3	3.7
Tchollire	3.7	3.6	4	4.1	3.8	3.2	3	2.8	2.6	2.9	3.3	3.7
Touboro	3.5	3.5	3.8	3.9	3.6	3.2	2.9	2.8	2.6	2.8	3.2	3.6
Pitoa	3.8	3.8	4.1	4.3	3.9	3.3	3	2.9	2.7	3	3.5	4
Ngaoundere	3.4	3.4	3.7	3.9	3.6	3.1	2.9	2.8	2.6	2.8	3.2	3.5
Belel	3.4	3.5	3.8	3.9	3.6	3.2	2.9	2.8	2.6	2.8	3.2	3.6
Ngaoundal	3.2	3.3	3.6	3.7	3.6	3.2	3	2.9	2.7	2.9	3.1	3.3
Tibati	3.2	3.3	3.5	3.7	3.6	3.2	3	3	2.7	2.9	3	3.3
Tignere	3.4	3.4	3.7	3.8	3.6	3.1	2.9	2.8	2.6	2.8	3.1	3.5
Banyo	2.9	2.9	3.1	3.1	3	2.8	2.6	2.6	2.4	2.4	2.6	2.8
Meiganga	3.2	3.3	3.6	3.7	3.6	3.2	3	2.9	2.7	2.9	3.1	3.3
Yaounde	1.7	1.9	1.6	1.3	1.2	1.4	1.5	1.7	1.6	1.3	1.2	1.3
Bot-Makak	1.7	1.9	1.5	1.2	1.2	1.5	1.8	1.9	1.7	1.3	1.2	1.3
Nanga-Eboko	2.1	2.3	2.1	2	1.8	1.7	1.8	1.9	1.8	1.7	1.7	1.8
Obala	2	2.1	1.9	1.8	1.6	1.7	1.8	1.9	1.8	1.6	1.5	1.7
Makenene	1.9	2	1.7	1.5	1.4	1.7	1.8	1.9	1.8	1.4	1.4	1.5
Ntui	2	2.1	1.9	1.8	1.6	1.7	1.8	1.9	1.8	1.6	1.5	1.7
Yoko	2.8	2.9	3	3.1	3	2.7	2.6	2.6	2.4	2.5	2.6	2.7
Mfou	1.7	1.9	1.6	1.3	1.2	1.4	1.5	1.7	1.6	1.3	1.2	1.3
Nkolmetet	1.7	1.9	1.5	1.2	1.2	1.5	1.8	1.9	1.7	1.3	1.2	1.3
Akonolinga	1.7	1.9	1.6	1.4	1.2	1.2	1.3	1.5	1.5	1.3	1.2	1.4
Douala	1.9	2	1.8	1.5	1.5	1.8	2.1	2.2	2	1.6	1.4	1.6
Edea	1.7	1.9	1.5	1.2	1.2	1.5	1.8	1.9	1.7	1.3	1.2	1.3
Ngambe	3.3	3.4	3.1	2.7	2.6	3.4	4.1	4.1	3.8	3.1	2.7	3.1
Mouanko	1.9	2	1.6	1.4	1.4	1.9	2.3	2.4	2.2	1.6	1.4	1.5
Nkongsamba	1.9	2	1.8	1.5	1.5	1.8	2.1	2.2	2	1.6	1.4	1.5
Melong	2	2	1.9	1.6	1.6	1.9	1.9	2	1.8	1.5	1.6	1.6
Yabassi	1.9	2	1.8	1.5	1.5	1.8	2.1	2.2	2	1.6	1.4	1.6
Yimgui	1.9	2	1.7	1.5	1.4	1.7	1.8	1.9	1.8	1.4	1.4	1.5
Ebolowa	1.6	1.8	1.5	1.2	1.2	1.3	1.5	1.7	1.6	1.3	1.2	1.3
Ngoulemakong	1.7	1.9	1.6	1.3	1.2	1.4	1.5	1.7	1.6	1.3	1.2	1.3
Djoum	1.6	1.7	1.6	1.4	1.1	1.1	1.3	1.5	1.5	1.3	1.2	1.3
Sangmelima	1.6	1.8	1.5	1.2	1.2	1.3	1.5	1.7	1.6	1.3	1.2	1.3
Zoetele	1.7	1.9	1.6	1.3	1.2	1.4	1.5	1.7	1.6	1.3	1.2	1.3
Kribi	1.8	2	1.5	1.3	1.4	1.9	2.3	2.5	2.2	1.7	1.5	1.5
Lolodorf	1.7	1.9	1.5	1.2	1.2	1.5	1.8	1.9	1.7	1.3	1.2	1.3
Ambam	1.6	1.8	1.5	1.2	1.2	1.3	1.5	1.7	1.6	1.3	1.2	1.3
Ma'an	1.6	1.8	1.4	1.1	1.2	1.5	1.8	1.9	1.8	1.4	1.2	1.3

Table 3.7: it continues from Table 3.6

Cities	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Bertoua	2.2	2.4	2.2	2.1	1.9	1.8	1.8	1.8	1.8	1.7	1.7	1.9
Garoua-Boulai	2.8	3	3.1	3.2	3	2.8	2.6	2.6	2.4	2.5	2.6	2.8
Yokadouma	2	2.3	2.1	1.9	1.6	1.5	1.4	1.4	1.5	1.3	1.4	1.6
Moloundou	1.9	2.2	2	1.7	1.4	1.3	1.3	1.4	1.4	1.2	1.2	1.4
Abong-Mbang	1.9	2	1.8	1.6	1.3	1.2	1.3	1.4	1.4	1.3	1.2	1.4
Batouri	2.3	2.5	2.4	2.2	1.9	1.8	1.8	1.8	1.7	1.6	1.7	1.9
Ouli	2.8	3	3.1	3.2	3	2.8	2.6	2.6	2.4	2.5	2.6	2.8
Bafoussam	2.1	2.2	2.1	1.9	1.8	2	1.9	2	1.8	1.6	1.7	1.8
Santchou	2	2	1.9	1.6	1.6	1.9	1.9	2	1.8	1.5	1.6	1.6
Bagangte	2.1	2.2	2.1	1.9	1.8	2	1.9	2	1.8	1.6	1.7	1.8
Tonga	1.9	2	1.7	1.5	1.4	1.7	1.8	1.9	1.8	1.4	1.4	1.5
Foumban	2.1	2.2	2.1	1.9	1.8	2	1.9	2	1.8	1.6	1.7	1.8
Magba	2.4	2.5	2.5	2.5	2.4	2.4	2.3	2.3	2.1	2	2.1	2.3
Buea	1.9	2	1.8	1.5	1.5	1.8	2.1	2.2	2	1.6	1.4	1.6
Bangem	2	2.3	2.1	1.9	1.6	1.5	1.4	1.4	1.5	1.3	1.4	1.6
Tombel	1.9	2	1.8	1.5	1.5	1.8	2.1	2.2	2	1.6	1.4	1.6
Menji	2.1	2.2	2.1	1.9	1.8	2	1.9	2	1.8	1.6	1.7	1.8
Manfe	2	2	1.9	1.6	1.6	1.9	1.9	2	1.8	1.5	1.6	1.6
Akwaya	2.3	2.3	2.3	2.1	2.1	2.1	2	2.1	1.9	1.7	1.9	2
Kumba	1.9	2	1.8	1.5	1.5	1.8	2.1	2.2	2	1.6	1.4	1.6
Mundemba	2.2	2.4	2.1	1.7	1.7	2.2	2.8	2.9	2.6	2	1.7	1.9
Bamenda	2.1	2.2	2.1	1.9	1.8	2	1.9	2	1.8	1.6	1.7	1.8
Fundong	2.5	2.5	2.6	2.5	2.4	2.3	2.1	2.2	2	1.9	2.2	2.3
Benakuma	2.3	2.3	2.3	2.1	2.1	2.1	2	2.1	1.9	1.7	1.9	2
Mbengwi	2.5	2.5	2.6	2.5	2.4	2.3	2.1	2.2	2	1.9	2.2	2.3
Njikwa	2.3	2.3	2.3	2.1	2.1	2.1	2	2.1	1.9	1.7	1.9	2
Ndop	2.5	2.5	2.6	2.5	2.4	2.3	2.1	2.2	2	1.9	2.2	2.3

3.7 Conclusion

The study carried out can concluded that the Northern regions (Far North, North and Adamawa) of Cameroon have the highest wind potential. This potential decreases towards the Southern regions. It can be noticed that even in the Southern regions (Centre, Littoral, South, East, West, South West, North West), there are some cities which experiences a good wind speed range. In the Centre region, we can notice the town of Yoko which has an average wind speed range of 2.4-3.1 m/s. In the Littoral region, we can talk about Ngambe which has an average wind speed range of 2.6-4.1 m/s. In the South region, kribi experiences an average wind speed range of 1.4-2.5 m/s. In the East region, the town of Ouli and Garoua-Boulai which experience an average wind speed of 2.4-3.2 m/s. In the West region, the town of Magba experiences an

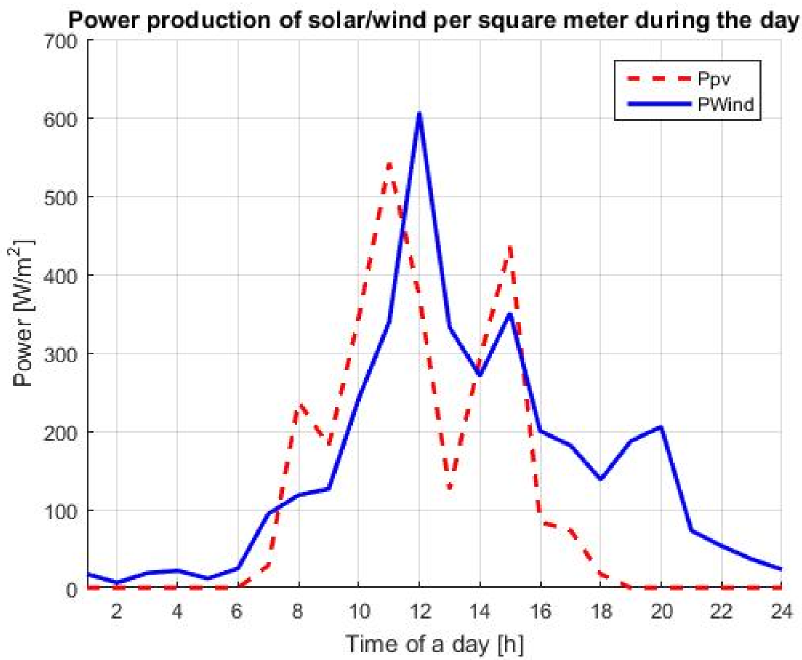

Figure 3.10: Daily power production from solar and wind energy per square meter (see Tables 3.1,3.3)

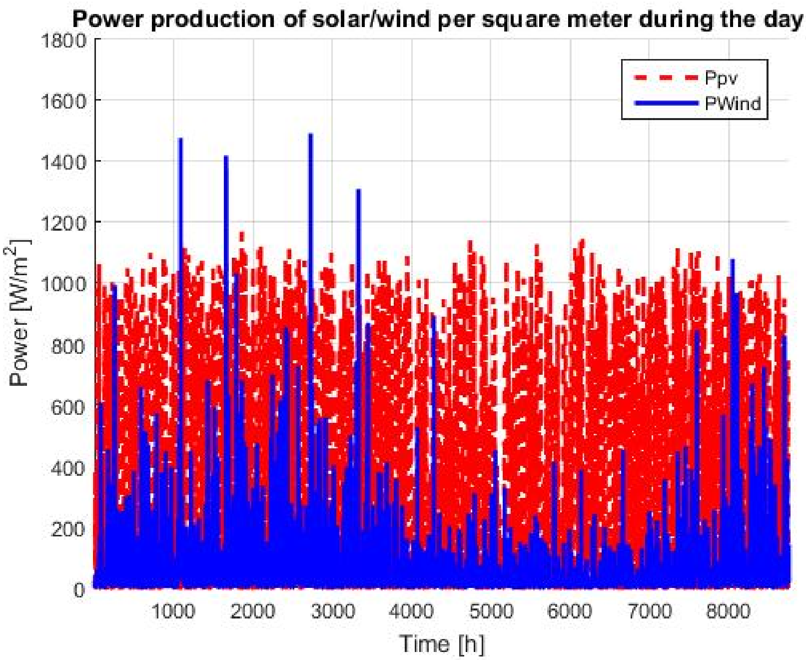

Figure 3.11: Yearly power production from solar and wind energy per square meter (see Tables 3.1,3.3)

Table 3.8: Summary of photovoltaic and wind daily output power and yearly energy production

Regions	P_{PV} [W/m^2]	$Nb-H$ [Hrs/yr]	AEP_{PV} [kWh/m^2/yr]	P_{Wind} [W/m^2]	$Nb-H$ [Hrs/yr]	AEP_{Wind} [kWh/m^2/yr]
Far North	440.5	4822	2124	79.3	5550	440.115
North	435	4822	2097.57	63.8	4750	303.05
Adamawa	424	4822	2044.52	56.37	4450	250.84
Centre	377	4822	1818	-	-	-
Littoral	357	4822	1721.45	59.6	4493	267.78
South	353	4822	1702.16	-	-	-
East	379	4822	1827.53	-	-	-
West	375	4822	1808.25	-	-	-
South West	377	4822	1818	-	-	-
North West	383	4822	1846.82	-	-	-

average wind speed range of 2-2.5 m/s. In the South West region, the town of Akwaya which experiences wind speed in the range of 1.7-2.3 m/s. While in the North West region, Ndop and Fundong specially with all the region experience an average wind speed range of 2-2.6 m/s. The means yearly energy production from solar radiation (2078 kWh) and from wind speed (520 kWh) can easily supply a number of households load demand when it is known that a typical rural household in Cameroon is composed by 3 persons living in a two rooms appartment, the load is composed by two incadescent lamps in two rooms, a fluoriscent lamp outdoor for security and a radio [37] and have an annual energy demand load of 70 kWh which equal to 0.2 kWh/day. This particular study concluded that not only the Northern regions of Cameroon have the highest wind potential, but also the North West and some towns in another regions. The study also demonstrates the complementarity between solar and wind energy. While these results reflect a general trend, it is important to conduct field studies in the substantial number of sites in order to further estimate with accuracy the potential of solar and wind energy in Cameroon.

3.8 Published papers:

1. M. Pendieu Kwaye, J. Bendfeld, N. Anglani. Assessment of Renewable Energy Resources in Cameroon and Special Regards on Energy Supply IEEE International Youth Conference on Energy, (IYCE) 2015, Pisa, Italy. Pages: 1-7.

4 Hydro power and compensation of fluctuating non-dispatchable sources in Cameroon

In the previous chapter 3, the solar radiation and wind speed in Cameroon have been assessed to have an overview on output power production potentials accross the country. The stochastic and the fluctuating behaviour of solar and wind energy restrict the exclusively used of these sources for load supply, without any backup in any particular site. The use of solar and wind energy sources could operate with autonomous hydro power plants in complementarity to supply the load all the time.

4.1 Introduction

The common renewable energy resources in Cameroon are: hydro, wind, solar energy and biomass (i.e. wood chips, coffee/cocoa chips, pellets). Despite of the great potential, the development in the energy sector has been limited. The non electrification of rural areas is due to the high cost of grid connection, the large losses associated with the transmission and distribution networks, the dispersion of the population, the difficult access by road, the geographical access of the local areas just to cite a few. A solution to this problem can be the decentralization of the electrical production and the choice of hybrid micro-grids (solar/wind/hydro) with the objectives of making local areas being autonomous which can contribute to higher access of development. In this chapter, hydro power compensation is proposed to help increasing the electrification and power quality in rural areas in Cameroon due to the fluctuation, insufficient or unavailability of solar or wind power or both of them. It is organized as follows: Section 4.2 relays relevant works on complementarities between hydro and renewable sources. In Section 4.3, the principles instruments to characterized an hydro power plant are given. Section 4.4, deals with the advantages and disavantages of distributed small hydro plants and huge hydro plants. Section 4.5 deals with the status of hydro power system in Cameroon. Section 4.6 explores complementarity between fluctuation sources (solar and wind) with hydro power with a demonstratif case study. Section 4.7 discusses the result obtained in durind the study. In section 4.8 , conclusions are drawn.

4.2 State of art

This section relays relevant works on hybrid system composed by hydro power plant combined with photovoltaic system, wind farms either both solar and wind sources or other generating sources. In [74] the authors analyze optimization and modeling of a hybrid energy system for off-grid electrification in the town of Randhunibari in Bangladesh. The hybrid system scheme proposed is composed by: a photovoltaic array, a small hydro power, the battery and the conventional diesel generator for the backup. The hybrid optimization model for renewable energy (HOMER) software is used for the design and economical optimization of the hybrid system. The model of the photovoltaic array, the hydro turbine, the battery, the diesel generator and the power converter has being modeled and simulated in MATLAB simulink environment. In [99] the authors analyze and simulate a Pico-hydro and photovoltaic hybrid systems, incorporating a bio-gas generator and battery storage systems for the electrification of remote villages in Cameroon with an energy demand of 73 kWh/day and 8.3 kWp photovoltaic generation system. The authors analysis and simulate two different types of hybrid systems: S1 (Pico-hydro/Bio-gas generator/battery systems); S2 (Photovoltaic/Bio-gas generator/battery systems). The results show that off-grid electrification can be met with renewable energy options that include bio-gas generators with local production of bio-gas coming from animal and/or human waste that could be a suitable alternative for rural electrification in Cameroon. The micro-hydro hybrid system proved to be the cheapest option for villages located in the southern parts of Cameroon with a flow rate of at least 200 l/s, while the photovoltaic hybrid system is the cheapest option for villages in the northern parts of Cameroon which have at least 5.55 kWh/m2/day of solar radiation level. A study is carried out on hybrid energy system composed by various renewables (solar and wind), a micro-hydro power, battery and fuel generator for electricity supply in in remote area in India. The optimization is performed using HOMER software with the objectif of minimizing the fuel consumption while, supplying the demand load at any time at the lowest energy cost [138]. In [11] the authors simulate an off-grid generation options for remote villages in Cameroon using a load of 110kWh/day and 12kWp photovoltaic generation system. The authors simulate four types of hybrid systems: S1 (Micro Hydro/Waste Gasification turbine/battery); S2 (Micro Hydro/Diesel/battery); S3 (Photovoltaic/Waste Gasification turbine/battery); S4 (Photovoltaic/Diesel/battery). The energy costs of the proposed options is simulated using HOMER (Hybrid optimization model for renewable energy), a typical village load profile, the solar resource of

Garoua in the Far North province and the flow patterns of river Mungo in the Littoral and South West provinces. The result of the study shows that, the cost of the energy offered by option S1 is cheaper than option S2 for villages in the Southern parts of the country that possess the exploited flow, while, the option S3 is more economical than option S4 for villages in the northern parts of the country which have at least 5.55 kWh/m2/day of the solar radiation level.In [55] the authors demonstrate the feasibility of a hybrid renewable energy system composed by photovoltaic, wind and hydro energy system for remote electrification area. The authors introduced two hybridizing techniques for integrating photovoltaic, wind and hydro power into mini-grid. One of the techniques is implemented to connect the hybrid photovoltaic-wind system to the hybrid charger controller and the second hybrid photovoltaic-wind to the hydro dominant system via mini-grid connecting the Thingan and Kolkhop villages District in Nepal. A theoretical analysis on compensation of fluctuating wind energy generation with hydro power plant has been carried-out in mexico. The levelized cost of energy is obtained using two different dicount rates. The study concludes that hydro power can easily compensate the the fluctuation effect of wind energy and supply the load continuously without faillure [139]. The hydro power energy is used to compensate the fluctuating wind energy in a context of global energy balance and good strategy planning on energy options [140]. In [141] the authors apply the global information system (GIS) model on wind available database to evaluate a long-term wind power incentive program in Brazil. The optimization of the hydro power plants operation could be fulfilled by the compensation of wind sources. In fact, the low flow rate level of the river correspond to the period of largest wind speeds. Ref. [142] analysis the complementarity between wind farms and hydro power plants in Southeastern of Brazil. The fluctuating aspect of wind energy and the seasonal fluctuation of hydrology occurring in different temporality can mutually be compensated so that the load could be allways supplied. In [143] a feasible study has been carried-out in the state of Minas Gerais in Brazil on complementarities of solar and wind generators with hydro power plants. Considering the hydrology fluctuating and the fluctuating behaviour of solar and wind energy, the hydro power plants or the solar and wind generators when, working alone could not fulfilled the seasonal electrical energy supply but working together in complementarity hydro/solar-wind, would satisfied the seasonal stabilisation of electrical energy supply demand. A feasility study is carry out to demonstrate the seasonal stabilisation in energy supply in interconnected Brazilian grid. The large wind resources availability can easily complemented the hydro electrical power generation for better electricity supply [144]. In [80] a feasible study is carried-out on small scale hydro, solar and wind power for electricity supply in six rural areas in Ethiopia. The hydro power potentials is obtained using the global information system (GIS) model while, data from solar and wind are obtained from NASA meteorological software. The data obtained from NASA software has been used for solar and wing energy potentials estimation. The HOMER software optimization tool has been used for the sizing and the cost estimation of the energy. [145] also carry a feasibility study on complementarities on wind and hydro power system for low cost energy in Ikaria island in Greece. The optimization is performed by monte carlo simulation program. The study reveals that the load cannot be allways supplied without loss of load. Thus, the opportunity to have a fuel generator for backup in case of faillure. An energy management strategy is applied for wind farms and hydro power plants combination to Aegean Sea island in Greece. The wind hydro system will replaced fuel generators with two objectives: (i) maximization of the autonomous energy and (ii) the installation minimization cost. Here, the excess of energy fron wind farms is used for water desalination and clean water production. [146]

4.3 Basic principles of hydro power generation

When a hydro power plant station location is known, the following main items should be considered carefully:

- Potential power of the river or river section selected. Any section for which this value is reasonably constant can be characterized by the mean value.
- Geographic situation of the existing and projected water and other power plants along with the transmission network.
- Nature of power demand or predicted future power demand of the location where the hydro power plant would be installed.
- Topographical conditions of the river valley and the stream bed play an important role in deciding upon the types and location of the plant.
- The geology of the site will greatly influenced the general layout.
- Existing hydraulic developments and structures : power plants, weirs, flood protection embankments, pumping stations, irrigation works, etc... cannot be neglected either.
- Consideration should be given in addition to the prevailing situation to future trends of development as well.
- Reservoir capacity should be taken in consideration when designing the low-head plants, since operation of downstream plants benefits from the ensuing regulation.

- A significant reduction of cost of the hydro-electric power could resulted from multipurpose utlisation (irrigation, navigation, domestic and industrial water supply, etc.)
- Great capacity storage reservoirs can usually be developed on steep upper sections of the river valley and in valleys of tributaries. The water stored in these reservoirs of relatively great capacity (seasonal, annual, over-year storage) not only aliment the high head plant immediately supplied, but also a favorable effect on the flow in the whole downstream section, as mentioned above.

Only great capacity storage reservoirs are capable to control the sections downstream flow. If the plant having sufficient storage, capacity operates in daily peak loads periods, i.e. intermittently, a downstream regulating reservoir should be constructed, in order.

- to protect the bed and banks of the river against detrimental effects of surge waves,
- to protect navigation on the river downstream and
- to ensure uniform water supply for the downstream plants.

4.3.1 Measurement of power potential

The first step is to determine the hydro potential of water flowing from the river or stream. You will need to know the flow rate of the water and the head through which the water can fall, as defined in the following:

- The flow rate is the quantity of water flowing past a point at a given time. Typical units used for flow rate are cubic metres per second (m^3/s), litres per second (l/s), gallons per minute (gal/m) and cubic feet per minute (cf/m). The commonly used techniques for measuring stream flow rate are: container method; float method; weir method; salt and conductivity meter method and current meter method.
- The head is the vertical height in metres (m) or feet (ft.) from the level where the water enters the intake pipe (penstock) to the level where the water leaves the turbine housing(see Fig.4.1)

The flow measured at a certain time of the year has to be related to the annual flow characteristics (hydrograph). If measured in (extreme) dry season you may refer to this flow as $safe\ flow$ of the future plant. Hydrograph data may be available from gauging stations. The hydrograph data is evaluated in the flow duration curve (365 days equal to 100%).(see Fig.4.3)

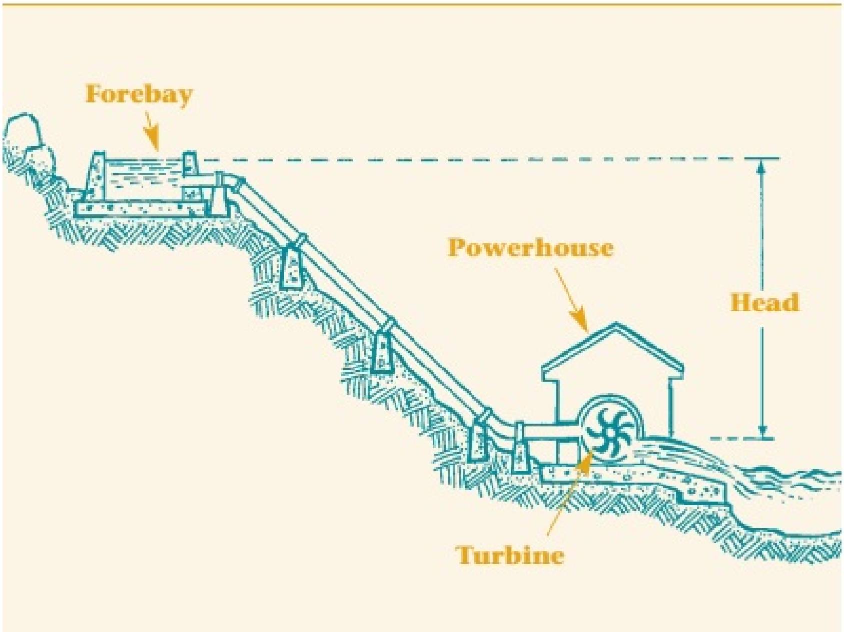

Figure 4.1: Head of a micro-hydropower [8]

The flow duration curve (FDC) is a way to show the probability in graph form of how many days in a year a particular flow will be exceeded. (The area below the curve is a measure of the energy potential of the river or stream.) (see Fig.4.2)

Power calculation

The amount of power available from a hydro power system is directly related to the flow rate, head and the force of gravity. Once you have determined the usable flow rate (the amount of flow you can divert for power generation) and the available head for your particular site, you can calculate the amount of electrical power you can expect to generate. This is calculated using the following equation:

$$P_{th} = \rho * g * Q * H \tag{4.1}$$

where:
ρ = density of water (1000 kg/m^3)
P_{th}= Theoretical power output (W)
Q = The flow rate (m^3/s)

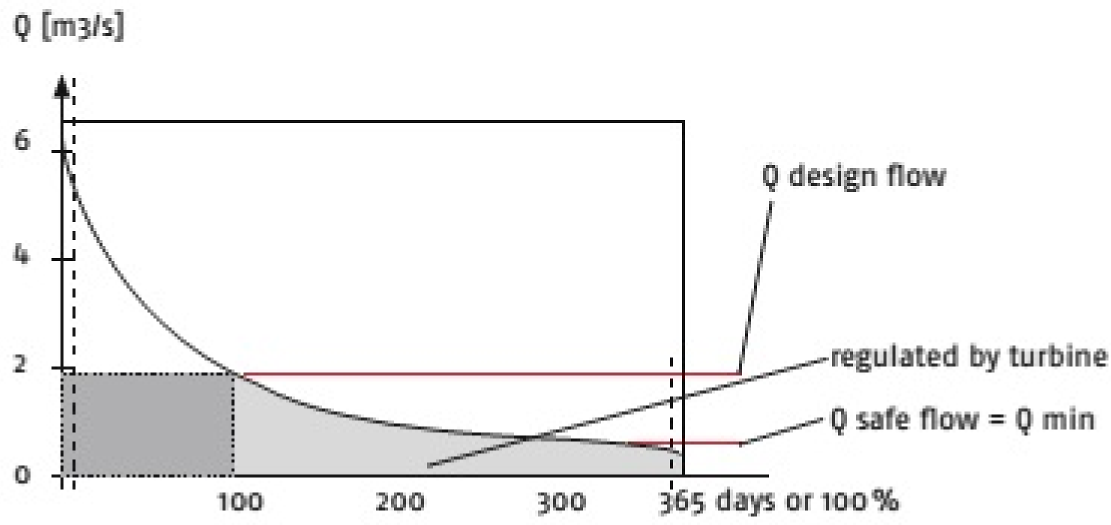

Figure 4.2: Flow duration curve [9]

H = The gross head (m)
g = The gravitational constant (9.81 m/s^2)
P_{th} is only the theoretical available power, assuming that 100 percent of the power available in the water can be usefully converted. Efficiency of the system also needs to be taken into account. Energy is always lost when converted from one form to another, and all of the equipment used to convert the power available in the flowing water to electrical power is less than 100 percent efficient. To calculate the most realistic power output from your site, you must take into account the friction losses in the penstock pipes and the efficiency of the turbine and generator. When determining the head, you will need to consider gross head and net head. Gross head is the vertical distance between the top of the penstock that conveys the water under pressure and the point where the water discharges from the turbine. Net head is the available head after subtracting the head loss due to friction in the penstock from the total (gross) head (net head = gross head - losses in the penstock).

Therefore, to determine a realistic power output, the theoretical power must be multiplied by the overall efficiency η_t.

$$P = \rho * g * Q * H * \eta_t \tag{4.2}$$

here
P= Output power of the hydro power plant (W)

η_t is the overall electricity efficiency, which depend on kind of turbine, generator, transformer, etc.(%).

4.3.2 Definition, use, classification and characteristics

It is often necessary to know well the mode of the river (dry season, wet season) for the dimensioning of the turbines and the control of the production.

The hydro power plant can contribute to the inter-connected grid with other power stations, but it can also be used in isolated grid to provide electricity necessary to a village, a city, a small city, an industry far away from the lines of interconnections of the principal grid.

The hydro power plant can be classified into four categories: (i) the size (pico, micro, mini, small, big) with the limites in classification which vary from a country to another, (ii) the storage capacity (run-of-river or reservoir), (iii) the purpose (single or multiporpose), and (iv) the head (ultra low, low, medium, high)(see Table 4.1) The distinguished classification depending on various heads can be coupled by various types of turbines(see.Table 4.2).

Table 4.1: Types of turbines and water head

Countries	Pico [kW]	Micro [kW]	Mini [kW]	Small [MW]	Big [MW]
Europe	< 5	< 100	100 to 1000	1 to 10	> 10
India	< 5	< 100	101 to 1000	1 to 25	> 25
China	< 5	< 500	-	0.5 to 25	> 25
USA/Canada	< 5	< 100	100 to 1000	1 to 30	> 30

Table 4.2: Types of turbines and water head

Turbine Runner	Ultra-low head < 5 m	Low head 5 to 20 m	Medium head 20 to 100 m	High head > 100 m
Impulse	Water wheel	Cross-flow Multi-jet Turgo	Cross-flow Turgo Multi-jet Pelton	Pelton Turgo
Reaction	Propeller Kaplan	Propeller Kaplan	Francis Pump-as-turbine	– –

The hydro power plant must be robust, simple and reliable. The maintenance must be very easy, so that its maintenance could required only simple manskill or minor qualified personal when the station plan is far from the urban center. The hydro power plants must be perfectly autonomous for their starting and their operation.

4.3.3 Environmental impact of the hydro power plant

From the environmental point of view, the hydro power plant can contribute nagative impacts on the environment. The negative impacts on the environment often quoted can be as follows:

- Water quality;
- Sediment transport and erosion;
- Downstream hydrology and environmental flows;
- Rare and endangered species;
- Passage of fish species;
- Damage on species within the reservoir (flora and fauna);
- Health issues;

4.3.4 Hydrology characteristics

Cameroon can be subdivided into four climatic zones: the Sudan climate type, the Guinea climate type, the tropical mansoon climate, and the equatorial mansoon climate. The Far North, the North and the Adamawa regions experience respectivelly the sudan climate and the tropical climate of the sudan type. They have all two seasons (dry and wet). The dry season bengins on November to June while, the rainy season begins from June to November. The far North experiences only 25 to 30 rainy days per year while, the North and the Adamawa facing an average rainfall between 900-1500 mm per year. The Centre, the South, the South West and the East regions experience the equatorial climate or so called "Guinea type" and have four different alternating seasons per year: the long dry season (December-May), the short rainy season (May-June), the short dry season (July-October), and the long rainy season (October-November) and a yearly average rainfall precipitation between 1500-2000 mm. The Littoral and the West regions have respectivelly the tropical mansoon climate and the and the equatorial mansoon climate with two different seasons: the dry season (November-March), and the rainy season (April-October). The driest month is December while, the wettest month is August. Looking at the following figures, we can observed the perfect complementarity between solar/wind and hydro flow rate. In fact, the low flow rate level of the rivers during the dry season corresponds of largest wind speeds and solar insolations(see Fig. 4.3,4.8,4.9).

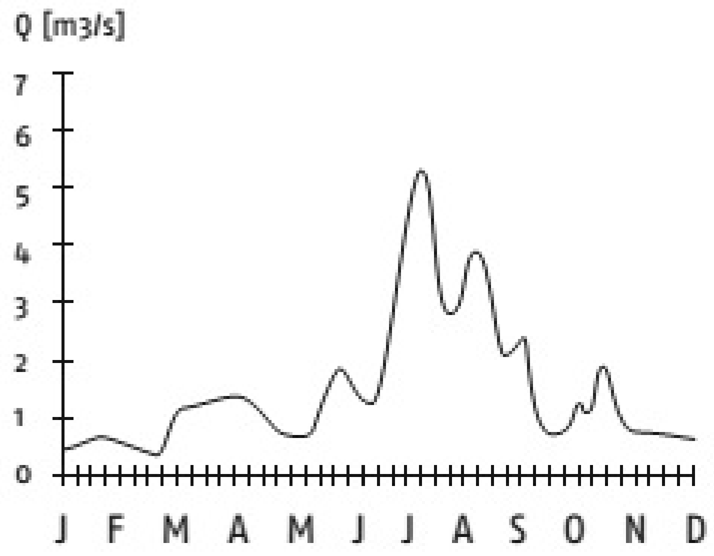

Figure 4.3: Cameroon example of annual hydrograph

4.4 Alternative between distributed small hydro power and huge power plants in Cameroon

4.4.1 Background

Cameroon is the most populated country in Central Africa and the second highest hydro potential in Africa. In the country, most of the remote and rural area still remain un-electrified till yet. The total electricity production come from the three huge hydro plants: Song loulou (384 MW); Edea (264 MW) and Lagdo (72 MW). The off-grid (pico and micro) hydro power installed capacity is 0.5 MW and are all built by private entities. Network losses along the transmission lines (build during the year 1950) are estimated to more than 25 %. The balance between power supply and rapid population growth demand remain insufficient, particulary during the dry season when the hydro capacity drops. The main challenge in energy sector will be either to continue with the construction of huge power plants far away from consumers and the extension of the network or to start thinking about distributed small hydro power plants in proximity of consumers in independent grid, thus to maintain the balance between supply and demand.

4.4.2 Small distributed hydro power plants

Cameroon has been blessed with abundance of water and rivers that could be used for hydroelectricity. Since all the regions, divisions and sub-divisions across the country have rivers that can produced electricity, it could be judicious to have many small distributed hydro turbine to supply the load demand which yet not have been satisfied. Small distributed hydro turbine can be selected for many reasons. For small hydroelectric power station of low power, economic considerations are at the base and will have the following characteristics: A hydroelectric power plant can be sustainable economically with the base of following characteristics:

- It preferably functions run of the river plant with a small reserve of regulation day skill man. Whenever the installation of a more significant reserve of storage is particularly economic, the tank will be made up in particular for an irrigation, a agro-agro-cattle reserve or a regulation of the flow downstream.

- The equipment must above all be simple and robust in order to limit operating expenses. Hydro power generation would not been built with complexity of operations.

- The quantity and the quality of energy required in rural and remote areas is quiete low due to the lack of infrastructure and diversification of economy. They small distributed hydro are well sized to provide the exact required customer load demand.

- The extention of grid in the remote areas is not economically feasible. The extention grid of a single wire cost €5000/km andthe operation and maintenance cost of a single wire grid is arround €125/yr/km [11].

- Distribution small hydro turbines could serve as a substitute for investment in transmission and distribution cost. According to (IEA-2002), on site production could result in cost saving in transmission and distribution of about 30 % of electricity cost.

- Small hydro turbines are extremely robust and can last for more than 50 years with little maintnance. They can also be installed in a very short period at any location and can be increased or decreased any time without any particular inconvenient.

- Using small distributed hydro turbines can be considered having the lowest cost per kW. Investment and operation cost are fairly lower. The low cost can offer attractive opportunities for citizens and foreign stakeholders to make more investment. Estimation of installed capacity (<500 kW) cost of small hyrdo turbine arround the globe is €2500-3000/kW [147]. If the indigenous expertise are used, the installed capacity cost can be reduced bellow €1000/kW [148].

- Distributed small hydro turbines can created opportunities in the remote areas and thus can prevent migration to cities. Therefore small distributed hydro plants are important for sustainable development and economic growth in Cameroon.

he choice of the site would follow the following criterion:

- The valid sites must be at a reasonable distance from the centers of consumption in order to remain within the economic limits imposed by the cost of the lines of transport. Location is normally at the low-voltage and often near the demand load.

- The selection must take into account either the centers isolated at cost price from diesel production high, or of the agglomerations not yet served by the official public distribution and deprived of reliable means of production, if not for a few hours of lighting.

- As far as possible, the study must evaluate the secondary macro-economic effects induced by the control of the water created by installation: drinking water, agro-pastoral water points and irrigation in particular.

In the operationnal and environmental point of view, the distributed small hydro turbine can have the following characteristics:

- The distributed small hydro turbine has a positif impact on voltage profile and power quality. It can reduce the distribution network losses. It maintains the system stability by supplying the spinning reserve required.

- The most environmental benefit of distributed small hydro power plants is that no carbone dioxide is produced during electricity generation.

- Many small hydro power plants are mainly run-of-river, so, do not involve the construction of larges dams or reservoirs. Therfore, they have minimal impact in environmental problems. Being small, they can also riduce the displacement of population or land use issues.

- Distributed small hydro power plants would blocked the fish passages and possible extinction of certains species. There is also minimal deforestation and a small impact on flora, fauna and biodiversity.

4.4.3 Huge hydro power plants

Cameroon has been divided in five different basins: the North basin (Lagdo hydro power and others thirteen sites identified), the Sanaga basin (Song loulou and Edea hydro power plants and other thirty-four sites identified), the West basin (tweenty five sites), the Nyong and Ntem basin (thirteen sites identified) and the East basin with fifteen sites identified. All these sites identified have a theoretical power of more than 50 MW. In cameroon there are only three big hydro power plants intalled and funzioning till today with a capacity of 720 MW. The 100 % electriciy production are made by the Song loulou and Edea in the sanaga basin and the Lagdo in the North basin. Cameroon network has an extention of 28,720 km and relies three interconnected grids. The southern interconnected grid (SIG) relies the Centre, Littoral, South, South West, West and the North West regions are connected by Song loulou and Edea hydro stations. The northern interconnected grid (NIG) relies the Far North, North and Adamawa regions and are connected to the Lagdo hydro power station. The eastern interconnected grid (EIG) which would have connected the East region still remain without hydro power station and is connected only by some thermal power plants [149].

In the economical point of view, these centralized big hydro power plants have a very high installation cost of arround €5000/kW compare to €2500-3000/kW for the small hydro plants. The big hydro power plants are built not near the costumers consumption point but, where there are sites with high power potential. For financing high hydro power plant projects, the country can only look for funding through loans with bilateral o multilateral partners and commissioning by foreign companies due to the complexity of these installations.

The transmission line in Cameroon is 28,720 km but still very limited. The Eastern grid is not connected to any hydro power plant. The other three hydro power plants are connected to two different grids which are not connected one to another. All the country is not connected by the grid due to the dispersion of population across the country, the high cost of extention grid, the low energy consumption by the remote population, thus make the extention of grid being limited. That will caused an important un-electrified number of the population, the permanent shortage of electrity supply during the dry season when the level of water is lowest. If the extention of grid is made to remote and rural area, it would be characterized by poor reliability and high line losses.

The centralized hydro power would be exposed to vulnerability and a worst stability if a failure occurs along the tranmission line (fall of electrical pool, failure on transformer, the fallen of a tree on the transmission line, etc.).

For the environmental point of view, the impact on the ambient, fauna, flora and biodiversity is high compare to small hydro power plants cited above.

4.5 Hydro power in Cameroon

Cameroon possesses the second largest hydro potential in Central Africa after the Democratic Republic of Congo (DRC) [99]. The gross theoretical potential of Cameroon's hydropower is 294 TWh/year. For this amount, 115 TWh/year is considered technically feasible while 103 TWh/year is economically feasible. However, only 5.5% of the technically feasible capacity has been developed. On the other hand, Democratic Republic of Congo has a technical feasible potential of 774TWh/year and an economic feasible potential of 419.21 TWh/year. But only less than 1% of the technically feasible potential has been developed. In terms of the number of plants that exploit the hydropower, three main plants are currently in use in Cameroon. These are the Edea, Songloulou and the Lagdo hydro production plants. Cameroun has a hydroelectricity intalled capacity of 720 MW with a yearly energy production of 6.12 TWh. Considering that, the hydropower plants work at their nominal power for a maximum of 8500 hours per year and 260 hours for maintenance. The Edea hydropower plant has an installed generating capacity of 264 MW; Songloulou has an installed capacity of 384 MW while Lagdo on the River Benoue has an installed capacity of 72 MW (see Table 4.3). Three regulation storage power plants existe in Cameroon (Mape, Bamendjin and Mbakaou). Mape storage power plant lunch over river Mape in the East region and take up the 1.08 years to be fully stored the reservoir. Its storage capacity is 3200 hm^3. Its inlet flow rate is 97 m^3/s while its outlet flow varies from 25 to 400 m^3/s. The out-flow water from Mape takes 6 days to arrive the Song loulou hydroelectric power plant. Bamendjin lunch on river Noun in the West region. Its total capacity is 1800 hm^3 and has a outlet flow rate which varie from 15 to 200 m^3/s while the inlet flow rate is 53 m^3/s . It needs 1.13 years to fully stored the reservoir and 5 days before reaching the Song loulou hydroelectric power plant. Mbakaou lunch on the river Djerem in the Adamawa region (North). Its stored capacity is 2600 hm^3 and it needs 0.23 years to be full and 7 days to reach the Song loulou hydroelectric power plant. The inlet flow rate is 355 m^3/s while its oulet flow rate vary between 50 to 400 m^3/s (see Table 4.4). A number of picro-and mico-hydropower projects with a total installed capacity of 515.5 kW have also been developed by Action pour un Developpement Equitable, Integre et Durable (ADEID) (see Table 4.6).

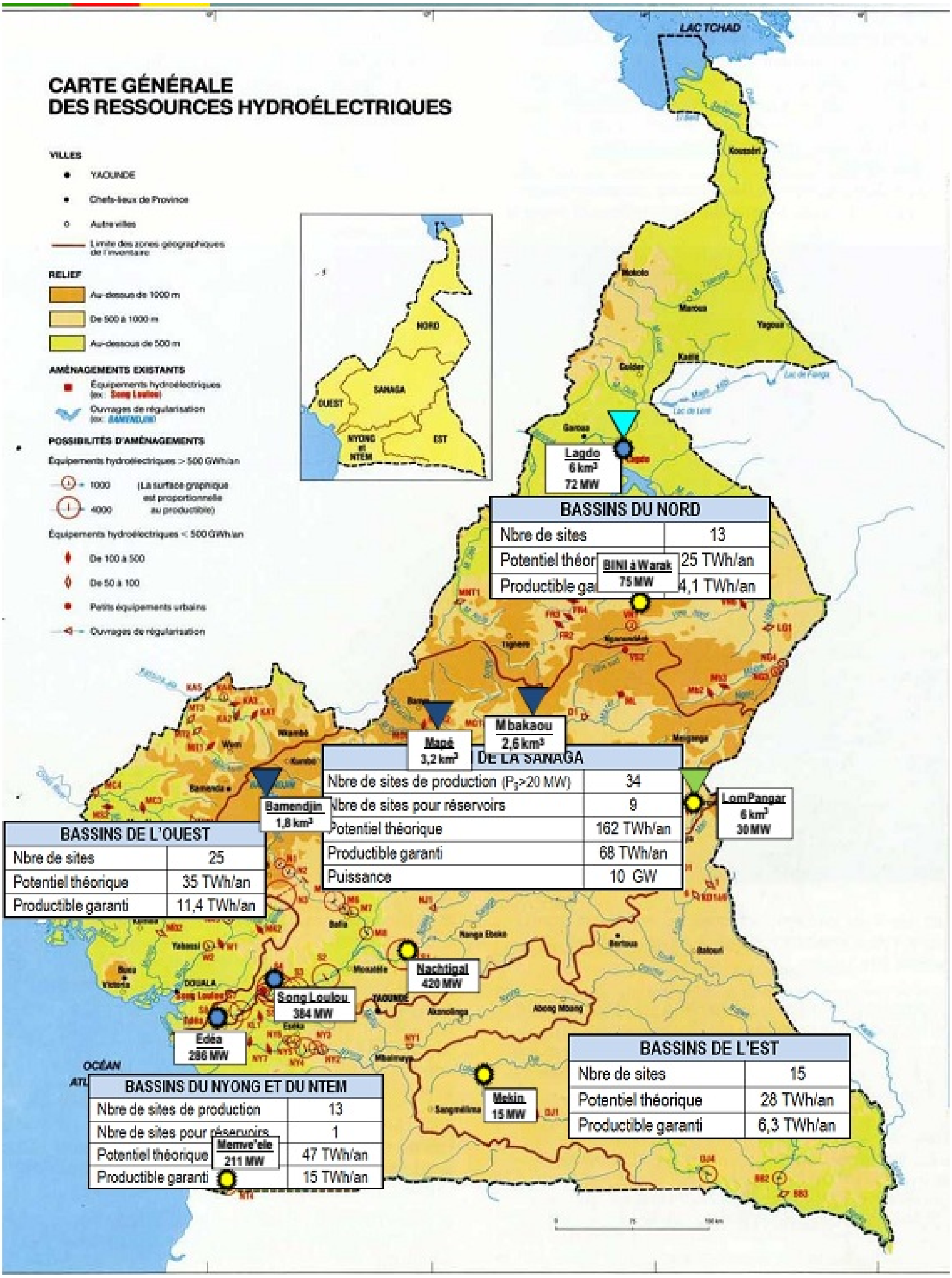

Figure 4.4: Maps of hydroelectric potential in Cameroon in 2017 [10]

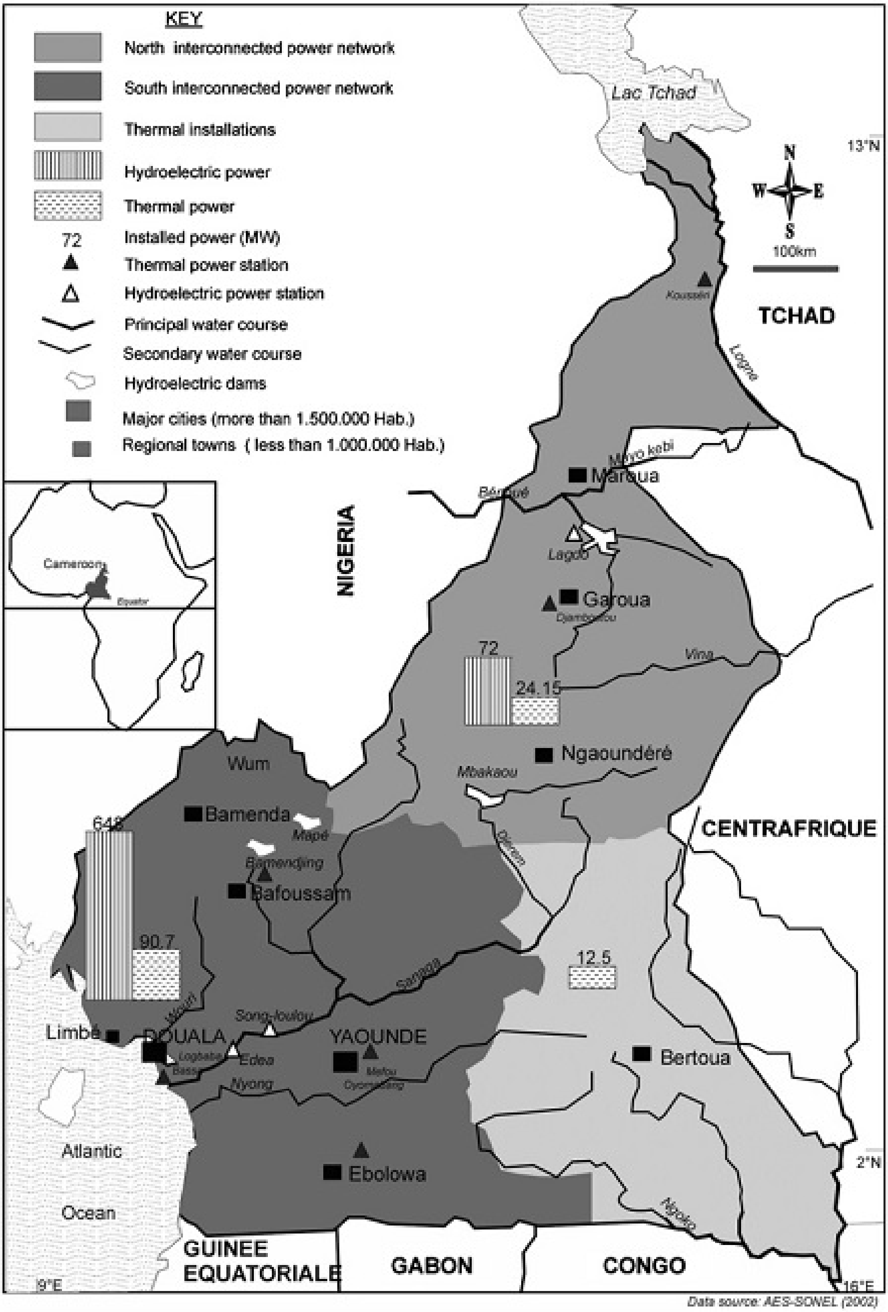

Figure 4.5: Map of electricity generation and distribution networks in Cameroon in 2002 [11]

Table 4.3: Installed hydroelectricty power plants in Cameroon in 2017 [10]

Regions	Hydro plant	Rivers	Height [m]	Flow [m^3/s]	Power [MW]	Productivity [TWh]	Commissioning [year]
Nord	Lagdo	Benue	20	109*4	72	0.612	1982
Centre	Songloulou	Sanaga	41.5	130*8	384	3.264	1981
Littoral	Edea	Sanaga	25	91*14	264	2.244	1954

Table 4.4: Reservoir hydro power plants in Cameroon in 2017 [15]

Regions	Sites	Rivers	Height [m]	In-Flow [m^3/s]	Out-Flow [m^3/s]	Volume [10^6 m^3]	Stored time [yr]	Commissio-ning [yr]
West	Bamendjin	Noun	7.5	53	200	1875	1.13	1968
East	Mape	Mape	6.25	97	400	3200	1.08	1988
North	Mbakaou	Djerem	7.5	355	400	2600	0.23	1974

Table 4.5: New hydro power to be constructed by 2035 [10]

Regions	Sites	Rivers	Height [m]	Flow [m^3/s]	Power [MW]	Energy [TWh]	Cost [M€]	Commissioning [year]
Centre	Nachtigal1	Sanaga	40	980	420	3.57	2135	2022
Centre	Nachtigal2	Sanaga	30	860	350	2.975	1525	2024
Centre	Kikot	Sanaga	35	1400	330	2.805	-	2026
Littoral	Eweng	Sanaga	73	1400	1150	9.775	-	2028
Littoral	Song Mbengue	Sanaga	81	1400	1050	8.925	-	2024
Littoral	Song Ndong	Sanaga	24	1400	270	2.295	457	2030
Littoral	Edea1	Sanaga	40	1400	200	1.7	701	2035
Centre	SonglouloulRD	Sanaga	42	1400	150	1.275	-	2035
South	Memve'ele	Ntem	35	450	204	1.734	640	2017
South	Dja	Ntem	35	-	15	0.127	-	2017

Table 4.6: Pico-and micro-hydro power installed plants in 2017 ref.(ADEID) [10], [16]

Regions	Sites	Power kW	Commissioning [year]
West	Mamamram	7.5	2006
West	Tongou	5	2006
West	Nefolem	6.5	2006
South West	Bellah	7.5	2006
South West	Wabane	30	2009
South West	Quibeku	10	2009
North West	Bamumkumbit	10	2010
West	Tchouandeng	20	2010
North West	Nkah	48	2011
North West	Jakiri	23	2011
West	Famtchuet	15	2012
West	Foumbot	46	2012
West	Koutaba	93	2014
West	Massagam	116	2014
West	Schungou	78	2016

The hydro power plant is well known to be a system where energy is stored within a potential that is capable of quickly releasing amounts of power. It is also well known that solar and wind power are stochastic energy sources compared to hydroelectric generation which is easily scheduled. If the combined outputs of many various renewable energy (var-RE) power plants, based on different resources and, importantly, located within a specific area, are considered jointly, their net variability-as seen by the power system as a whole-is smoother than that of individual plants.

4.6 Methodology and case study

4.6.1 Context

Since the country is cover by an abundance of solar radiation which is quite uniform across the country, the Yaounde city in the Centre has been selected for the solar contribution. The Maroua city in the Far North has been selected for his good amount of wind speed during the year. The hydro power has been selected in the South of the country for his good hydrograph during the year and the river mungo has been chosen for this study. The load profile over the year with a peak load of 80 kW has been schedule for Nkongsamba North city in the littoral region. (see Fig.4.7) This study aims to demonstrate the complementarity between solar/wind energy and hydro power.

4.6.2 Description of the algorithm for power management strategy

The management strategy here aims to supply the load at any time. The priority is given to solar and wind energy and hydro power use for compensating the fluctuating solar and wind energy. According to the algorithm shown in Fig.4.6, the priority is given to the renawable sources.

- if $Pre(t) < PL(t)$

If the power from renewables (solar and wind) is less than the load demand, the hydro power system supplies the remaining load: P*(t)=Ppv(t)+Pw(t)+Ph(t).

- if $P^*(t) > PL(t)$

The excess from renewables can be stored in a storage system or dumped: Pexcess(t)=P*(t)-PL(t). If not so, the hydro power cannot supply the remaining load and there is a deficit of load power register and this can be solved using a storage system or a generating fuel generator.

- In the other hand, if the power from renewables is higher than load demand the excess can be stored or dumped: Pexcess(t)=Ppv(t)+Pw(t)-PL(t). In this case the hydro power plant if not working.

$Pre = Ppv + Pw$ is the sum of the solar and wind power.

On Fig. 4.16, Pload(t) represents the electric monthly demand load of the city of Nkongsamba; Pexcess(t) represents the excess of power generated from PV, wind and Hydro generators; Ppv(t) represents the power generated by the solar generators; Pwind(t) represents the power generated by the wind generators; Phydro(t) represents the power generated by the hydro generator, Pmissed(t) represents the missed power by the generating system (solar, wind and hydro).

4.6.3 Solar generation output

The photovoltaic output power has been modeled using the manufacturer datasheet. There are two kind of photovoltaic output calculation technique in the literature. These techniques are known as electrical parameter based techniques and efficiency based technique. In this study, the electrical parameter based technique would be used. For the modeling of the PV generator, the load profile has been assessed and known, the solar radiation profile is assessed and the power potential is evaluated. From various selected photovoltaic panels and taking into account the power potential from the solar radiation assessed, the good panel amongs them has been chosen. The total number of solar panels are 150 with 50 panels in parallel and 3 in series. The output power of

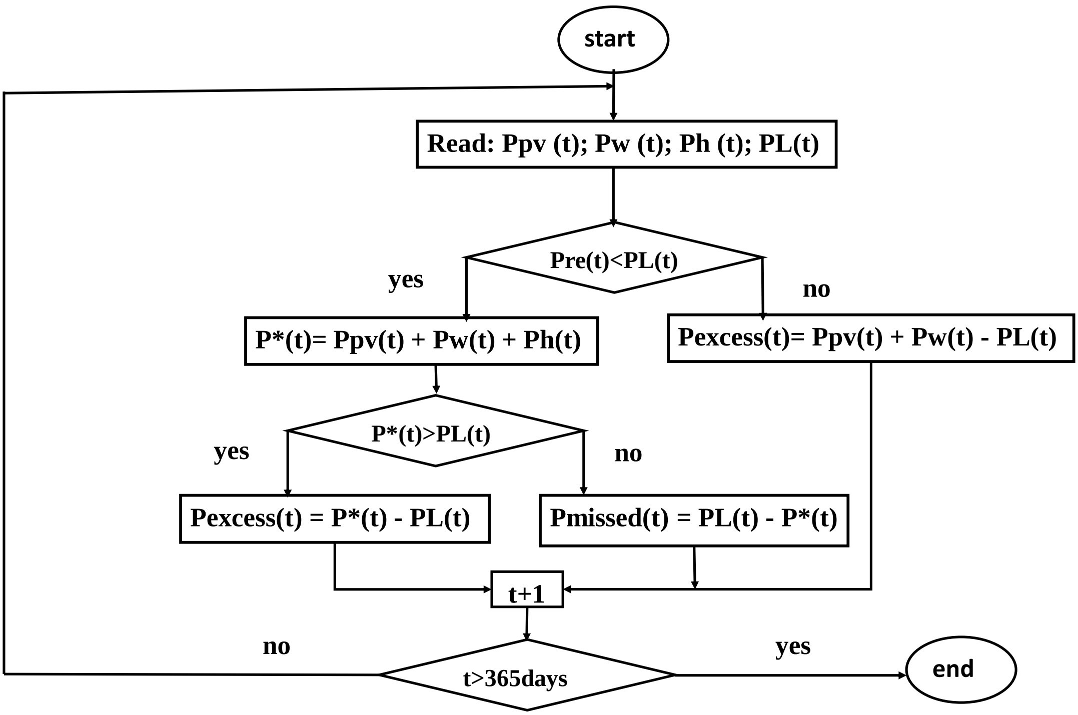

Figure 4.6: Flowchart of the power management of the various power systems

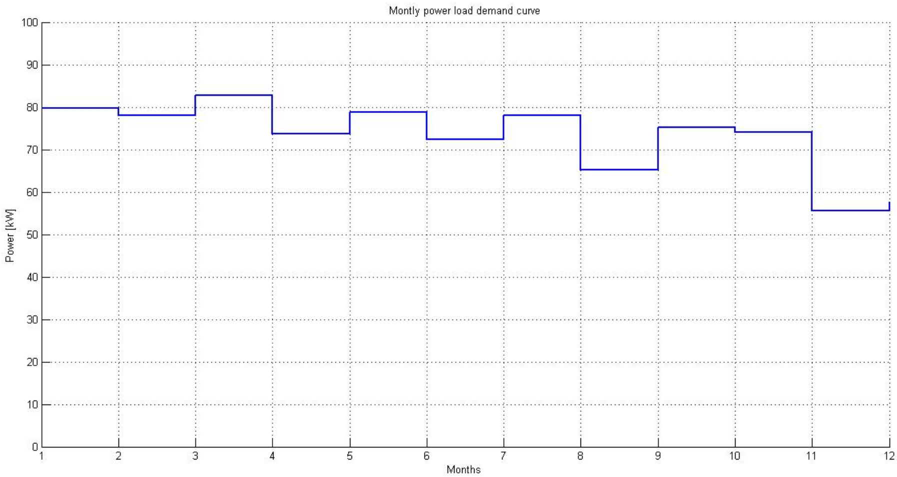

Figure 4.7: Nkongsamba North monthly electricity power demand

the photovoltaic generator is sized with a peak power of 27 kWp for all the PV generators. The hourly output power (P_{pv}) of the photovoltaic generator panel is calculated as

$$P_{pv}(t) = \eta_{pv}(t) A_{pv} G_{pv}(t) \tag{4.3}$$

where η_{pv} is the photovoltaic generator efficiency, A_{pv} (m^2) is the area of the photovoltaic module, G_{pv} (W/m^2) is the hourly insolation and P_{pv} (W) the hourly output power of the photovoltaic generatore module.

The efficiency of the photovoltaic module is calculated as

$$\eta_{pv} = \eta_{re}\eta_{pc}[1 - \beta(T_{cell} - T_{ref})] \tag{4.4}$$

here η_{re} represents the reference module efficiency (assumed here as 15.57%), η_{pc} is the power conditioning efficiency (assumed to be 0.86), T_{cell} the actual cell temperature and T_{re} the reference cell temperature. T_c should be calculated from equation 4.5 and replaced in equation 4.4. β is the voltage temperature coefficient for module efficiency (assumed here to be(-0.38 $V/°$C).

Module efficiency is a function of its nominal efficiency, η_{re} which is measured at a reference temperature T_{re} assumed to be 20°C.

$$T_c(t) = T_a(t) + [(NOCT - T_{aNOCT})/800]G_{pv}(t) \tag{4.5}$$

where $T_a(t)$ is the instantaneous ambient temperature, NOCT is the nominal operating cell temperature defined as the temperature reached by open circuited cells in a module (assumed to be 33°C), 800 is the irradiance on cell surface (W/m^2), and T_{aNOCT}=20°C is given by the manufacturer.

4.6.4 Wind generation output

For the wind turbine modeling, the wind speed profile of the site has been assessed and the energy potential has been evaluated. Taking into account the known load profile, various curve of different wind turbine have been analysed and the best wind turbine taking into account the wind profile and the best power production has been selected. For the present work, the power output from wind has been calculated by the follwing formulas

$$P_w(t) = N_w.\eta_w.\frac{1}{2}\rho A v^3(t) \tag{4.6}$$

The average speed is between (3-6 m/s) from 09:00 AM to 03:00 PM for more than eight months a year [136]. A wind turbine of a manufacturer has been selected with a rated output power of 1500 W. With a three blades horizontal axis, a gearless, brushless permanent magnet, a voltage rate of 125 VAC. The cut-in speed is 2.5 m/s and a rated speed of 16 m/s. The swept area

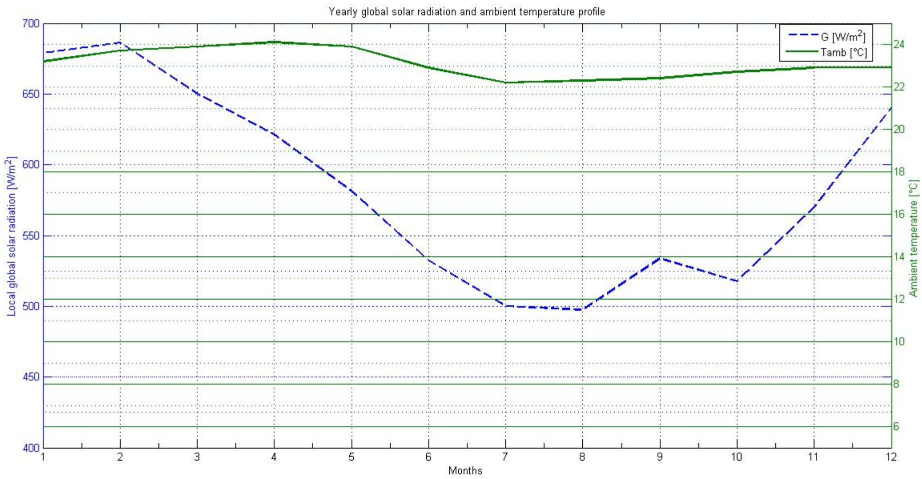

Figure 4.8: Monthly mean solar radiation and ambient temperature profile of yaounde (1983-2005)

of the wind turbine is 6.8 m^2 while the frequency is 50 Hz. The model based on cubic law [150] and [151] evaluates the hourly average wind speed that can be converted into power density [W/m^2] through a wind turbine generator as here P_w (W) is the hourly output wind power, N_w is the number wind of generators (210 wind turbines have been chosen), η_w is the efficiency of the wind turbine (assumed here to be 80 %), A is the area section of the rotor of the wind turbine (m^2), v (m/s) the wind speed of the air and ρ (kg/m^3) the air density. The swept area of the wind turbine and the air density considered for the output power calculation are respectively 1 m^2 and 1.225 kg/m^3. The maximum power generated from all the 210 wind turbines is 68 kW.

4.6.5 Hydro power generation output

For the potential of hydro power calculation, the flow rate (m^3/s) of the mungo river in the South West region and the head of some river have been taken into consideration.

$$P_h = \eta_t.\rho.g.H_m.Q \tag{4.7}$$

where P_h is the power of the hydro power $[W]$, η_t is the overall electricity efficiency, which depend on kind of turbine, generator, transformer, etc.[%], ρ is the density of water (1000 kg/m^3), g is the acceleration due to gravity (9.81m/s^2), H_m is the total head of 14 m, and Q is the water flow rate $[m^3/s]$.

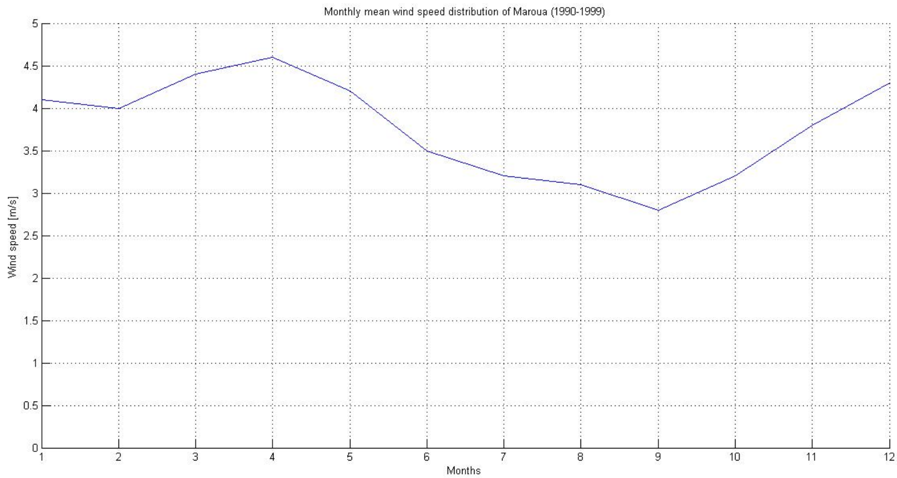

Figure 4.9: Monthly mean wind speed distribution of Maroua (1990-1999)

4.7 Results and discussion

The hydro power plant is well known to be a system where energy is stored within a potential that is capable of quickly releasing amounts of power. It is also well known that solar and wind power are stochastic energy sources compared to hydroelectric generation which is easily scheduled. If the combined outputs of many various renewable energy power plants, based on different resources and, importantly, located over a defined area, are considered jointly, their net variability seen by the power system as a whole is smoother than that of individual plants. It can be noticed that the hydro power is quite complementary to the solar and wind sources. The compensation of hydro power is very useful from the month of july to October when the solar and wind energy are quiete low corresponding to the rainy season and the rivers are full. From January to June, the power from hydro is low and the one from solar and wind are high corresponding to dry season.

From the result of montly solar irradiation Table 3.4 and montly wind speed Table 3.6 assessment across the country, the maps of hydro electric potential Fig.4.4 of rivers in Cameroon, the mixed of different generating sources (solar and wind) could be compensated by small hydropower plants all across the national territory. The fact that, the period of low flow rate level (dry season) corresponds to largest wind speeds and solar insolations and the period of high flow rate of the rivers corresponding to lowest wind speed and solar insolations (rainy season) creates a complementarity between solar/wind and

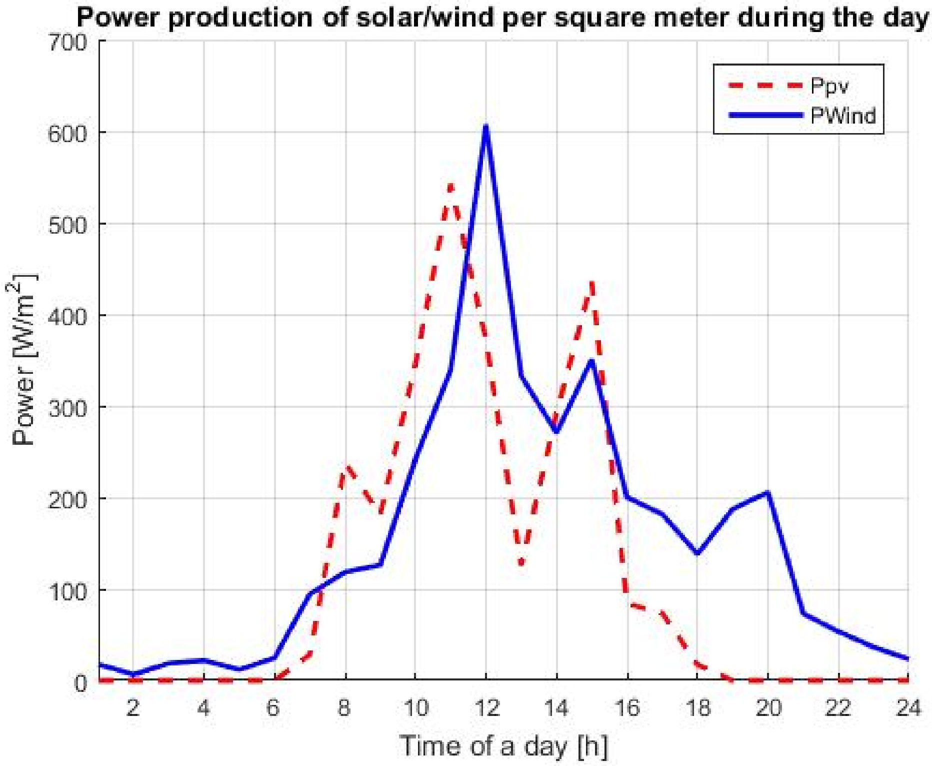

Figure 4.10: Daily power production from solar and wind energy per square meter

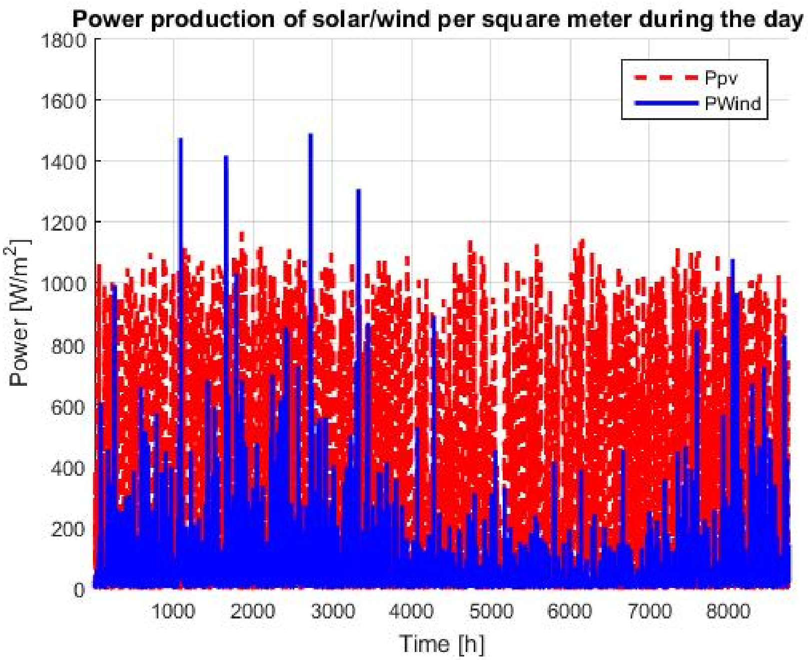

Figure 4.11: Yearly power production from solar and wind energy per square meter

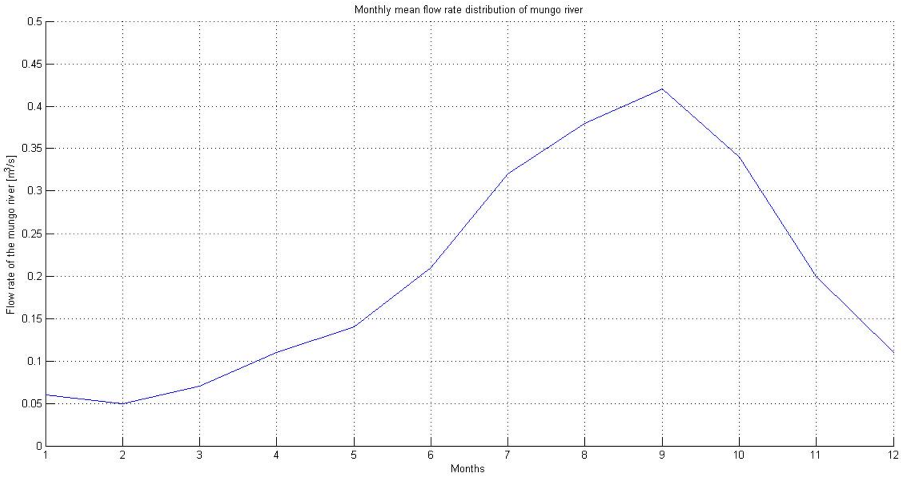

Figure 4.12: Monthly mean flow rate distribution of Mungo river

hydro power.

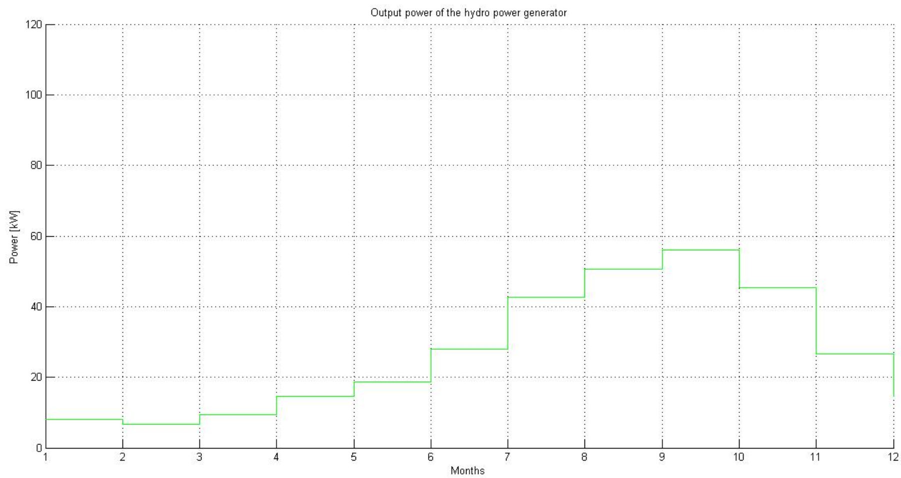

Figure 4.13: Monthly output power from hydro power plant

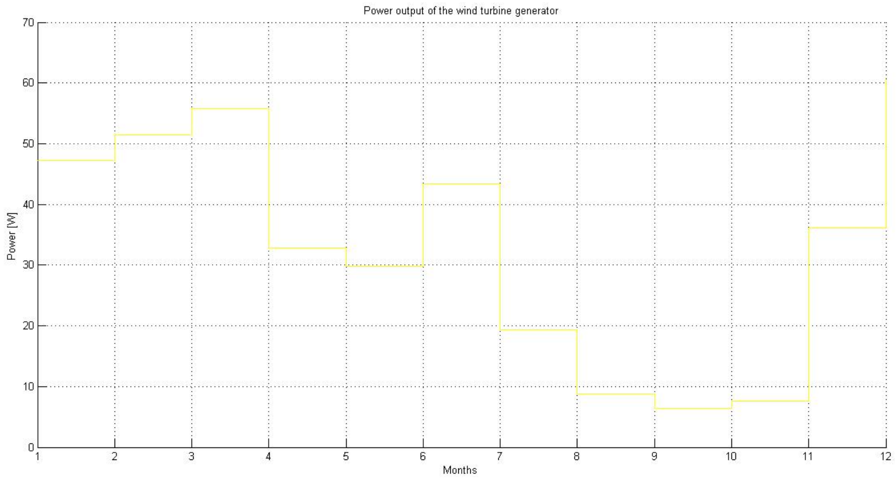

Figure 4.14: Monthly output power from wind generator power plants

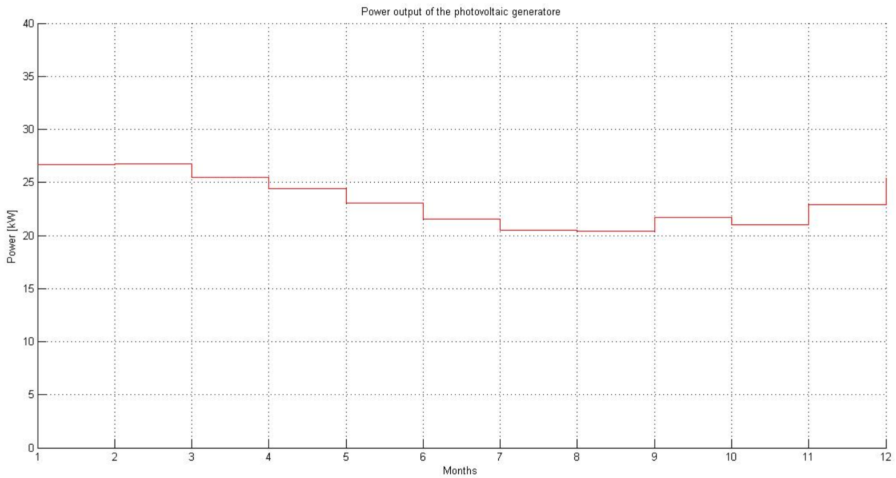

Figure 4.15: Monthly output power from photovoltaic generator power plants

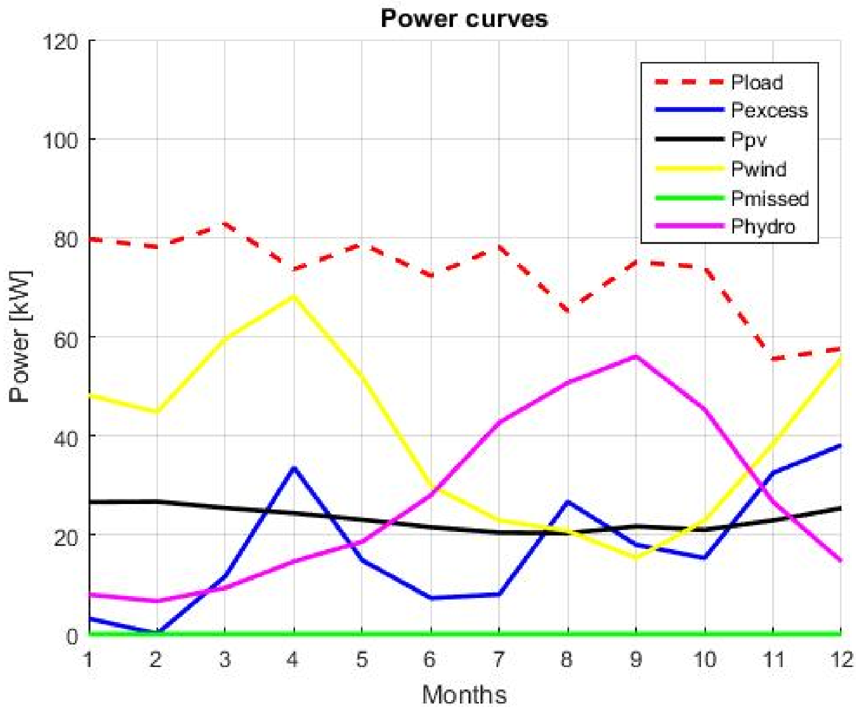

Figure 4.16: Yearly power generation from solar, wind and hydro power plants for supply the load demand

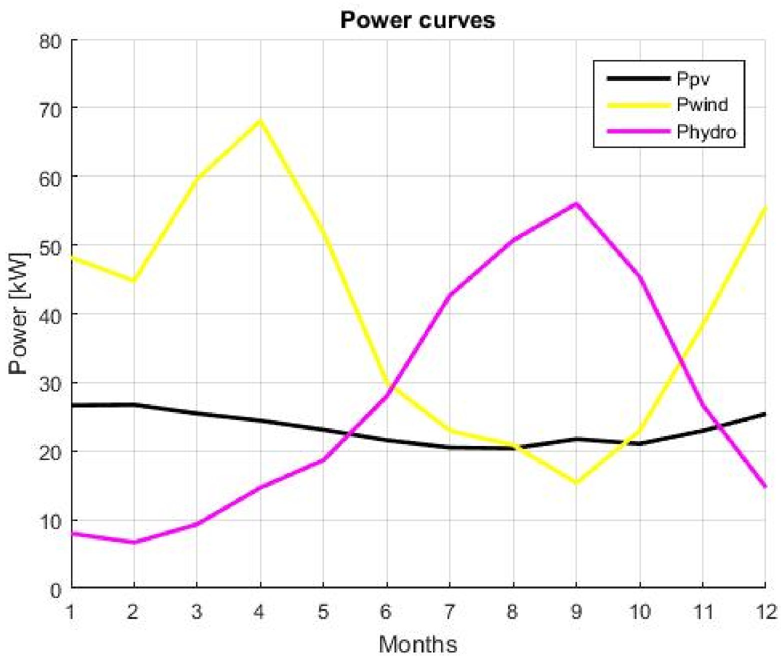

Figure 4.17: Yearly power generation from solar, wind and hydro power plants

4.8 Conclusion

Cameroon as the second possessor of hydroelectric potential in Central Africa has to play a central role not only electrifying Cameroon and the neighbouring countries but also improving the power quality through hydro power fluctuation compensation. The geographical distribution of different renewable energy in Cameroon is very important because it would help the hydro power plants just to deliver less energy for fluctuation compensation. This study has discussed also the alternative between distributed small hydro power plants and huge hydro power plants and the result show that, due to the the geographical distribution of rivers across the country, the dispersion of the population, the socio-economical and environmental aspect, distributed small hydro power are preferable to huge hydro power plants. The result of this study shows that, according to the energy system distribution structure in Cameroon, the combination of different renewable energy sources (wind and solar) with high fluctuations and hydro power plants could be complementary, reliable and cost effective solution for the growing energy demand.

4.9 Published papers:

1. M. Pendieu Kwaye, J. Bendfeld, N. Anglani. Assessment of Renewable Energy Resources and the use of Hydro Power for Fluctuation Compensation in Cameroon IEEE International Youth Conference on Energy, (IYCE) 2015, Pisa, Italy. Pages: 1-5.

2. M. Pendieu Kwaye, N. Anglani. Use of Hydro Power to Compensate Solar and Wind Energy for Rural Electrification in Cameroon Under submission for the Renewable Energy journal Elsevier.

5 Optimal design of hybrid energy systems for rural electrification in Cameroon

In this chapter, the heuristic algorithm developed is applied to manage and supply the demand load of the Salak community without interruption while, reducing the daily fuel consumption. An optimized method (dynamic programming method) is also developed and applied and its results are compared with the results obtained with heuristic algorithm. At the end, an economic analysis is carried out to determine the life cycle cost analysis of the entire system and the levelized cost of energy when the system is powered either only by the diesel generator or by the hybrid system.

5.1 Introduction

Cameroon is a Sub-Saharan African country, situated in central Africa. Despite the great potential, the development in the energy sector is limited [152], [153]. The three transmissions grids are completely separated from each others and no any possible exchange among them [3]. A solution to this problem can be the decentralization of the electrical production and the choice of *hybrid micro-grids* with the objectives of making local areas autonomous. According to local climate conditions and the geographical position of the area, different kind of schemes for hybrid micro-grids can be formulated. The Salak village community selected for this study is located a couple of kilometers from the Maroua airport in the Far North region. The village is completely isolated from the grid, composed by around 150 houses (up to 500 inhabitants), a nursery school, a primary school, a secondary school and a small rural hospital.

The objective of this chapter is to design and implement a model of hybrid energy system (HES) for rural electrification of the Salak village community in Cameroon combining renewable energy sources (RES) of the site with diesel generator and battery banks for storage and also hot water production.

The criteria taken into account to evaluate the "good performance" of the system is the minimization of the total system cost and precisely the the operating cost (the fuel consumption) of the system. In the rural community, there is no water available, there is no river near the site. Water can only be found under ground at a certain depth. That is why, a water distribution system has been sized based on the daily quantity of water need by any inhabitant of the rural area. Salak is a desert village where even animals and plants have many difficulties to grow because of un-availability of water. Waste from animals and crops would have been used to product biogas instead of using fuel to feed the diesel generator if there was available. During the rain season (July-Septembre), all the village is flooding [154]. To assess the system of Salak village, four different time-scales can be enumerated: daily, weekly, monthly and yearly. But, because of the monotony behaviour of the inhabitants, their constant energy demand during the four time-scales enumerated above, the daily time-scale could be good enough representative for this study. Several others management schemes have been developed in past works on optimal sizing, modeling and simulation of hybrid energy systems [50], [51]. The novelty of this work is: (i) the identification of the real potential of renewable energy sources (RES) of the site [152], [153]; (ii) the data assessment of the daily load consumption of the schools, the households and the rural hospital, useful for the construction of typical load demand profiles; (iii) the development of a heuristic algorithm method (rule-based) and its comparaison with a develop optimized approach (dynamic programming algorithm) for ensuring the load power supply when minimizing the operating cost (fuel consumption) with the impact on sustainability by delivering thermal energy for the hospital and potable water distribution for the population uses. This chapter is organized as follows: (i) The context and the objectives of the study carried-out; (ii) the description of the methodology used to carried out this study; (iii) the description of the proposed heuristic algorithm, the load charaterization profile, the modeling of the components of the HES and the description of the scenarios; (iv) the description of the developed optimized algorithm and its comparaison with the heuristic algorithm; (v) the description of the impact of maintenance, the human behaviour and the socio-economic benefits of the HES; (vi) conclusions are drawn.

5.2 Context and objectives

Salak village situated in the Far North region, is isolated from grid and have a population of about 500 persons living in 150 houses. The types of renewable energy sources available are solar and wind. There is not any river near the site for hydroelectricity. The site experiences the tropical climate of the sudan type. It has two seasons (dry and wet). The dry season bengins on November to June while, the rainy season begins from June to November. This study has been carried under these hypothesis:

- On the site of salack or arround the neighbouring site, there is not enough available waste produced by animals or agriculture to produce energy or biogas system instead of diesel generator;
- The solar thermal resources for hot water production have not been taken into consideration in this work, but the idea is to boil the water for sanitary used only when there is excess of power from renewables;
- The water tank have not been here considered as a design parameter but only as an electrical load;

The purpose of this energy management strategy is to enable the sizing and the management of the hybrid system in offline simulations for the feasibility study. The philosophy behind the algorithm is the supply of electrical load demand without interruption while minimizing the operation cost and globaly the total cost of the entire system. The algorithm intends to optimize the operation cost (fuel consumption) of the system.

The first step of this work is to apply a power management strategy amongs the different generating and storage sources using a heuristic approach algorithm to supply the load at any time following different criteria:

- The load have to be supply at any time of the day without interruption;
- For supplying the load, priority is first given to solar and wind sources, after the battery and at last the diesel generator;
- The diesel generator and the battery are imposed to work between a minimum and a maximum operation point, thus to increase the long lifetime of both diesel generator and battery and also reduce the fuel consumption;
- In case of excess of power, this could be used for hot water production.

The second step of this work would be to apply an optimization technique (Deterministic Dynamic Programming) to optimize to the hybrid energy system with the following criteria:

- The load have to be supply at any time of the day without interruption;
- The optimization techniques is apply to well manage the overall system, while reducing the fuel consumption of the diesel generator.
- The diesel generator and the battery are imposed to work between a minimum and a maximum operation point, thus to increase the long lifetime of both.

- The electricity supply, the thermal energy supply and the potable water supply distribution would ensured the sustainability of this project and shed light on it relevance.

5.3 Methodology

In this section, the chosen equations identifying the functioning of each main devices (PV panels, wind turbine, diesel generator and battery bank) will be illustrated for being the base of the modeling. The proposed hybrid energy system (HES) is composed by a photovoltaic generator system, a wind generator system, a battery bank, a diesel generator, an electric boiler for hot water production (Fig.5.1) and a water pumped system (see Fig.5.2).

For the modeling of the PV generator, the load profile has been assessed and known, the solar radiation profile is assessed and the power potential is evaluated. From various selected photovoltaic panels and taking into account the power potential from the solar radiation assessed, the good panel amongs them has been chosen. For the wind turbine modeling, the wind speed profile of the site has been assessed and the energy potential has been evaluated. Taking into account the known load profile, various curve of different wind turbine have been analysed and the best wind turbine taking into account the wind profile and the best power production has been selected. The battery has been modeled taking into account the load profile, the minimum energy to be delivered on a specific time-step, the maximum and minimum charge and discharge period. The diesel generator chosen has been modeled taking into account the minimum and the peak load demand, the minimum fuel consumption analysis of the various diesel generator analysed. The photovoltaic panel selected in this study have a step size of 3, 6 and 9 kWp because of the abundance of solar energy in the site. The wind turbine selected in this study have a power output of 1.5 kW. The battery size selected is 3 kW (18 kWh) with 6 hours of charge and discharge. The diesel generators power selected are 5, 6 and 7 kW. The power generated by the solar panel generator, the wind turbine generator and the battery have been selected in such a way that their summation could supplied the load at a certain period before being taken over by the diesel generator. This study is divided in two differents steps: (i) first, the development of a heuristic algorithm (rule-based) to size and manage the hybrid energy system; (ii) the comparaison of the heuristic method with an optimized method (dynamic programming method) developed to evaluate its performance. The first step of this work is to apply a power management strategy amongs the different generating and storage sources using a heuristic approach algorithm to supply the load at any time. For the sizing and the management of the hybrid energy system, the solar panel size have been let varied from 3, 6 and 9 kWp and the diesel generator from 5, 6 and 7 kW when, the size of the battery (3 kW) and the wind turbine (1.5 kW) have been let invariant. Various scenarios have been drawn to evaluate it performance. The second step of this work is the development and the application of the optimized approach (dynamic programming method) to optimize the hybrid energy system. The optimize method developed is apply in the different scenarios for managing and size the hybrid energy system. After the different scenarios on the two different methods, the conclusions should been drawn. At the end, this procedure would help well evaluated the optimize approach.

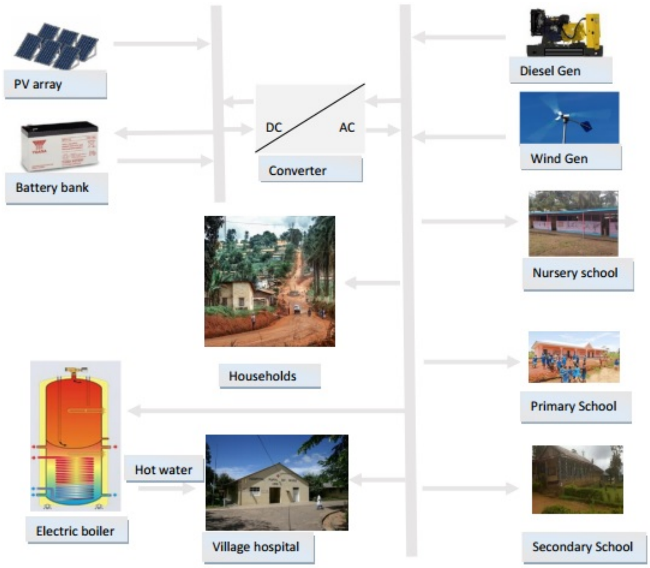

Figure 5.1: The PV/Wind/Diesel/Battery/Electric Boiler proposed scheme

5.4 Proposed Rule-based strategy

The philosophy behind the algorithm is the supply of electrical load demand without interruption while minimizing the operation cost and globaly the total cost of the entire system. The algorithm intends to optimize the operation cost (fuel consumption) of the system but also to ensure sustainability of the local area by supplying thermal load and potable water distribution. The proposed management algorithm implemented in this work is different from other studies by the fact that, we wanted a solution enabling a sort of cogeneration scheme where the excess of energy from renewables would go to sanitary hot water production for the hospital. But, when the energy from re-

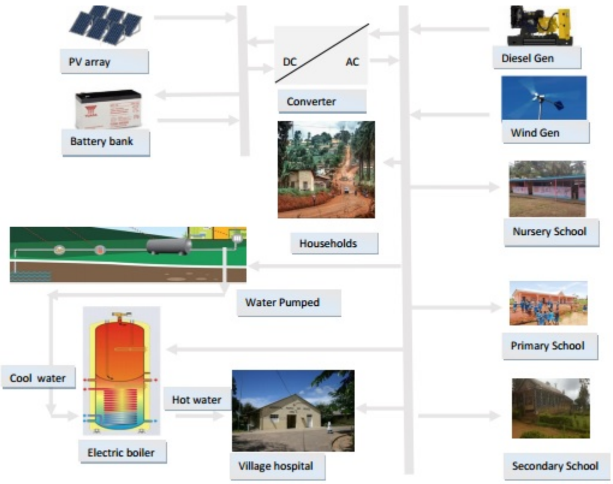

Figure 5.2: The PV/Wind/Diesel/Battery/Electric Boiler/Water pumped proposed scheme

newable sources cannot covered the load demand and the value of the battery state of charge is at it lowest level, only in this case the diesel generator can operate charging the battery (see Fig.5.3). The heuristic algorithm sizes and manages the hybrid system in an optimal way such that, the fuel consumption is minimized. The diesel generator must work inside its best efficient area of operation thus, reducing the operation cost. The battery is also modeled to work within a maximum and minimum state of charge value for maximizing its lifetime. All these criterion contributes to the originality of this heuristic algorithm. [155] the authors develope a methodology for optimal size, design and optimization of four types of hybrid energy systems using direct search algorithm. The Pv-Wind-Diesel-Battery hybrid system was found to be the best configuration. Investigating on optimum size of a stand-alone wind hybrid system in Greek island under the minimum of long-term electricity generation cost using a heuristic algorithm. A Wind/battery/diesel generator hybrid system with a system compose only with diesel generator is compared. In this configuration the battery is used to store the excess amount of wind production that cannot be consumed by the load and the diesel generator works as backup when the wind production and the battery bank energy is not adequate to meet the demand load [156]. Following the same goal as a previous works, the authors [56], instead of a wind hybrid system, investigate on photovoltaic hybrid system for a stand-alone in Kea island-Greece (photovoltaic+battery+diesel generator). The study carried out, investigates on optimal size of the island stand-alone system under the minimum long-term electricity generation cost using a heuristic algorithm. The monte carlo algorithm program is used to analyse and simulate the feasibility of a hybrid stand-alone wind-hydro-diesel power system in the island of Ikaria in Greece. In this configuration, the wind energy production is dedicated to fed the consumers need and the excess production from wind, is dedicated to carry water from the lower tank to the upper tank and store in the form of hydrodynamic energy. The diesel generator works only when the hydropower cannot supply the suffiscient load demand [145]. An iterative algorithm approach based for techno-economic optimization size, of various combined type of hybrid stand-alone system (PV/Wind/Diesel/Battery) in Algeria have been carried. This algorithm take into consideration the total net present cost and the enrgy cost and models all configurations giving the rate of 0% of total energy deficit. The optimal configuration is predicted on the basis of the minimum cost [54]. In the same context, discrete harmony search algorithm has been applied as optimize size model for rural electrification in Iran. The optmimal Pv/wind/diesel/battery hybrid system has been compare with a diesel generation alone in terms of total annual cost and environmental emissions. The discrete harmony search algorithm is compare with simulated annealing algorithm to determine the best configuration and it is found that the pv/wind/diesel/battery is the best configuration found and the most cost-effectiuve system [44]. In [69], the authors implemente a heuristic technique to model a hybrid energy system composed by photovoltaic, diesel generator and battery for remote consummers in South Africa. Two different days of two different seasons (winter and wind) of the year have been analysed. The optimization of the hybrid system for low fuel consumption has been performed with the quadratic programming toolbox of matlab. The hybrid system reached up to 73% and 77% and 80.5% and 82% fuel saving respectively in winter and summer. The authors investigate on optimum hybrid photovoltaic system based for remote telecommunication stations in Greece under the minimum of long-term electricity generation cost using a heuristic algorithm. The optimized configuration is defined only when the load could be supplied during all the year under two circunstances (higher and lower solar potential months). In this configuration the battery is used to store the excess amount of photovoltaic production that cannot be consumed by the load and the diesel generator works as backup when the wind production and the battery bank energy is not adequate to meet the demand load [103]. In [102], the author studies the optimal design of an autonomous solar-wind-pumped storage system using a heuristic algorithm. The optimal system configuration is performed investigating four types of stand-alone (solar-wind; Solar alone and wind alone with pumped storage under zero loss of power supply probability compared from 0% to 5%. A simple algorithm is developed to size the hybrid system. The hybrid system is composed by photovoltaic, wind and battery. The optimal sizing of thehybrid system is obtained by the minimization of the life cycle cost system [157]. An algorithm control is developed for interaction in operation of different devices of the hybrid system for remote hospital in Nigeria. The hybrid system is composed by pv/wind/diesel/battery. The excess of energy production from renewables charged the battery, and when the battery is full and there is still energy produced by renewables, this is used for dumped load. The diesel generator works only when, the energy from renewables and battery cannot supply the load and by this way, the diesel generator operation hours and fuel cost reduced as well as the pollutant emissions [158]. An intelligent management algorithm has been proposed for hybrid wind/pv/battery/diesel system for an isolated electricity supply house. Here the dump load is used to dissipate the excess of production from renewables when the battery is fully charged [159].

A schematic logic operation with the decision making of different situations would be described under tree different conditions: (a) equal-generation, (b) under-generation (Discharge mode) and (c) over-generation (Charge mode) where the excess of generation is used to charge the battery or for hot water production.

In equal-generation conditions, the power output from renewable sources (P_{re}) is equal to the power load demand (P_L), the load is supplied by the renewable sources, the diesel generator is not working, no hot water is produced and the state of charge (SOC) and the power (P_{bat}) of the battery are the same state of the previous step (see Fig.5.4).

In under-generation conditions, where the output power from renewable sources (P_{re}) is less than power load demand (the power deficit ($P^* = P_{re} - P_L$) is negative), two options are available, which are (i) to operate the storage system or (ii) to operate diesel generating system. However, the decision of selecting either option is mainly determined by the generation-demand mismatch given by P^*. If P^* can be given by the battery, discharge process, the state of charge of the battery is more than the minimum ($SOC > SOC_{min}$). But if the state of charge of the battery reaches the lowers value, the P^* remaining is powered by the diesel generator. If the P^* is less than minimum loading condition of the diesel generator, the diesel generator works at the minimum condition (Pdg_{min}) otherwise, works under the nominal power (see Fig.5.5).

In over-generartion conditions, the power output from renewable (P_{re}) is greater than the load power demand (P_L), the battery absorbs the additional power ($P_{re} - P_L$). If the excessive generation ($P_d = P_{re} - P_L$) is greater than the maximum capacity of the battery storage (P_{bat}max) then the dump load (P_d) needs to consume the additional power of the system (see Fig.5.6).

The energy management strategy algorithm develops in this work is working as follow: At the beginning time of the day, the system read the value of the load demand, the value of the power generation from renewables (solar

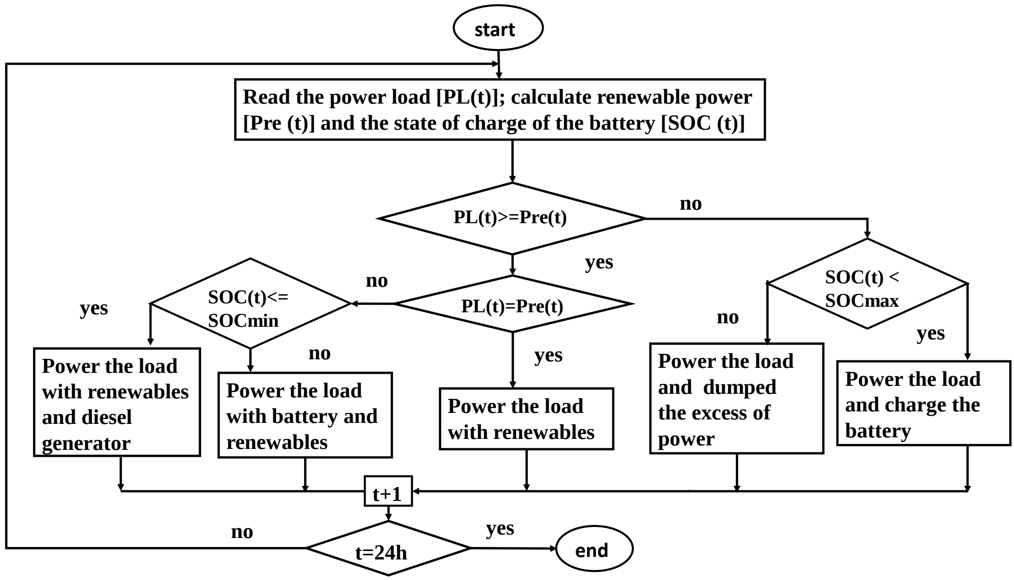

Figure 5.3: Rule based strategy

and wind), the value of the state of charge of the battery at the beginning time (SOC_0), the state of charge maximum and minimum of the battery, the maximum and mininum respectively value of the power of the battery and the diesel generator, the value maximum average stored energy of the battery. If the power generated from renewables (P_{re}(t)) is equal to the load demand (P_L(t)), the battery ($P_{bat}(t) = 0$), the diesel generator are not working ($Pdg(t) = 0$)and the there is not any dumped load ($P_d(t) = 0$). Else, the power generated from renewables sources is less than the power load demand ($P_{re}(t) < P_L$(t)). If the state of charge of the battery is less or equal to the minimum one ($SOC(t) <= SOCmin$), in this case, the diesel generator supply the load ($P^*_{dg}(t) = P_L(t) - P_{re}$(t)). The value of the power to be generated by the diesel generator have to be not less than the mimimun value ($P^*_{dg}(t) > P_{dg}$min), but also not great to the maximum value ($P_{dg}(t)^* <= P_{dg}$max). In case it is great to the maximum value, the system display a message of error "*the diesel generator is under − size*" and the programme stop. Else the power demand is less than the minimum value, the diesel generator supplies the load at it's minimum value and the fuel consumption is calculated any time that the diesel generator is used. After that, the battery ($P^*_{bat}(t)$=$P_{dg}(t) - P_L(t) - P_{re}(t)$) can be charged by the difference from renewable, diesel generator and load. If the value of the battery is under or equal to maximun one ($P^*_{bat}(t) <= P_{bat}$max), all the power goes to the battery ($P_{bat}(t)$=P^*_{bat}(t))and in another case, the power from the battery equal to the maximum power ($P_{bat}(t) = P_{bat}\max$) and the excess goes to the dumped ($P_d(t) = P_{bat} * (t) - P_{bat}\max$). When the state of charge of the battery is greater to state of charge minimum, discharge process. The difference from generated power from renewables and load demand is calculated ($P * (t) = P_{re}(t) - P_L(\text{t})$). After that, the new state of charge of the battery is calculated (SOC_{t+1}). If the state of the battery is greater than the minimum state of charge ($SOC_{t+1} > SOC_{min}$), the battery can discharged ($P^*_{bat}(t) = P^*(\text{t})$). If the power from the battery ($P^*_{bat}(\text{t})$) is greater than the minimum value ($P^*_{bat}(t) > P_{bat}\min$), the battery can be discharged. If not so, the battery assumes it's minimum value ($P_{bat}(t) = P_{bat}\min$). The battery reaches at the lowers value, the diesel generator can now powered the load and charge the battery. The new diesel generator value is calculated ($P_{dg}* = P_L(t) - P_{re}(t) + P_{bat}(\text{t})$). The value of the power to be generated by the diesel generator have to be not less than the mimimun value ($P_{dg} * (t) > P_{dg}\min$), but also not great to the maximum value ($P_{dg}(t)* <= P_{dg}\max$). In case it is great to the maximum value, the system display a message of error "$the\ diesel\ generator\ is\ under - size$" and the programme stop. Else the power demand is less than the minimum value, the diesel generator supplies the load at it's minimum value and the fuel consumption is calculated any time that the diesel generator is used. After that, the battery ($P_{bat} * (t) = P_{dg}(t) - P_L(t) - P_{re}(\text{t})$) can be charged by the difference from renewable, diesel generator and load. If the value of the battery is under or equal to maximun one ($P_{bat} * (t) <= P_{bat}\max$), all the power goes to the battery ($P_{bat}(t) = P_{bat}{}^*(\text{t})$)and in another case, the power from the battery equal to the maximum power ($P_{bat}(t) = P_{bat}\max$) and the excess goes to the dumped ($P_d(t) = P^*_{bat}(t) - P_{bat}\max$). When the new state of charge ($SOC_{(t+1)}$) is different from equal or greater to the minimum value, the new diesel generator value is calculated ($P^*_{dg}(t) = P_L(t) - P_{re}(\text{t})$). The value of the power to be generated by the diesel generator have to be not less than the mimimun value ($P^*_{dg}(t) > P_{dg}\min$), but also not great to the maximum value ($P^*_{dg}(t) <= P_{dg}\max$). In case it is great to the maximum value, the system display a message of error "$the\ diesel\ generator\ is\ under - size$" and the programme stop. Else the power demand is less than the minimum value, the diesel generator supplies the load at it's minimum value and the fuel consumption is calculated any time that the diesel generator is used. After that, the battery ($P^*_{bat}(t) = P_{dg}(t) - P_L(t) - P_{re}(\text{t})$) can be charged by the difference from renewable, diesel generator and load. If the value of the battery is under or equal to maximun one ($P^*_{bat}(t) <= P_{bat}\max$), all the power goes to the battery ($P_{bat}(t) = P^*_{bat}(\text{t})$)and in another case, the power from the battery equal to the maximum power ($P_{bat}(t) = P_{bat}\max$) and the excess goes to the dumped ($P_d(t) = P^*_{bat}(t) - P_{bat}\max$). When the power generated from renewables is greater than load demand ($P_{re}(t) > P_L(\text{t})$), the diesel generator is not working ($P_{dg}(t)$ =0). If the state of charge is equal to state of charge maximum ($SOC(t) = SOC_{max}$), the dumped load equal to the difference from renewables and load ($P_d(t) = P_{re}(t) - P_L$(t)) and the battery is not working. Else, the new power is calculated ($P^{**}(t) = P_{re}(t) - P_L$(t)) and also a new state of charge (SOC_{t+1}). If the new state of charge is greater than the maximum value, the calculated excess power ($P_{bat}(t) = [SOC_{max} - SOC_{t+1}]ASE_{max}$/Dt) after charging the battery goes to dumped ($P_d(t) = P^{**}(t) + P_{bat}$(t)). Else the new battery power to the battery is ($P_{bat}*(t) = P^{**}$(t)). If ($P_{bat}*(t) <= P_{bat}$max), the power going to th battery is $P_{bat}(t) = P^{*}_{bat}$(t). If not so, the system display a message of error "*the battery system is under − size*" and the programme stop. At the time (t=24h), the state of charge of the battery during the 24 hours is calculated and known, the rainflow counting algorithm extract from all the state of charge value the amplitude with which the calaculation of the depth of discharge is made. The number of cycle of damage and the lifetime of the battery is also calculated.

The flowchart of the proposed power management strategy scheme is shown in Fig.5.4.

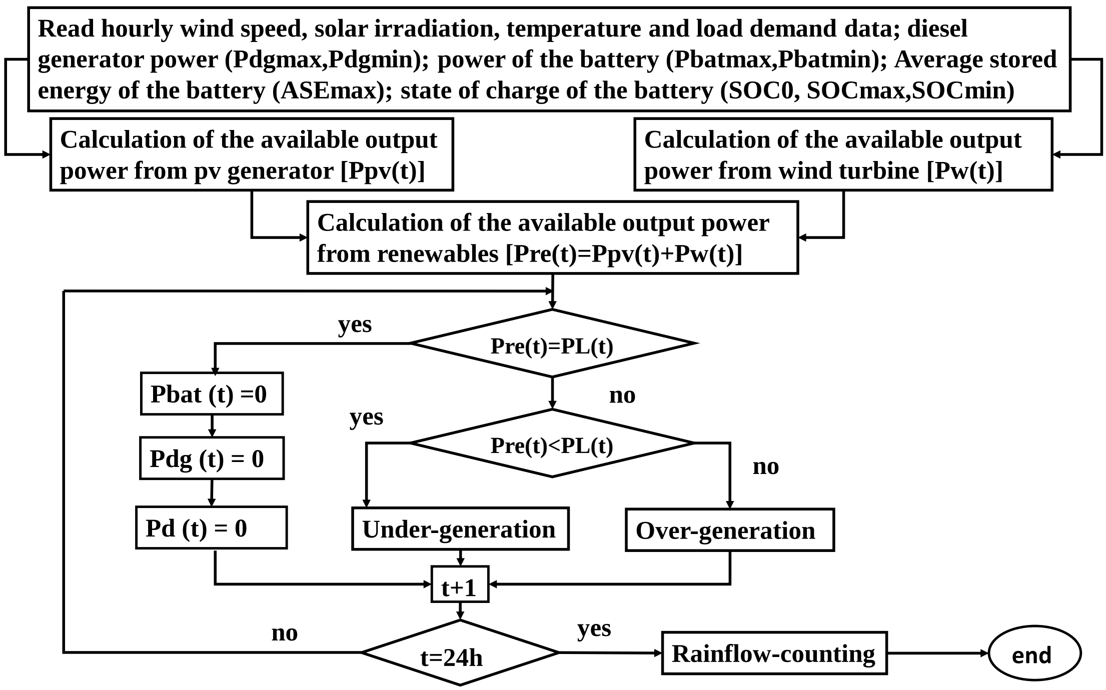

Figure 5.4: Flowchart of the proposed Rule-based strategy

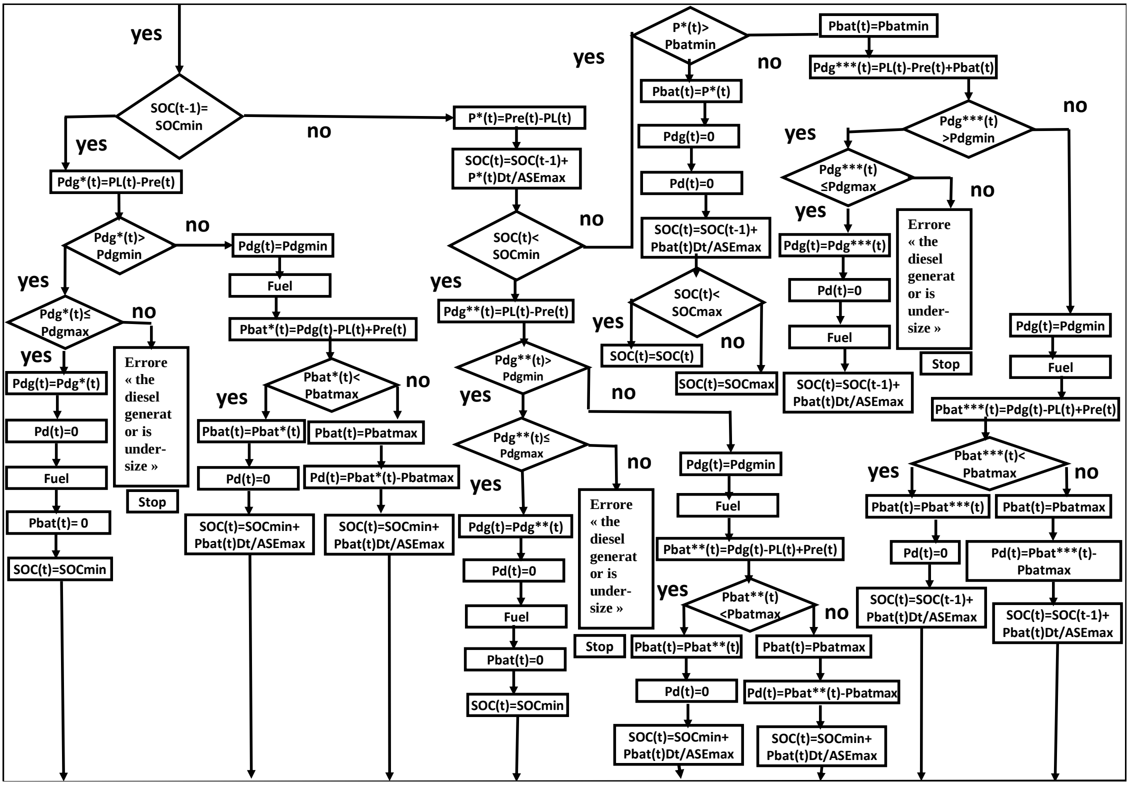

Figure 5.5: Under generation mode extracted from the Flowchart 5.4

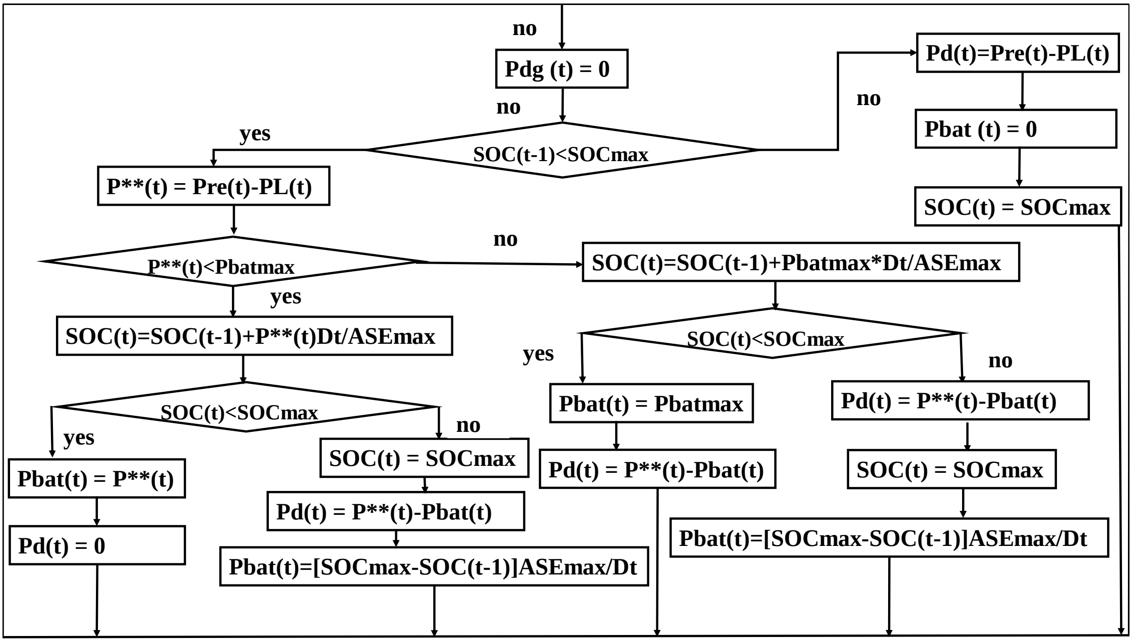

Figure 5.6: Over generation mode extracted from the Flowchart 5.4

5.4.1 Load profile characterization

The load profile in this study has been schedule as follow: (i) all the medical, electric and the lighting equipments of the hospital have been contabilized and scheduled, their power and their working time period during the day, the week, the month and the year have been scheduled; (ii) all the electric and lighting equipments of the households and all the school classrooms have been contabilized and scheduled based on their working time period during the day, the week, the month and the year; (iii) the sum of the energy scheduled and assessed during a day time-scale period have been used for the demand load profile in this study. A typical rural household in Cameroon is composed by 3 persons living in a two rooms appartment, the load is composed by 2 incadescent lamps in two rooms, a fluoriscent lamp outdoor for security and a radio [37]. The typical household has an annual energy demand load of 70 kWh which equal to 0.2 kWh/day. The nursery school (*école maternelle laique de Salak*) is composed by an administrative office, 3 classrooms, a library, a toilet and 2 residences. The primary school (*école primaire laique de Salak*) is composed by 2 administrative offices, 6 classrooms, a library, a toilet and 2 residences. The secondary school is composed by 3 administrative offices, 7 classrooms, a library, a toilet and 2 residences (*école secondaire laique de*

Salak). The daily energy load of each school is around 7 kWh, an annual energy load of 2555 kWh. The electrical load of the rural hospital is composed as the following Table 5.2. The staff of the rural hospital (*Centre intégré privé laique de Salak*) is composed by 5 persons: a medical doctor working 3 hours a day, 2 nurses (one for the day time and the other for the night), a laboratory technician and a cleaning operator. The hospital receives less than 75 patients a day, some for consultations, others for laboratory exams, others for maternities and others for traitements. The hospital uses a considerable quantity of hot water per day which have not been yet quantified that's why in this study, the thermal energy has been considered. Hot water in the hospital supplies showers, washing hands and sterilization of medical instruments. The load demand of the different schools, the households and the hospital of Salak used in this study have been carried out by bachelor students of the University of Maroua (Institut Superieur du Sahel). The daily electrical load demand profile for the hospital, the schools, the households, and the total load have been scheduled, built and shown respectively in Fig.(5.7,5.8,5.9,5.10).

5.4.2 Modeling of the hybrid system

The modeling of the different components of the hybrid energy system with a satisfy grade of feasibility would be useful for the secondary control of the energy management strategy (EMS). The different components of the hybrid system have been all selected taking into account the peak demand load. The diesel generator working as the backup of the hybrid system have been sized taking into account the minimum and the maximum peak load demand. The diesel generator must work inside its best efficient area of operation and a wide research have been done to retrieve such data for small size generators. The battery is modelled to work within a maximum and minimum state of charge value. The battery is also modelled including its lifetime for economic evaluations using the rainflow counting method. At last, the battery of 3 kW (18 kWh) power has been selected so that the cumulative power from solar, wind and battery could supplied the peak load demand for a certain time. Since the solar energy is abundant in the region, a 3, 6 and 9 kWp peak power have been selected for the study. Concerning the wind generator, a wind turbine of 1.4 kW output power has been selected. The choice of using a large step size of photovoltaic panels (3/6/9 kWp) has been done taking into account the peak load demand profile during a particular day and the fact of the abundance of solar radiation in the village. Since PV and wind are fluctuating sources, it is difficult to rely on them to supply continuously a certain load demand all the day and all the time. For this reason, the Salak village situated in remote area and far from the grid, it is not cost effective to use only the diesel generator to supply the load demand because of the high

Table 5.1: Demand load acquisition monitored by B.Sc students of Institut Superieur du Sahel (ISS) 2015

Hours [h]	Hospital [W]	Household [W]	Households [W]	School [W]	Schools [W]	Load [W]	Pumped [W]	Total load [W]
0-1	580	5	750	100	300	1630	343	1973
1-2	580	5	750	100	300	1630	343	1973
2-3	580	5	750	100	300	1630	343	1973
3-4	580	5	750	100	300	1630	343	1973
4-5	580	5	750	100	300	1630	343	1973
5-6	580	5	750	100	300	1630	343	1973
6-7	460	20	3000	100	300	3760	343	4103
7-8	460	15	2250	100	300	3010	343	3353
8-9	460	2	300	700	2100	2860	343	3203
9-10	705	2	300	700	2100	3105	343	3448
10-11	1061	2	300	700	2100	3461	343	3804
11-12	661	20	3000	700	2100	5761	343	6104
12-13	2905	15	2250	300	900	6055	343	6398
13-14	2375	1	150	300	900	3425	343	3768
14-15	2025	1	150	600	1800	3975	343	4318
15-16	660	1	150	600	1800	2610	343	2953
16-17	660	1	150	600	1800	2610	343	2953
17-18	660	17	2550	250	750	3960	343	4303
18-19	780	17	2550	150	450	3780	343	4123
19-20	780	17	2550	150	450	3780	343	4123
20-21	780	17	2550	150	450	3780	343	4123
21-22	780	17	2550	150	450	3780	343	4123
22-23	780	5	750	150	450	1980	343	2323
23-24	160	5	750	100	300	1210	343	1553

Table 5.2: Rural hospital load monitored by B.Sc students of Institut Superieur du Sahel (ISS) 2015 [Table 5.1]

Electical appliances	Power [W]	Working period	Time [h]
Freezer	600	12:00 AM - 11:00 PM	11
Refrigerator	300	10:00 AM - 03:00 PM	5
Lab Autoclave	550	12:00 AM - 01:00 PM	1
Microscope	15	09:00 AM - 01:00 PM	4
Hematology Analyser1	28	10:00 AM - 12:00 AM	2
Hematology Analyser2	28	10:00 AM - 12:00 AM	2
Lab Centrifuge1	575	12:00 AM - 02:00 PM	2
Lab Centrifuge2	575	12:00 AM - 02:00 PM	2
Lab Incubator	400	00:00 AM - 11:00 PM	11
Computer desktop	200	09:00 AM - 02:00 PM	5
Printer	65	01:00 PM - 03:00 PM	2
Communication Line	30	09:00 AM - 01:00 PM	4
Electric Boiler	1000	02:00 PM - 03:00 PM	1
Room Light1	20	06:00 PM - 06:00 AM	12
Room Light2	20	06:00 PM - 06:00 AM	12
Reception Light	20	00:00 AM - 11:00 PM	23
Security Light1	40	06:00 PM - 06:00 AM	12
Security Light2	40	06:00 PM - 06:00 AM	12
Security Light3	40	06:00 PM - 06:00 AM	12
Security Light4	40	06:00 PM - 06:00 AM	12

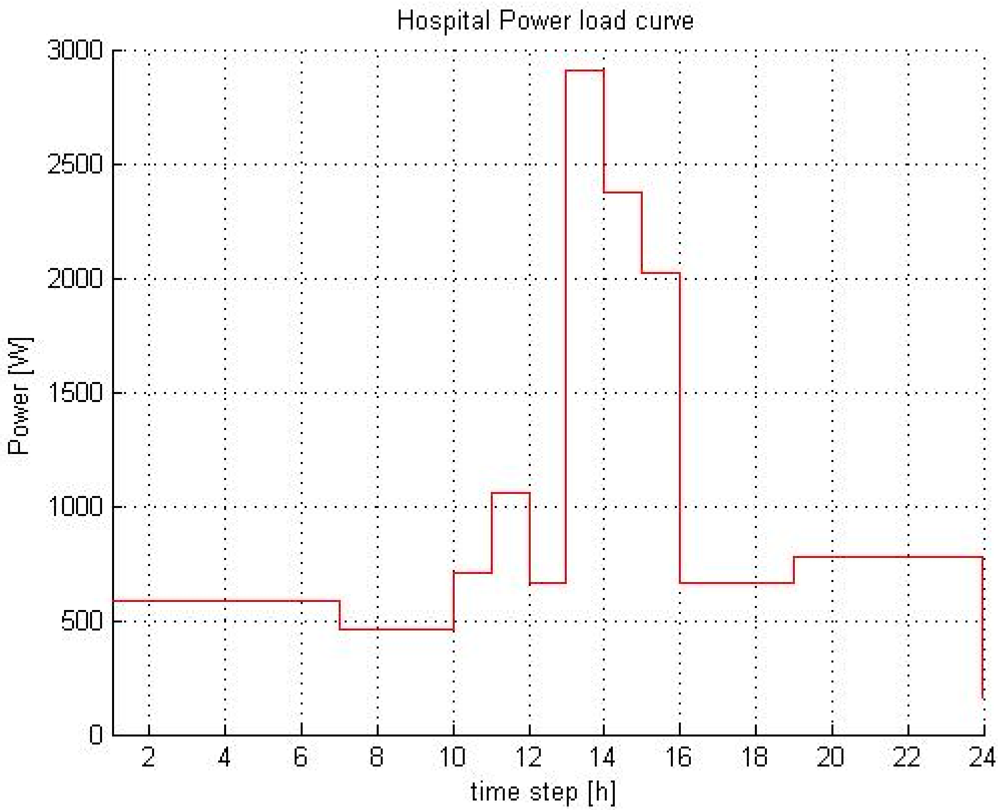

Figure 5.7: Hourly load demand profile of the hospital [Table 5.1]

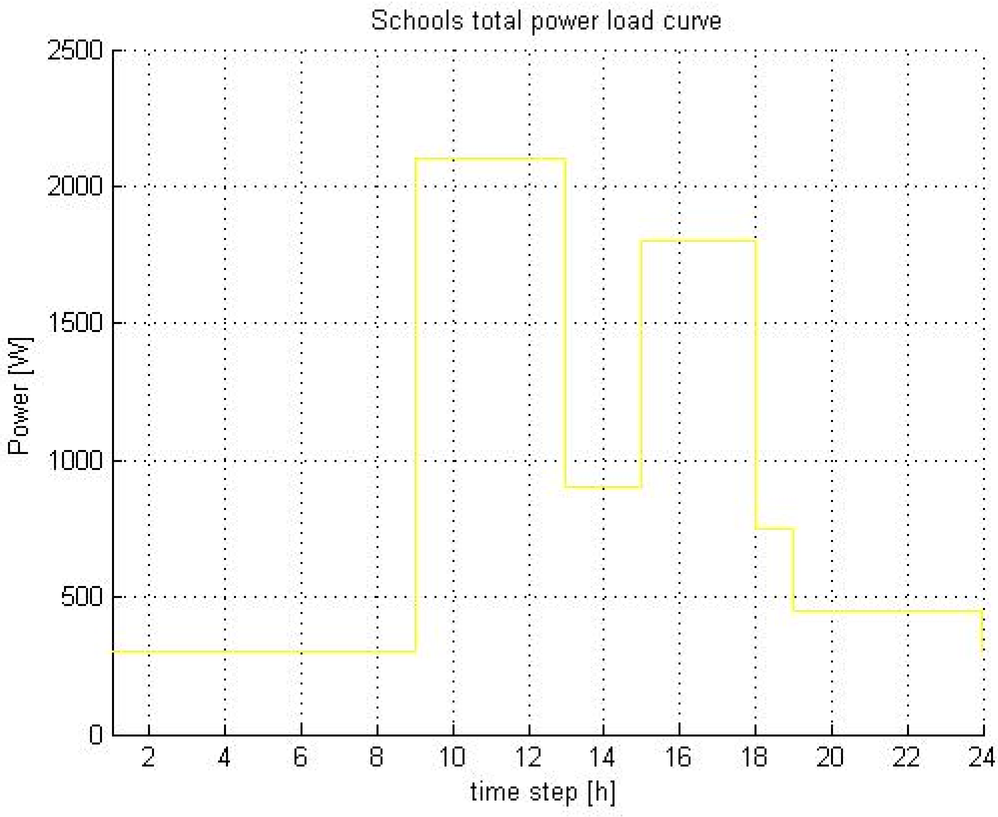

Figure 5.8: Hourly total power load demand profile of the schools [Table 5.1]

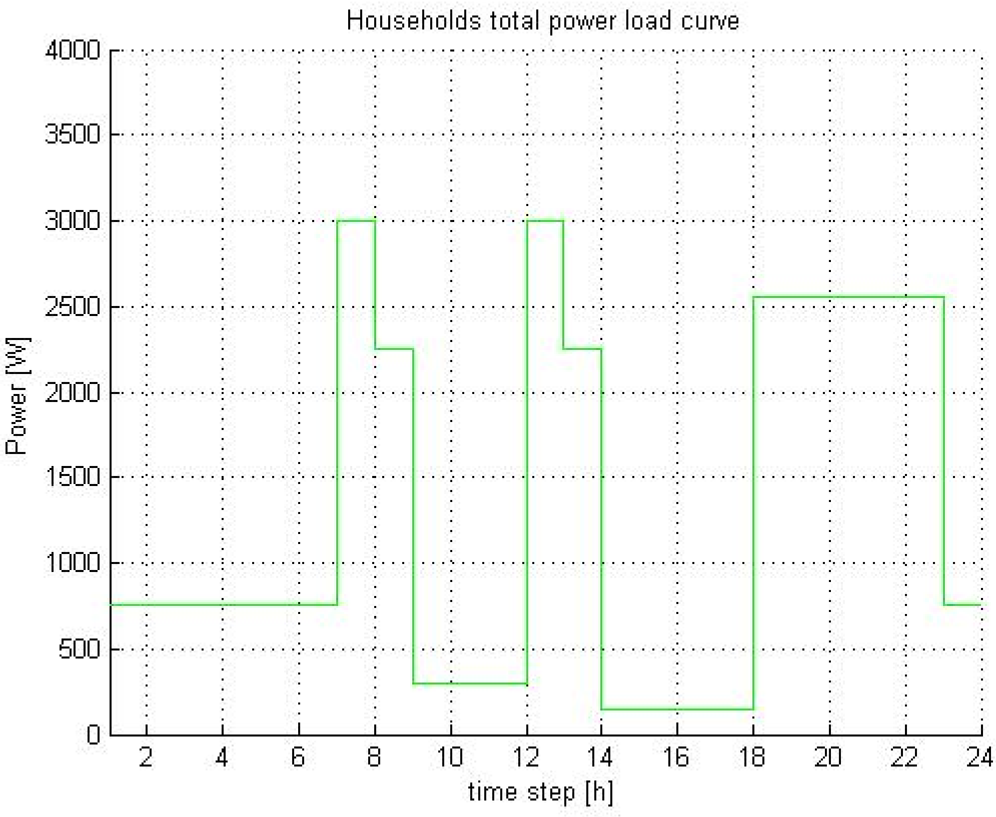

Figure 5.9: Households total power load demand profile [Table 5.1]

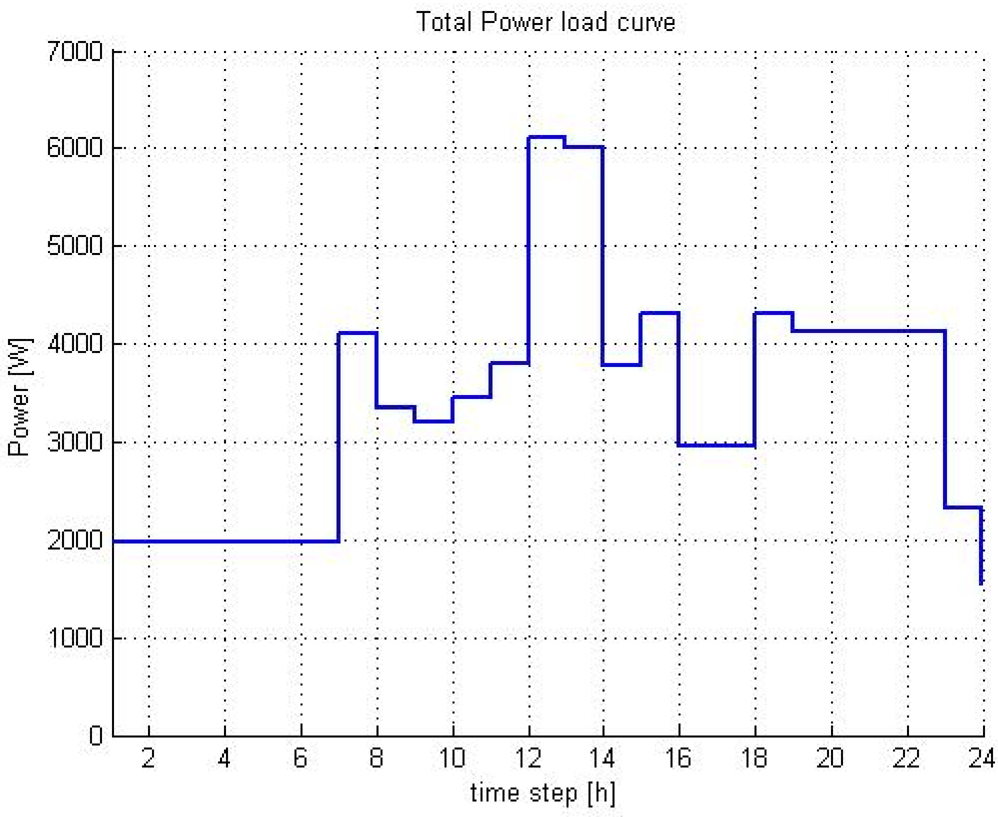

Figure 5.10: Hospital/Schools/Households/Water pumped power load demand profile [Table 5.1]

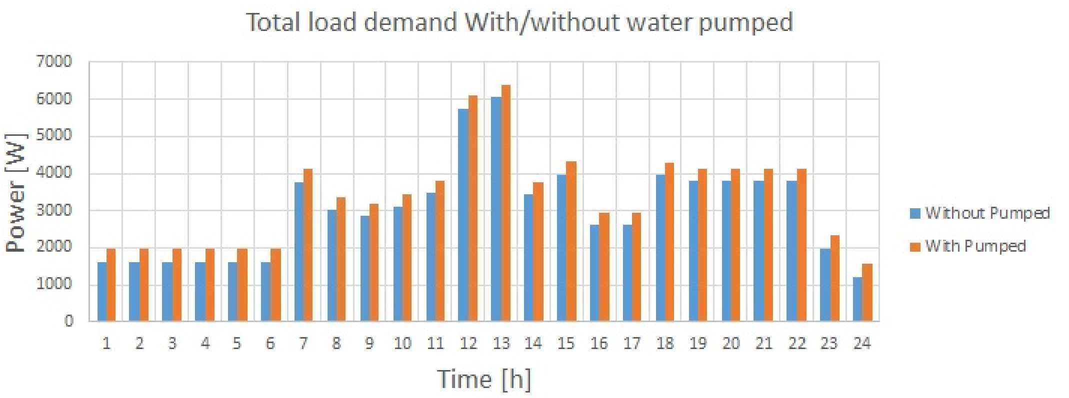

Figure 5.11: Hospital/Schools/Households/with and without Water pumped power load demand profile [Table 5.1]

cost of gasoil fuel oil in the village and it's un-availability all the time. Even though the PV source and /or wind source could ensure the power balance in the grid, the fact that wind source (see Fig.5.13) have a good production during the night time and the PV source (see Fig.5.12) a good production during the day time could be excellent but, the excess of energy production during these two period of the day have to be stored. Where the importance of a storage system uses in case of un-availability of renewable sources to reduce the fuel consumption of the diesel generator thus and reduce the cost. The fact of using the PV source and /or wind source for power balance in the grid could modified significantly the optimum sizing of the hybrid system.

Photovoltaic

The photovoltaic panel output power has been modeled using the manufacturer datasheet. The data provided by the manifacturers (I_{sc}, V_{mp}, I_{mp}, V_{oc}, α, β, I_{st}, T_{st}) are respectively short circuit current (8.95 A), voltage at maximum power (24.91 V), current at maximum power (8.23 A), open circuit voltage (29.55 V), current temperature coefficient (0.07 $A/°$C), voltage temperature coefficient (-0.38 V/C), irradiance in standard test conditions (1000 W/m^2) and temperature in standard test conditions (25°C). The peak power of the monocrystalline photovoltaic panel is 205 W. The irradiance profile of the Salak village is shown in Fig.5.12

Assuming that maximum power tracking (MPPT) is used and the photovoltaic panel is allways working at the maximum power point, to calculate the optimum operating point of voltage and current, the equations below can be

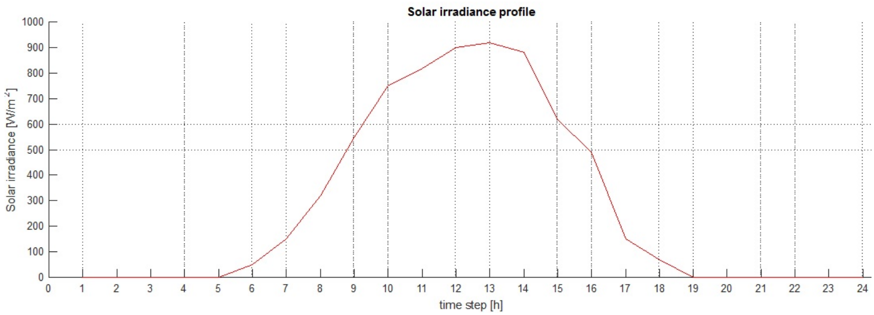

Figure 5.12: Solar irradiance of a typical day in the Salak village [5]

written as follow [160]:

$$V_{PV}(t) = N_{PVS} * V_{mp}.\left[1 + 0.0539\log.\left(\frac{I_{rr}(t)}{E_{st}}\right)\right] + \beta\left[T_a(t) + 0.02.I_{rr}(t) - T_{st}\right] \quad (5.1)$$

$$C2 = \left(\frac{V_{mp}}{V_{oc} - 1}\right) / \ln\left(1 - \frac{I_{mp}}{I_{sc}}\right) \quad (5.2)$$

$$C1 = \left(1 - \frac{I_{mp}}{I_{sc}}\right) exp\left[\frac{-V_{mp}}{C2V_{oc}}\right] \quad (5.3)$$

$$I_{PV}(t) = N_{PVP} * Isc.\{1 - C1\left(exp\left(\frac{Vmp}{C2.Voc}\right) - 1\right)\} + \alpha.\left(\frac{I_{rr}(t)}{E_{st}}\right)(T_{cell} - T_{st}) + I_{sc}.\left(\frac{I_{rr}(t)}{E_{st}} - 1\right) \quad (5.4)$$

where, $T_{cell} = T_a(t) + 0.02.I_{rr}(t)$ and I_{rr}(t) is the solar irradiation of the 24 hours of the day [W/m^2/h]. The daily solar irradiation matrix (m x n) and tempearture matrix (m x n) are composed each by twenty four rows and one column (24 1).

The output power of the photovoltaic array is calculated as

$$P_{PV}(t) = I_{PV}(t) * V_{PV}(t) \quad (5.5)$$

where, N_{PVP} and N_{PVS} are respectively the number of photovoltaic panels in parallel and in series, I_{PV}(t) [A] is the instantaneous current of the photovoltaic panel and V_{PV}(t) [V] is the instantaneous voltage of the photovoltaic panel. The peak power generated from a single solar panel is 180 Wp. To obtain a total 3 kWp peak power generated from solar panels, it has been assumed a number of panels in parallel N_{PVP}=6 and in series N_{PVS}=3.

Wind turbine

Wind energy is transformed into mechanical power through wind turbine and then converted into electrical power through wind generator. The measurement of wind speed in the Salak village has been made at height 10 m (Fig.5.13).

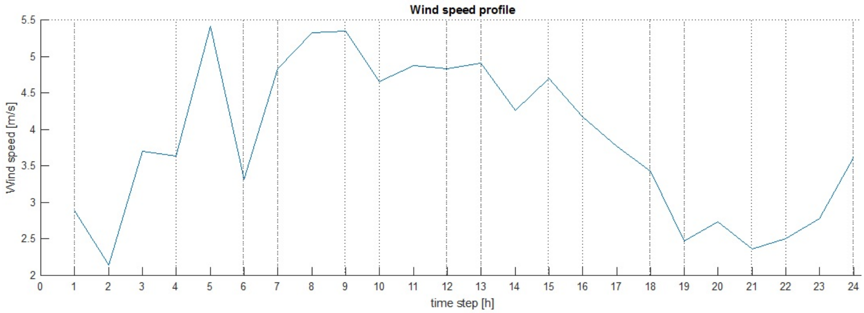

Figure 5.13: Wind speed in a typical day in Salak village [5]

The average speed is between (3-6 m/s) from 09:00 AM to 03:00 PM for more than eight months a year [136]. The wind turbine selected has a rated output power of 1500 W. With a three blades horizontal axis, a gearless, brushless permanent magnet, a voltage rate of 125 VAC. The cut-in speed is 2.5 m/s and a rated speed of 16 m/s. The swept area of the wind turbine is 6.8 m^2 while the frequency is 50 Hz. The model based on cubic law [150] and [151] evaluates the hourly average wind speed that can be converted into power density [W/m^2] through a wind turbine generator as

$$\begin{cases} P_{Wind}(t) = aV(t)^3 - bP_r \\ V_{ci} \leq V \leq V_r \end{cases} \tag{5.6}$$

$$\begin{cases} P_{Wind} = 0 & V \leq V_{ci} \\ P_{Wind} = P_r & V_r \leq V \leq V_{co} \\ P_{Wind} = 0 & V \geq V_{co} \end{cases} \tag{5.7}$$

where, $a = \frac{P_r}{V_r^3 - V_{ci}^3}$ and $b = \frac{V_{ci}^3}{V_r^3 - V_{ci}^3}$; Power rated of the wind generator P_r [W]; V_r is the rated speed of the wind generator [m/s]; V_{ci} is the wind at the cut-in [m/s]; V_{co} is the wind speed at the cut-out [m/s]; $V(t)$ is the wind speed at any instant [m/s].

The two-parameter Weibull probability distribution function has been generally used in scientific literature to express the wind speed frequency distribution and to estimate the wind power density. Its is the most appropriate distribution function for wind speed data as it gives a good fit to the observed wind speed data both at surface and in the upper air. Weibull distribution can be characterized by its probability density function f(V) and cumulative distribution function F(V)

$$f(V) = k\frac{V^{k-1}}{c^k}exp\left(\frac{-V}{c}\right)^k \tag{5.8}$$

$$F(V) = 1 - \exp[-(\frac{V}{c})^k] \tag{5.9}$$

Many numerical methods are used to estimate the dimensionless shape k, and the shape c, parameters of the Weibull probability distribution function. In this work, the graphical method are been used. The graphical method requires that wind speed data be in cumulative frequency distribution format. Time-series data must therefore, first be sorted into bins. In this distribution method, the wind speed data are interpolated by a straight line, using the concept of least squares regression [161]. The logarithmic transformation is the foundation of this method. By converting the Eq.5.9 into logarithmic form, the Eq.5.10 is obtained:

$$\ln[-\ln(1 - F(V))] = k * \ln(V) - k * \ln(c) \tag{5.10}$$

The Weibull shape and scale parameters are estimated by plotting $\ln(V)$ against $\ln[-\ln(1 - F(V))]$ in which a straight line is determined. In order to generate the line of best fit, extract the line parameters (y=a*ln+b) using the polyfit function. The Weibull shape parameter k=a is the slope of the line and the y-intercept is the value of the term -k$*$ln(c) and c= exp($\frac{-b}{a}$)

where k, c, V are respectively the weibull shape parameter, the weibull scale parameter and the wind speed. Electrical power available from the wind turbine is given by the following equation:

$$P_W(t) = A * F(V) * P_{Wind}(t) \tag{5.11}$$

Where, Pwind is the power density of the wind generator [W/m^2]; A is the area swept by the wind blade [m^2]. The power produced by the wind turbine is alternating with 125 VAC. Since the voltage of the end user is 220 Volts with a frequency of 50 Hz, the transformer have to be used to elevate the voltage to 220 V. The total renewable power is deducted as

$$P_{re}(t) = P_{PV}(t) + P_W(t) \tag{5.12}$$

Battery

The battery is used for a dual purpose: (i) stored the excess of power generated from renewable sources or the diesel generator after the load demand have been satisfied; (ii) discharged the power stored to supply the load demand when needed. The battery has a dual consideration: (i) as a generator when it delivers power to supply the load and (ii) also as an accumalator when the surplus of power from renewables is used to charge the low battery. The diesel generator can also charged the battery when there is less or no generation from renewables. During the discharging process, the state of charge of the battery can be expressed as

$$SOC(t) = SOC(t-1) + \eta_{discharge}\left(\frac{-P_{bat}(t)}{ASE\max}\right).\Delta_t \tag{5.13}$$

During the charging process, the state of charge of the battery can be expressed as

$$SOC(t) = SOC(t-1) + \eta_{charge}\left(\frac{P_{bat}(t)}{ASE\max}\right).\Delta_t \tag{5.14}$$

At every instant of the day or the year, the state of charge and the power of the battery is between the minimum and the maximum value.

$$SOC\min \leq SOC(t) \leq SOC\max \tag{5.15}$$

$$P_{bat}\min \leq P_{bat}(t) \leq P_{bat}\max \tag{5.16}$$

where, $P_{bat}(t)$ is the power of the battery at time t [W], $ASE\max$ is the maximum average stored energy [Wh], Δ_t is the time step, η_{charge} and $\eta_{discharge}$ are respectively the efficiency of the battery during charging and discharging process [%]. The power of the battery used is 3 kW (3000 W) with a charging and discharging time period of 6 hours, the maximum average stored energy of the battery is 18 kWh (18000 Wh).

Lifetime of the battery and the rainflow counting method

The lifetime of the battery can be considered in many ways: either with the length of time the battery can run on a fully charged mode or the number of charge/discharge cycles possible before the cells fail to operate satisfactorily. According to the Miners rule, the partial damage of a battery is defined by the ratio between the number of cycles performed at a certain depth of discharge and the number of cycles that would cause the rupture of the battery at the same depth of discharge (5.17). The Miners rule also stipulates that the damages are additive. Therefore, the rupture occurs when the sum of the damages reaches the unit [162]. It is then possible to predict the battery lifetime based on 5.19. However, the evolution of the battery state of charge consists in many cycles with different depths. That is why, the *rainflow* counting method is used [163]. This method, commonly used in material fatigue analysis, divides the evolution of the SOC in partial cycles. Then, each partial cycle is associated with a partial damage. The battery lifetime depends mainly on the number of cycles and on the depth of discharge. The characteristic of the damage of the battery is given in Fig.5.14 and equation 5.17 and can be calculated by the equation:

$$CF_i = a_i e^{b_i DOD} + b_i e^{b_i DOD} \tag{5.17}$$

where a_i and b_i are fitting constants used to approximate the curve; DOD [%] is the depth of discharge. At the end of the simulation, the fractional total damage (D) can be calculated as:

$$D = \sum_{i=1}^{n} N_i \frac{1}{CF_i} \tag{5.18}$$

The lifetime of the battery can be calculated as:

$$Lifetime_{Battery} = \frac{1}{\sum_{i=1}^{n} (\frac{N_i}{CF_i})} \tag{5.19}$$

where N_i represents the number of partial cycles, n represents the number of fraction of the amplitude (DOD).

The datasheet of a lead acid battery characteristics have been used to approximate the number of cycle of damage CF_i and calculate the fitting constants value.

Table 5.3: Depth of discharge versus number of cycle of a Lead-acid battery [12]

Depth of Discharge [%]	approximate N° cycle
100	250
50	550
30	1200
10	4100

Using the Table 5.3 and the fitting curve toolbox in matlab, we can approximate the equation of the cycle of damage and calculate the fitting constants

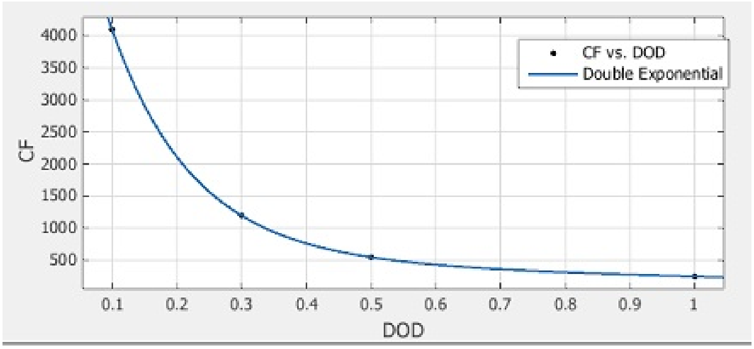

Figure 5.14: Battery lifetime and depth of discharge [12]

value which would be use to calculate the lifetime of the battery:

$$Y = 7782e^{-8.038.DOD} + 679.7e^{-1.01.DOD} \tag{5.20}$$

Diesel generator

The nominal voltage of the diesel generator can matched the AC and DC bus nominal voltage. In case of DC bus voltage, a conversion system has to be put in place for that. In this case study, the diesel generator works only when energy from renewable are less than load and the battery bank is not able to delivery energy at the time step. The diesel generator can be modeled as an hourly fuel consumption function

$$\begin{cases} F(t) = mP_{DG} + qP_n \\ F(t) = mX_t + q \\ or \\ F(t) = 0 \end{cases} \tag{5.21}$$

$$\begin{cases} 0.25 \leq X_t \leq 1 \\ or \\ X_t = 0 \end{cases} \tag{5.22}$$

At every instant of the day or the year, the diesel generator works between the minimum (P_{DG} min) and the maximum (P_{DG} max) value (nominal output power P_n). The diesel generator can also be out of service ($P_{DG} = 0$).

$$\begin{cases} P_{DG}\min \leq P_{DG}(t) \leq P_{DG}\max \\ P_{DG}\min \leq P_{DG}(t) \leq P_n \\ or \\ P_{DG}(t) = 0 \end{cases} \tag{5.23}$$

where $F(t)$ is the hourly fuel consumption of the diesel generator $[L/h]$, P_{DG} is the hourly power generated by the diesel generator $[kW]$, P_n is the nominal power of the diesel generator $[kW]$, X_t is the operating point of the diesel generator $(\frac{P_{DG}}{P_n})$ in $[\%]$, m is the slope of the line $[L/kWh]$ and q is the intercept of the line crosses the y-axis $[L/kWh]$.

A wide research has been done to retrieve such operating point for small size generators and would be listed in Table 5.4. Therefore, the diesel generator work as a discontinuous system 5.23.

To modeled the diesel generator as a hourly fuel consumption function ($F(t)$), (i) it has been schedule in Table 5.4, different diesel generators and their corresponding fuel consumption at any different operating point, (ii) it has been built and plotted a graph with corresponding XY axis using data of Table 5.4, (iii) an analysis of the graphs and the linear trendlines have been made 5.15.

The diesel generator must work between the minimum to maximum operating point inside its best efficient area of operation, the diesel generator can be also out of service, increasing the long life of the diesel generator and also reducing the fuel consumption.

Table 5.4: Fuel Consumption vs operating point retrieve on eleboration made on different diesel generator manufacturers

Operating Pdg/Pn [%]	Fuel 4 kW [L/h]	Fuel 5 kW [L/h]	Fuel 6 kW [L/h]	Fuel 7 kW [L/h]	Fuel 9 kW [L/h]	Fuel 10 kW [L/h]	Fuel 11 kW [L/h]	Fuel 15 kW [L/h]
0	0	0	0	0	0	0	0	0
25	0.8	1	1.3	1.1	1.1	1.2	1.01	1.8
50	1	1.3	1.7	1.5	1.8	1.9	1.71	3.6
75	1.3	1.7	2.1	1.9	2.6	2.5	2.47	3.8
100	1.7	2.1	2.6	2.6	3.4	3.5	3.29	5

Water pumped system

The Salak village, located in the sahara zone with difficulty of water availability, it has been proposed to look for water under ground to supply hot water

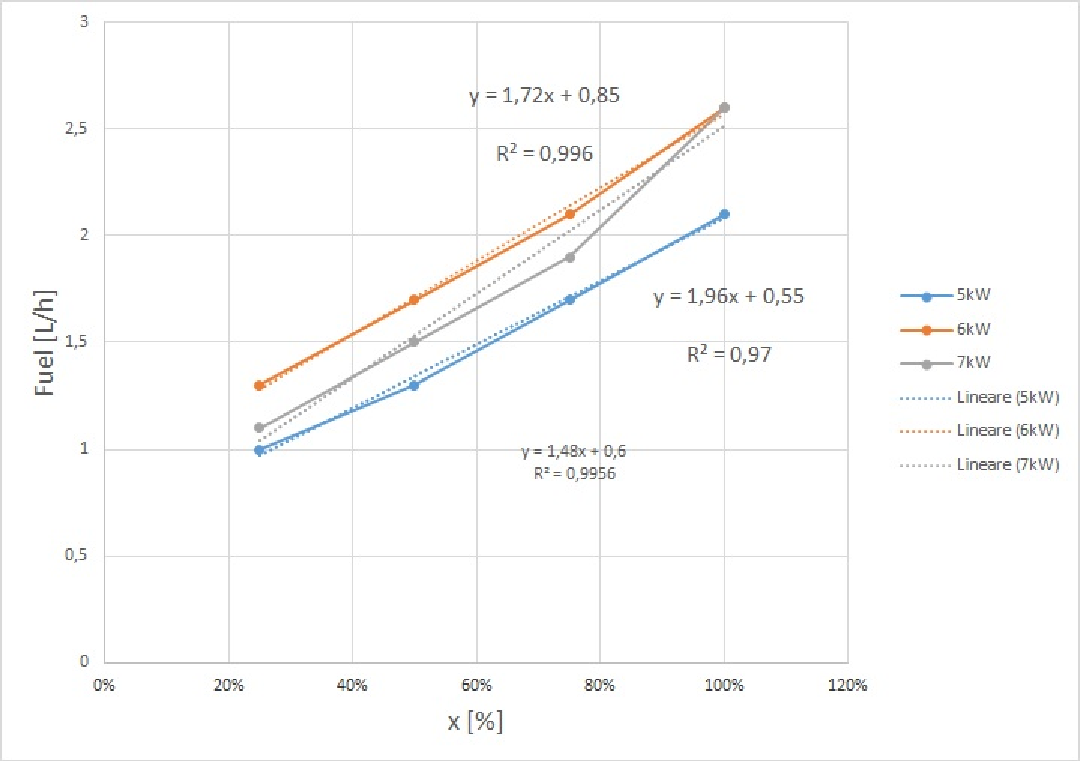

Figure 5.15: Graph build using value of Table 5.4 with the linear trendline

production for the hospital needs and clean water for the village inhabitants network distribution. The daily water consumption of the inhabitants of Salak village have been schedule (Fig.5.17) and been used water pumped size and water tank reservoir. The daily amount of water consume is 12600 liters (12.6 m^3). The water reservoir has a storage capacity of 15 m^3. The suction head of the well is 15 meters under the village surface level. The water reservoir tank has to be installed at the head of 20 meters upper the water pumped motor. The water pumped power can be calculated with the follow equation

$$P_{pump} = \frac{\rho.g.H_m.Q}{\eta_p} \tag{5.24}$$

where P_{pump} is the power of the water pumped motor $[W]$, ρ is the density of water (1000kg/m^3), g is the acceleration due to gravity ($9.81m/s^2$), H_m is the total head $[m]$, Q is the water flow rate $[m^3/s]$, η_p is the overall water pumped efficiency [%].

The total head has been calculated taking into account the total losses in the suction head and the discharge head. The friction losses (Y_c) and the losses in the pipe (Y_d) can be calculate as

$$\begin{aligned} Y_c &= \sum_{i=1}^{N} k_i \frac{v_i^2}{2g} \\ Y_d &= \sum_{i=1}^{N} f_i \frac{v_i^2}{2g} \frac{L_i}{D_i} \\ Y_m &= Y_c + Y_d \end{aligned} \tag{5.25}$$

where, N is the number of obstacles, k_i is the coefficient related to the ostacles, v_i is the speed of the water in the pipe $[m/s]$, f_i is the coefficient of friction and has been determined through interpolation in Moody Diagram 5.16, L_i is the head of the pipe $[m]$, D_i is the diameter of the section of the pipe and Y_m is the total losses in water pumping system $[m]$. The total head of the water pumping system is calculated as

$$H_m = \frac{P}{\rho.g} + Z_1 - Z_0 + Y_m \tag{5.26}$$

where, P is the pressure of the water in the well $[N/m^2]$, Z_1 is the head of discharge $[m]$ and Z_0 is the suction head $[m]$.

For the Salak case study, it would have been interesting to size and design a solar thermal system instead of using an electric boiler or use the combination of both systems for hot water production for sanitary use. This would have ensured the robustness of the system and prevented weather uncertainties.

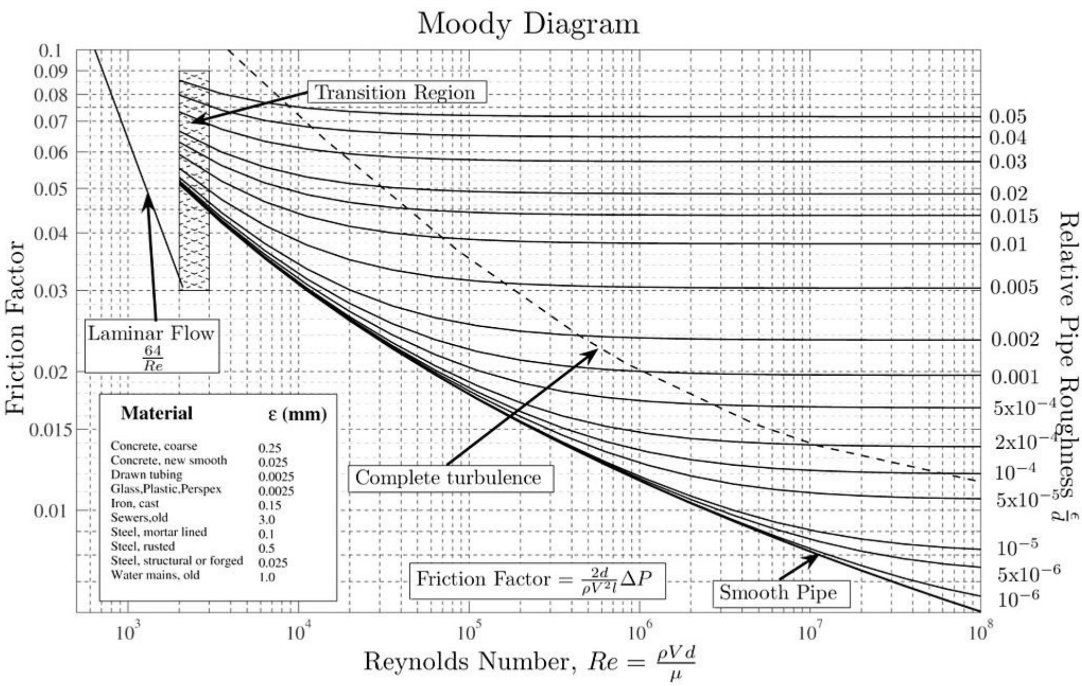

Figure 5.16: Moody Diagram [13]

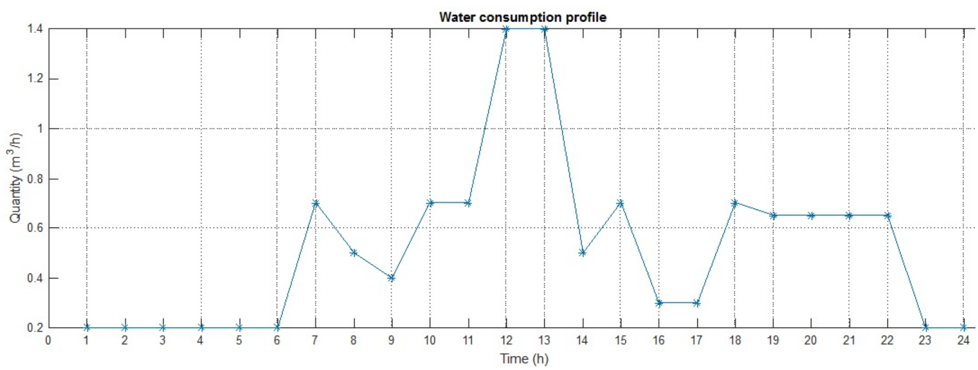

Figure 5.17: Hourly daily water consumption profile

But the reason of using electricity for hot water production derives from the rule-based philosophy and the fact that, the hot water for sanitary use is not the priority but an optional. Thus, hot water is produced only when the load demand is satisfied, the battery is fully charged and there is excess of power generated from renewable sources (PV+Wind). The size of the water tank is not taken as a design parameter but as an electrical load because the priority of the study is the electrification of the Salak village. Because of lack of water in the village community, it has been decided to size a water tank for potable water distribution and avoid inhabitants to work for several kilometers to have a bocket of water with all the inconveniences. For all these reasons, the size of the water pump system has been made to determine the electrical power of the water pump and used the water pump as an electrical load.

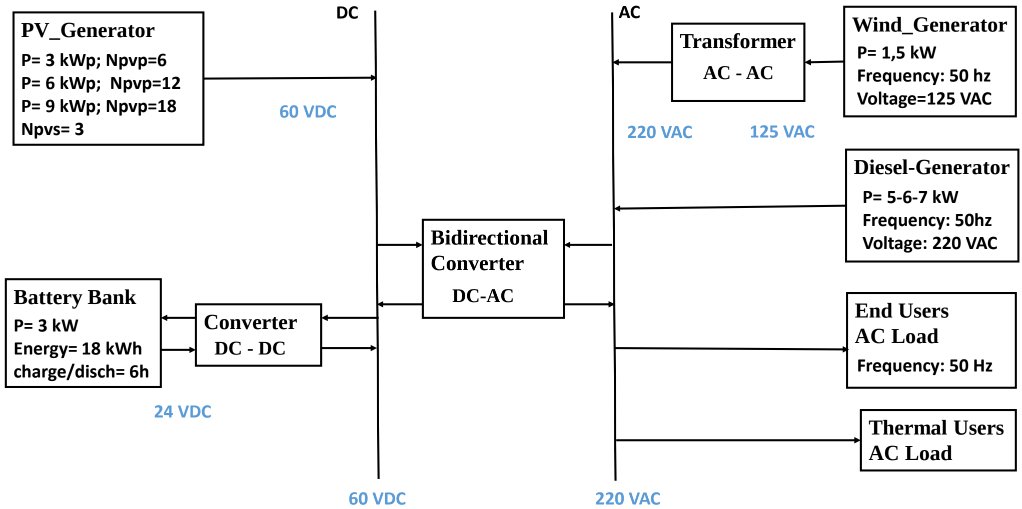

Figure 5.18: One possible configuration for interconnecting different sources of the hybrid energy system

5.4.3 Scenarios 0-1-2-3 and simulations

The scenarios have been constructed with the following criteria: (i) only the diesel generator supplying the load to evaluate what can be the fuel consumption; (ii) the supply of the load by the hybrid system with the variable step size of the PV generator (3/6/9kWp) and the diesel generator (5/6/7kW) while, the size of the battery (3kW) and the wind turbine generator (1.4kW) do not vary. This scenarios would help to well analyzed the better sizing of the PV panel, the diesel generator and whether the battery over/under sized. The peak powers selected in the different scenarios for solar panels are: 3, 6 and 9 kWp; the powers of the diesel generators are 5, 6 and 7 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours (6h).

Scenario0: Only the diesel generator supplies the load

In this scenario, the load demand is powered only by the diesel generator. The power rated of the diesel generator here is 7 kW. Fig.5.19 and 5.20 show respectively the behaviour of the system powered only by the diesel generator and the cumulative fuel consumption during the day depending on the power generated by the diesel generator. The load demand is covered by the diesel generation while working in its operating points limit values.

Table 5.5: Summary of results obtained when the load is supplied only by the diesel generator 5.4.3 (Scenario0)

P_{DG} [kW]	Fuel consumption [L/day]
7	37.461

Scenario 1-1

The peak power selected in this three scenarios for solar panels is 3 kWp; the powers of the diesel generator are 5 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

Table 5.6: Results obtained 5.4.3 (Scenario 1-1)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
3	1.4	5	3	18.17	547

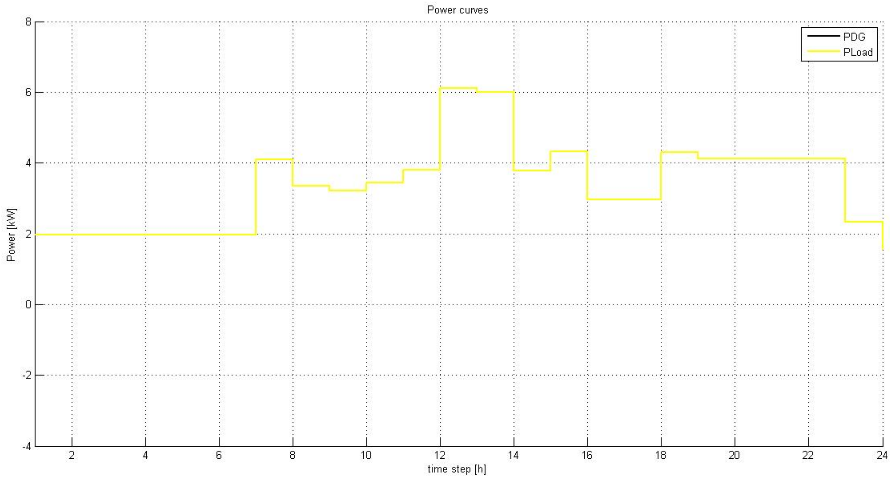

Figure 5.19: The load only powered by the diesel generator (Scenario0)

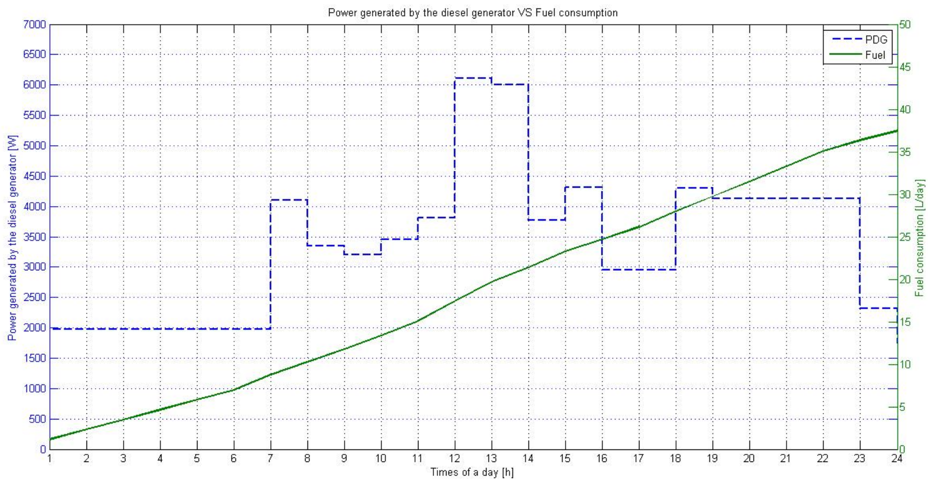

Figure 5.20: Behaviour of the diesel generator with fuel consumption during the day (Scenario0)

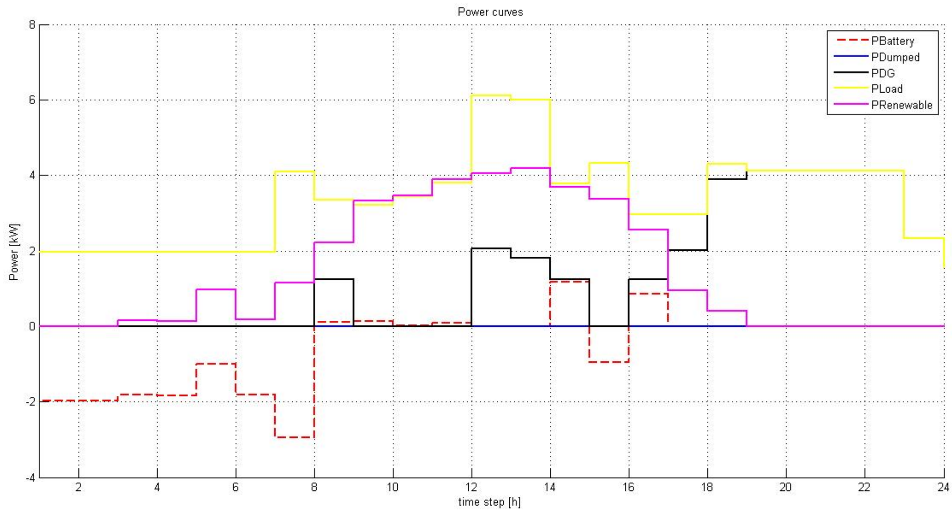

Figure 5.21: Behaviour of the generating power during the day (Scenario 1-1)

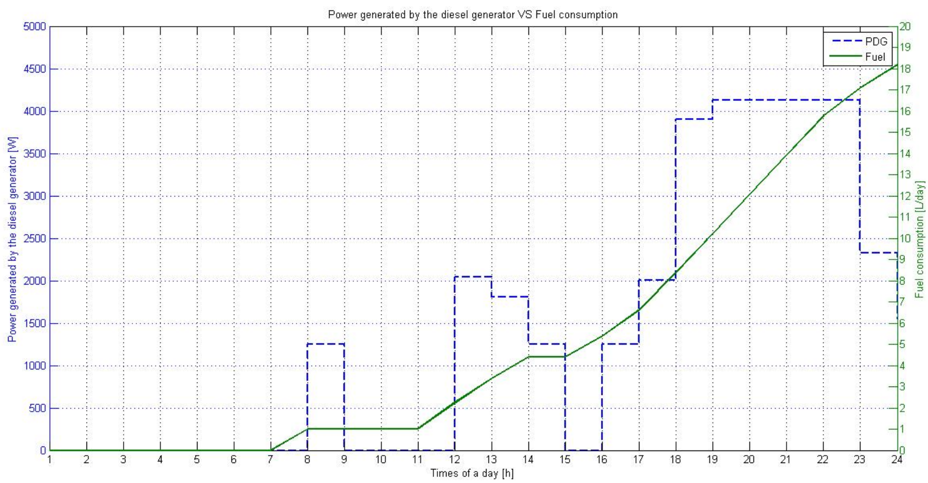

Figure 5.22: Behaviour of the diesel generator with fuel consumption during the day (Scenario 1-1)

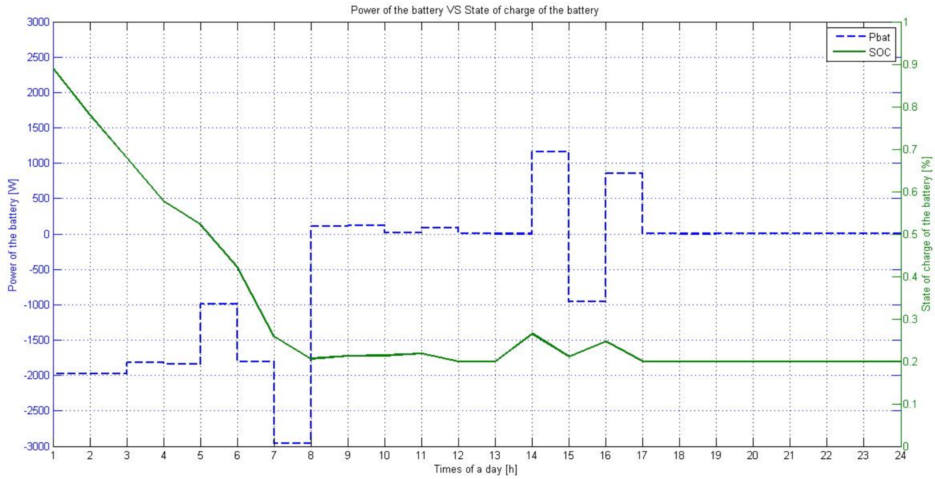

Figure 5.23: Behaviour of the battery and the state of charge during the day (Scenario 1-1)

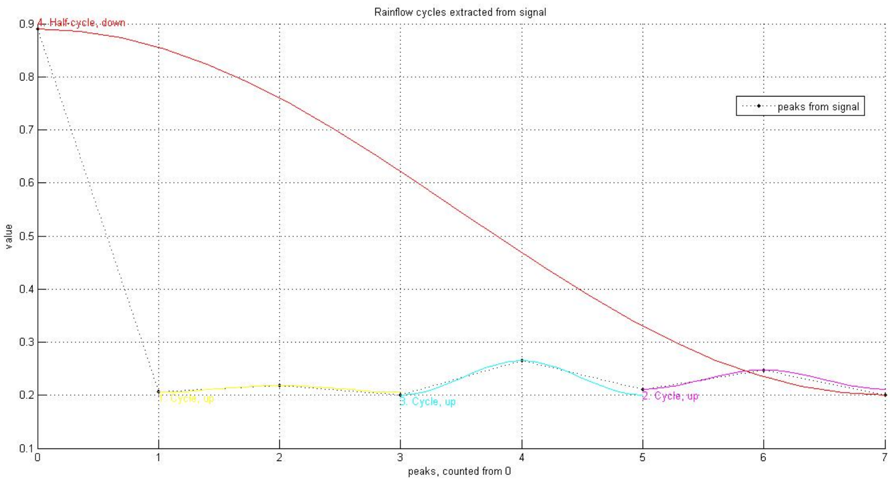

Figure 5.24: Rainflow count extracted from the state of charge value (Scenario 1-1)

Scenario 1-2

The peak power selected in this three scenarios for solar panels is 6 kWp; the powers of the diesel generator are 5 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

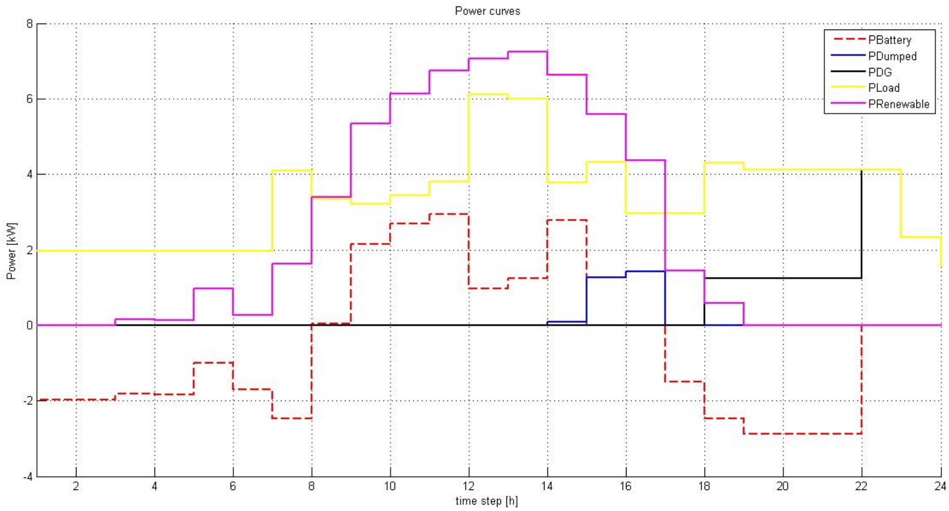

Figure 5.25: Behaviour of the generating power during the day (Scenario 1-2)

Table 5.7: Results obtained 5.4.3 (Scenario 1-2)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
6	1.4	5	3	8.24	242

Scenario 1-3

The peak power selected in this three scenarios for solar panels is 9 kWp; the powers of the diesel generator are 5 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

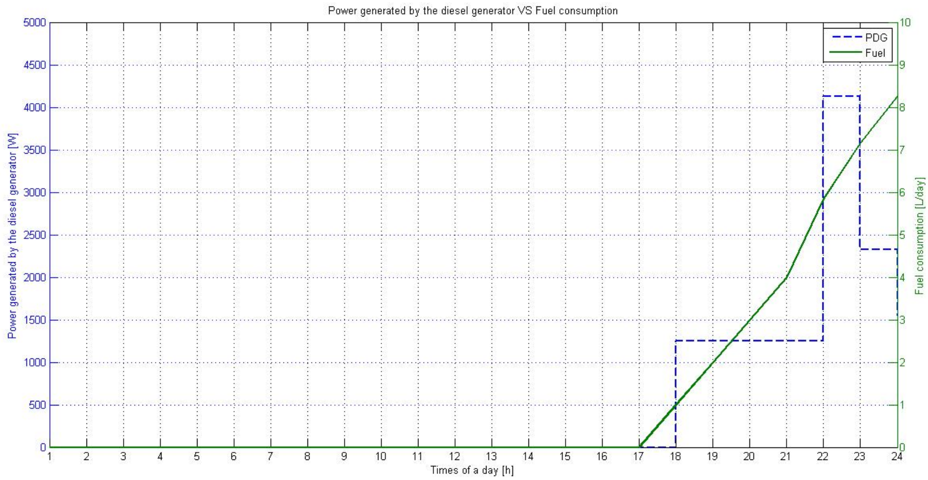

Figure 5.26: Behaviour of the diesel generator with fuel consumption during the day (Scenario 1-2)

Table 5.8: Results obtained 5.4.3 (Scenario 1-3)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
9	1.4	5	3	8.24	251

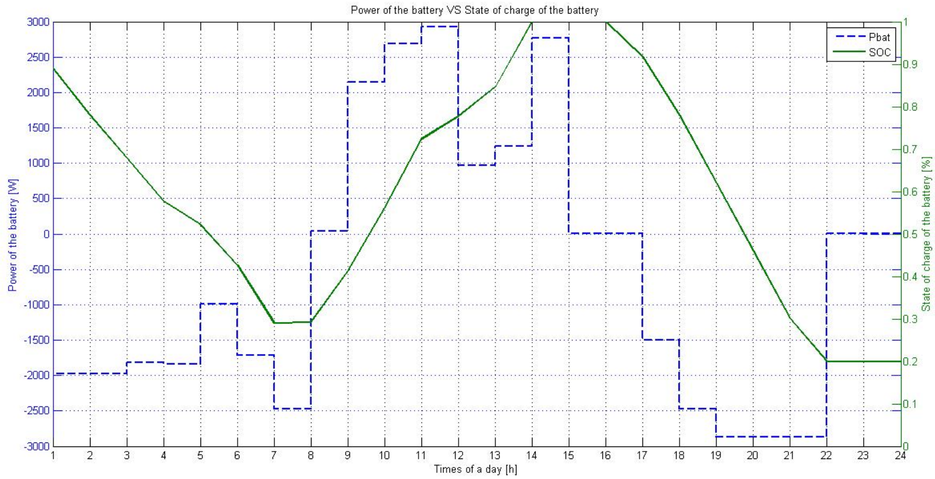

Figure 5.27: Behaviour of the battery and the state of charge during the day (Scenario 1-2)

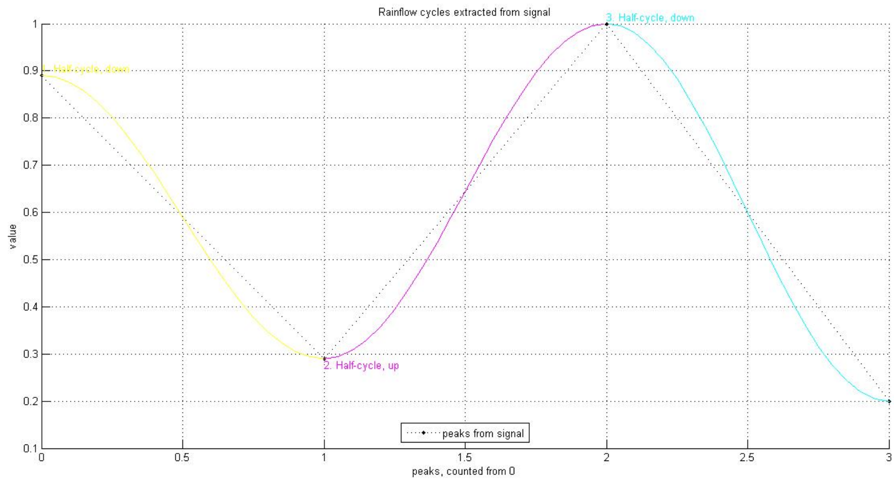

Figure 5.28: Rainflow count extracted from the state of charge value (Scenario 1-2)

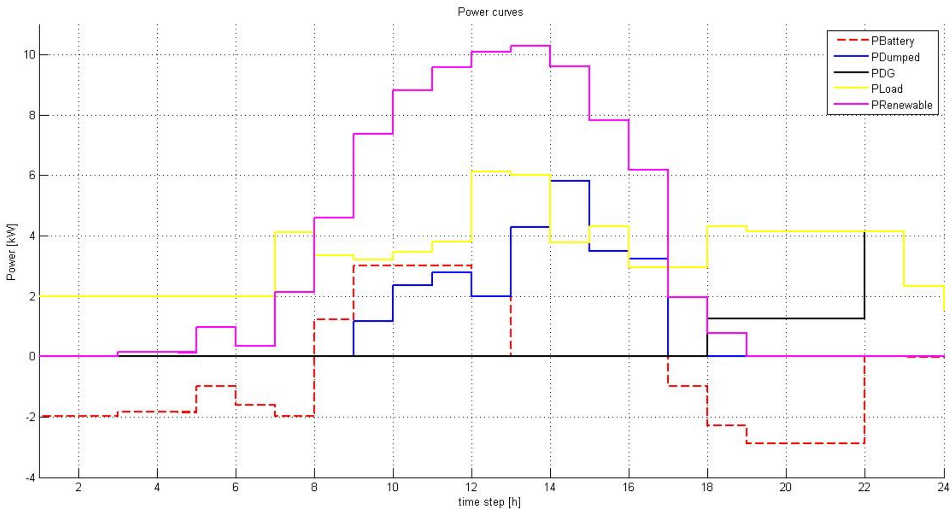

Figure 5.29: Behaviour of the generating power during the day (Scenario 1-3)

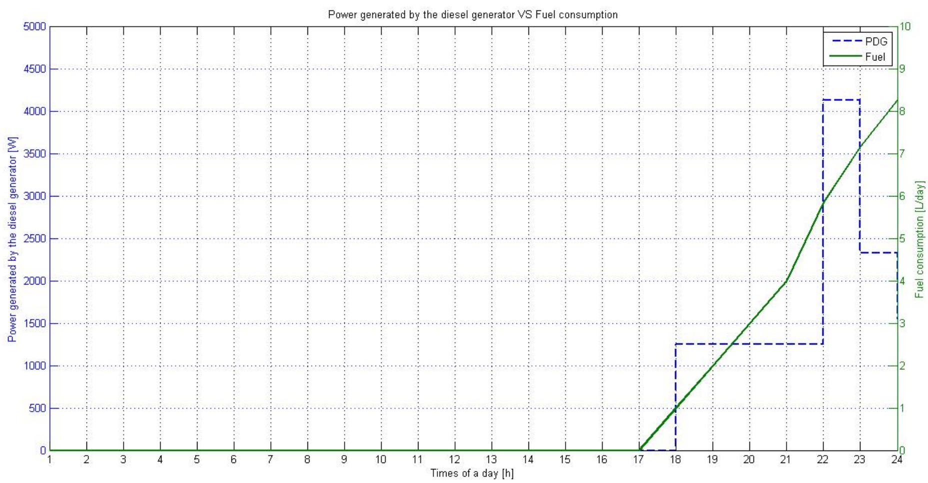

Figure 5.30: Behaviour of the diesel generator with fuel consumption during the day (Scenario 1-3)

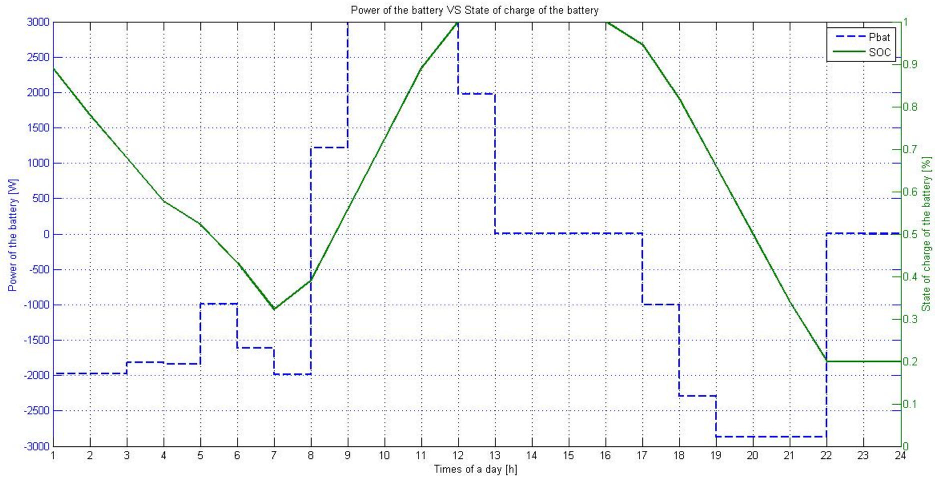

Figure 5.31: Behaviour of the battery and the state of charge during the day (Scenario 1-3)

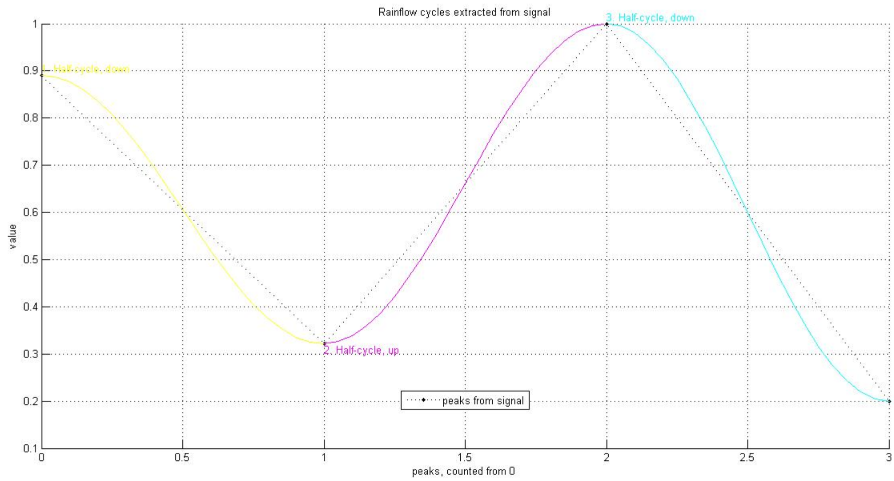

Figure 5.32: Rainflow count extracted from the state of charge value (Scenario 1-3)

Scenario 2-1

The peak power selected in this three scenarios for solar panels is 3 kWp; the powers of the diesel generator are 6 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

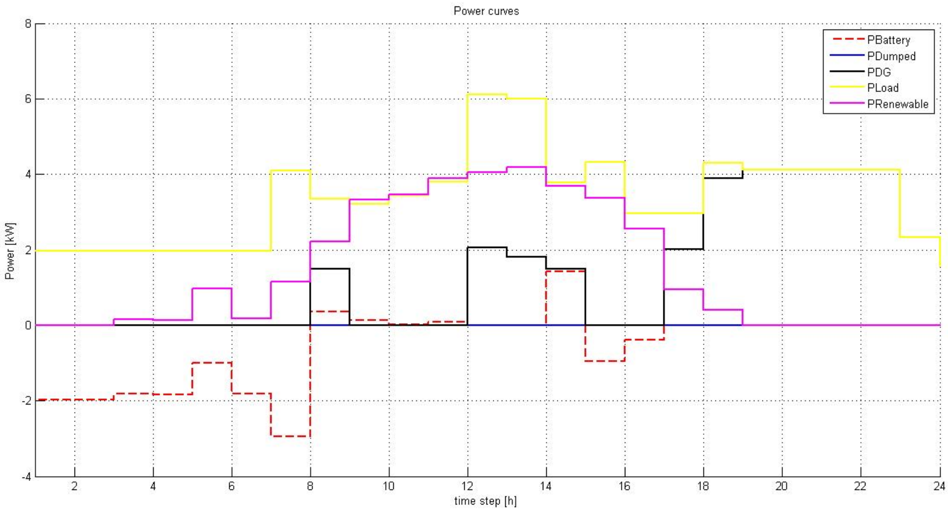

Figure 5.33: Behaviour of the generating power during the day (Scenario 2-1)

Table 5.9: Results obtained 5.4.3 (Scenario 2-1)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
3	1.4	6	3	19.97	590

Scenario 2-2

The peak power selected in this three scenarios for solar panels is 6 kWp; the powers of the diesel generator are 6 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

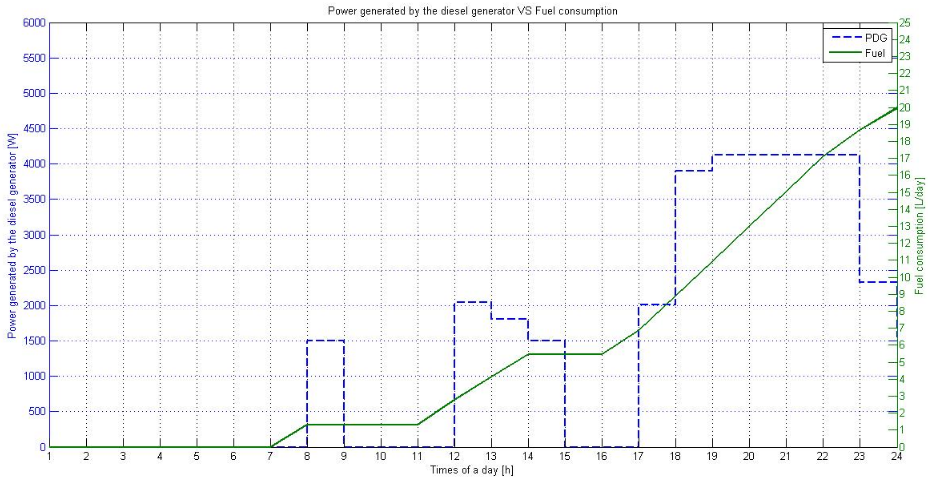

Figure 5.34: Behaviour of the diesel generator with fuel consumption during the day (Scenario 2-1)

Table 5.10: Results obtained 5.4.3 (Scenario 2-2)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
6	1.4	6	3	10.11	242

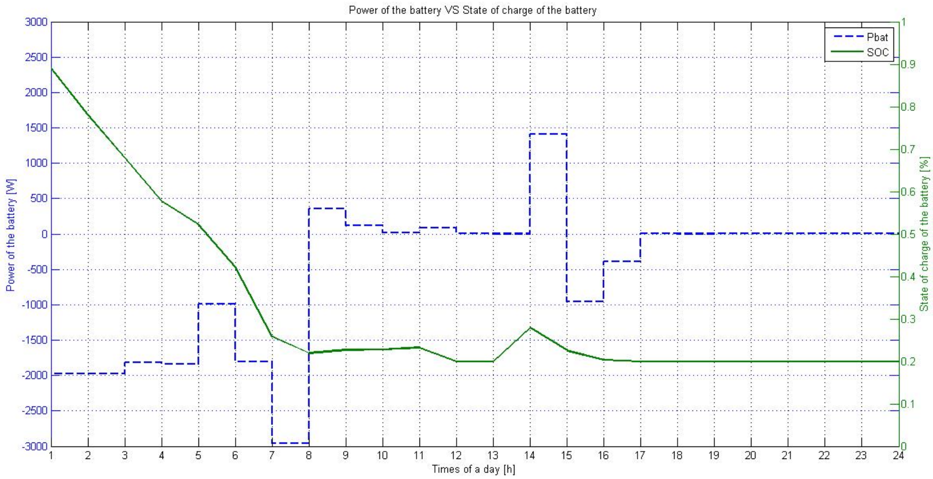

Figure 5.35: Behaviour of the battery and the state of charge during the day (Scenario 2-1)

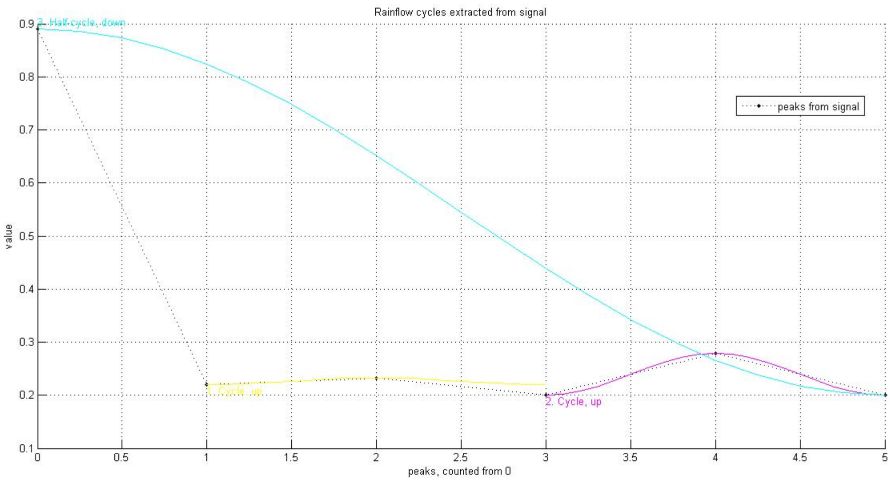

Figure 5.36: Rainflow count extracted from the state of charge value (Scenario 2-1)

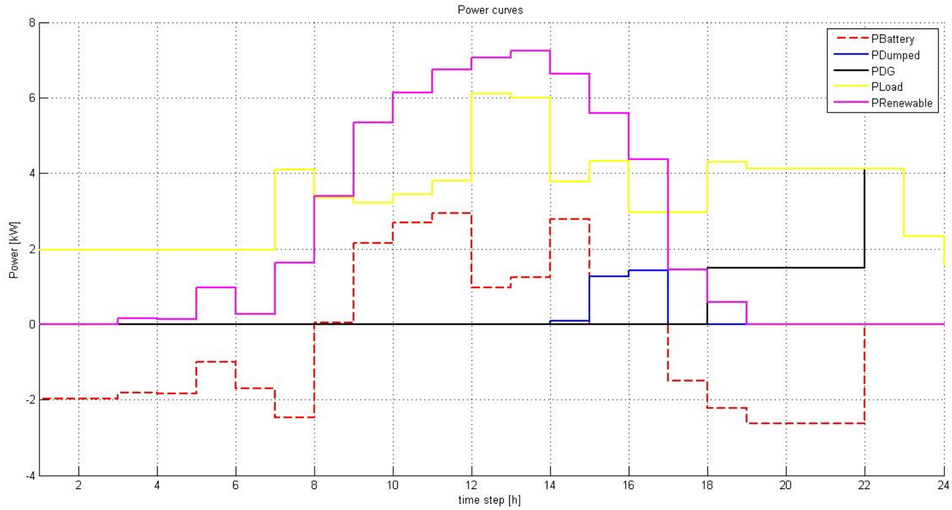

Figure 5.37: Behaviour of the generating power during the day (Scenario 2-2)

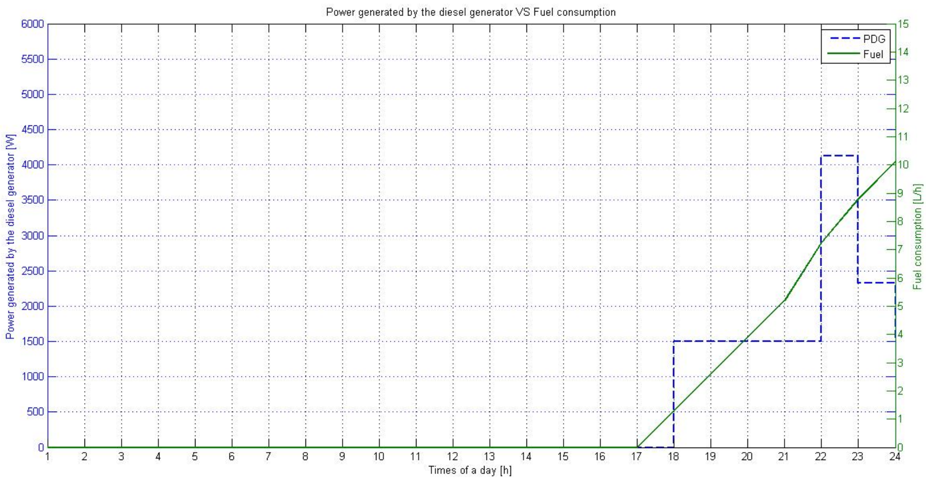

Figure 5.38: Behaviour of the diesel generator with fuel consumption during the day (Scenario 2-2)

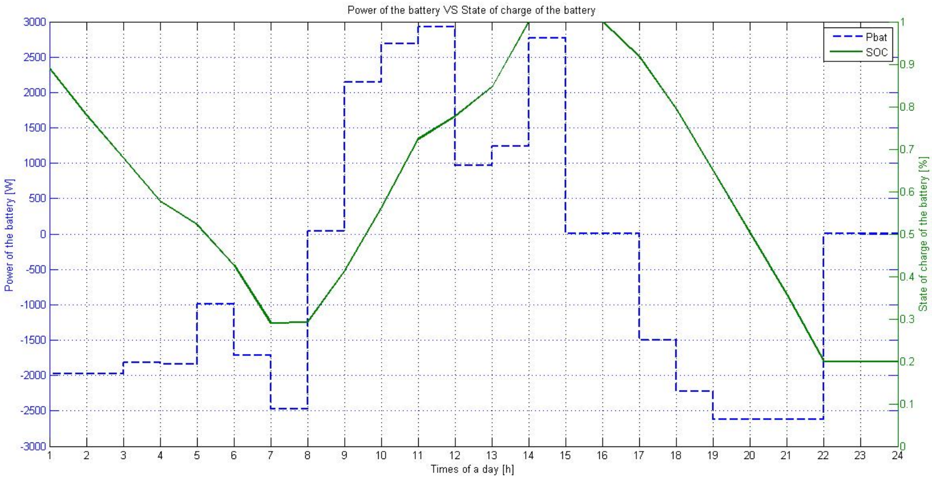

Figure 5.39: Behaviour of the battery and the state of charge during the day (Scenario 2-2)

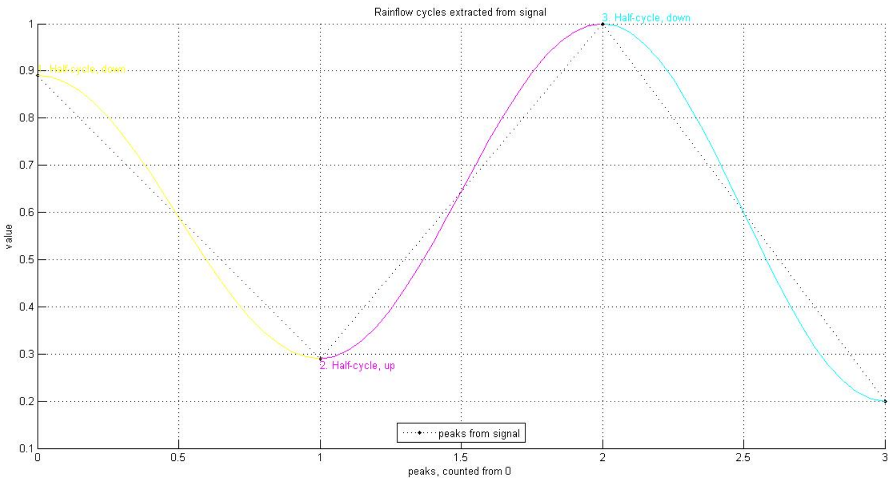

Figure 5.40: Rainflow count extracted from the state of charge value (Scenario 2-2)

Scenario 2-3

The peak power selected in this three scenarios for solar panels is 9 kWp; the powers of the diesel generator are 6 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

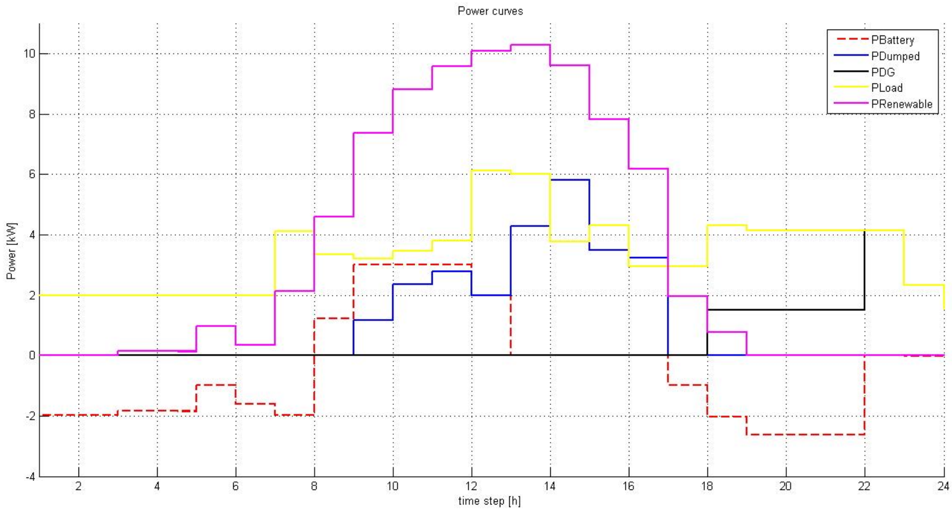

Figure 5.41: Behaviour of the generating power during the day (Scenario 2-3)

Table 5.11: Results obtained 5.4.3 (Scenario 2-3)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
9	1.4	6	3	10.11	251

Scenario 3-1

The peak power selected in this three scenarios for solar panels is 3 kWp; the powers of the diesel generator are 7 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

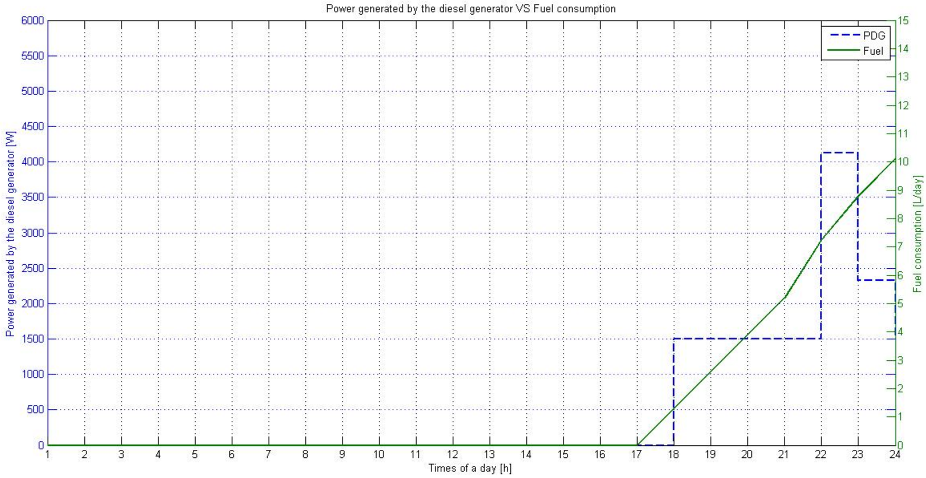

Figure 5.42: Behaviour of the diesel generator with fuel consumption during the day (Scenario 2-3)

Table 5.12: Results obtained 5.4.3 (Scenario 3-1)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
3	1.4	7	3	16.86	562

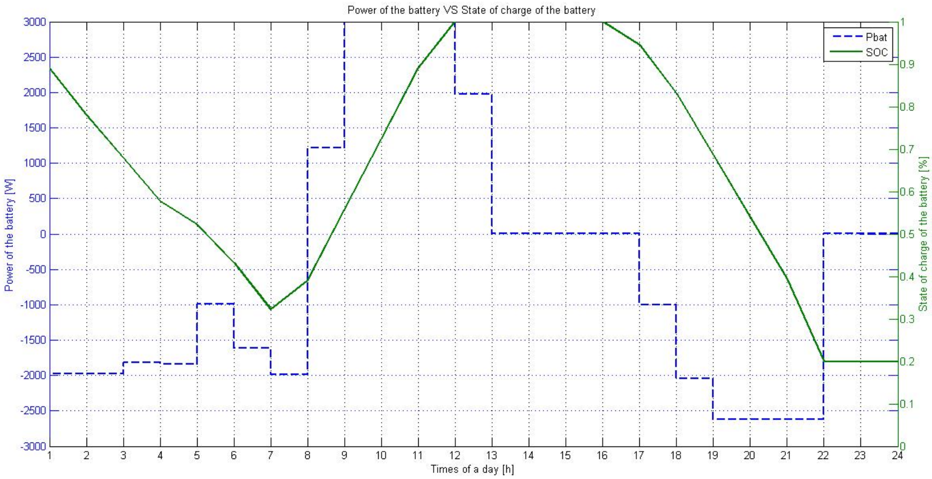

Figure 5.43: Behaviour of the battery and the state of charge during the day (Scenario 2-3)

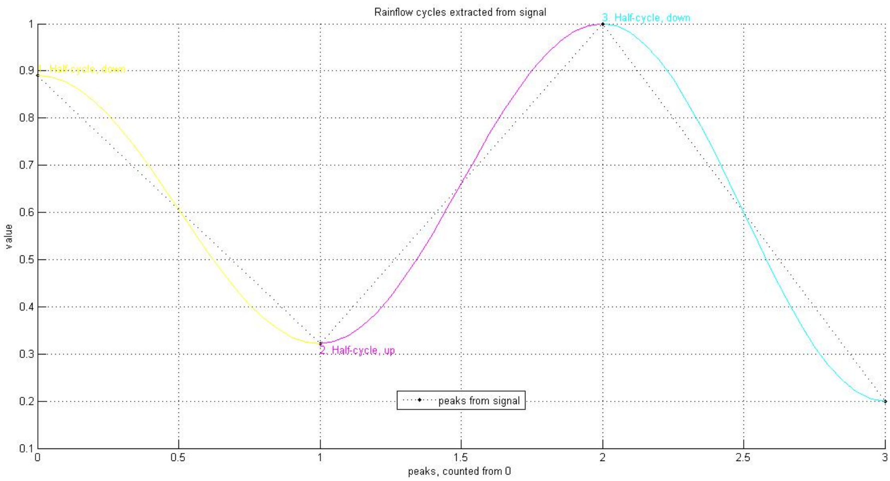

Figure 5.44: Rainflow count extracted from the state of charge value (Scenario 2-3)

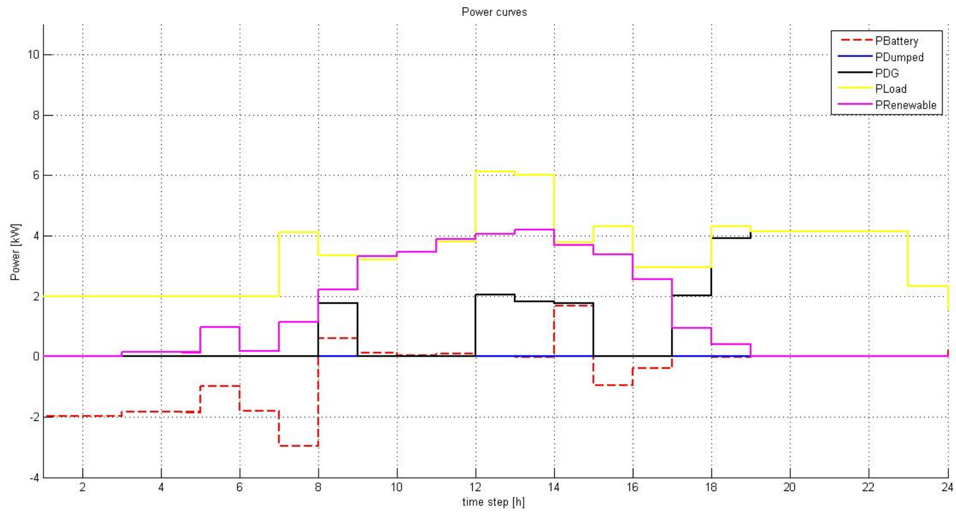

Figure 5.45: Behaviour of the generating power during the day (Scenario 3-1)

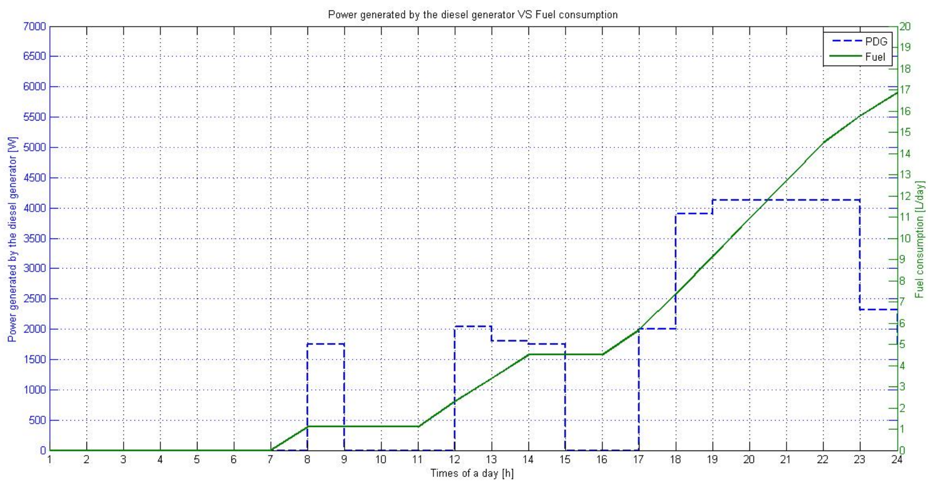

Figure 5.46: Behaviour of the diesel generator with fuel consumption during the day (Scenario 3-1)

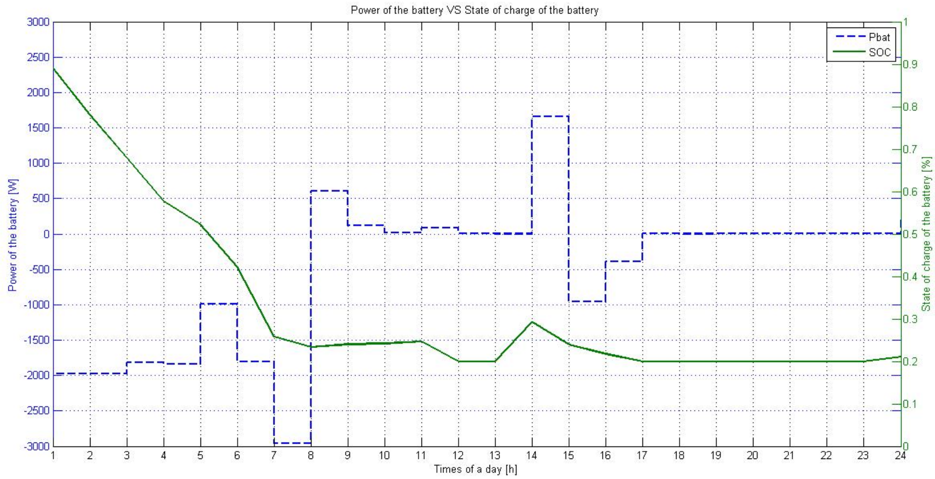

Figure 5.47: Behaviour of the battery and the state of charge during the day (Scenario 3-1)

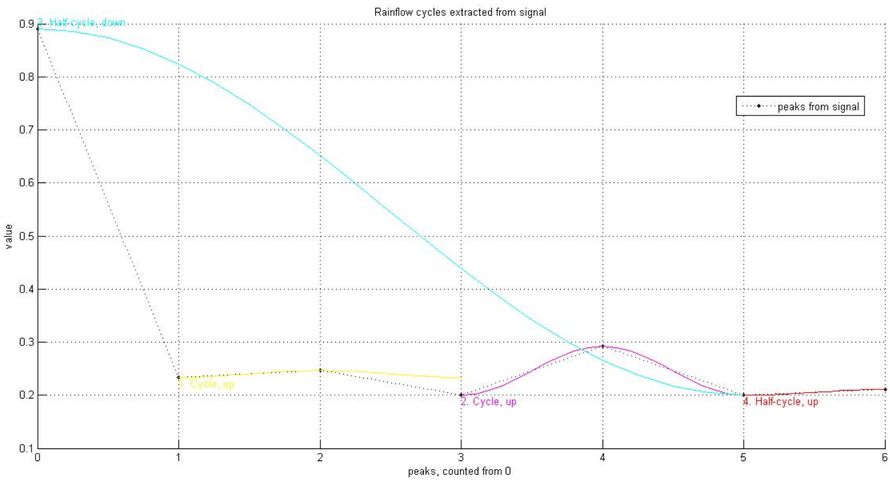

Figure 5.48: Rainflow count extracted from the state of charge value (Scenario 3-1)

Scenario 3-2

The peak power selected in this three scenarios for solar panels is 6 kWp; the powers of the diesel generator are 7 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

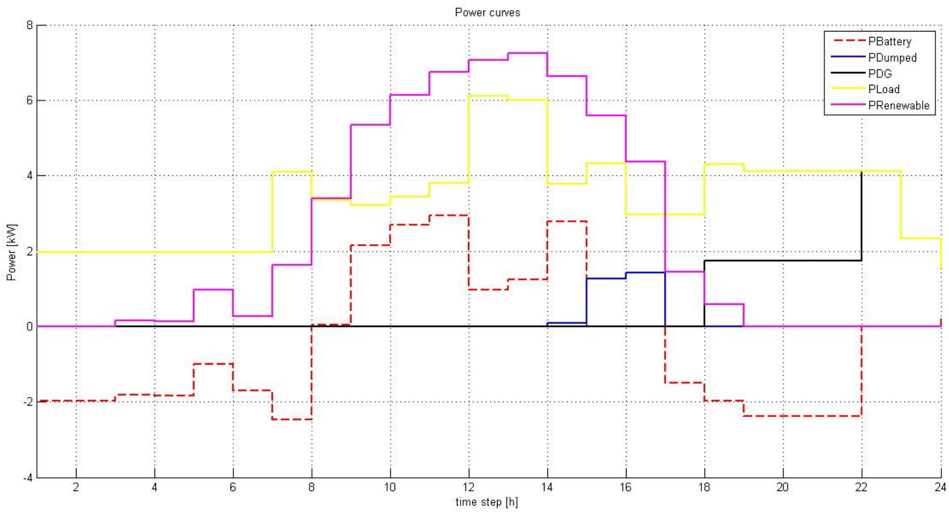

Figure 5.49: Behaviour of the generating power during the day (Scenario 3-2)

Table 5.13: Results obtained 5.4.3 (Scenario 3-2)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
6	1.4	7	3	8.54	239

Scenario 3-3

The peak power selected in this three scenarios for solar panels is 9 kWp; the powers of the diesel generator are 7 kW; the power from the wind turbine is 1.4 kW; the power of the battery is 3 kW with a maximum energy stored of 18 kWh and a charge and discharge time of six hours.

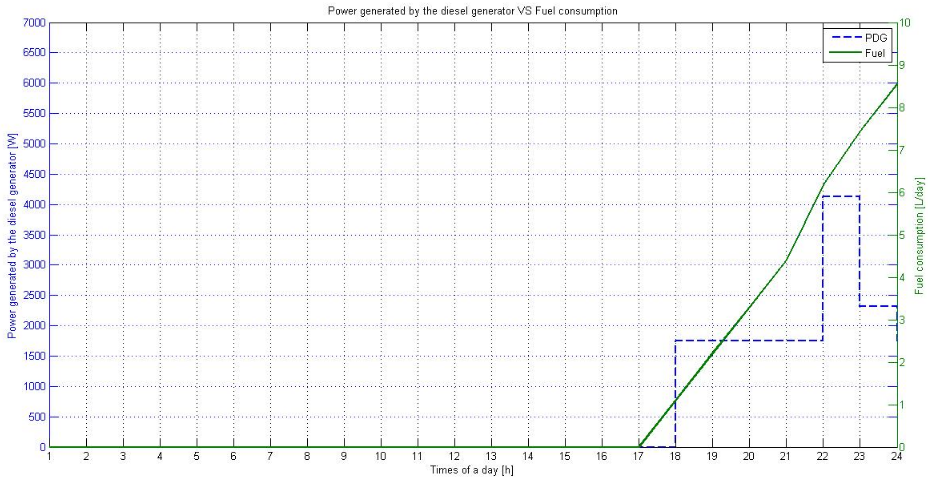

Figure 5.50: Behaviour of the diesel generator with fuel consumption during the day (Scenario 3-2)

Table 5.14: Results obtained 5.4.3 (Scenario 3-3)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
9	1.4	7	3	7.86	247

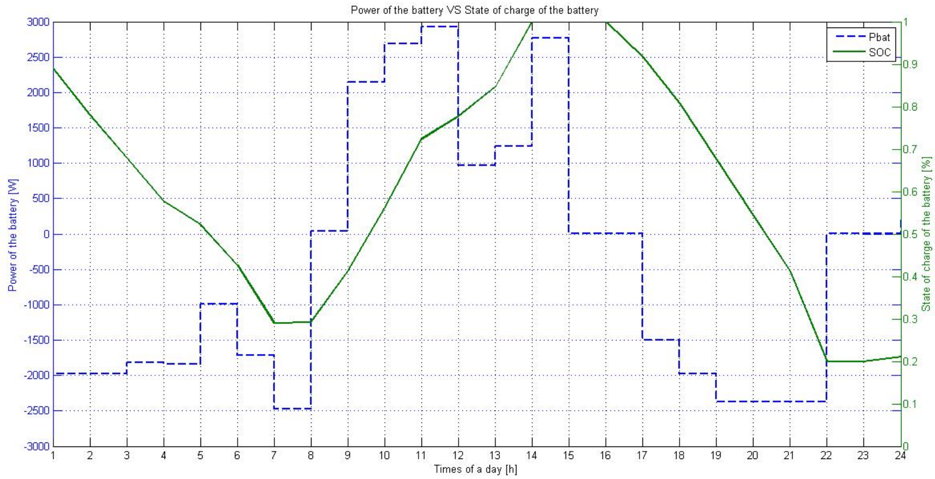

Figure 5.51: Behaviour of the battery and the state of charge during the day (Scenario 3-2)

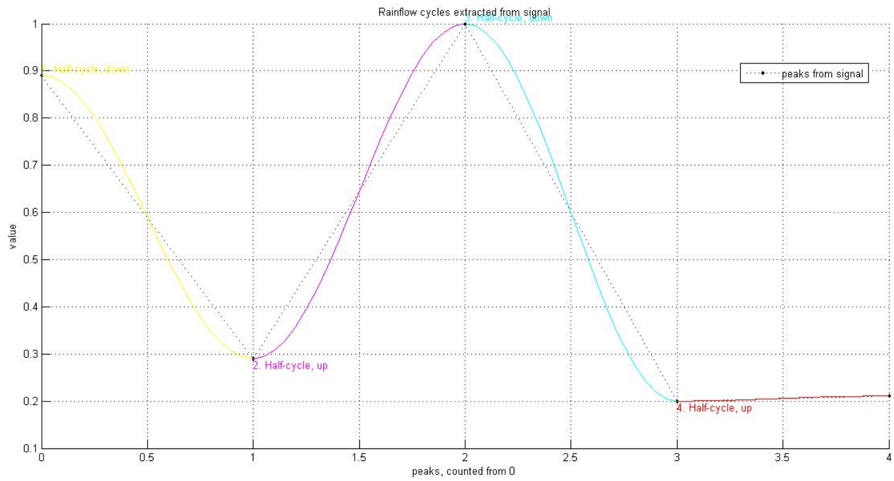

Figure 5.52: Rainflow count extracted from the state of charge value (Scenario 3-2)

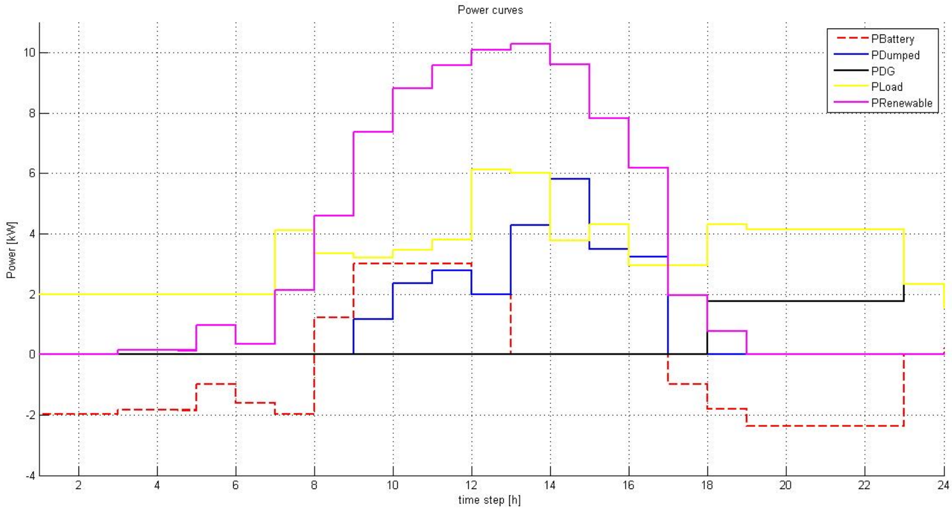

Figure 5.53: Behaviour of the generating power during the day (Scenario 3-3)

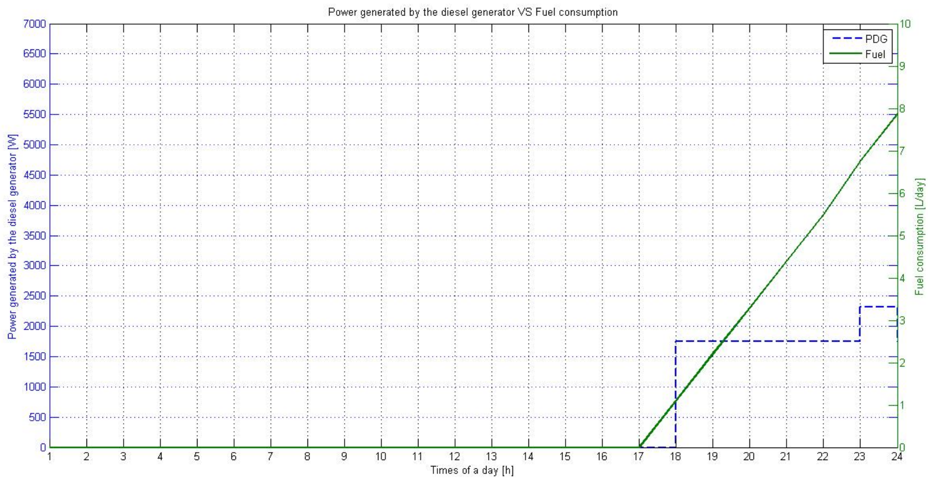

Figure 5.54: Behaviour of the diesel generator with fuel consumption during the day (Scenario 3-3)

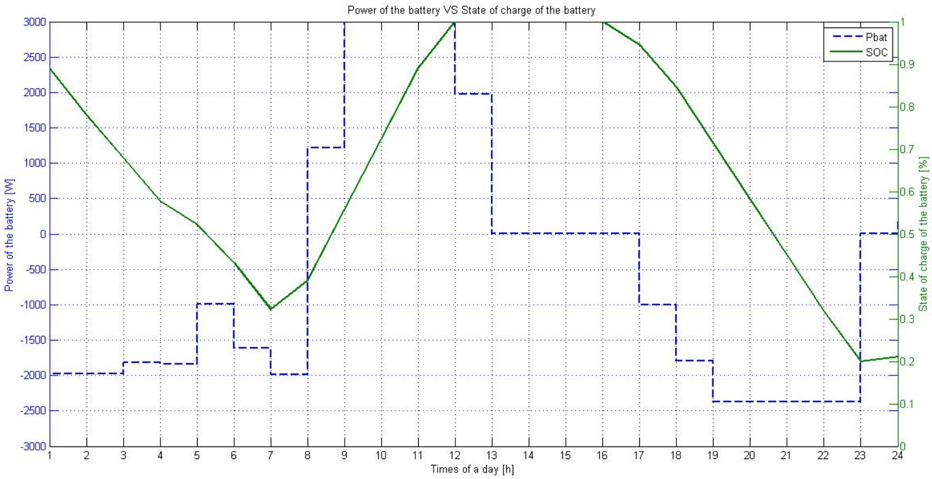

Figure 5.55: Behaviour of the battery and the state of charge during the day (Scenario 3-3)

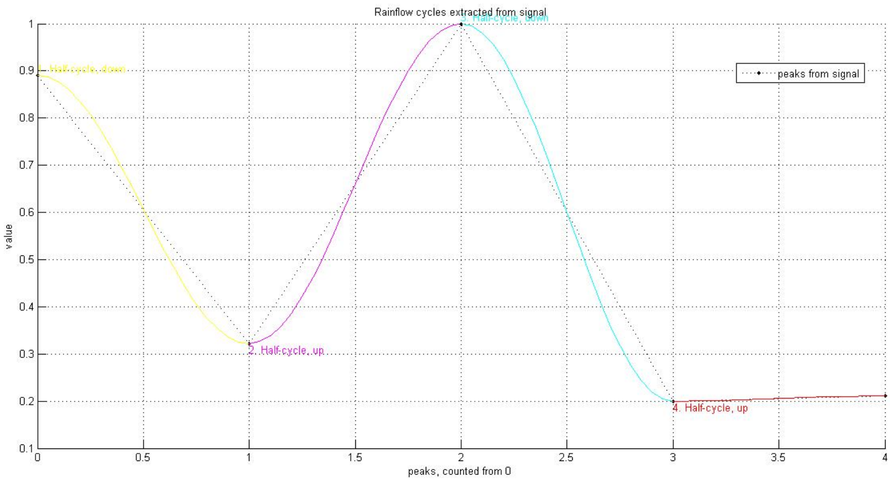

Figure 5.56: Rainflow count extracted from the state of charge value (Scenario 3-3)

Table 5.15: Summary of the results obtained from different scenarios 5.4.3,5.4.3,5.4.3,5.4.3,5.4.3,5.4.3, 5.4.3,5.4.3,5.4.3 (Scenarios 1-2-3)

P_{pv} [kW]	P_w [kW]	P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	Battery lifetime [days]
3	1.4	5	3	18.17	547
3	1.4	6	3	19.97	590
3	1.4	7	3	16.86	562
6	1.4	5	3	8.24	242
6	1.4	6	3	10.11	242
6	1.4	7	3	8.54	239
9	1.4	5	3	8.24	251
9	1.4	6	3	10.11	251
9	1.4	7	3	7.86	247

5.4.4 Results and discussions

Since the maximum demand load is more than 6 kW, the 5 and 6 kW diesel generators can't fully supplied the load without several interruptions of power. Only the diesel generator with 7 kW power could supplied the load with the daily fuel consumption is 37.461 liters. The simulations carried out show that maintaining the same diesel generator, the same battery, but increasing the power generated from renewables, the battery lifetime increases when the diesel generator fuel consumption decreases also. (see Tables 5.15). If the power of the diesel generator reduces, the battery would be more used and would be reduced its lifetime. When the power generated by renewables are enough to supply the load and charge the battery, the remaining power goes to the dumped for hot water production. When the peak power of the solar panels increases of 6 kWp and 9 kWp respectively, we have an excess of power which is dumped for hot water production from 02:PM to 05:PM and from 09:AM to 05:PM for all the three different diesel generators. The battery is also full charged in the same condition as previous from 12:AM to 04:PM. At the end of the of the simulation, it can be observed that the diesel generator with 7 kW power rated is the best according to less fuel consumption and the long lifetime of the battery.(see Tables 5.15)

5.5 Optimization model of the hybrid energy system

Optimization is considered an effective tool for identifying strategies in complex energy management systems. It contributes obtaining a set of parameters that minimizes an available attribute or maximizes a desired attribute subject to a number of constraints. The level of difficulty of optimization problems depends on the nature of the variables (continuous, discrete, integer), the existence of constraints (constrained, unconstrained), the nature of the objectives and constraints function (linear, non-linear), the number of objectives (single-objective, multi-objective) and the convexity of the problem. In litterature, there are many well-documented optimization methods and various optimization techniques for hybrid solar-wind-battery-diesel systems, but not single method that can solve all problems has been reported.

It is important to note that this work does not focus in inventing a new optimization algorithm, so whatever possible, the effort is made to model the solar-wind-battery-diesel hybrid system into optimal control problem using deterministic dynamic programming algorithm. In the work, the mathematical optimization method employed is the dynamic programming method (DPM).

5.5.1 Background and some studies based on dynamic programming method

Background

Dynamic programming was developed at the Bell labs in 1950s by Richard Bellman. This algorithm only search a part of the acceptable solution within all possible solution space using *Bellman principle of optimality*. This method can be applied for both deterministic and stochastic problems and simply deal with non-linear dynamics and constraints and guarantees achievement of global optimality. One area where dynamic programming have been mostly used is the energy management problem in hybrid electric vehicules. DPM is an optimization approach that transforms a complex problem into sequence of simple problems. Its essential characteristic is the multi-stage nature of the optimization procedure. The three most important characteristics that illustrate the dynamic programming problems (DPP) are: stage, state and recursive optimization (see Fig.5.57).

1. Stages: the essential feature of the dynamic programming method is the structuring of optimization problems into multiple *stages*, which are solved sequentially on stage at a time. Although each one-stage problem is solved as an ordinary optimization problem, its solution helps to define the charateristics of the next one-stage problem in the sequence.

Often, the stages represent different time periods in the problem planning horizon.

2. States: associated with each *states* of the process. The states reflect the information required to fully assess the consequences that the current decision has upon future actions. The specification of the states of the system is perhaps the most critical design parameter of the dynamic programming model. The essential properties that should motivate the selection of states are: (i) the state should contained enough information to make the future decisions without regard to how the process reached the current state; and (ii) the number of state variables should be small, since the computational effort associated with the dynamic programming method is prohibitively expensive when there are more than two, or possibly three states variables involved in the model formulation.

3. recursive optimization: the development of a recursive optimization procedure is the final characteristic of the dynamic programming method, which builds in the solution of overall N-stage problem by firs solving a one-stage problem and sequentially including one stage at time and solving one-stage problems untill the overall optimum has been found. This procedure can be based on *backward induction* process, where the first stage to be analysed is the final stage of the problem and problems are solved moving back one stage at the time untill all stage are included. Alternatively, the recursive procedure can be based on *foward induction* process, where the first stage to be solved is the initial stage of the problem and the problems are solved moving foward one stage at time, untill all stage are included.

Dynamic programming method is a mathematical technique used nowadays to design optimal energy management controllers for managing the optimal operation of the renewable sources, batteries and diesel generators.

Some studies based on dynamic programming method

Respectively [164] the authors introduce the implementation of dynamic programming in matlab function begining from the formulation of the problem, the states the different options and the analysis of the output. Two example of problems are exposed and implemented (Lotka-Volterra Fishery where at the end of the problem, one must stop fishing as late as possible, such that the population reaches the specified minimum final size and the energy management of the hybrid electric vehicule with the minimization of the total fuel consumption cost.) and [165], the authors implemente the dynamic programming for different issues of optimal control problem such as energy

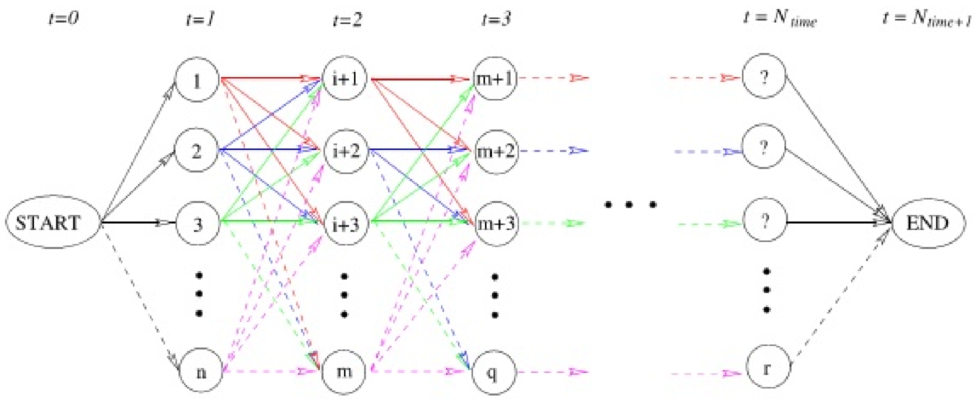

Figure 5.57: Schematic representation of a problem with dynamic programming method Ref. [14]

management for hybrid electric vehicule, the effect of resolution of state space discretization on the output result of dynamic programming and at last implement the boundary-line method such to improve the dynamic programming method. Dynamic programming is implemented for power management strategy in an electric vehicule focusing on two point boundary optimization in a finite horizon. The two variables in this study are the state of charge of the battery which vary from lower to upper level and the electric power of the engine which has to be minimized [166]. The comparison of a simple backward model of the parallel hybrid electric bus and the dynamic programming method is carried-out for global optimal energy management strategy. The result of the study shows that the dynamic programming improve the energy management strategy by more than 50% compare to the simplified backward model [167]. The optimal charge/discharge management of a battery and the increasing of its lifetime while minimizing the electricity cost is done using dynamic programming [168]. In [14] the authors propose an optimal control strategy of a combined heat power and cooling system using dynamic programming. The optimization strategy aims to minimize the total energy cost from 8% to 100% depending on the seasonal load. A simple management system is compared with a energy management system for smart home based on dynamic programming. The system is composed by a fuel cell used for power cogeneration, a photovoltaic generation system, and electric car, a battery and a thermal energy storage system. The result of the study shows that the proposed management system enables the response of demand and generation of electrical energy in the household to an electricity tariff that varies over time and serves to describe the supply conditions of the grid [169]. An optimal power flow management for more photovoltaic integration into the grid connected with batteries is carried-out comparing a simple rule based management and the dynamic programming for peak shaving service at lowest cost. The resul of the study reveals that the management developed helps integration of photovoltaic power into the grid as peak loads are shaved [170]. An analysis of energy management strategy of a wind-solar-battery hybrid system using dynamic programming is carried-out. The optimization is obtained minimizing the energy cost and maximizing the gain in the selling energy market. This hybrid system can be supplied either in stand-alone or in grid connected [171]. The authors present an optimization method for energy and power management for a solar-wind-battery-electrolyse/fuel cell-diesel hybrid system using dynamic programming algorithm. The aim of the optimization is to minimize the daily cost of the system and also maximize the total efficiency of the charging and discharging process of the storage sytem [172].

5.5.2 Description of the optimized proposed algorithm

One of the crucial factor for optimization is to determinate the best time for starting and stopping the diesel generator. A suitable operation strategy can optimize the fuel consumption, which is one of the main concerns for the entire operation cost of a diesel generator over its lifetime. The operating strategy of the optimized proposed algorithm is as follows:

- If the total power generated from photovoltaic panels (Ppv) and wind turbine (Pw) is more than the load demand (PL), the excess power is used to charge the batteries. When the battery is full and there is still power from renewables, the excess is dumped and used for hot water production. In this case, the sizing optimization will be carried out with only two supplies (photovoltaic and wind).

- If the total generated power (Ppv+Pw+Pbat) is less than the load demand and the state of charge of the battery (SOC) is higher than SOCmin, the batteries will supply the extra power. The sizing optimization will be carried out with photovoltaic, wind, and battery.

- If the battery state of charge (SOC) is equal or less than the minimum state of charge value (SOCmin), the diesel generator will start and supply the power in order to protect the battery against excessive draining. Surplus power from diesel will charge the battery as amount as maximum state of charge value (SOCmax). In this case, the calculation of sizing optimization will be carried out with PV-wind including the diesel generator.

- The diesel generator switches off when the solar/wind and battery bank can fully satisfied the load.

5.5.3 Problem formulation

Objective function

In this work, the objective function describes the levelized cost of energy and can be formulated as

$$OF = Min\left(\frac{\sum_{t=1}^{T}(I_{cost} + M_{cost} + O_{cost} + R_{cost} - S_{cost})}{\sum_{t=1}^{T} W}\right) \tag{5.27}$$

For all t=1,...,T, where T represents the lifespan of the hybrid power plant (25 years);

OF: is the levelized cost of energy ($LCOE$) [€/kWh];

I_{cost}: represents the total investment cost of the components of the HES [€];

M_{cost}: represents the total maintenance cost of the components of the HES [€];

O_{cost}: represents the total operation cost of the components of the HES [€];

R_{cost}: represents the total replacement cost of the components of the HES [€];

S_{cost}: represents the total salvage value cost of the components of the HES[€];

W: represents the total yearly energy of the HES [kWh].

Parameters

The variables are the unknown that have to be determined by solving the model equations. X(t) is the only variable, representing the operating point of the diesel generator at each time step.

$$\begin{cases} +0.25 \leq X(t) \leq 1 \\ or \\ X(t) = 0 \end{cases} \tag{5.28}$$

Constraints

Constraints restrict the range of the decision variables as a result of technological, socio-economic, legal or physical constraints on the system. In the present method, the constraints are given by technical characteristic of the battery and the diesel operation and by matching demand and supply.

$$P_{pv}(t) + P_{wind}(t) + P_{bat}(t) + P_{DG}(t) = P_L(t) \qquad \forall t \tag{5.29}$$

$$\begin{cases} P_{DG}\min \leq P_{DG}(t) \leq P_{DG}\max \qquad \forall t \\ or \\ P_{DG} = 0 \qquad \forall t \end{cases} \tag{5.30}$$

$$P_{bat}\min \leqslant P_{bat}(t) \leqslant P_{bat}\max \qquad \forall t \tag{5.31}$$

$$SOC\min \leqslant SOC(t) \leqslant SOC\max \qquad \forall t \tag{5.32}$$

$$P_{pv}(t) \geqslant 0; \qquad P_{wind}(t) \geqslant 0; \qquad P_{batcharged}(t) \geqslant 0; \qquad P_{DG}(t) \geqslant 0 \tag{5.33}$$

Constraint (5.29) ensures that the power supplied by the solar generator, the wind generator, the battery and the diesel generator at any hour of the day equals to the demand at the same hour.

Constraint (5.30) ensures that the power supplied by the diesel generator is constrained to work within the minimum and maximum value or switched off.

Constraint (5.31) ensures that the power delivered or received by the battery is constrained to work within the minimum and maximum value.

Constraint (5.32) ensures that the state of charge of the battery is constrained to work within the minimum and maximum value.

Constraint (5.33) ensures that the power generated from solar-wind, battery and diesel generator supplying the load at any time are each greater than or equal to zero.

Due to the high investment cost of renewables and hybrid energy systems, the lack of incentives, the lack of private and public donors, the economic crisis situation in many developing countries and sub-saharan Africa in particular, it is important to ensure the rentability of these systems to make them more attractive for public and private sector to invest on rural electrification. However, to establishe a good equality between technical constraints and economic variability criteria of a project/system, we need to put in place a techno-economic approach. The techno-economic approach is more used in hybrid electricity production systems, but for this study, only the Life Cycle Cost (LCC) and the Levelized Cost of Energy ($LCOE$) would be used as economic criteria. The economic criteria are usually classified in four families: the Net Present Value methods (NPV) based on the discount rate, the Rate methods based on the rate of return, the Ratio methods evaluating the benefits proportionally to the investment and finally the Payback methods measuring the minimal time to recover the initial investment. The advantages and disadvantages of the different methods have been widely discussed in the literature. In generale, the economic evaluation have three principal roles: (i) accept or reject an investment project/system; (ii) classify and choose a project/system among many and (iii) choose the optimal configuration of project/system among many [37], [65], [173].

5.5.4 Basic considerations of economic analysis

Cash flow, inflation rate and discount rate are used for the evaluation of the economical relevance of a project.

Cash flow

The concept of cash flow varies according to the type of activity. Since investment and operational activities are the main activities considered in engineering projects. These two main activities would be considered in this given project or study. In an investment activity, the cash flow is taken as the difference of the inflows (subsidies, grants, etc.) and the capital expenditures. In an operational activity, the cash flow is considered as the difference of the incomes and the expenses linked to the operation of the system/project. In a given project, the evaluation of the cash flow needs many inputs such as investment costs, operation and maintenance costs, replacement costs, salvage value, the subsidies, the project incomes, and some macro-economic parameters among which we have the discount and the inflation rates.

$$CF_j = I_j - C_j \tag{5.34}$$

where I_j s the incomes of year j (€/y) and C_j are expenses of year j (€/y)

Inflation and discount rate

Inflation is under consideration when it is noticed an overall increase of goods and services costs on the market. This implies a fluctuation of the currency. The inflation rate e is taken as the fluctuation of a currency from one year to another. Let us consider two years k and j where j>k. During the year n, a goods value C_k will become C_j in the year j. The two values are linked by the following expression:

$$C_j = C_k(1+i)^{(j-k)} \tag{5.35}$$

where i: is the inflation rate

Inflation rate depends on the project area and varies from one year to another. For sake of simplicity, we will consider a mean constant inflation rate e in this study. The discount rate i is used for depreciation of future flows and to determine their current values. Two kinds of discount rates exist:

- d: discount rate or interest. It is given by the banks for loans or savings. It does not take into account the fluctuation of the currency along with the time;
- i_r: the real discount rate. This rate takes into account the inflation.

The two discount rates are linked by Fischer formula:

$$(1+i) = (1+i_r)(1+d) \tag{5.36}$$

All along this study a project Y will be characterized by the following data:

- the lifetime n of the project;
- the vector of annual cash flows: CF_j being the cash flow for year j obtained from the incomes I_j and the expenses C_j;
- the salvage value S of the component at the end of the project. This salvage value is often taken as a percentage of the initial investment.

Let us observe that in our approach we only consider projects where the investment is concentrated only on the first year. It is denoted as C0 and therefore the corresponding cash flow at year 0 is CF_0=-$C0$. On the other hand, the economical environment of the project is described by: i_r the real discount rate and e the inflation rate. For a given a project Y(I_j,C_j,n,S), we recall the definition of the main economic assessment criteria.

The net present value

The Net Present Value (NPV) sums the annual cash flows returned to the equivalent value at the beginning date of the project. It is define as:

$$NPV(Y, i_r) = CF_0 + \frac{CF_1}{(1+i_r)} + \frac{CF_2}{(1+i_r)^2} + ... + \frac{CF_n}{(1+i_r)^n} + \frac{S}{(1+i_r)^n} \tag{5.37}$$

The project Y is accepted if NPV (Y,i_r) $\geqslant$ 0, and the higher NPV(Y,i_r), the more desirable the project. If all the annual cash flows are the same, except the initial one CF_0, CF_1= CF_2=...=CF_n= CF, then the NPV can be simplified as:

$$NPV(Y, i_r, n) = CF_0 + USPWF(i_r, n).CF + PWDF(i_r, n).S \tag{5.38}$$

where $USPWF(i_r, n)$ is the uniform serie present worth factor

$$USPWF(i_r, n) = \left(\frac{(1 + i_r)^n - 1}{i_r(1 + i_r)^n} \right) \tag{5.39}$$

and for any year j, $PWDF(i_r, j)$ is the present worth discount factor

$$PWDF(i_r, j) = \frac{1}{(1 + i_r)^j} \tag{5.40}$$

The discount rate appearing in the uniform series factor has to be modified and replaced by the corrected discount rate i_{adj}

$$i_{adj} = \frac{(1 + i)^{Y_{equipment}}}{(1 + d)^{Y_{equipment}-1}} \tag{5.41}$$

where $Y_{equipment}$ is the lifetime duration of the equipement.

5.5.5 The life cycle cost analysis (LCC)

The LCC represents the total amount of costs (investment, maintenance, operation and replacement) that occure during the lifetime of a project in which are subtracted all revenues generated by the residue at the end of the project. As for the Net Present Value, the annual costs C_j are returned to the beginning date of the project using the actualization factor.

$$LCC(Y, i_r, n) = \sum_{i=0}^{j} . \frac{C_j}{(1 + i_r)^j} - \frac{S}{(1 + i_r)^n} \tag{5.42}$$

By the same calculation as for the NPV, in the case of a constant annual cost, CF_1= CF_2 = ... = CF_n = CF, the LCC formula yields:

$$LCC(Y, i_r, n) = C_0 + USPWF(i_r, n).C - PWDF(i_r, n).S \tag{5.43}$$

If LCC consists to evaluate all expenses (investment, maintenance, operation and replacement) that occur during the life of a project, the LCC formula ca be written at follow:

$$LCC(Y, i_r, n) = C_I + USPWF(i_r, n).[C_M + C_O] + USPWF(i_{adj}, n).C_R - PWDF(i_r, n).S \quad (5.44)$$

where C_I, C_M, C_O, C_R and S are respectively investement cost, maintenance cost, operation cost and Salvage value.

5.5.6 Levelized cost of energy ($LCOE$)

This ratio criterion is, by definition, only useful for energy projects and is one of the most appreciated economic measures in this domain. The Levelized Cost of Energy ($LCOE$) or Cost of Energy (COE) represents the annualized cost of a unit of energy (€/kWh). More precisely, it corresponds to the ratio of the LCC of the project and the total amount of actualized energy produced over the project lifetime. It is expressed as it follows:

$$LCOE(Y, i_r, n) = \frac{LCC(Y, i_r, n)}{\sum_{i=1}^{n} \frac{W}{(1 + i_r)}} \quad (5.45)$$

where W_j stands for the quantity of energy produced during year j. If this annual production is constant and equal to W then the formula of $LCOE$ becomes:

$$LCOE(Y, i_r, n) = \frac{LCC(Y, i_r, n)}{USPWF(i_r, n).W} \quad (5.46)$$

Notice that the $LCOE$ can also be seen as an annuity related to the LCC, which is calculated multiplying the LCC by the Uniform Capital Recovery factor ($UCRF$).

$$LCOE(Y, i_r, n) = UCRF(i_r, n) \frac{LCC(Y, i_r, n)}{W} \quad (5.47)$$

$$UCRF(i_r, n) = \frac{1}{USPWF(i_r, n)} = \left(\frac{i_r(1 + i_r)^n}{(1 + i_r)^n - 1} \right) \quad (5.48)$$

Let us observe that, like the LCC criterion, the $LCOE$ doesn't take into account the incomes generated by the project and it is therefore not adapted to take an investment decision on a project but rather to define an optimal design of a project.

5.5.7 Economic model of the hybrid energy system

The costs value of different components of the hybrid system are listed in Table 5.31

Investment costs

The total investment cost of each component of the hybrid system (PV+Inverter, Wind turbine, Battery and Diesel generator) are their initial costs and can be calculated as

$$I_{Cost} = I_{PV+Inverter} + I_{Wind} + I_{Battery} + I_{diesel} \tag{5.49}$$

Maintenance costs

The total maintenance cost of each component of the hybrid system (PV+Inverter, Wind turbine, Battery and Diesel generator) can be calculated as

$$M_{Cost} = M_{PV+Inverter} + M_{Wind} + M_{Battery} + M_{diesel} \tag{5.50}$$

- Solar system maintenance cost (PV+Inverter)

The maintenance of solar panels and inveter consists on cleaning, landscape and electronic components and supervision. The maintenace cost is take as a percentage of the investment cost. In this study of 3% annual maintenance cost from the initial investment cost has been assumed.

$$M_{PV+Inverter} = 3\% * I_{PV+Inverter} * UCRF(i_r, n) \tag{5.51}$$

- Wind turbine maintenance cost

From experience, the maintenance costs of a new turbine will be very low but as the turbine ages these costs will increase. Older wind turbines have an annual maintenance cost average of 3% of the original cost of the turbine. These costs are related to a limited number of cost components including transistors, resistors, relays etc land rent, etc. In this study, 3% of annual maintenance cost from the original cost has been considered.

$$M_{Battery} = 3\% * I_{Battery} * UCRF(i_r, n) \tag{5.52}$$

- Battery maintenance cost

The maintenance of the battery consits in filling the level of fluid, prevent the corrosion of the cables, clean and tightened the cable connection, etc. This can be estimated to 3% of annual maintenance cost from the initial investment cost.

$$M_{Battery} = 3\% * I_{Battery} * UCRF(i_r, n) \tag{5.53}$$

- Diesel generator maintenance cost

Apart from the general maintenance (drain fuel filter and water from fuel tank, change oil filter, fuel filter and cooling filter, drive belt tension, etc.), the most critical points for the maintenance of diesel generators are diesel starters, due to the multiple starts/stops. In this study, 5% of annual maintenance cost from the original investment cost has been considered

$$M_{Diesel} = 5\% * I_{Diesel} * UCRF(i_r, n) \tag{5.54}$$

Operation costs

The total operation cost concernes only the diesel generator and is related to the fuel consumption and can be calculated as:

$$O_{Cost} = Cf.[\tau(t).(a.X(t) + b) + C\tau_{on} + C\tau_{off}] \tag{5.55}$$

where, $\tau(t)$: represents the start-up or the shut-down of the diesel generator at each time period which have to be minimized;
$C\tau_{start}$: represents the penalty of start-up of the diesel generator (1-2);
$C\tau_{stop}$: represents the penalty of shut-down of the diesel generator (0);
Cf: is the fuel price (€/L);
$X(t)$: is the operating point of the diesel generator at each time period [%];
N: is the total number of hour of the day (h);
a: is the slope of the line $[L/h]$;
b: is the intercept of the line crosses the y-axis $[L/h]$.

Replacement costs

The total replacement cost is the cost value for replacing units during project life time. Assuming that the equipments are used when replacement occurs, the replacement cost is equal to the investment cost. The equipments or components concern are the battery and the diesel generator and can be calculated as:

$$R_{Cost} = R_{Battery} + R_{Diesel} \tag{5.56}$$

- Battery replacement cost

$$R_{Battery} = UCRF(i, i_{adj}, n) * I_{Battery} \tag{5.57}$$

- Diesel generator replacement cost

$$R_{Diesel} = UCRF(i, i_{adj}, n) * I_{Diesel} \tag{5.58}$$

Salvage value costs

The salvage value is evaluated through the ratio of the remaining lifetime n' of the component and the lifetime n of the components. Only the Solar+Inverter system, the wind turbine and the diesel generators are concerned. The fraction n'/n can be estimated to 10% from the initial investment cost [102].

$$S_{Cost} = S_{PV+Inverter} + S_{Wind} + S_{Diesel} \tag{5.59}$$

- Solar system salvage value (PV+Inverter)

$$S_{PV+Inverter} = PWDF(i_r, n) * 10 \tag{5.60}$$

- Wind salvage value

$$S_{Wind} = PWDF(i_r, n) * 10 \tag{5.61}$$

- Diesel generator salvage value

$$S_{Diesel} = PWDF(i_r, n) * 10 \tag{5.62}$$

The life cycle cost (LCC)

$$LCC(Y, i_r, n) = I_{Cost} + M_{Cost} + O_{Cost} + R_{Cost} - S_{Cost} \tag{5.63}$$

Levelized cost of energy ($LCOE$)

$$LCOE(Y, i_r, n) = \frac{LCC(Y, i_r, n)}{UCRF(i_r, n) * W} \tag{5.64}$$

5.5.8 ScenarioA: The load is supplied only by the diesel generator and the battery

In this scenario, the load demand is powered by the diesel generator and the battery. The different power of the diesel generators here are 5, 6 and 7 kW. The battery have a power of 3 kW and a maximum average energy stored of 18 kWh. The PV panel size have been sized with a step size of 3/6/9kWp, the diesel generator with the size of 5/6/7 kW, the battery (3kW) and the wind turbine generator (1.4kW) sizes kept constant. In the different scenarios, the initial state of charge of the battery is maintained equal to the final state of charge value.

ScenarioA-1: The load is supplied by the 5 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by the diesel generator and the battery. The diesel generator is 5 kW and the battery have a power of 3 kW and a maximum average energy stored of 18 kWh. In the different scenarios, the initial state of charge of the battery is kept equal to the final state of charge value. This, is because the continuity during a determined period have to be respected and the best scenario been chosen.

Table 5.16: Results obtained 5.5.8 (ScenarioA-1)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
5	3	37.019	SOCmax	398
5	3	38.523	SOCmin	427

ScenarioA-2: The load is supplied the 6 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by the diesel generator and the battery. The diesel generator is 6 kW and the battery have a power of 3 kW and a maximum average energy stored of 18 kWh.

Table 5.17: Results obtained 5.5.8 (ScenarioA-2)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
6	3	39.602	SOCmax	269
6	3	41.50	SOCmin	317

ScenarioA-3: The load is supplied the 7 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by the diesel generator and the battery. The diesel generator is 7 kW and the battery have a power of 3 kW and a maximum average energy stored of 18 kWh.

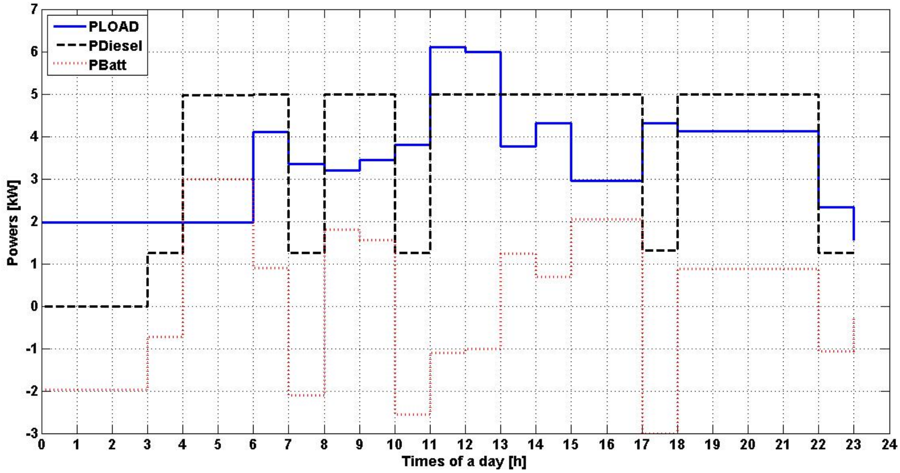

Figure 5.58: Behaviour of the HES when powered by the diesel generator and the battery with SOCi=SOCf=SOCmax (ScenarioA-1)

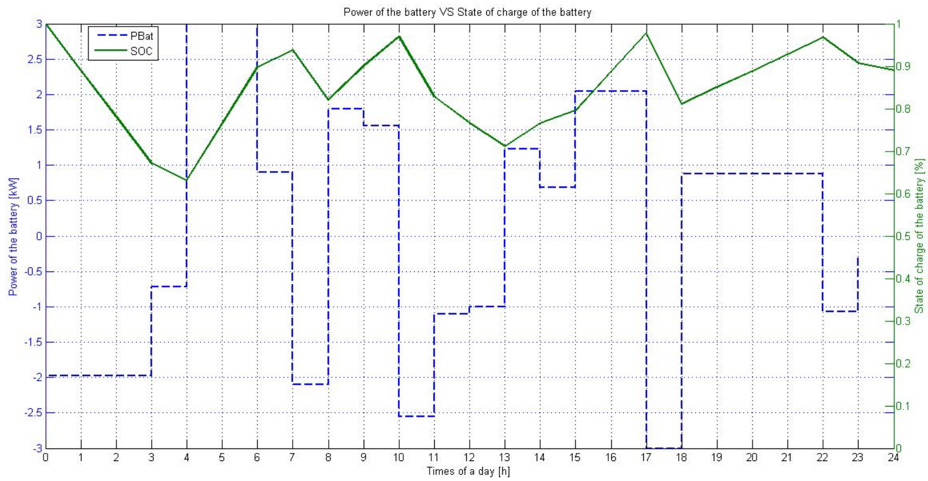

Figure 5.59: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmax (ScenarioA-1)

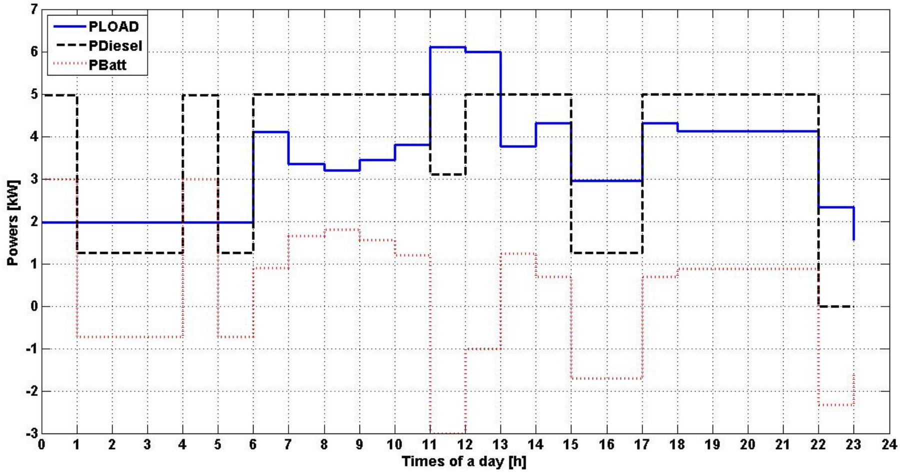

Figure 5.60: Behaviour of the HES when powered by the diesel generator and the battery with SOCi=SOCf=SOCmin (ScenarioA-1)

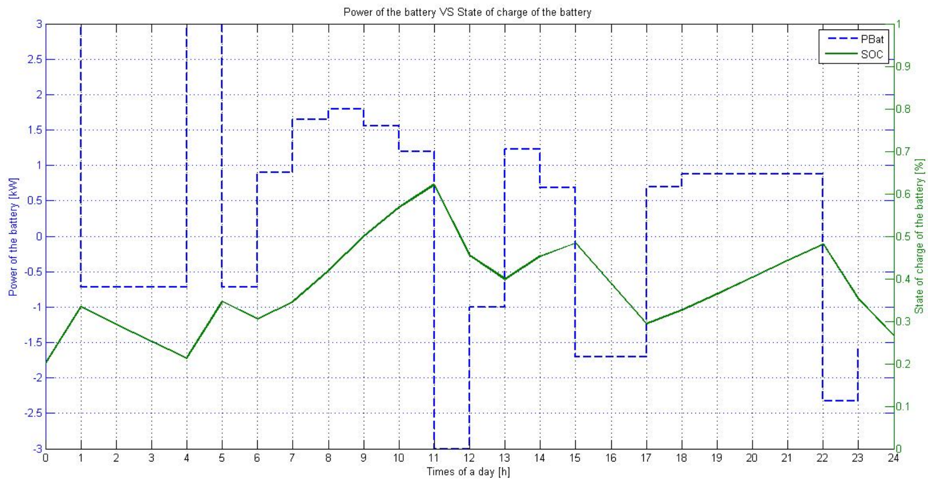

Figure 5.61: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmin (ScenarioA-1)

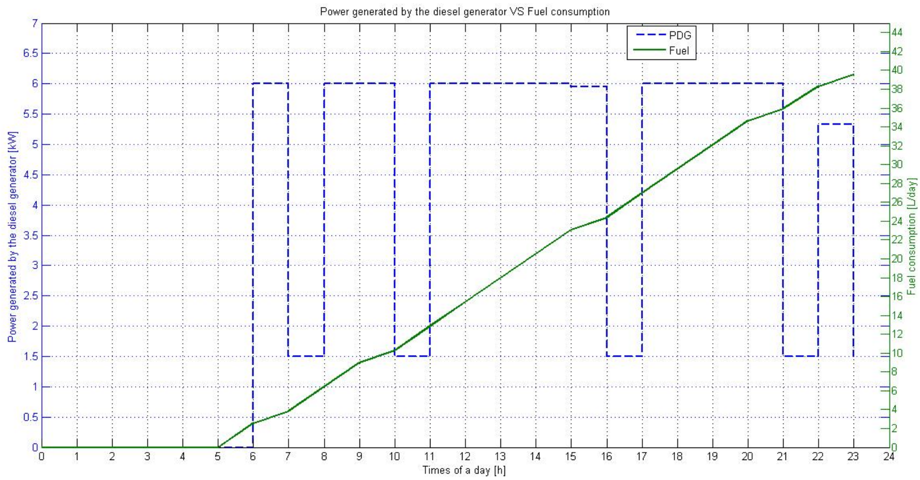

Figure 5.62: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmax (ScenarioA-1)

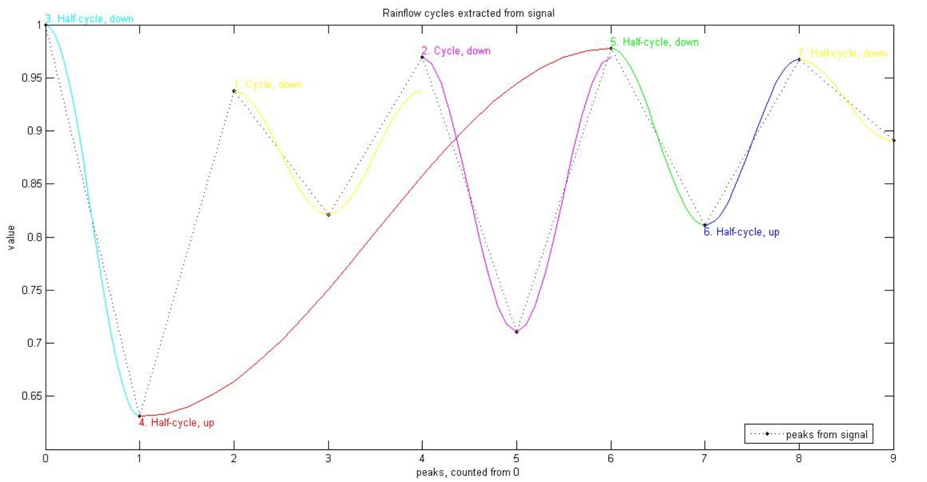

Figure 5.63: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmax (ScenarioA-1)

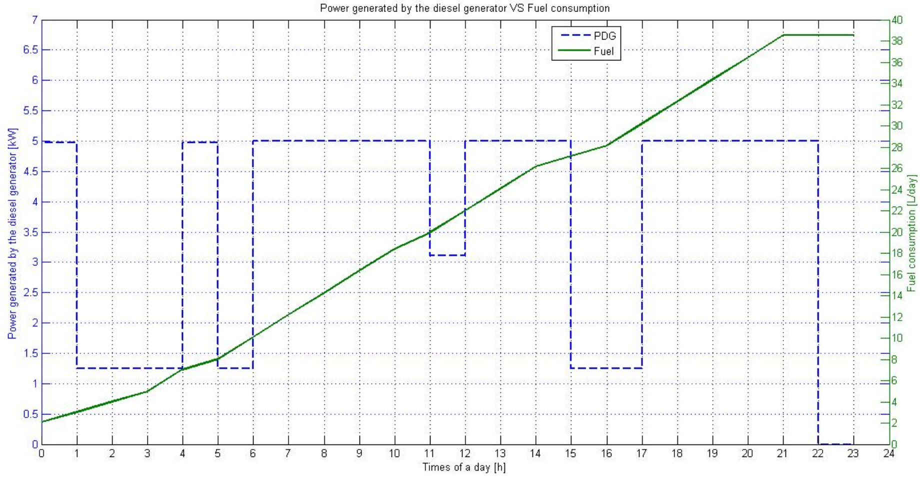

Figure 5.64: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmin (ScenarioA-1)

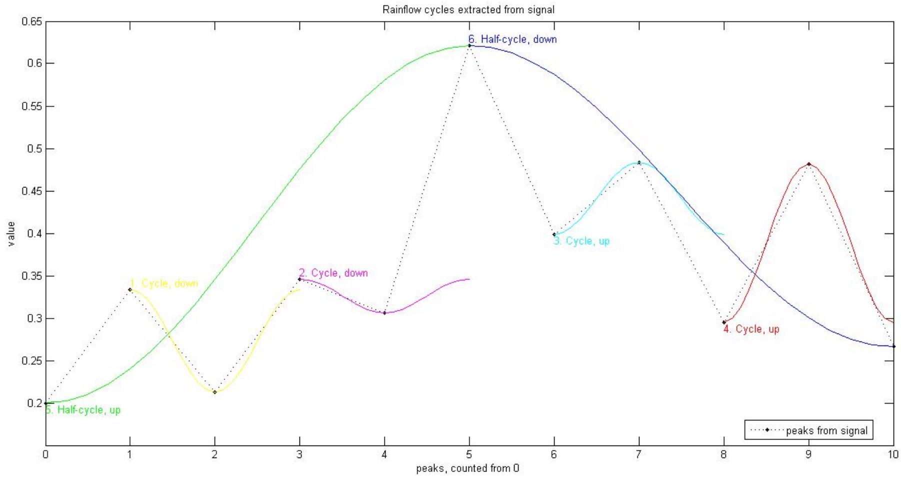

Figure 5.65: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmin (ScenarioA-1)

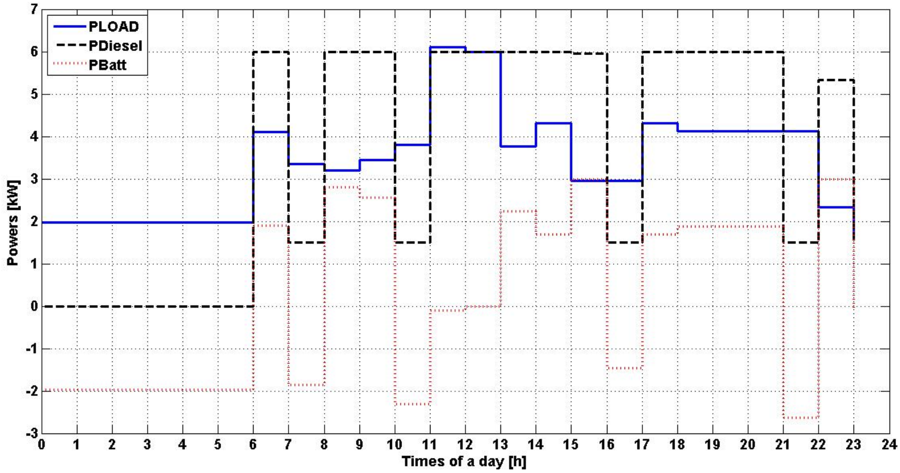

Figure 5.66: Behaviour of the HES when powered by the diesel generator and the battery with SOCi=SOCf=SOCmax (ScenarioA-2)

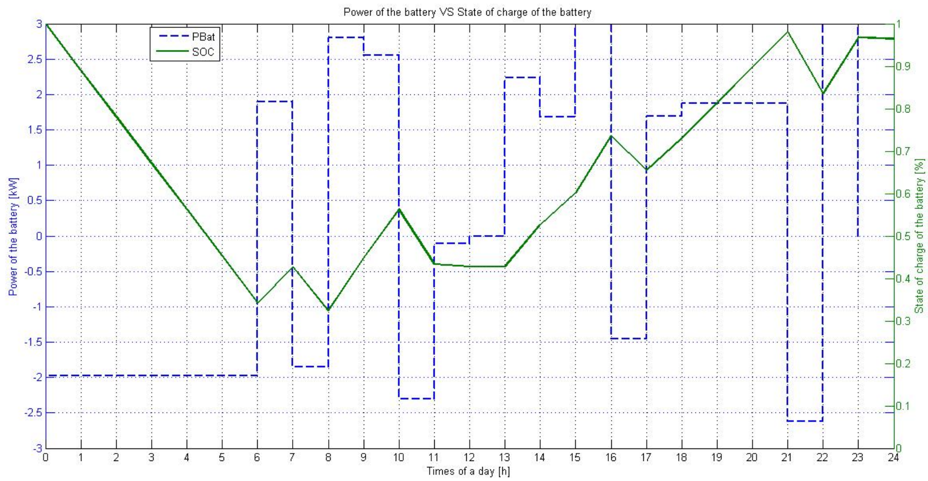

Figure 5.67: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmax (ScenarioA-2)

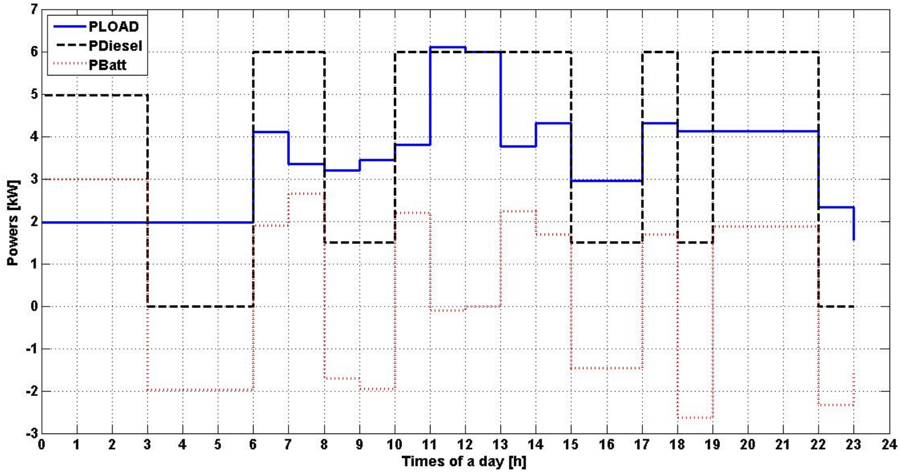

Figure 5.68: Behaviour of the HES when powered by the diesel generator and the battery with SOCi=SOCf=SOCmin (ScenarioA-2)

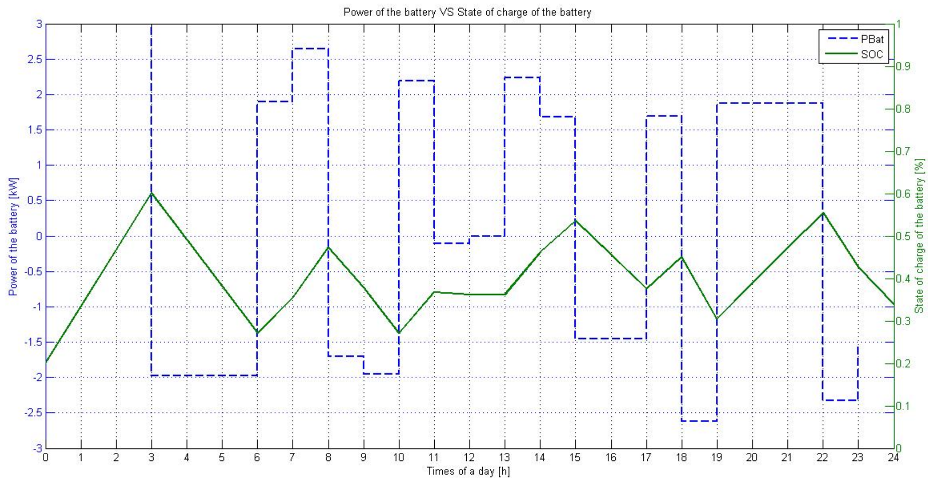

Figure 5.69: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmin (ScenarioA-2)

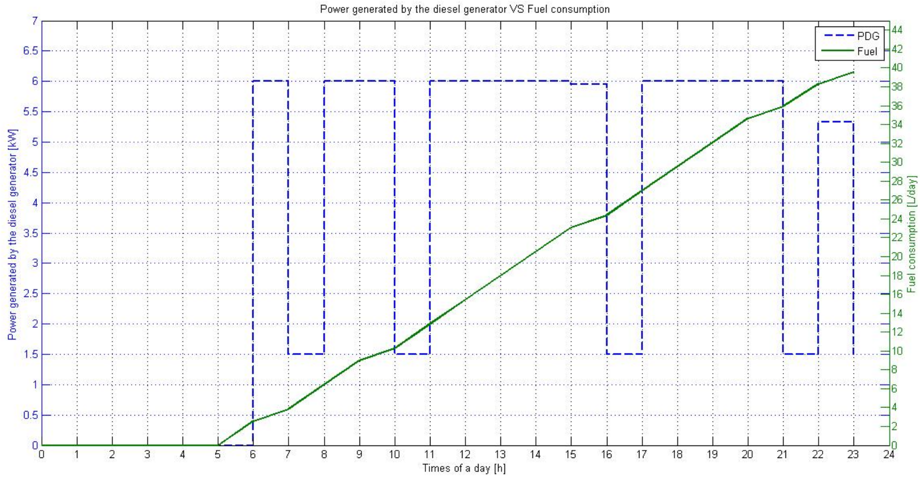

Figure 5.70: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmax (ScenarioA-2)

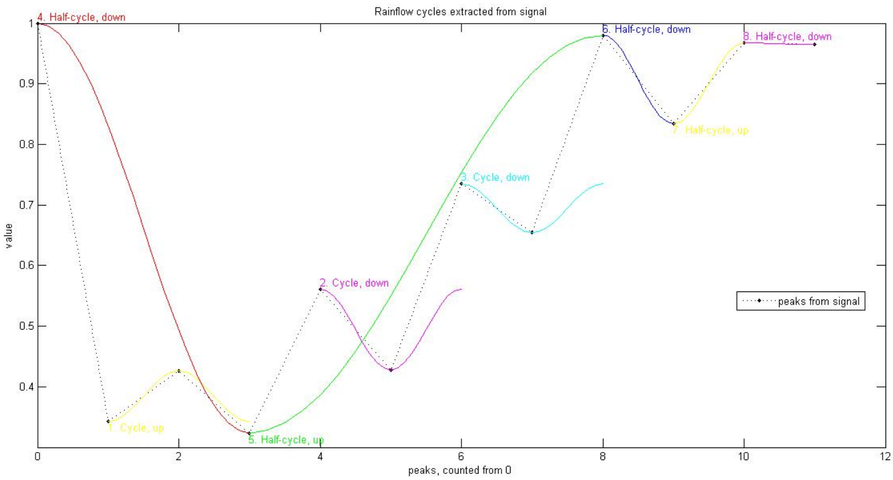

Figure 5.71: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmax (ScenarioA-2)

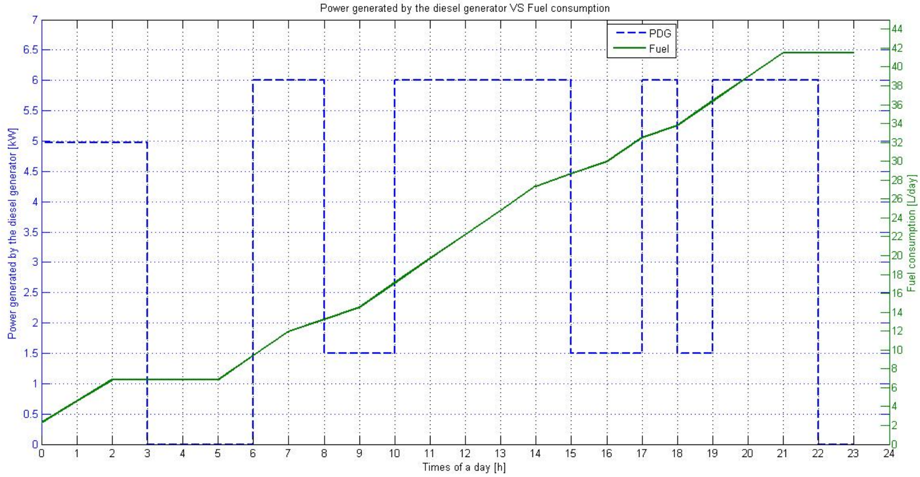

Figure 5.72: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmin (ScenarioA-2)

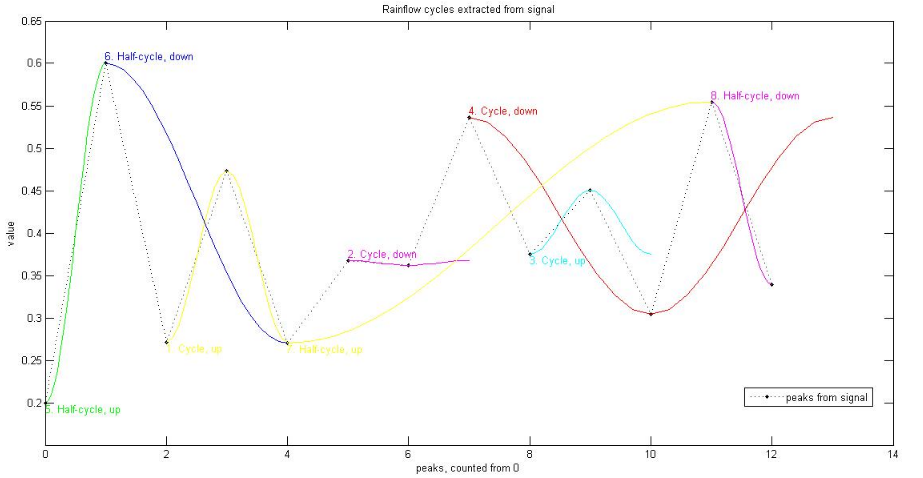

Figure 5.73: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmin (ScenarioA-2)

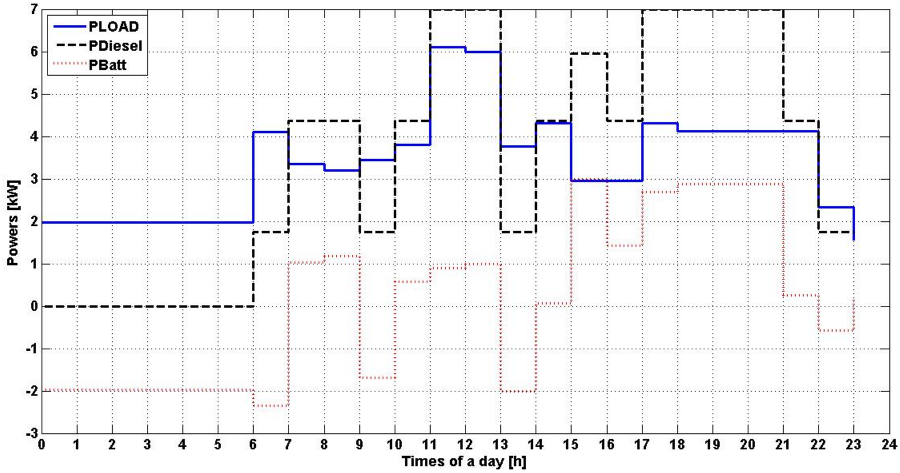

Figure 5.74: Behaviour of the HES when powered by the diesel generator and the battery with SOCi=SOCf=SOCmax (ScenarioA-3)

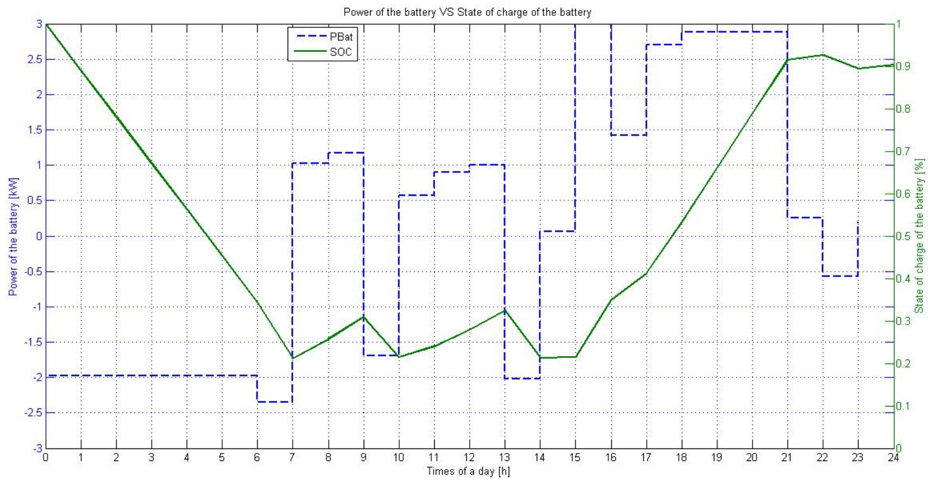

Figure 5.75: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmax (ScenarioA-3)

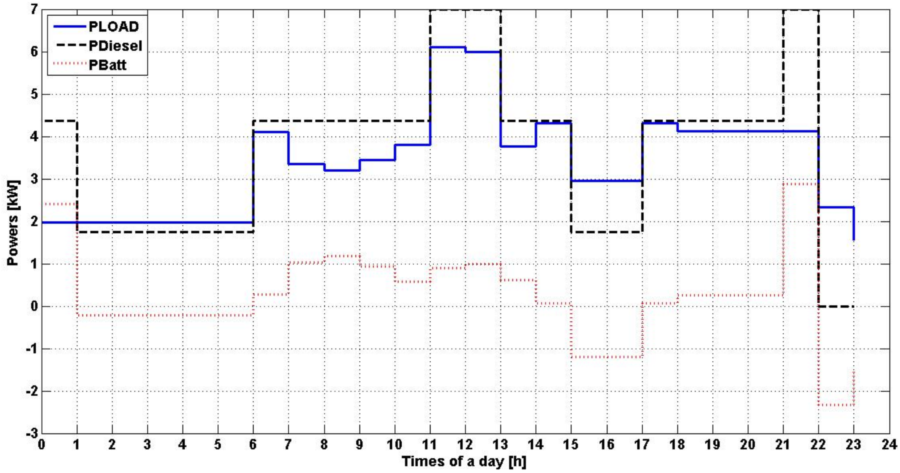

Figure 5.76: Behaviour of the HES when powered by the diesel generator and the battery with SOCi=SOCf=SOCmin (ScenarioA-3)

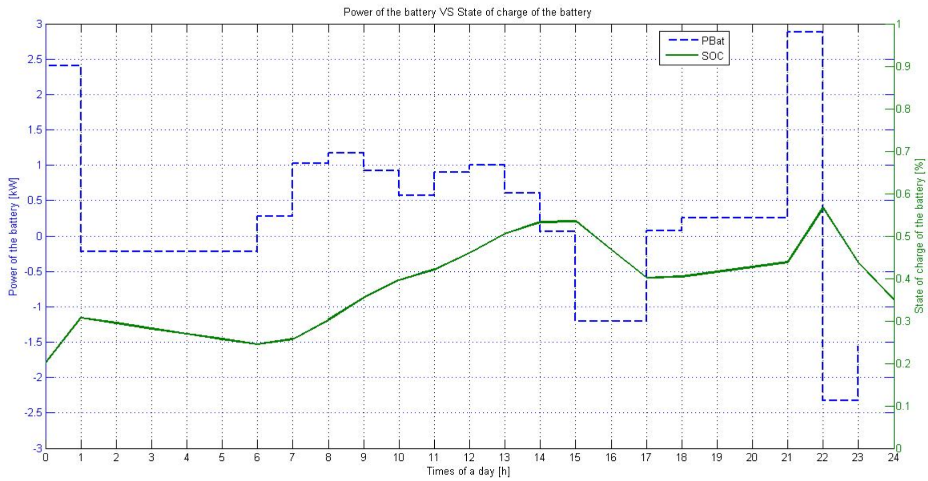

Figure 5.77: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmin (ScenarioA-3)

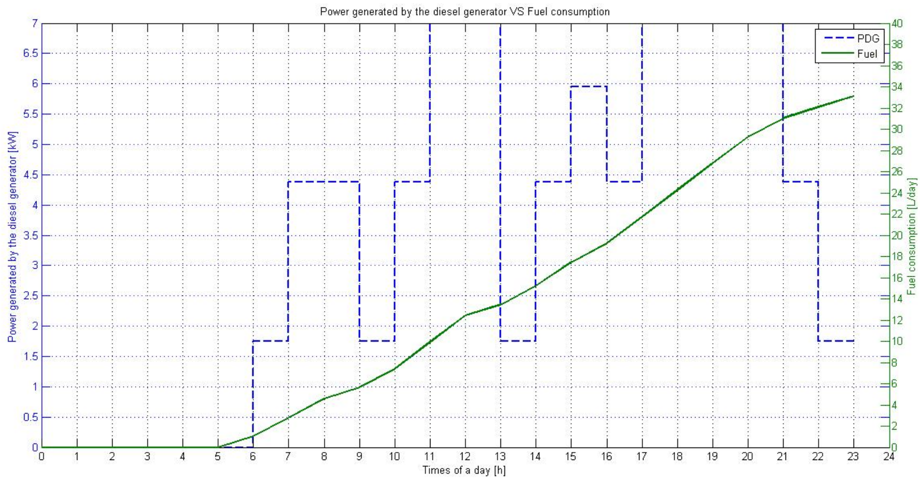

Figure 5.78: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmax (ScenarioA-3)

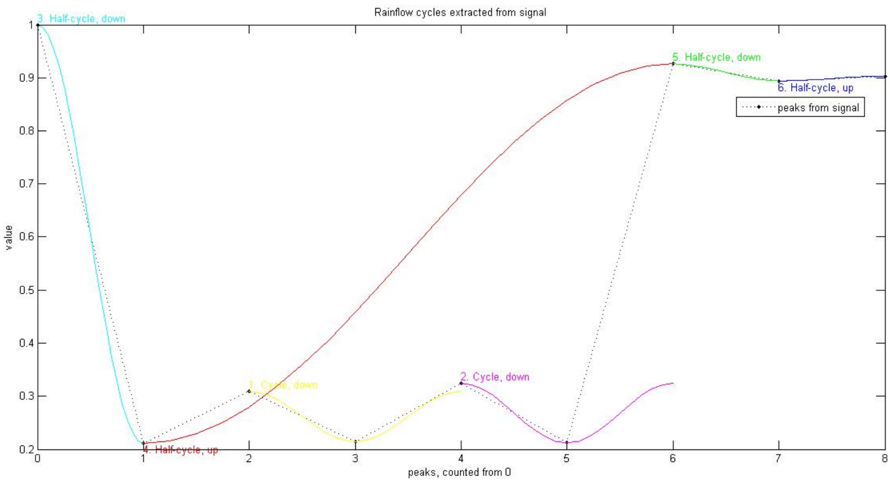

Figure 5.79: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmax (ScenarioA-3)

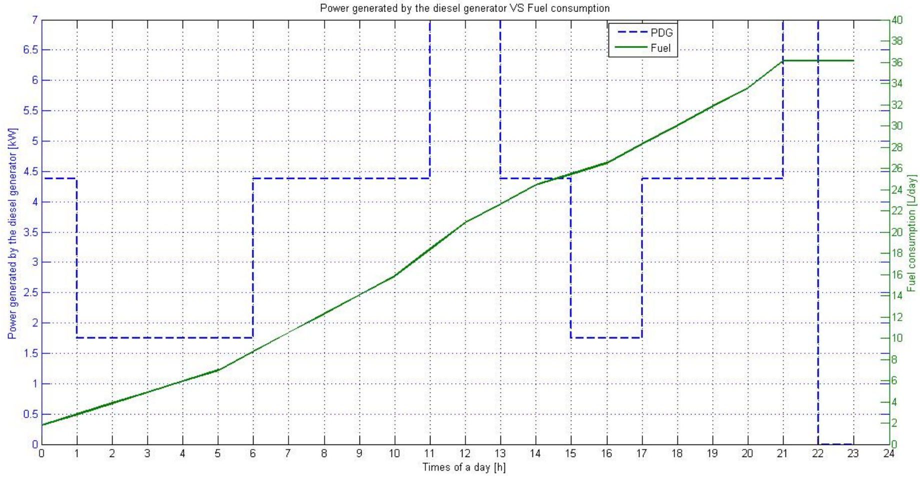

Figure 5.80: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmin (ScenarioA-3)

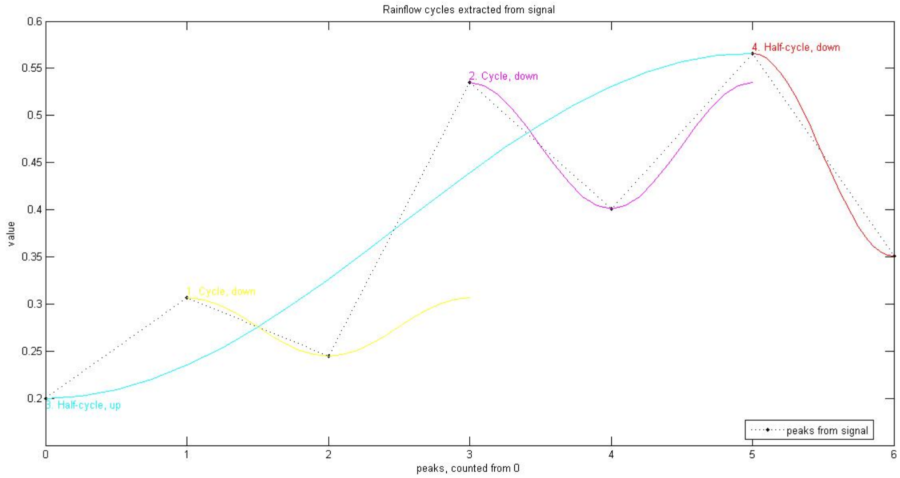

Figure 5.81: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmin (ScenarioA-3)

Table 5.18: Results obtained 5.5.8 (ScenarioA-3)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
7	3	33.127	SOCmax	278
7	3	36.11	SOCmin	758

Table 5.19: Summary of results obtained when the load is supplied only by the diesel generator and the battery 5.5.8 (ScenarioA)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
5	3	37.019	SOCmax	398
5	3	38.523	SOCmin	427
6	3	39.602	SOCmax	269
6	3	41.50	SOCmin	317
7	3	33.127	SOCmax	278
7	3	36.11	SOCmin	758

Discussions

Fig.5.58, 5.60,5.66, 5.68,5.74, 5.76 show respectively the behaviour of the demand load powered by the diesel generator and the battery when the initial state of charge of the battery is uqual to the final state of charge. Firstly, when SOCi=SOCf=SOCmax and secondly when SOCi=SOCf=SOCmin. The behaviour of the diesel generator and the battery in the two case are different. The fuel consumption of the diesel generator in the first case is less than the second case (see Fig.5.62,5.64,5.70,5.72,5.78,5.80). The behaviour or the use of the battery have an impact on it's lifetime since the battery have a limite number of cycle of life (see Fig.5.63,5.65,5.71,5.73,5.79,5.81). We can observed that when the initial state of charge and the final state of charge the batttery is equal to the sate of charge maximum, the consumption of the scenario with 7 kW of diesel generator is the best solution. The less used battery have a long life time but a high fuel consumption.(see table 5.19)

5.5.9 ScenarioB: The load is supplied by the renewables sources (Solar+Wind), the diesel generator and the battery

In this scenario, the load demand is powered by the renewables (solar+wind), the diesel generator and the battery. The photovoltaic generator have a peak power of 3 kWp while the power from wind generator is 1.4 kW. The diesel generator has different step size of 5/6/7 kW. The battery have a power of 3 kW and a maximum average energy stored of 18 kWh. In the different scenarios, the initial state of charge of the battery is kept equal to the final state of charge value. This, is because the continuity during a determined period have to be respected and the best scenario been chosen.

ScenarioB-1: The load is supplied by the renewables sources (Solar+Wind), the 5 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by a photovoltaic generator with a peak power of 3 kWp while the power wind generator is 1.4 kW. The diesel generator is 5 kW and the battery have a maximum power of 3 kW and a maximum average energy stored of 18 kWh. For the economical calculation, the investment costs of the PV, wind turbine, the battery and the diesel generator are respectively 10000 €, 5000 €, 3000 €and 2500€. The other data are listed in Table 5.31.

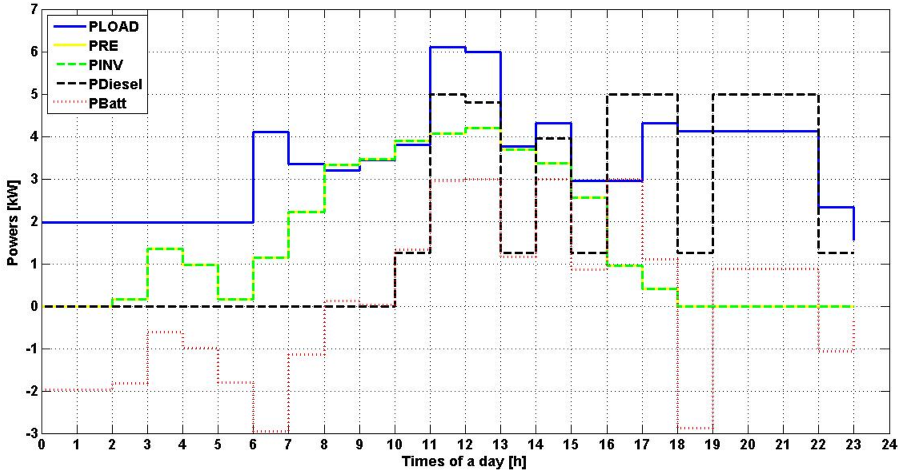

Figure 5.82: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with SOCi=SOCf=SOCmax (ScenarioB-1)

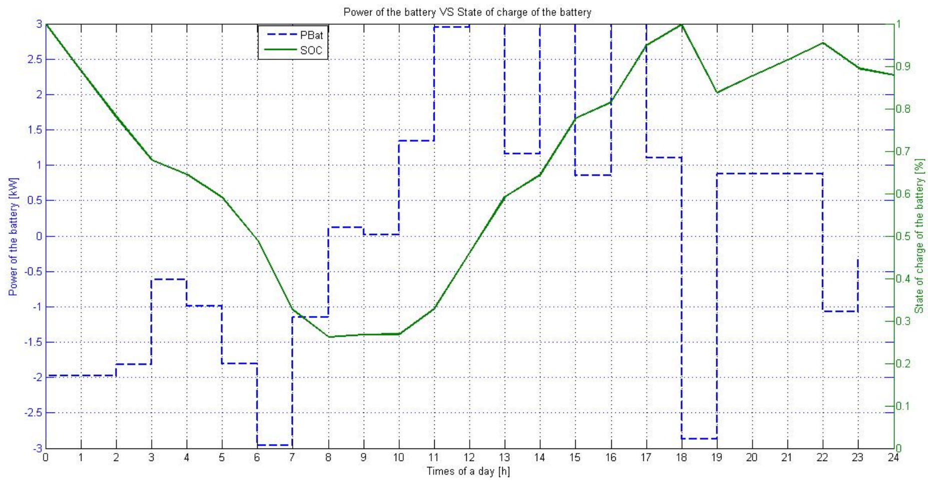

Figure 5.83: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmax (ScenarioB-1)

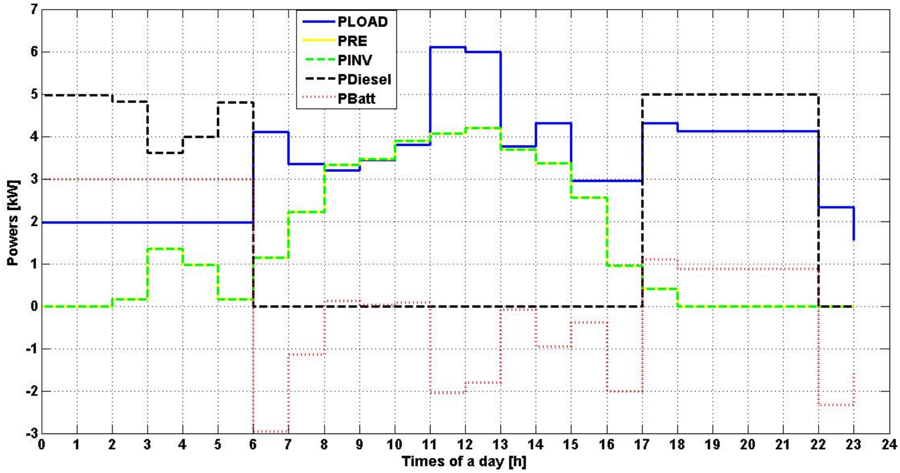

Figure 5.84: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with SOCi=SOCf=SOCmin (ScenarioB-1)

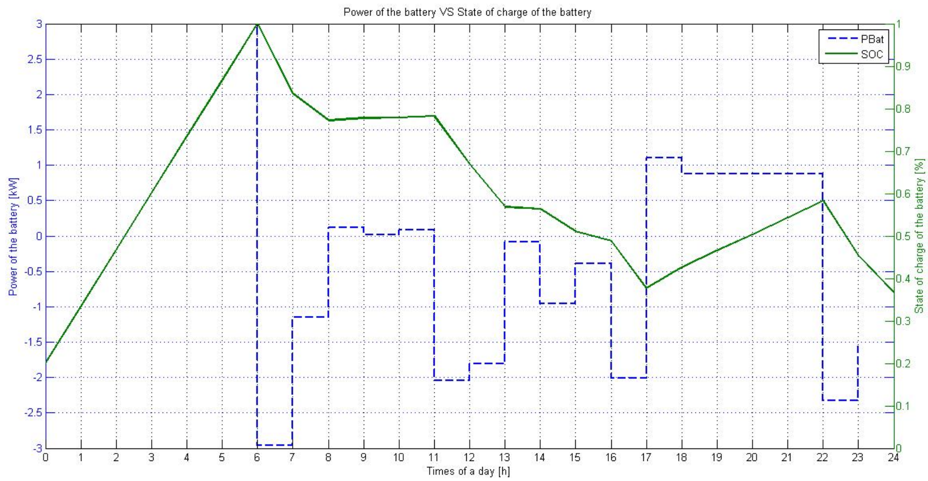

Figure 5.85: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmin (ScenarioB-1)

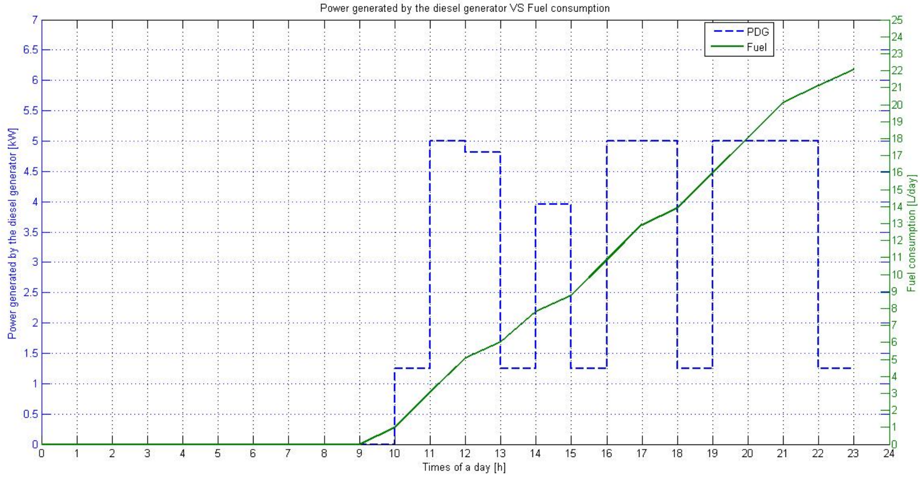

Figure 5.86: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmax (ScenarioB-1)

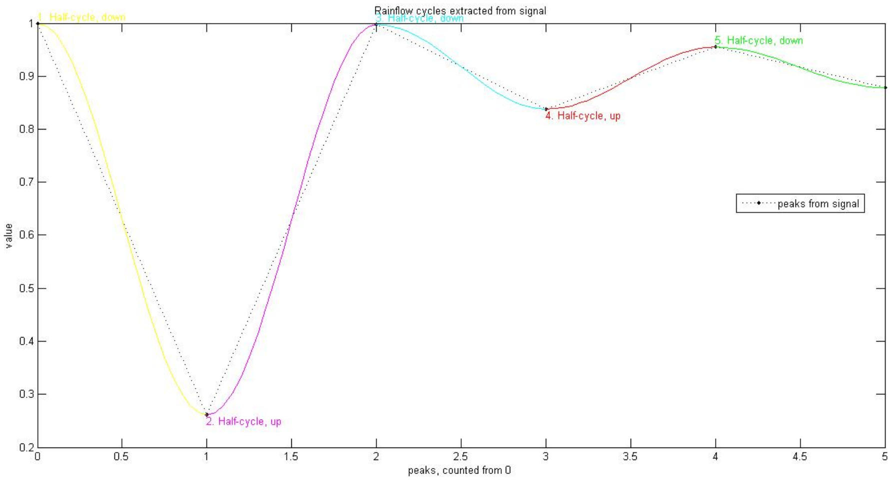

Figure 5.87: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmax (ScenarioB-1)

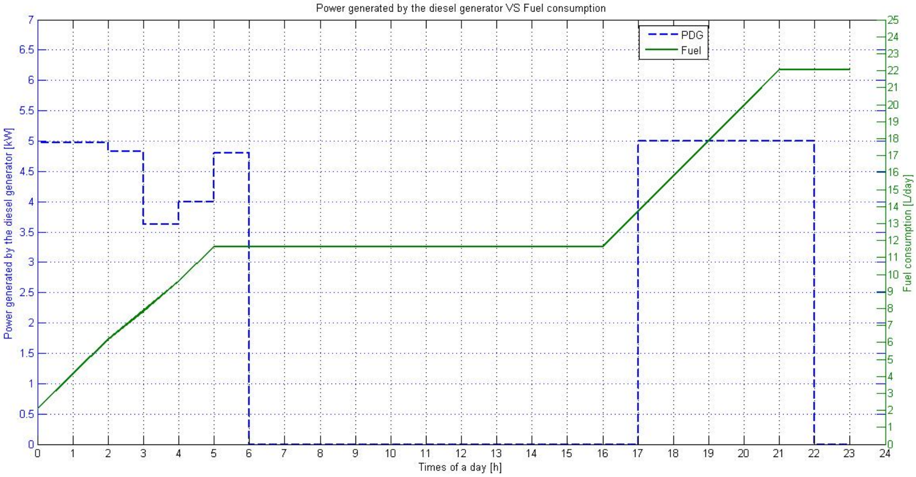

Figure 5.88: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmin (ScenarioB-1)

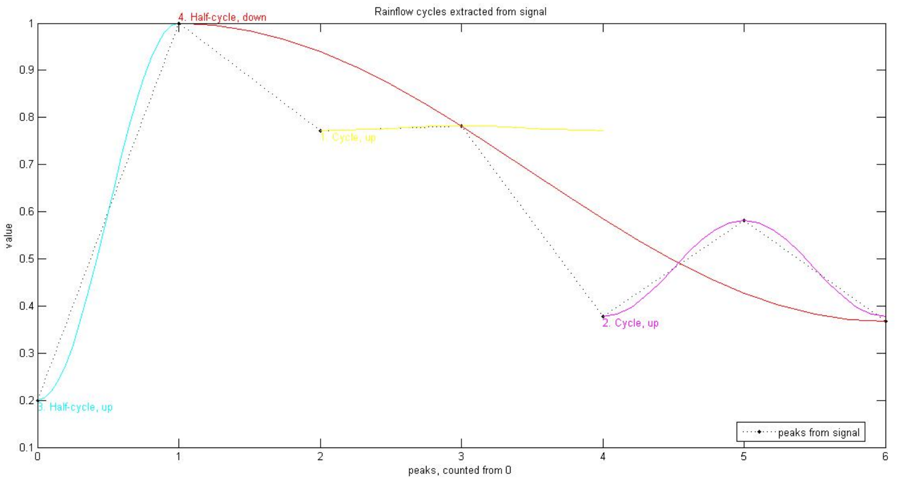

Figure 5.89: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmin (ScenarioB-1)

Table 5.20: Results obtained 5.5.9 (ScenarioB-1)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
5	3	22.094	SOCmax	301
5	3	22.047	SOCmin	292
5	3	22.778	$SOCi\#SOCf$	329

ScenarioB-2: The load is supplied by the renewables sources (Solar+Wind), the 6 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by a photovoltaic generator with a peak power of 3 kWp while the power wind generator is 1.4 kW. The diesel generator is 6 kW and the battery have a maximum power of 3 kW and a maximum average energy stored of 18 kWh.For the economical calculation, the investment costs of the PV , wind turbine, the battery and the diesel generator are respectively 10000 €, 5000 €, 3000 €and 3000€. The other data are listed in Table 5.31.

Table 5.21: Results obtained 5.5.9 (ScenarioB-2)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
6	3	24.276	SOCmax	296
6	3	24.454	SOCmin	267
6	3	17.425	$SOCi\#SOCf$	354

ScenarioB-3: The load is supplied by the renewables sources (Solar+Wind), the 7 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by a photovoltaic generator with a peak power of 3 kWp while the power wind generator is 1.4 kW. The diesel generator is 7 kW and the battery have a maximum power of 3 kW and a maximum average energy stored of 18 kWh. For the economical calculation, the investment costs of the PV , wind turbine, the battery and the diesel generator are respectively 10000 €, 5000 €, 3000 €and 3500€. The other data are listed in Table 5.31.

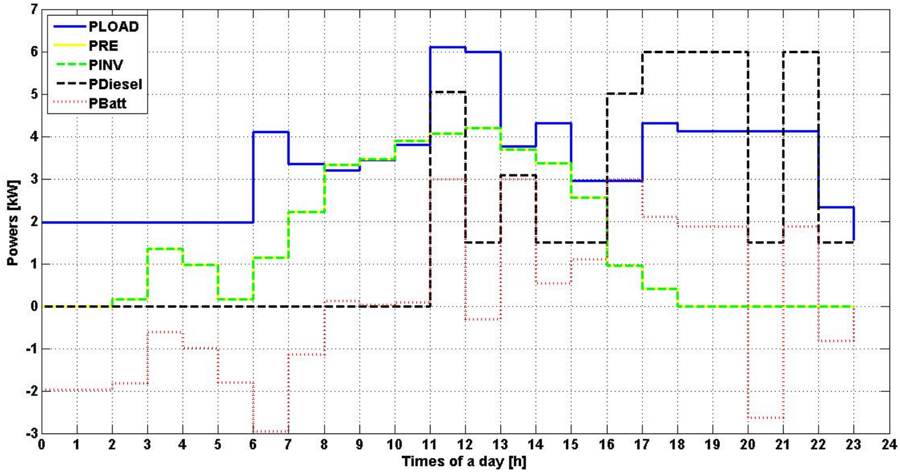

Figure 5.90: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with SOCi=SOCf=SOCmax (ScenarioB-2)

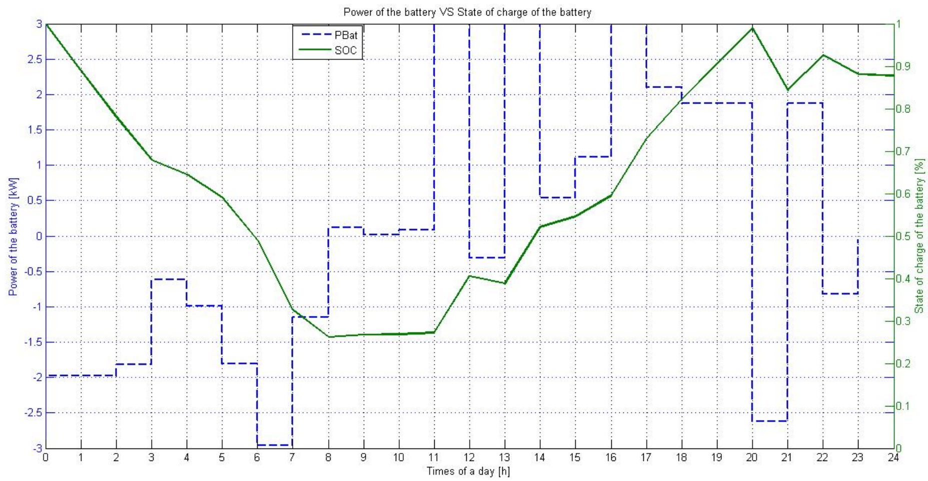

Figure 5.91: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmax (ScenarioB-2)

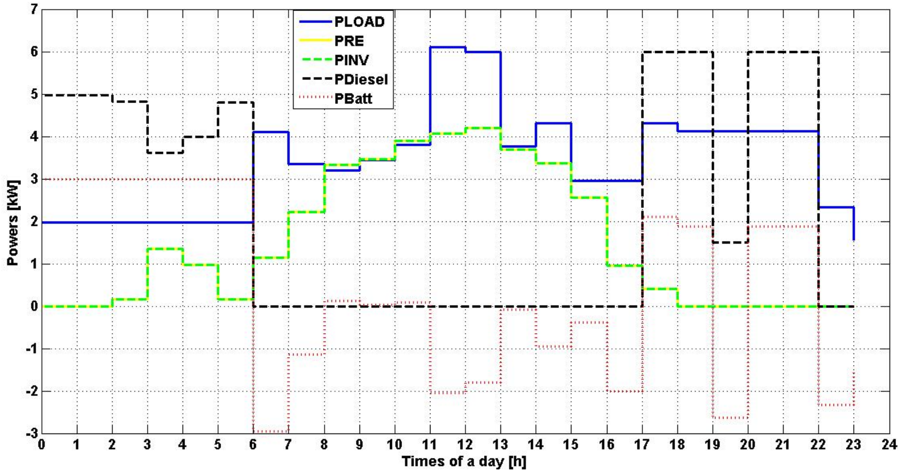

Figure 5.92: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with SOCi=SOCf=SOCmin (ScenarioB-2)

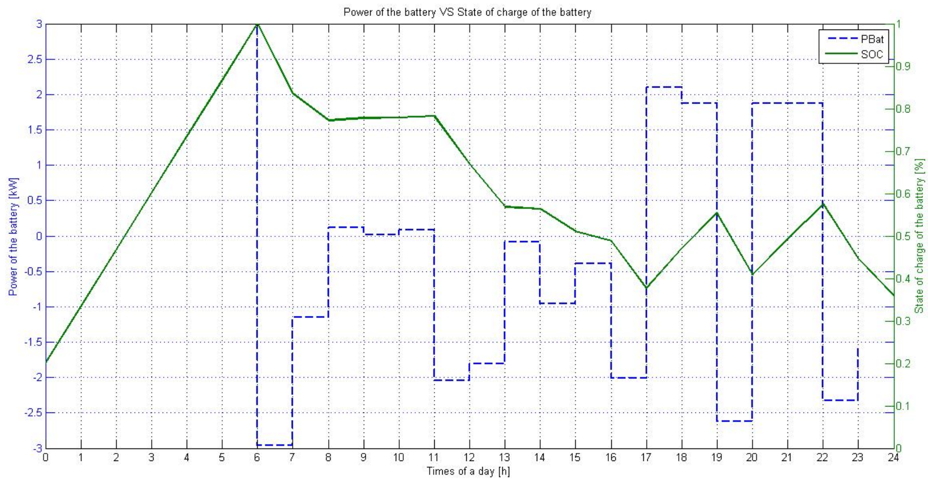

Figure 5.93: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmin (ScenarioB-2)

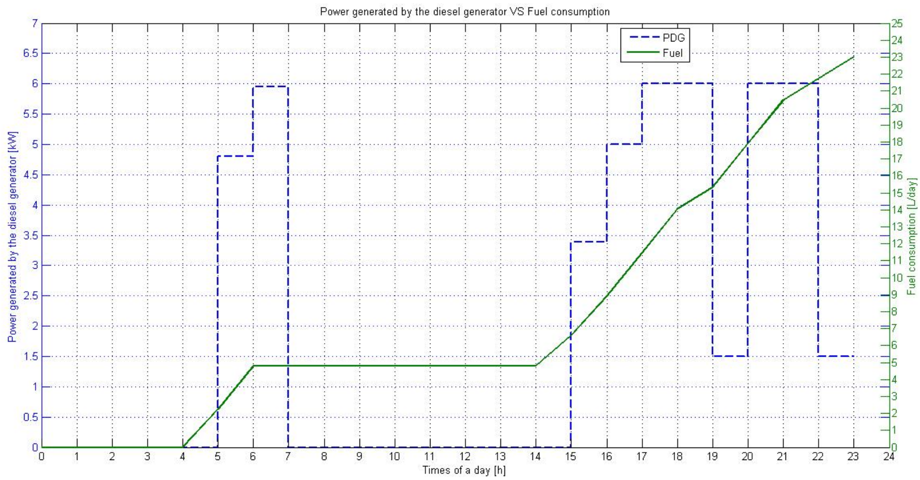

Figure 5.94: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmax (ScenarioB-2)

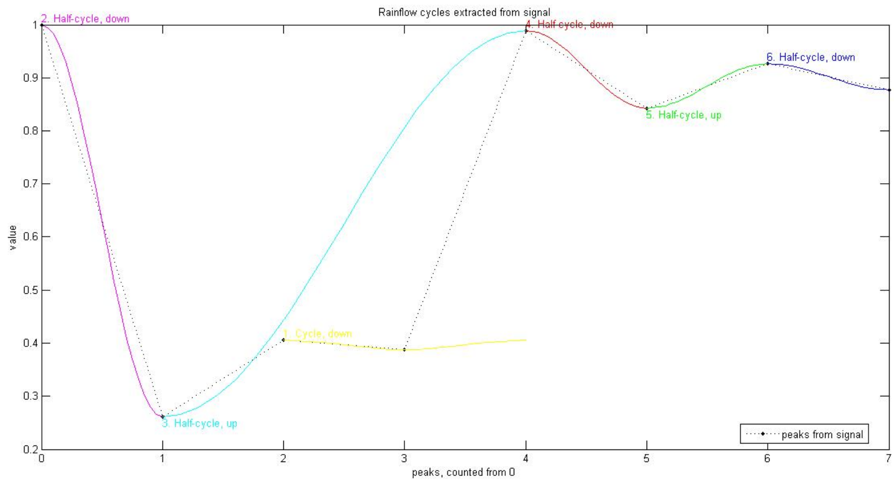

Figure 5.95: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmax (ScenarioB-2)

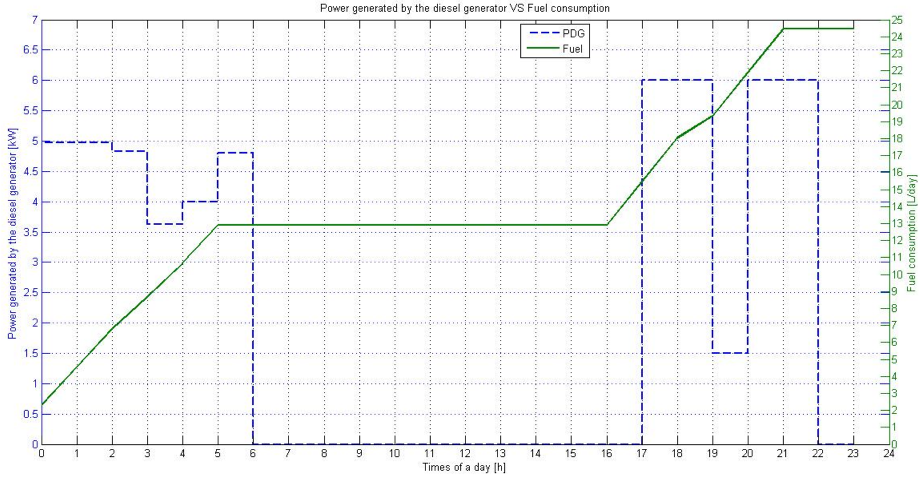

Figure 5.96: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmin (ScenarioB-2)

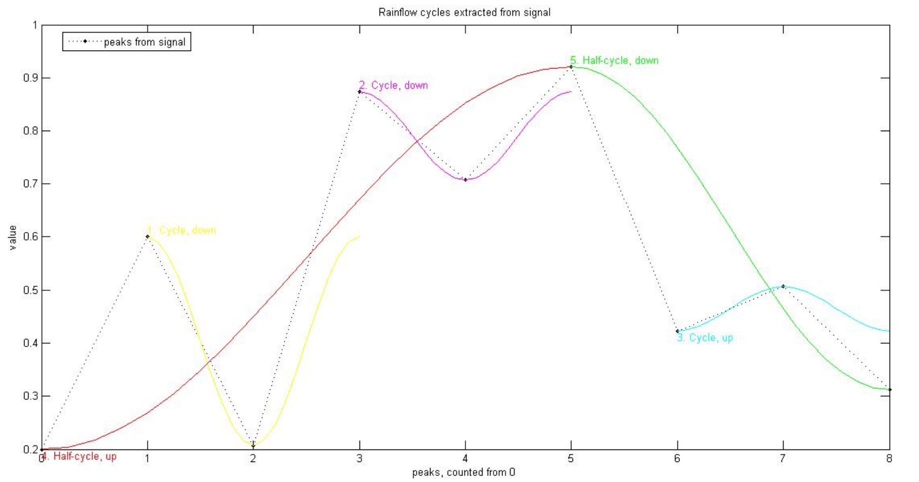

Figure 5.97: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmin (ScenarioB-2)

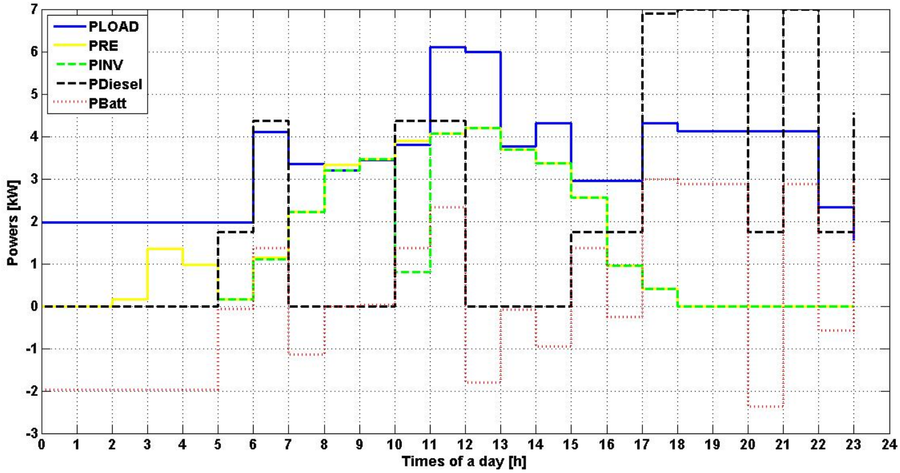

Figure 5.98: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with SOCi=SOCf=SOCmax (ScenarioB-3)

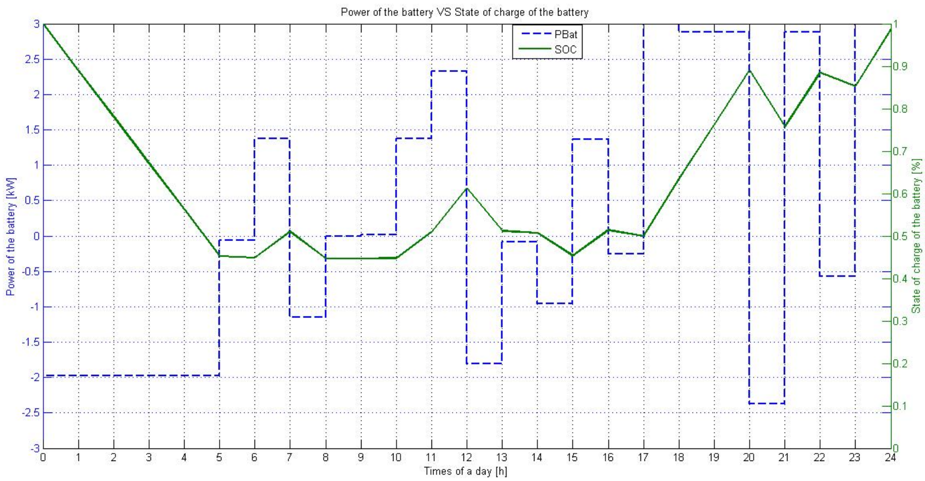

Figure 5.99: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmax (ScenarioB-3)

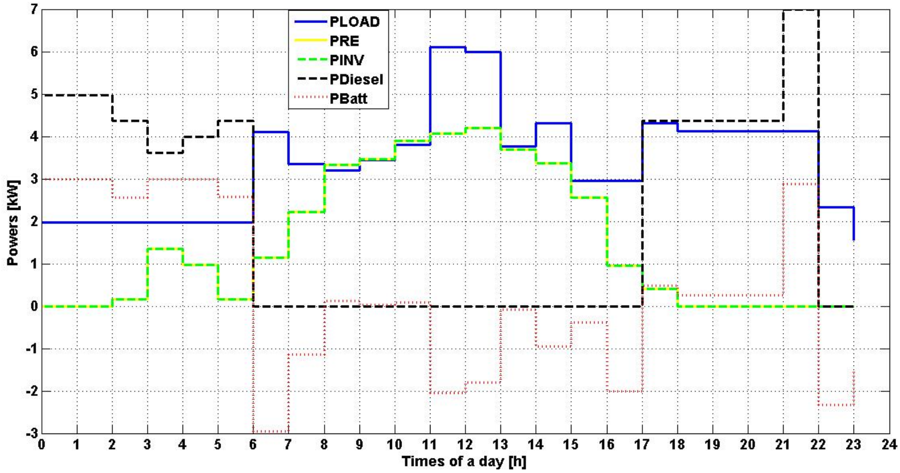

Figure 5.100: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with SOCi=SOCf=SOCmin (ScenarioB-3)

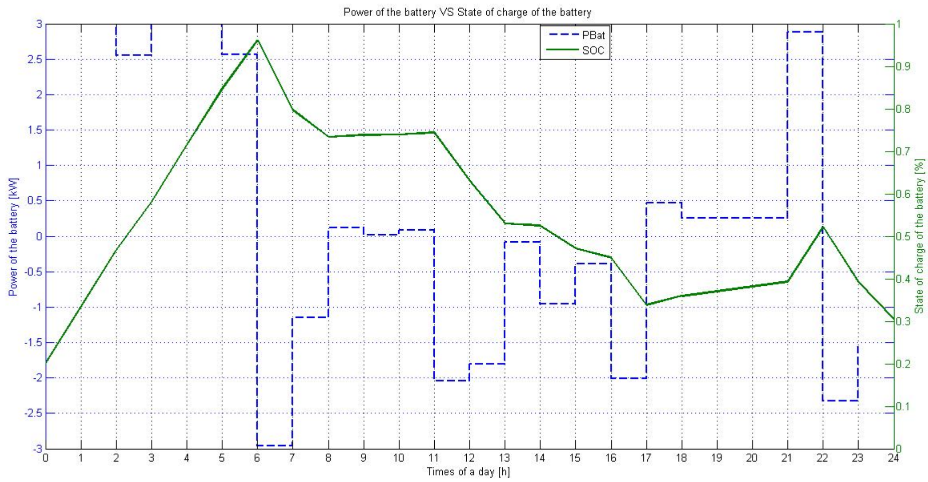

Figure 5.101: Behaviour of the battery and the state of charge when SOCi=SOCf=SOCmin (ScenarioB-3)

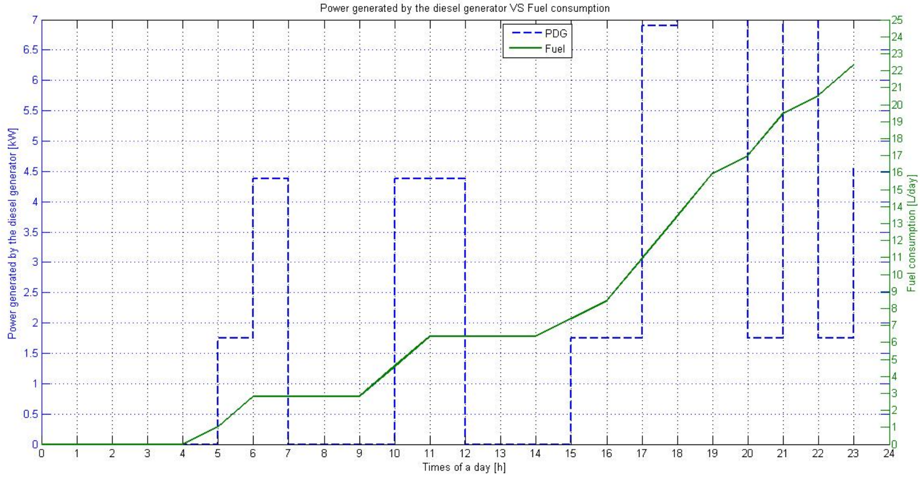

Figure 5.102: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmax (ScenarioB-3)

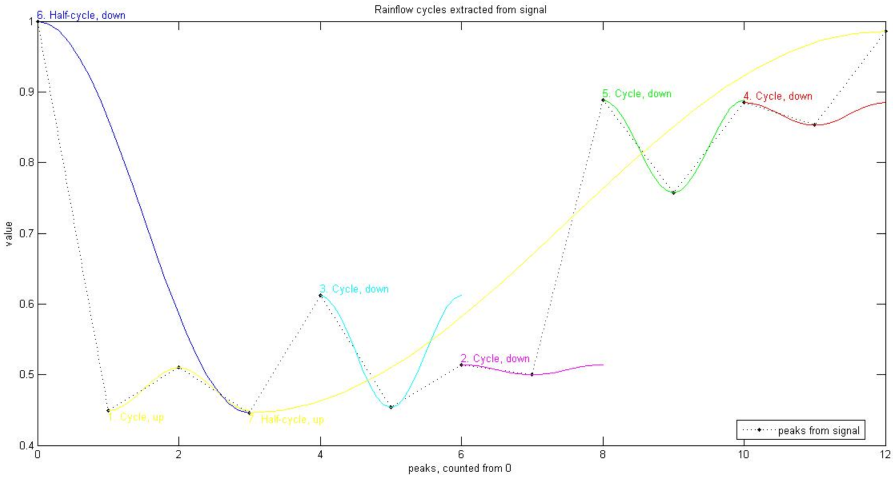

Figure 5.103: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmax (ScenarioB-3)

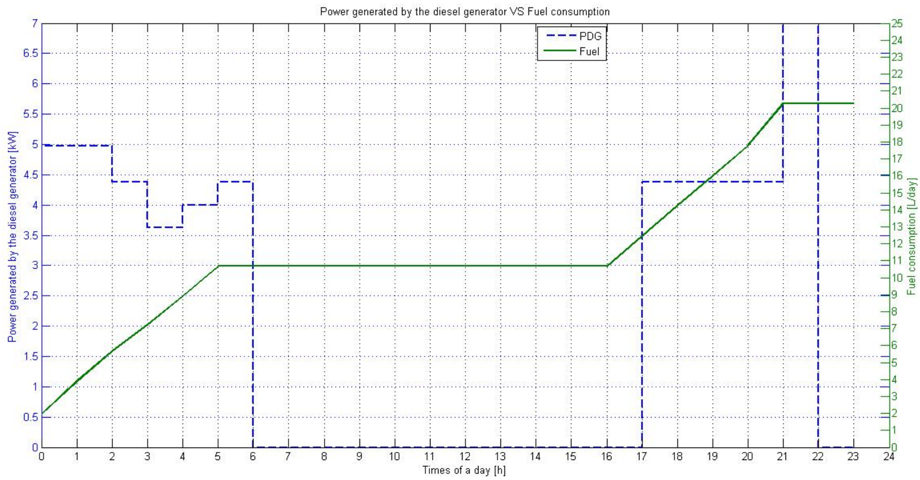

Figure 5.104: Behaviour of the diesel generator with fuel consumption when SOCi=SOCf=SOCmin (ScenarioB-3)

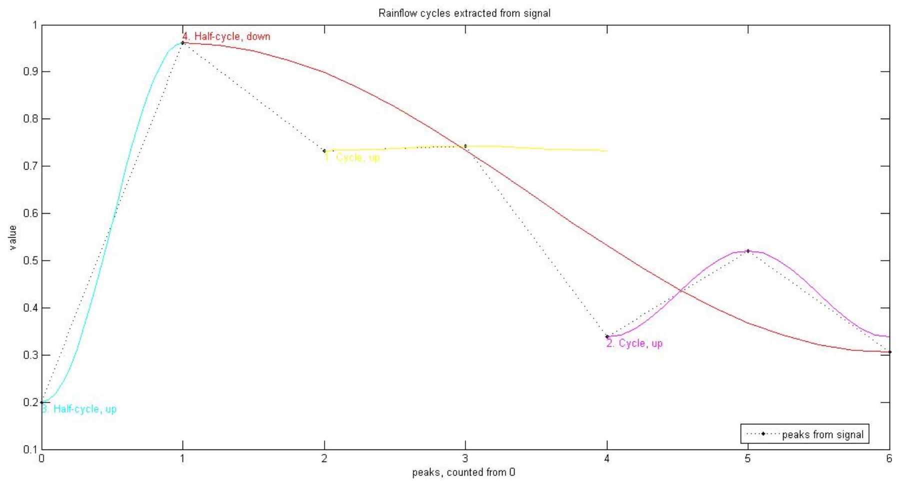

Figure 5.105: Rainflow count extracted from the state of charge value when SOCi=SOCf=SOCmin (ScenarioB-3)

Table 5.22: Results obtained 5.5.9 (ScenarioB-3)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
7	3	22.362	SOCmax	314
7	3	20.277	SOCmin	300
7	3	14.505	$SOCi \# SOCf$	418

Table 5.23: Summary of results obtained when the load is supplied by renewable sources, the diesel generator and the battery 5.5.9 (ScenarioB)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
5	3	22.094	SOCmax	301
5	3	22.047	SOCmin	292
5	3	22.778	$SOCi \# SOCf$	329
6	3	24.276	SOCmax	296
6	3	24.454	SOCmin	267
6	3	17.425	$SOCi \# SOCf$	354
7	3	22.362	SOCmax	314
7	3	20.277	SOCmin	300
7	3	14.505	$SOCi \# SOCf$	418

Discussions

Fig.5.82, 5.84,5.90, 5.92,5.98, 5.100 show respectively the behaviour of the load powered by the diesel generator and the battery when the initial state of charge of the battery is uqual to the final state of charge. In the first figure, SOCi=SOCf=SOCmax when in the second figure SOCi=SOCf=SOCmin. The behaviour of the diesel generator and the battery in the two case are different. The fuel consumption of the diesel generator in the first case is less than the second case. the less used have a long life time but a high fuel consumption (see Fig.5.86,5.88,5.94,5.96,5.102,5.104). The behaviour or the use of the battery have an impact on it's lifetime since the battery have a limite number of cycle of life (see Fig.5.87,5.89,5.95,5.97,5.103,5.105). We can observed that when the initial state of charge and the final state of charge the batttery is equal to the state of charge maximum, the consumption of the scenario with 7 kW of diesel generator is the best solution. (see Table 5.23)

5.5.10 ScenarioC: Optimized simulation in correspondance to the heuristic method

In this scenario, the load demand is powered by the renewables (solar+wind), the diesel generator and the battery. The photovoltaic generator have a peak power of 3 kWp while the power from wind generator is 1.3 kW. The different power of the diesel generators here are 5, 6 and 7 kW. The battery have a power of 3 kW and a maximum average energy stored of 18 kWh. In the different scenarios, the initial state of charge of the battery is different to the final state of charge value.

ScenarioC-1: The load is supplied by the renewables sources (Solar+Wind), the 5 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by a photovoltaic generator with a peak power of 3 kWp while the power wind generator is 1.4 kW. The diesel generator is 5 kW and the battery have a maximum power of 3 kW and a maximum average energy stored of 18 kWh.

Table 5.24: Results obtained 5.5.10 (ScenarioC-1)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
5	3	22.778	$SOCi\#SOCf$	329

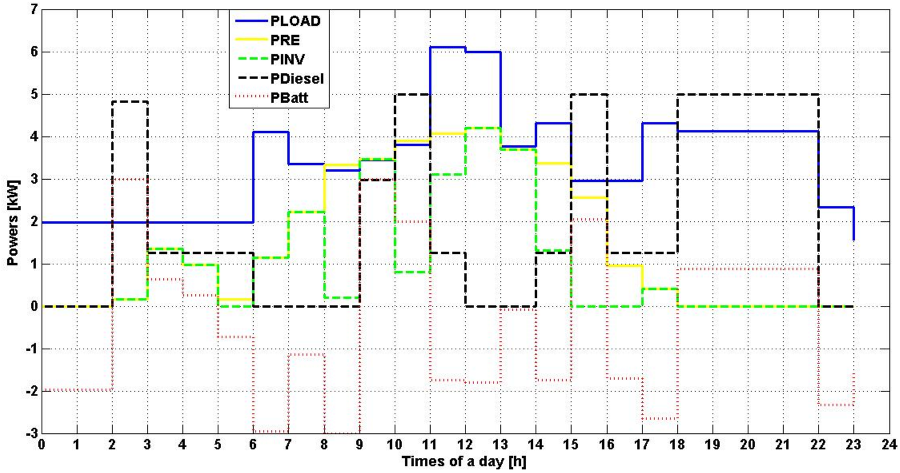

Figure 5.106: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with $SOCi\#SOCf$ (ScenarioC-1)

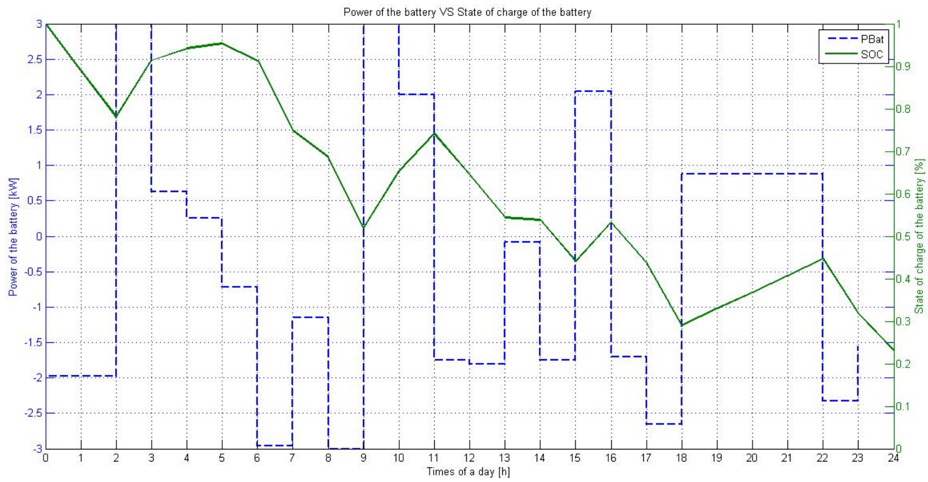

Figure 5.107: Behaviour of the battery and the state of charge when $SOCi\#SOCf$ (ScenarioC-1)

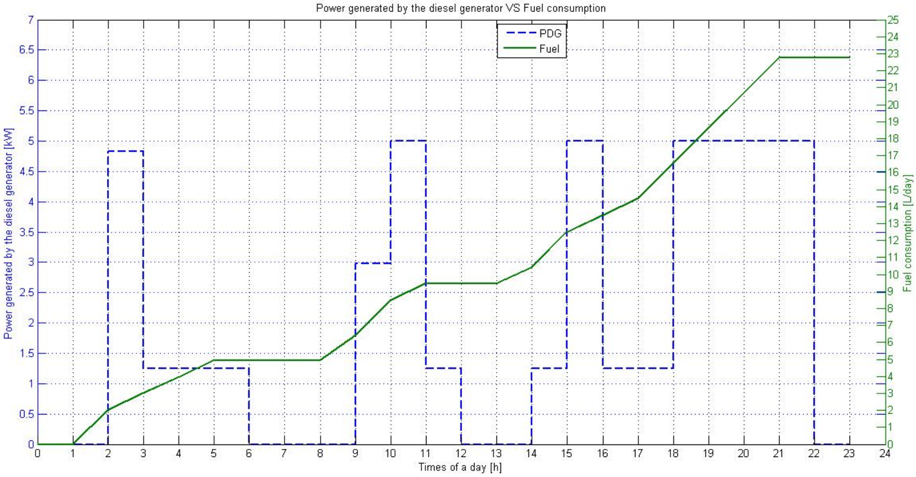

Figure 5.108: Behaviour of the diesel generator with fuel consumption when $SOCi\#SOCf$ (ScenarioC-1)

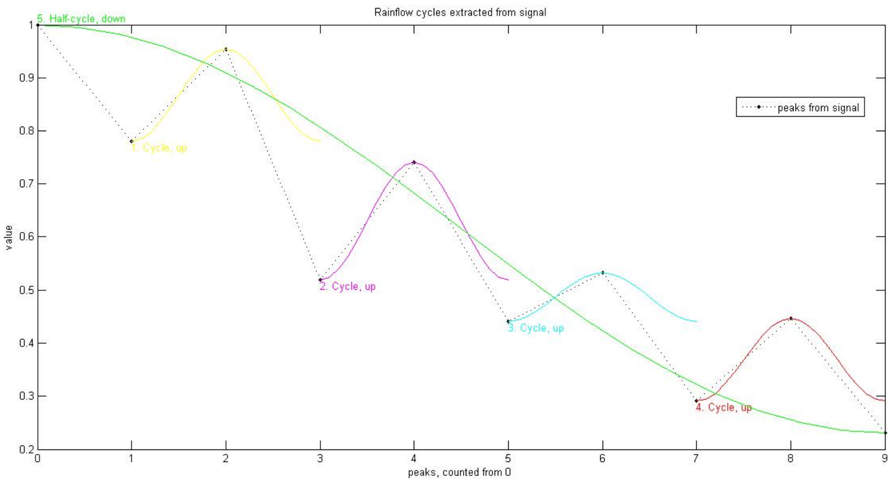

Figure 5.109: Rainflow count extracted from the state of charge value when $SOCi\#SOCf$ (ScenarioC-1)

ScenarioC-2: The load is supplied by the renewables sources (Solar+Wind), the 6 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by a photovoltaic generator with a peak power of 3 kWp while the power wind generator is 1.4 kW. The diesel generator is 6 kW and the battery have a maximum power of 3 kW and a maximum average energy stored of 18 kWh.

Table 5.25: Results obtained 5.5.10 (ScenarioC-2)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
6	3	17.425	$SOCi\#SOCf$	354

ScenarioC-3: The load is supplied by the renewables sources (Solar+Wind), the 7 kW diesel generator and the 3 kW battery

In this scenario, the load demand is powered by a photovoltaic generator with a peak power of 3 kWp while the power wind generator is 1.4 kW. The diesel generator is 7 kW and the battery have a maximum power of 3 kW and a maximum average energy stored of 18 kWh.

Table 5.26: Results obtained 5.5.10 (ScenarioC-3)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
7	3	14.505	$SOCi\#SOCf$	418

Discussions

The load demand is powered by renewables sources (solar and wind), the diesel generator and the battery. Using an optimized method for supplying the demand load, we have a fuel consumption minimization for the diesel generators of 6 and 7 kW respectively 12.75% and 14% compare to the heuristic method. The diesel generator with 7 kW power rated is the best with the less daily fuel consumption.

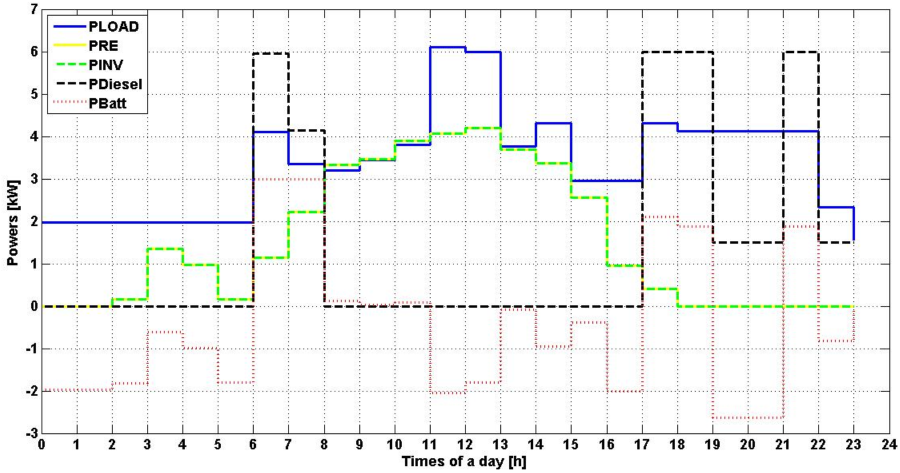

Figure 5.110: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with $SOCi \# SOCf$ (ScenarioC-2)

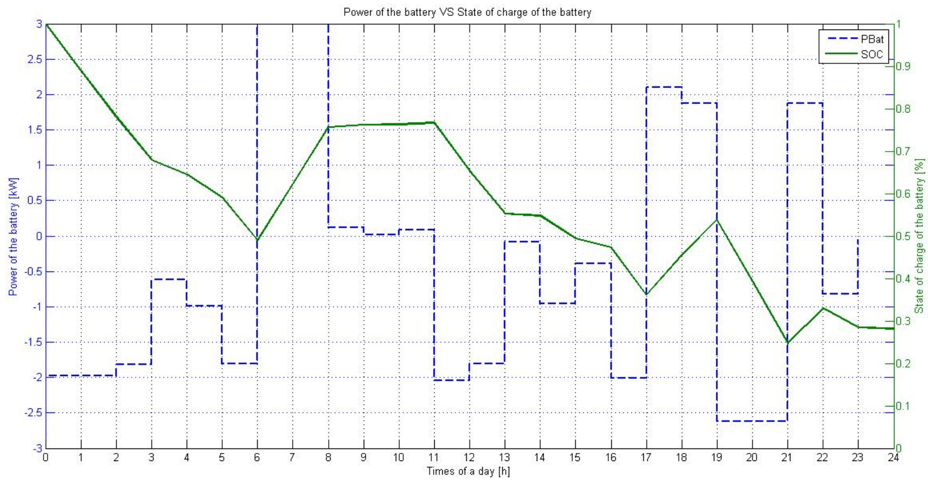

Figure 5.111: Behaviour of the battery and the state of charge when $SOCi \# SOCf$ (ScenarioC-2)

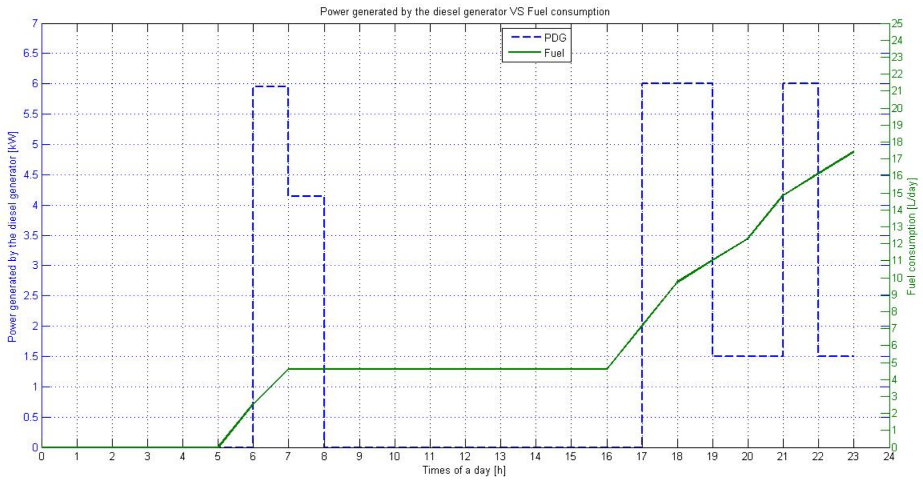

Figure 5.112: Behaviour of the diesel generator with fuel consumption when $SOCi\#SOCf$ (ScenarioC-2)

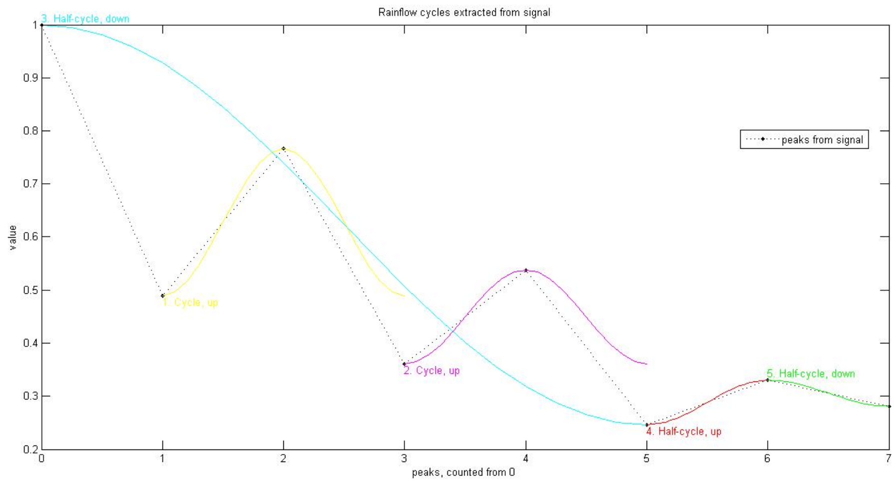

Figure 5.113: Rainflow count extracted from the state of charge value when $SOCi\#SOCf$ (ScenarioC-2)

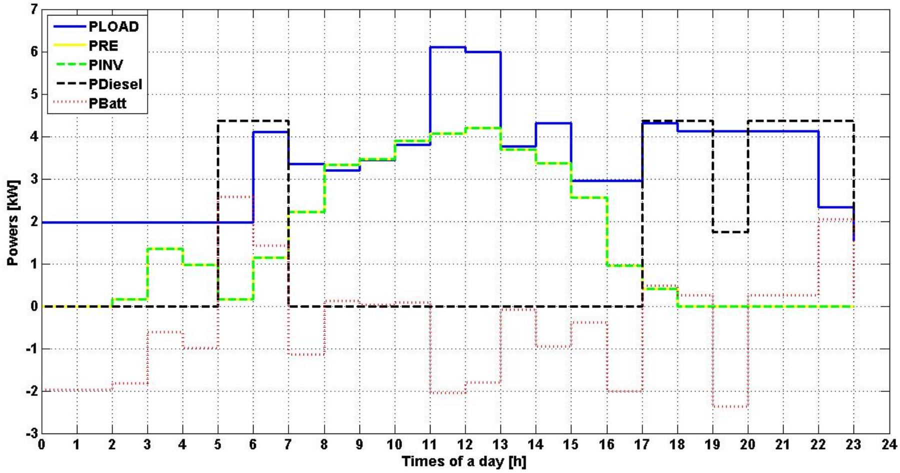

Figure 5.114: Behaviour of the HES when powered by the renewables, the diesel generator and the battery with $SOCi\#SOCf$ (ScenarioC-3)

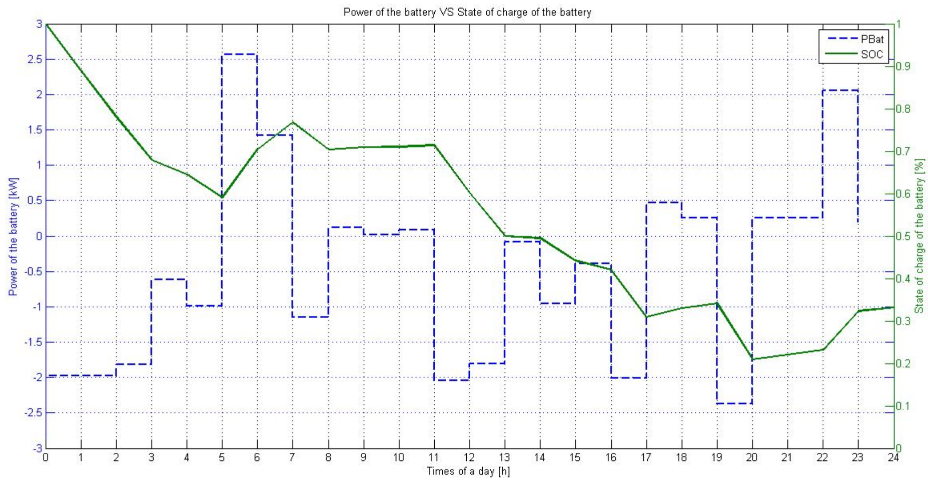

Figure 5.115: Behaviour of the battery and the state of charge when $SOCi\#SOCf$ (ScenarioC-3)

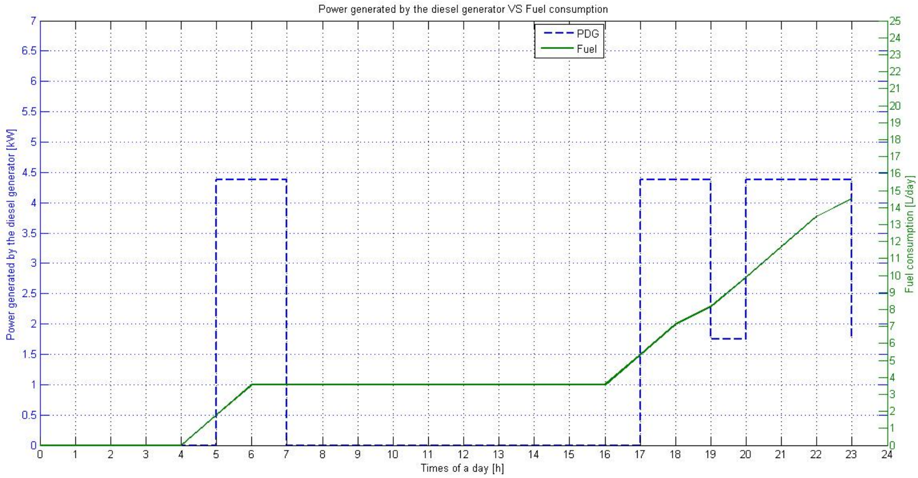

Figure 5.116: Behaviour of the diesel generator with fuel consumption when $SOCi\#SOCf$ (ScenarioC-3)

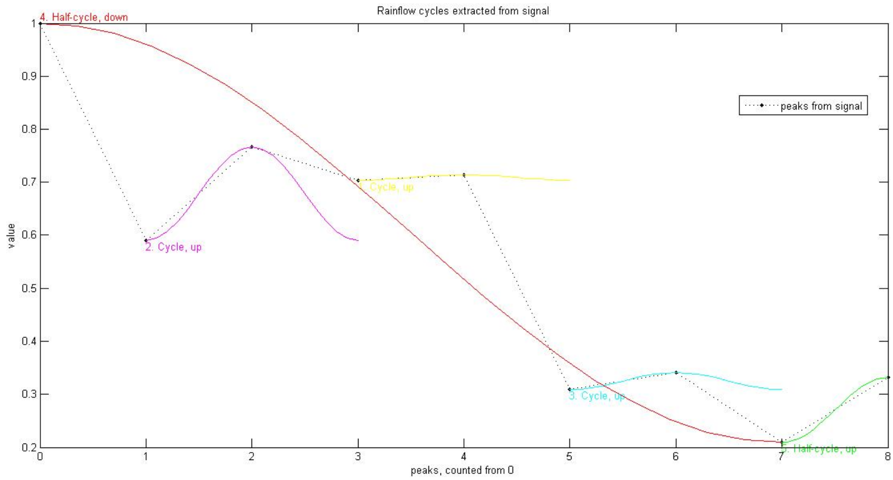

Figure 5.117: Rainflow count extracted from the state of charge value when $SOCi\#SOCf$ (ScenarioC-3)

Table 5.27: Summary of results obtained when the load is supplied by renewable sources, the diesel generator and the battery with $SOCi\#SOCf$ 5.5.10 (ScenarioC)

P_{dg} [kW]	P_{bat} [kW]	Fuel [L/day]	SOCi=SOCf	Battery lifetime [days]
5	3	22.778	$SOCi\#SOCf$	329
6	3	17.425	$SOCi\#SOCf$	354
7	3	14.505	$SOCi\#SOCf$	418

Table 5.28: Summary of results obtained from heuristic model and optimize model (ScenarioC, Scenario1-2-3)

P_{PV} [kW]	P_{WIND} [kW]	P_{Bat} [kW]	P_{DG} [kW]	Fuel [L/day]	Battery lifetime [days]	Method
3	1.3	3	5	18.17	547	Heuristic
3	1.3	3	5	22.778	329	Optimized
3	1.3	3	6	19.97	590	Heuristic
3	1.3	3	6	17.425	354	Optimized
3	1.3	3	7	16.86	562	Heuristic
3	1.3	3	7	14.505	418	Optimized

Table 5.29: Summary of daily fuel saving obtained from all the scenarios and compared to the optimization method scenario (ScenarioC, Scenario0, ScenarioA, Scenario1-2-3)

P_{DG} [kW]	*Optimized* [L/day]	*Diesel* [L/day]	*Saving* [L/day]	*Bat/Diesel* [L/day]	*Saving* [L/day]	*Heuristic* [L/day]	*Saving* [L/day]
5	22.778	-	-	37.019	14.241	18.17	-
6	17.425	-	-	39.602	22.177	19.97	2.245
7	14.505	37.461	23.461	33.127	18.622	16.86	2.235

Table 5.30: Summary of the economic analysis

Costs	*Diesel Only* : [7*kW*]	*PV/Wind/ Batt/Diesel* : [3/1.4/3/5*kW*]	*PV/Wind/ Batt/Diesel* : [3/1.4/3/6*kW*]	*PV/Wind/ Batt/Diesel* : [3/1.4/3/7*kW*]
Investment (€)	3500	20500	21000	21500
Maintenance (€)	55.3	57.5	61	64.3
Operation (€)	15314	9312	6360	5294.3
Replacement (€)	3643.2	5563.3	6043.3	6520.2
Salvage (€)	577.2	1045.6	1140.7	1235.7
LCC (€)	23090	36478	34605	34615
LCOE (€/kWh)	0.102	0.0881	0.0835	0.0836

5.5.11 Results and discussions

It has been simulated the hybrid energy system using the heuristic algorithm (Rule-based) with different peak powers of photovoltaic to manage to entire system. It comes out that the best configuration is the one with 7 kW power diesel generator with less fuel consumption (5.4.3). The only diesel generator enable to supply the load is the 7 kW power generator. Obviously, its high daily fuel consumption is observed (5.4.3). When each of the three diesel generators have been simulated with a battery bank for storage, it comes out that the configuration with the 7 kW diesel generator is the best configuration with less daily fuel consumption and high lifetime battery (**??**). The optimized method has been carried out and it could be observed that the diesel generator with 7 kW power is the best configuration with less fuel consumption and high lifetime battery. (5.5.10) In Table 5.28, it is clear to note that with the optimization approach, the daily fuel consumption of the hybrid system is reduced respectively from 12.75 % to 14% for the 6 kW and 7 kW diesel generator compare to the heuristic algoritm. The best configuration is the one with the 7 kW diesel generator. Compare to the system powered only by diesel generator, with the optimization method, we have a reduction of daily fuel consumption of 61.28% for the 7 kW diesel generator. Compare to the system powered only by the diesel generator and the battery, with the optimization method, the daily fuel consumption reduces respectively of 38.46%, 56% and 56.21% for the diesel generators 5, 6 and 7 kW (see Table 5.29). We can concluded that, the algorithm developed for the sizing/designing and management of the hybrid system of Salak could be taken into consideration for a pre-feasible study as an simple algorithm but the optimized approach is considered relevant and fulffiled all the objectives. The cost of electricity energy cost in Cameroon is divided into four categories for residentials: <110kWh, 111kWh-400kWh, 401kWh-800kWh and 801kWh-2000kWh with respective energy cost of 0.076 €/kWh, 0.12€/kWh, 0.143€/kWh and 0.15 €/kWh. In this analysis (see Table 5.30), we can observed that the life cycle cost of the configuration powered only by the diesel generator is less than the others configuration but with a high cost of energy. The hybrid energy system configuration with the diesel generator of 5 kW has a high life cycle cost and a high cost of energy compare to the others two hybrid systems with respectively diesel generator power rated of 6 and 7 kW. In terms of economic analysis, the two configurations hybrid systems with diesel generator power rated of 6 and 7 kW and quite the same respectively with life cycle cost and livelized cost of energy. Compare to the different categories of energy consumption prices in Cameroon, the different hybrid system of this study have a less cost of energy. In this study, the monthly energy consumption is more than 2000 kWh, respect to the cost of energy applied in Cameroon, 0.15 €/kWh [174] is the cost of energy without including the value added tax (VAT) of 19.25 %. In this study, the cost of energy of the optimized hybrid system is less than the cost of energy applied in Cameroon. Compare to another study carried out by Kabeeche in Algeria, the cost of energy is 0.0836 €/kWh less than 1.184 €/kWh of [54]. In another study carried out by [96] in Cameroon, with a PV+Battery+Diesel hybrid system, for a daily electrical energy consumption of 31.79 kWh/day, the cost of energy is 1.32 €/kWh compare to 0.0836 €/kWh obtained in this work. The economic analysis of this study reveals that the cost of energy of the optimized hybrid system configurations is less than the configuration with the load supplied only by the diesel generator.

5.6 Impact of the maintenance, the human behaviour and socio-economic benefits of the hybrid system

5.6.1 Impact of the maintenance of the hybrid system

In the educational level, training programmes on techno-economic and social-cultural skill have to be put in place in order to have a critical mass of locally trained persons. At the colleges and universities in the rural area, technical and engineering courses and curricula have to be taught so that good technicians and engineers could come out with good skill. During the study and the implementation of the hybrid system in Salak village, the inhabitants have to be involved in the project so that the transfer of competences could be done to some one in the village. This village operator with its small competences

Table 5.31: Economic parameters of PV, Wind, Diesel and Battery hybrid system used as input data for the calculation of the Livelized Cost of Energy ($LCOE$)

PV generator	
PV Size + Inverter	3 kW
Initial cost	10000€
Annual operation cost	- €
Annual maintenance cost	3% of annualized initial cost
Annual replacement cost	0 €
Salvage value	3% of initial cost
Lifetime (year)	25
Wind generator	
Wind turbine size	1.4 kW
Initial cost	5000€
Annual operation cost	- €
Annual maintenance cost	3% of annualized intial cost
Replacement cost	0 €
Salvage value	3% of Wind initial cost
Lifetime	25 years
Battery storage system	
Battery size	3 kW (18kWh)
Initial cost	135 €/kWh
Annual operation cost	0 €
Annual maintenance cost	15% of annualized intial cost
Replacement cost	Equal to initial cost
Savage value	0 €
Lifetime	5 years
Diesel generator	
Diesel generator size	- kW
Fuel cost	1.12 €/L
Annual operation cost	– €
Annual maintenance cost	15% of annualized intial cost
Replacement cost	Equal to initial cost
Salvage value	15% of diesel initial cost
Lifetime	10 years
Financial indicators	
Inflation rate, i	5%
Interest or discount rate, d	6%

would help the community by operating during some failures, ordinary and extraordinary maintenance for better operation of the system. To ensure its good maintainability, the size and design, the technology and the selected components for the hybrid system have to be less complicated and complex so that even a less educated villager could operated the system.

5.6.2 Human behaviour before and after the new electric grid

Salak community faces electrification access with a poor population, with limited knowledge of modern energy services and uses. In this case, eletrification has to be planned in the perspective of rural development due to the poorly electricity load demand. The poorly population needs electricity only for lighting, radio and tv. It is good to mention that access of electricity or modern services would not directly reduce poverty but only a socio-economic development business around the electrified environment. A typical rural household load profile in Cameroon is composed by three persons living in two rooms appartment, the load is composed by two incadescent lamps in two rooms, a fluoriscent lamp outdoor for security and a radio. Electrification planning in various developing countries have been done without taking into account the needs of the population, when we know that the needs increase with the time. At the beginning, the population need electricity only for lighting, radio and tv. But when there is already light, they need refrigerators, washing machine, grounding machine, etc and their electricity needs increase and their consumption also. This is why it is important to carry out a good study on social behaviour of the population before and after electricity availability, to understand their way of being/living, their needs in terms of electrical appliances. So that different types of categorized loads could be identified. This sociological study would help to precisely predict the load demand profile of the electrified population and well defined the best configuration of hybrid energy system, the good energy management strategy and ensure the best continuous electricity supply. The hybrid system could also be over-sized or sized such that in the future, it could be easily integrated new generating and storage systems to the existing one to well faced the new demand load. [36], [35]

5.6.3 Socio-economic benefits of the hybrid system

The hybrid energy system applied in Salak rural area could create jobs, and motivate the creation of small industries. It could also improve the quality of life and provide other social-economic benefits that are difficult to quantify. It is clear that renewable energy will receive widespread acceptance in the rural areas, because of the inadequate conventional electricity supply there. The availability of electricity in Salak village could improved the standard of living. Lack of energy, on the other hand, could bring down food shortages, reduced life expectancy, and an increase in illiteracy and infant mortality. Thus to achieve an acceptable and sustainable standard of living, a certain level of energy availability is necessary, and this must be obtained in an environmentally friendly way like the Salak one. Some benefits of Salak electrification can be listed as follow: (i) Socio-economic benefits (improvement of economic productivity in small-scale industries and agriculture through deployment of modern and efficient processes (i.e. cooling and ventilation); stimulus to economic activity in the service sector, including small-scale enterprises), (ii) Socio-political benefits (improvement of living conditions including education, health care, and gender equality; improved accessibility through telecommunication facilities, stimulus for entrepreneurs and inhabitants to stay and developed the area without thinking to move to the city; enhanced societal stability), (iii) Environmental and Health benefits (fuel switch for lighting: safer and often cheaper).

5.7 Conclusion

In this chapter, a heuristic algorithm approach has been proposed with the capacity of managing a hybrid system for both electrification of the hospital, the schools, the houses and hot water production for the Salak rural hospital, combining two renewable energy sources (wind, solar), a diesel generator and a battery storage system (BSS). Even though, there is an airport from about 40 km, the village of Salak suffers for un-electrification due to geographical positions (241 km away from the electrical production center in Lagdo-Garoua), the higher cost of grid extension, the higher cost of diesel fuel even though despite the great potential of renewable energy sources (RES). Such problem could be solved decentralizing the electrical production, integrating renewables energies with fossil fuel generating system. Renewable energy sources are the best alternative for conventional primary fossil fuel for isolated and rural remote areas for electrification in Cameroon and in many developing countries. The excess of electricity generated from renewable sources after been satisfied the load demand is used to produce thermal energy for the hospital. The optimization approach developed using dynamic programming method have been applied and compared with the heuristic method. It comes out that, the optimization approach enable the charge of the battery by the diesel generator, while in the same time, the daily fuel consumption is minimized up to 86% compare to heuristic method. The economic analysis carried out in this work have taken into consideration the lifetime of the battery estimated with the rainflow counting. This economic analysis reveals that the optimized hybrid system is cost effective in terms of electricity energy cost compared to the system powered only with diesel generator and the others studies carried out in different countries. This proposed hybrid energy system would not only resolved the electrification problem of the Salak rural area but could also preserved environment, help improving the quality of life by raising the level of the services, thus, enable sustainable development.

5.8 Published papers:

1. M. Pendieu Kwaye, N. Anglani. Optimal Design of Hybrid Energy System for Rural Electrification in Cameroon Under submission for the Renewable Energy journal Elsevier.

6 Conclusions and outlook

6.1 Conclusions

In developing countries, in sub-saharan Africa and particulary in Cameroon, remote communities are presently not connected to the main grid for many reasons such as: far away from grid and urban center, high cost of grid extension just to cite these. Due to all these reasons, more than 70% of rural populations in developing contries live without access of electricity. During the economical crisis of the year 1990s, most of sub-saharan African countries have been forced by the world bank to sell their national energy companies to foreign companies which have only made profits without making any investment on new grids or new huge power plants. The consequences of this choice are facing today the poor and remote population in sub-saharan countries with the electricity un-accessibility. The un-accessibility of electricity in remote areas is contributing to switch easily from centralized configurations to distributed systems. However, critical issues related to renewable energy sources generation (such as variability, discontinuity and poor predictibility) are giving rise to new challenges in terms of reliability and control of electrical power systems. One of the solutions proposed to deal with these challenges is the hybridization of energy systems, which represent the key factor for rural electrification. Nevertheless, the process leading to the characterization of the load demand, the identification of renewable energy sources available, the identification of the best configuration for the hybrid system, the study of complementarities between renewables (solar+wind) and hydro for electricity generation and load supply, the developement of heuristic algorithm for management strategy of the hybrid system, the implementation of an optimized algorithm for the energy management strategy and continuous load supply minimizing the daily fuel consumption cost and at last, developing a friendly user open source model for size/design, modeling and optimization of hybrid energy systems. Thus, this thesis focus on rural electrification areas solutions in developing countries.

In this thesis, each chapter provide precious information that supports the implementation of optimal management strategy for hybrid energy systems in isolated areas with the objective of minimizing system operation cost and ensuring supply reliability. The optimal energy management strategy for managing the hybrid energy system of Salak is presented. The optimization model developed in this thesis is shown to achieved more fuel savings with the configurations: battery+diesel, solar+wind+battery+diesel compare to the heuristic model also developed. The results show how the daily fuel consumption is minimized, while supplying continuously the load demand all the day without interruption.

Hybrid system configurations and role of storage systems in remote electrification areas: in chapter2 the aims was to choose the better configuration scheme and mathematical approach for the modeling/sizing and management of a rural electrification area. For this purpose, an overview of widely relevant journals papers selected in the literature dealing with topics of rural electrification have been assessed. The mathematical approaches for sizing, designing, modeling and optimization have been analysed and used choose the best configuration scheme and good mathematical approach for the Salak case study. The result of the investigation reveals the important role played by storage systems in electrification of remote areas. The main contribution of this chapter have been shed a light on different topologies of hybrid energy systems for rural electrification in all the six continents, the indispensable role of storage systems in rural electrification and the widely mathematical approaches used in the previous and ongoing literature.

Potential of solar and wind energy resources in Cameroon: in chapter3 the aims was to have an overview on solar and wind resources across the country. For this reason, the assessment of solar radiation and wind speed across the ten regions have been carried out using the NASA meteorological database with hourly measurement of tweenty two years (1983-2005). Then, the potential of electricity production from a solar panel and a wind turbine have been evaluated using mathematical formulations. Therefore, this work helps to have a better understanding of the regions or cities with a good energy potential and to choose the good site (Salak village) for the case study. This work finally confirmed that Cameroon has a good potential of solar and wind that can help to electrify remote villages across the country. In Cameroon, no similar works exist in literature have been carried out on renewable energy assessment taking into account both solar radiation and wind speed in all the ten regions. In this sense, this work is unique and the main contibution would helped to map out the potential of solar and wind energy for better energy planning strategy across the country.

Compensation of fluctuating non-dispatchable sources in Cameroon by hydro power:in chapter4 the aims was to show the complementarity of solar/wind and hydro for electricity supply in Cameroon. Therefore, an investigation of flow rates and potential of rivers accross the country for hydroelectricity have been assessed. Taking into consideration the yearly profiles of solar radiation, the wind speed and the flow rate of a river, an algorithm has been developed for the management of the different sources and th electricity demand load supply. The electricity supply combining the fructuating sources (solar and wind) and hydro power plant have been carried out to demonstrate the complementarities between them. In Cameroon, no similar works have been carried out on complementarity of solar/wind and hydro for electricity supply. So, this work is unique and its main contibution would participate to map out the potential of hydro power across the country for better complementarities of various sources and better energy planning strategy for rural and poor urban electrification.

Rural electrification and optimal design of hybrid energy system in Cameroon: in chapter5 the aims was to supply electricity to a remote community at a minimized operation cost. The solar and wind sources are combined with battery and diesel generator as backup for supplying the load demand. A heuristic algorithm is developed to manage and supply the load demand. In this study, the battery is charged in case of over-generation from renewables (heuristic approach) but also with diesel generator in case of under-generation from renewables (optimization approach). The diesel generator must work inside its best efficient area of operation and a wide research has been done to retrieve such data for small size generators. An optimized method using dynamic programming is developed, applied and compared to the heuristic algorithm. The daily fuel consumption is minimized compare to heuristic method algorithm. Although the optimized method reduces to 13 % the daily fuel consumption, the heuristic algorithm developed is also valided as a management algorithm for hybrid energy systems. The sizing, modeling and management of hybrid energy systems in Cameroon have always been carried out with HOMER software. An economic study has been carried out to determined how can be the cost of energy (€/kWh) producted by the hybrid system. In this study, the main contributions have been: the development of a heuristic algorithm approach and an optimized algorithm approach for the management of the hybrid system while, minimizing the operation cost. At the end, an economic analysis is carried out to determine the cost of the hybrid system and the cost of any kWh of energy produced compared to the system powered only by the diesel generator and the heuristic model. The economic analysis reveals that the hybrid system is cost effective compare to the configuration powered only by diesel generator.

6.2 Outlook

There are several areas where the research of this thesis can be further explored.

- Future work may constitute an extension of the work to include a techno-economic analysis of the system taking into account various configurations (Diesel only; Diesel+Battery; Diesel+Solar+Wind; Solar+Wind+Battery+Diesel)and compare them.

- Further development of this work may incorporate biogas instead of diesel generator, more renewable sources (i.e. hydro, etc.) and other storage technologies (i.e. super capacitors, flywheel, etc.).
- The dynamic programming approach could be further used for energy management strategy of hybrid energy systems for rural electrification to reach a broader audience.
- In this work, Solar PV, Wind, Battery (lead acid) and Diesel generator are considered. The Salak hybrid model may be upgraded to supply thermal loads by including solar thermal or other clean thermal technologies as a constrainte.
- Since the results and methods described in this thesis rely on simulations, the implemention in an experimental pilot power plant to validate the different scenarios may helped for the development of the African populations who still live without access to electricity. And then, the experimental results and the simulations results may be compared.
- The development of the open source model using the optimization approach in addition to the heuristic approach will help to perform the management strategy and reduce operation cost.
- Voltage and frequency analysis in decentralized rural electrification systems could be carried out.

Bibliography

[1] WEO, *to be found under, http://www.worldenergyoutlook.org Retrieved March 2016.* WEO, 2016.

[2] WA, *to be found under, http://www.worldatlas.com Retrieved March 2016.* World Atlas, 2016.

[3] D. Nkwetta, J. Driesen, and R. Belmans, "Disturbances of the 90 kV E lectrical Network and the 380/220 V Distribution System in the Douala-Cameroon Area," *IEEE 19th International Conference on Electricity Distribution (CIRED)*, pp. 21–24, 2007.

[4] SOLARGIS, *to be found under, http://solargis.com/products/maps-and-gis-data/free/download/cameroончm.html=top¿ (Accessed 10/2016).* SOLARGIS, 2016.

[5] NASA, *to be found under, http://www.eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?uid=3030.* NASA, 2014.

[6] J. Bendfeld, S. Grtner, and E. Ortjohann, "Wind atlas for the circles Holzminden , Hameln-Pyrmont and parts of circles Schaumburg and Hildesheim," 1997.

[7] R. Barthelmie, *Wind resources and wind turbine wakes in large wind farms.* Atmospheric Science and Sustainability, Indiana University, USA.

[8] S. Davis and S. Graham, "Micro-Hydropower Systems: A Buyers Guide," *Natural Resources Canada*, pp. 1–56, 2004.

[9] J. Chapallaz, P. Eichenberger, and G. Fischer, *Manuel on Pumps Used as Turbines*, volume 11 ed. Friedr Vieweg, 1992, iSBN 3-528-02069-5.

[10] Minee., " PLAN DE DEVELOPPEMENT PRODUCTION PDSE 2030," *Ministere de Energie et de Eau*, vol. 4, pp. 1–153, 2006.

[11] E. Nfah, J. Ngundam, M. Vandenbergh, and J. Schmid, "Simulation of off-grid generation options for remote villages in Cameroon," *Renewable Energy*, vol. 33, pp. 1064–1072, 2008.

[12] N. Anglani, G. Oriti, and M. Colombini, "Optimized Energy Management System to Reduce Fuel Consumption in Remote Military Microgrids," *IEEE Energy Conversion Congress and Exposition*, pp. 1–8, 2016.

[13] A. D. Nardo, G. Calchetti, D. Cecere, E. Giacomazzi, E. Giulietti, R. Camussi, A. D. Marco, and A. Moscati, *Simulazioni CFD del bruciatore ETVB-mod1.* ENEA, 2013.

[14] A. L. . Facci, L. Andreassi, and S. Ubertini, "Optimization of CHCP (combined heat power and cooling) systems operation strategy using dynamic programming," *Energy*, vol. 66, pp. 387–400, 2014.

[15] S. H. Boyogueno, M. Mbessa, and T. T. Tatietse, "Prediction of Flow Rate of Sanaga Basin in Cameroon Using HEC-HMS Hydrological System: Application to the Djerem Sub-Basin at Mbakaou," *Energy and Environment Research*, vol. 2, pp. 205–216, 2012.

[16] Alucam., "Projet hydroelectrique de Nachtigal," *Alucam*, pp. 1–621, 2011.

[17] energiesdurablesniger, *to be found under, http://www.energiesdurablesniger.org/*. energiesdurablesniger, 2011.

[18] D. Palit and A. Chaurey, "Energy for Sustainable Development Off-grid rural electri fi cation experiences from South Asia : Status and best practices," *Energy for Sustainable Development*, vol. 15, pp. 266–276, 2011.

[19] A. Mishra and G. K. Sarangi, "Off-grid Energy Development in India : An Approach towards Sustainability," *OASYS South Asia Project*, pp. 1–38, 2011.

[20] F. O. Adurodija, I. O. Asia, and M. A. C. Chendo, "The market potential of photovoltaic systems in Nigeria," *Solar Energy*, vol. 64, pp. 133–139, 1998.

[21] D. P. Kaundinya, P. Balachandra, and N. H. Ravindranath, "Grid-connected versus stand-alone energy systems for decentralized power-A review of literature," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 2041–2050, 2009.

[22] D. F. Barnes and W. M. Floor, "RURAL ENERGY IN DEVELOPING COUNTRIES: A Challenge for Economic Development," *Annual Review of Energy and the Environment*, vol. 21, pp. 497–530, 1996.

[23] T. Levin and V. M. Thomas, "Can developing countries leapfrog the centralized electrification paradigm?" *Energy for Sustainable Development*, vol. 31, pp. 97–107, 2016.

[24] N. J. Williams, P. Jaramillo, J. Taneja, and T. S. Ustun, "Enabling private sector investment in microgrid-based rural electrification in developing countries: A review," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1268–1281, 2015.

[25] A. Zomers, "Remote access: Context, challenges, and obstacles in rural electrification," *IEEE Power and Energy Magazine*, vol. 12, pp. 26–34, 2014.

[26] S. Karekezi, "Renewables in Africa meeting the energy needs of the poor," *Energy Policy*, vol. 30, pp. 1059–1069, 2002.

[27] B. Mainali and S. Silveira, "Energy for Sustainable Development Renewable energy markets in rural electri fi cation : Country case Nepal," *Energy for Sustainable Development*, vol. 16, pp. 168–178, 2012.

[28] A. Brew-Hammond, "Energy access in Africa: Challenges ahead," *Energy Policy*, vol. 38, pp. 2291–2301, 2010.

[29] D. Tsikata, P. A. Fenny, and E. Aryeety, "China Africa Relations : A Case Study of Ghana By Institute of Statistical , Social and Economic Research University of Ghana," *African Economic Research Consortium*, pp. 1–28, 2008.

[30] G. Y. Obeng and H.-d. Evers, "Solar PV rural electrification and energy-poverty: A review and conceptual framework with reference to Ghana," *ZEF*, vol. 36, pp. 1–20, 2009.

[31] K. Reiche, A. Covarrubias, and E. Martinot, "Expanding Electricity Access to Remote Areas : Off-Grid Rural Electrification in Developing Countries," *World Power 2000*, vol. 36, pp. 52–60, 2000.

[32] H. Camblong, J. Sarr, A. T. Niang, O. Curea, J. A. Alzola, E. H. Sylla, and M. Santos, "Micro-grids project, Part 1: Analysis of rural electrification with high content of renewable energy sources in Senegal," *Renewable Energy*, vol. 34, pp. 2141–2150, 2009.

[33] elsaburkinafaso, *to be found under, http://www.elsa-burkina-faso.org/*. elsaburkinafaso, 2011.

[34] S. Karekezi, "Poverty and energy in AfricaA brief review," *Energy Policy*, vol. 30, pp. 915–919, 2002.

[35] S. Mandelli, M. Merlo, and E. Colombo, "Novel procedure to formulate load profiles for off-grid rural areas," *Energy for Sustainable Development*, vol. 31, pp. 130–142, 2016.

[36] S. Mandelli, C. Brivio, E. Colombo, and M. Merlo, "Effect of load profile uncertainty on the optimum sizing of off-grid PV systems for rural electrification," *Sustainable Energy Technologies and Assessments*, vol. 18, pp. 34–47, 2016.

[37] E. Nfah, J. Ngundam, and R. Tchinda, "Modelling of solar/diesel/battery hybrid power systems for far-north Cameroon," *Renewable Energy*, vol. 32, pp. 832–844, 2007.

[38] T. T. Tatietse, P. Villeneuve, J. Ngundam, and F. Kenfack, "Contribution to the analysis of urban residential electrical energy demand in developing countries," *Energy*, vol. 27, pp. 591–606, 2002.

[39] RETScreen, *to be found under, http://www.retscreen.net/ang/download.php*. RETScreen, 2014.

[40] L. Ayompe and A. Duffy, "An assessment of the energy generation potential of photovoltaic systems in Cameroon using satellite-derived solar radiation datasets," *Sustainable Energy Technologies and Assessments*, 2013.

[41] E. W. Atlas, *Ris National Laboratory, Roskilde, Denmark.* European Wind Atlas, 1989.

[42] WASP, *to be found under, ¡http://www.wasp.dk¿.* WASP, 2015.

[43] M. Adaramola, S. Paul, and S. Oyewola, "Assessment of electricity generation and energy cost of wind energy conversion systems in north-central Nigeria," *Energy Conversion and Management*, vol. 52, pp. 3363–3368, 2011.

[44] A. Maleki and A. Askarzadeh, "PV/wind/diesel system with battery storage for electrification to an off-grid remote region: A case study of Rafsanjan, Iran," *Sustainable Energy Technologies and Assessments*, vol. 7, pp. 147–153, 2014.

[45] H. Kanchev, D. Lu, F. Colas, V. Lazarov, and B. Francois, "Energy Management and Operational Planning of a Microgrid With a PV-Based Active Generator for Smart Grid Applications," *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, vol. 58, no. 10, pp. 4583–4592, 2011.

[46] IEA, *Tracking Clean Energy Progress 2013, to be found under, http://www.iea.org/etp/tracking/.pdf, pp.98.* IEA, 2013.

[47] C. Tomlinson and F. X. Saury, "HYBRID MICROGRIDS : THE TIME IS NOW ," *Caterpillar*, pp. 1–12, 2016.

[48] D. R. Aryani and H. Song, "Coordination Control Strategy for AC/DC Hybrid Microgrids in Stand-Alone Mode," *Energies*, vol. 36, pp. 1–20, 2016.

[49] A. H. Fathima and K. Palanisamy, "Optimization in microgrids with hybrid energy systems A review," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 431–446, 2015.

[50] G. Merei, D. Magnor, M. Leuthold, and D. Sauer, "Optimization of an Off-grid Hybrid Power Supply System Based on Battery Aging Models," *IEEE 36th International Telecommunications Energy Conference (INTELEC)*, pp. 1–6, 2014.

[51] P. Masoud and B. Asaei, "Optimal Modeling and Sizing of a Practical Hybrid Wind/PV/Diesel Generation System," *IEEE 5th International Power Electronics, Drive Systems and Technologies Conference (PEDSTC)*, pp. 506–511, 2014.

[52] J. K. Kaldellis, "Integrated electrification solution for autonomous electrical networks on the basis of RES and energy storage configurations," *Energy Conversion and Management*, vol. 49, pp. 3708–3720, 2008.

[53] M. Adaramola, S. Paul, and M. Agelin-Chaab, “Analysis of hybrid energy systems for application in southern Ghana,” *Energy Conversion and Management*, vol. 88, pp. 284–295, 2014.

[54] A. Kaabeche and R. Ibtiouen, “Techno-economic optimization of hybrid photovoltaic/wind/diesel/battery generation in a stand-alone power system,” *Solar Energy*, vol. 103, pp. 171–182, 2014.

[55] B. Bhandari, K.-T. L., C. Sunyong Lee, S. Chul-Ki, R. Maskey, and S.-H. Ahn, “A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources,” *Applied Energy*, vol. 133, pp. 236–242, 2014.

[56] J. Kaldellis, M. Kapsali, K. Kavadias, and E. Kondili, “Optimum PV-diesel hybrid systems for remote consumers of the Greek territory,” *Applied Energy*, vol. 97, pp. 61–67, 2012.

[57] J. Kaldellis and D. Zafirakis, “Optimum sizing of stand-alone wind-photovoltaic hybrid systems for representative wind and solar potential cases of the Greek territory,” *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 107-108, pp. 169–178, 2012.

[58] G. Bekele and B. Palm, “Wind energy potential assessment at four typical locations in Ethiopia ,” *Applied Energy*, vol. 86, pp. 388–396, 2009.

[59] M. J. Khan and M. T. Iqbal, “Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland ,” *Renewable Energy*, vol. 30, pp. 835–854, 2005.

[60] E. I. Zoulias and N. Lymberopoulos, “Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems ,” *Renewable Energy*, vol. 32, pp. 680–696, 2007.

[61] D. A. Katsaprakakis, D. G. Christakis, K. Pavlopoylos, S. Stamataki, I. Dimitrelou, I. Stefanakis, and P. Spanos, “Introduction of a wind powered pumped storage system in the isolated insular power system of Karpathos Kasos,” *Applied Energy*, vol. 97, pp. 38–48, 2012.

[62] T. Ma, H. Yang, and L. Lu, “Performance evaluation of a stand-alone photovoltaic system on an isolated island in Hong Kong,” *Applied Energy*, vol. 112, pp. 663–672, 2013.

[63] M. Brinkhaus, D. Jarosch, and J. Kapischke, “All year power supply with off-grid photovoltaic system and clean seasonal power storage,” *Solar Energy*, vol. 85, pp. 2488–2496, 2011.

[64] E. M. Nfah, “Evaluation of otimal photovoltaic hybrid systems for remote villages in Far North Cameroon,” *Renewable Energy*, vol. 54, pp. 482–488, 2013.

[65] E. O. K. Addo, J. Asumadu, and P. Y. Okyere, “Optimal design of renewable hybrid energy system for a village in Ghana,” *9th IEEE Conference on Industrial Electronics and Applications*, pp. 1520–1526, 2014.

[66] A. Kaabeche, M. Belhamel, and R. Ibtiouen, “Sizing optimization of grid-independent hybrid photovoltaic/wind power generation system,” *Energy*, vol. 36, no. 2, pp. 1214–1222, 2011.

[67] R. Belfkira, L. Zhang, and G. Barakat, “Optimal sizing study of hybrid wind/PV/diesel power generation unit,” *Solar Energy*, vol. 85, pp. 100–110, 2011.

[68] M. Ranaboldo, B. Domenech, D. Ferrenbach, M. Ferrer, R. Moreno, and V. Garcia, “Renewable energy projects to electrify rural communities in Cape Verde,” *Applied Energy*, vol. 118, pp. 280–291, 2014.

[69] H. Tazvinga, X. Xia, and J. Zhang, "Minimum cost solution of photovoltaic-diesel-battery hybrid power systems for remote consumers," *Solar Energy*, vol. 96, pp. 292–299, 2013.

[70] D. Saheb-Koussa, M. Haddadi, and M. Belhamel, "Economic and technical study of a hybrid system (windphotovoltaicdiesel) for rural electrification in Algeria," *Applied Energy*, vol. 86, pp. 1024–1030, 2009.

[71] M. Rehman, Shafiqur.and Mahbub Alam, J. Meyer, and L. M. Al-Hadhrami, "Feasibility study of a windpvdiesel hybrid power system for a village," *Renewable Energy*, vol. 38, pp. 258–268, 2012.

[72] S. Adaramola, M amd Paul and O. Oyewola, "Energy for Sustainable Development Assessment of decentralized hybrid PV solar-diesel power system for applications in Northern part of Nigeria," *Energy for Sustainable Development*, vol. 19, pp. 72–82, 2014.

[73] O. Hafez and K. Bhattacharya, "Optimal planning and design of a renewable energy based supply system for microgrids," *Renewable Energy*, vol. 45, pp. 7–15, 2012.

[74] M. Hossan, M. Hossain, and A. R. Haque, "Optimization and modeling of a hybrid energy system for off-grid electrification," *IEEE 10th International Conference on Environment and Electrical Engineering*, pp. 1–4, 2011.

[75] Y. Himri, A. Boudghene Stambouli, B. Draoui, and S. Himri, "Techno-economical study of hybrid power system for a remote village in Algeria," *Energy*, vol. 33, no. 7, pp. 1128–1136, 2008.

[76] J. Dekker, M. Nthontho, S. Chowdhury, and S. Chowdhury, "Economic analysis of PV / diesel hybrid power systems in different climatic zones of South Africa," *International Journal of Electrical Power and Energy Systems*, vol. 40, pp. 104–112, 2012.

[77] A. S. N. Huda, S. Mekhilef, L. Olatomiwa, and K. Sanusi, "Techno-economic analysis of hybrid PV-diesel-battery and PV-wind-diesel-battery power systems for mobile BTS: the way forward for rural development," *Energy Science and Engineering*, vol. 3, pp. 271–285, 2015.

[78] A. Asrari, A. Ghasemi, and M. H. Javidi, "Economic evaluation of hybrid renewable energy systems for rural electrification in Iran A case study," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 3123–3130, 2012.

[79] G. Bekele and B. Palm, "Feasibility study for a standalone solar wind-based hybrid energy system for application in Ethiopia," *Applied Energy*, vol. 87, pp. 487–495, 2010.

[80] ——, "Feasibility study of small Hydro / PV / Wind hybrid system for off-grid rural electrification in Ethiopia," *Applied Energy*, vol. 97, pp. 5–15, 2012.

[81] B. Panahandeh, J. Bard, A. Outzourhit, and D. Zejli, "Simulation of PV e Wind-hybrid systems combined with hydrogen storage for rural electrification," *International Journal of Hydrogen Energy*, vol. 36, pp. 4185–4197, 2011.

[82] D. Saheb-Koussa, M. Koussa, M. Haddadi, and M. Belhamel, "Hybrid options analysis for power systems for rural electrification in Algeria," *Energy Procedia*, vol. 6, pp. 750–758, 2011.

[83] S. M. Shaahid and I. El-Amin, "off-grid hybrid photovoltaic-diesel-battery power systems for rural electrification in Saudi Arabia-A way forward for sustainable development," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 625–633, 2009.

[84] M. Kalantar and S. Mousavi G., "Dynamic behavior of a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage," *Applied Energy*, vol. 87, pp. 3051–3064, 2010.

[85] B. O. Bilal, V. Sambou, C. M. F. Kb, P. A. Ndiaye, and M. Ndongo, "Methodology to size an optimal stand-alone PV/wind/diesel/battery system minimizing the levelized cost of energy and the CO 2 emissions," *Energy Procedia*, vol. 14, pp. 1636–1647, 2012.

[86] P. Bertheau, C. Cader, H. Mller, P. Blechinge, R. Seguin, and C. Breyer, "Energy storage potential for solar based hybridization of off-grid diesel power plants in Tanzania," *Energy Procedia*, vol. 46, pp. 287–293, 2014.

[87] B. Ould Bilal, V. Sambou, P. A. Ndiaye, C. M. F. Kb, and M. Ndongo, "Multi-objective design of PV-wind-batteries hybrid systems by minimizing the annualized cost system and the loss of power supply probability (LPSP)," *IEEE International Conference on Industrial Technology*, pp. 861–868, 2013.

[88] M. Fadaeenejad, M. Radzi, M. AbKadir, and H. Hizam, "Assessment of hybrid renewable power sources for rural electrification in Malaysia," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 299–305, 2014.

[89] S. Mousavi, "Electrical Power and Energy Systems An autonomous hybrid energy system of wind / tidal / microturbine / battery storage," *International Journal of Electrical Power and Energy Systems*, vol. 43, no. 1, pp. 1144–1154, 2012.

[90] R. Kelly, G. Oriti, and A. Julian, "Reducing Fuel Consumption in a Forward Operating Base using an Energy Management System." ECCE, 2013, pp. 1330–1336.

[91] G. Oriti, A. L. Julian, and N. J. Peck, "Power Electronics Enabled Energy Management Systems," *IEEE Applied Power Electronics Conference and Exposition*, pp. 3224–3231, 2013.

[92] H. Tazvinga, B. Zhu, and X. Xia, "Energy dispatch strategy for a photovoltaic wind diesel battery hybrid power system," *Solar Energy*, vol. 108, pp. 412–420, 2014.

[93] F. Baghdadi, K. Mohammedi, S. Diaf, and O. Behar, "Feasibility study and energy conversion analysis of stand-alone hybrid renewable energy system," *Energy Conversion and Management*, vol. 105, pp. 471–479, 2015.

[94] F. Z. Kadda and S. Zouggar, "Optimal Energy Management of an Autonomous Hybrid System by using the Linear Programming Method," *IEEE International Conference on Computer Communications*, 2013.

[95] F. A. Mohamed and H. N. Koivo, "System Modelling and Online Optimal Management of MicroGrid Using Multiobjective Optimization," *IEEE International Conference on Clean Electrical Power*, pp. 148–153, 2007.

[96] E. Nfah and J. Ngundam, "Evaluation of optimal power options for base transceiver stations of Mobile Telephone Networks Cameroon," *Solar Energy*, vol. 86, pp. 2935–2949, 2012.

[97] P. Heteu Tchouate, H. Jeanmart, and E. Nfah, "Sizing of photovoltaic hybrid power for remote villages." *AfricaPES*, vol. 684, pp. 61–67, 2010.

[98] A. Zahedi, "Maximizing solar PV energy penetration using energy storage technology," *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 866–870, 2011.

[99] E. Nfah and J. Ngundam, "Feasibility of pico-hydro and photovoltaic hybrid power systems for remote villages in Cameroon," *Renewable Energy*, vol. 34, pp. 1445–1450, 2009.

[100] D. Zafirakis, E. Kondili, and J. Kaldellis, "Optimum sizing of photovoltaic-energy storage systems for autonomous small islands," *Electrical Power and Energy Systems*, vol. 32, pp. 24–36, 2010.

[101] G. Manfrida and R. Secchi, "Seawater pumping as an electricity storage solution for photovoltaic energy systems," *Energy*, vol. 69, pp. 470–484, 2014.

[102] T. Ma, H. Yang, L. Lu, and J. Peng, "Pumped storage-based standalone photovoltaic power generation system: Modeling and techno-economic optimization," *Applied Energy*, vol. 137, pp. 649–659, 2015.

[103] J. K. Kaldellis, "Optimum hybrid photovoltaic-based solution for remote telecommunication stations," *Renewable Energy*, vol. 35, pp. 2307–2315, 2010.

[104] D. A. Katsaprakakis and D. G. Christakis, "Seawater pumped storage systems and offshore wind parks in islands with low onshore wind potential. A fundamental case study," *Energy*, vol. 66, pp. 470–486, 2014.

[105] M. Kapsali and J. Kaldellis, "Combining hydro and variable wind power generation by means of pumped-storage under economically viable terms," *Applied Energy*, vol. 87, pp. 3475–3485, 2010.

[106] S. V. Papaefthymiou and S. A. Papathanassiou, "Optimum sizing of wind-pumped-storage hybrid power stations in island systems," *Renewable Energy*, vol. 64, pp. 187–196, 2014.

[107] C. Maureen Wanjiku Murage and L. Anderson., "Contribution of pumped hydro storage to integration of wind power in Kenya: An optimal control approach," *Renewable Energy*, vol. 63, pp. 698–707, 2014.

[108] E. Kabalci, "Design and analysis of a hybrid renewable energy plant with solar and wind power," *Energy Conversion and Management*, vol. 72, pp. 51–59, 2013.

[109] M. Mikati, M. Santos, and C. Armenta, "Electric grid dependence on the configuration of a small-scale wind and solar power hybrid system," *Renewable Energy*, vol. 57, pp. 587–593, 2013.

[110] T. Ma, H. Yang, L. Lu, and J. Peng, "Technical feasibility study on a standalone hybrid solar-wind system with pumped hydro storage for a remote island in Hong Kong," *Renewable Energy*, vol. 69, pp. 7–15, 2014.

[111] M. Ranaboldo, V. Garcia, , L. Ferrer-Mart, and R. Moreno, "A heuristic method to design autonomous village electrification projects with renewable energies," *Energy*, vol. 73, pp. 96–109, 2014.

[112] E. Nfah, J. Ngundam, and G. Kenne, "Economic evaluation of small-scale photovoltaic hybrid systems for mini-grid applications in far north Cameroon," *Renewable Energy*, vol. 35, pp. 2391–2398, 2010.

[113] C. Maureen Wanjiku Murage and L. Anderson., "Contribution of pumped hydro storage to integration of wind power in Kenya: An optimal control approach," *Renewable Energy*, vol. 63, pp. 698–707, 2014.

[114] N. Blum, W. Sryantoro, and T. Schmidt, "Rural electrification through village grids Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia," *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 482–496, 2013.

[115] A. D. Katsaprakakis, D. G. Christakis, K. Pavlopoylos, S. Stamataki, I. Dimitrelou, I. Stefanakis, and P. Spanos, "Introduction of a wind powered pumped storage system in the isolated insular power system of Karpathos Kasos," *Applied Energy*, vol. 97, pp. 38–48, 2012.

[116] M. Kapsali, J. Anagnostopoulos, and J. Kaldellis, "Wind powered pumped-hydro storage systems for remote islands: A complete sensitivity analysis based on economic perspectives," *Applied Energy*, vol. 99, pp. 430–444, 2012.

[117] IEA, *to be found under, http://www.iea.org/countries/non-membercountries/cameroon/*. IEA, 2014.

[118] CIA, *to be found under, https://www.cia.gov/library/publications/the-world-factbook/geos/cm.html=top¿ (Accessed 12/2015).* CIA, 2014.

[119] AER, *Dianostic Strategique et Financier AER, to be found under, https://www.aer.cm.* AER, 2014.

[120] L. K. Wiginton, H. T. Nguyen, and J. M. Pearce, "Quantifying rooftop solar photovoltaic potential for regional renewable energy policy," *Computers, Environment and Urban Systems*, vol. 34, no. 4, pp. 345–357, 2010.

[121] T. Huld, R. Mller, and A. Gambardella, "A new solar radiation database for estimating PV performance in Europe and Africa," *Solar Energy*, vol. 86, pp. 1803–1815, 2012.

[122] W. B. Wan Nik, M. Z. Ibrahim, K. B. Samo, and A. M. Muzathik, "Monthly mean hourly global solar radiation estimation," *Solar Energy*, vol. 86, pp. 379–387, 2012.

[123] E. Zell, S. Gasim, S. Wilcox, S. Katamoura, T. Stoffel, H. Shibli, J. Engel-Cox, and M. A. Subie, "Assessment of solar radiation resources in Saudi Arabia," *Solar Energy*, vol. 119, pp. 422–438, 2015.

[124] Y. Himri, S. Himri, and A. B. Stambouli, "Assessing the wind energy potential projects in Algeria," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 2187–2191, 2009.

[125] R. O. Fagbenle, J. Katende, O. O. Ajayi, and J. O. Okeniyi, "Assessment of wind energy potential of two sites in North-East , Nigeria," *Renewable Energy*, vol. 36, pp. 1277–1283, 2011.

[126] Y. Mulugetta and F. Drake, "ASSESSMENT OF SOLAR AND WIND ENERGY RESOURCES IN ETHIOPIA. II. WIND ENERGY," *Solar Energy*, vol. 57, no. 5, pp. 323–334, 1997.

[127] I. Cumali, "Wind energy and assessment of wind energy potential in Turkey," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 1165–1173, 2012.

[128] P. Alamdari, O. Nematollahi, and M. Mirhosseini, "Assessment of wind energy in Iran: A review," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 836–860, 2012.

[129] S. AL-Yahyai, Y. Charabi, A. Gastli, and S. Al-Alawi, "Assessment of wind energy potential locations in Oman using data from existing weather stations," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1428–1436, 2010.

[130] V.-t. Tran and T.-h. Chen, "Assessing the Wind Energy for Rural Areas of Vietnam," *International Journal of Renewabl Energy Research*, vol. 3, no. 3, pp. 423–528, 2013.

[131] M. Aksas and A. Gama, "Assessment of wind and solar energy resources in Batna, Algeria," *Energy Procedia*, vol. 6, pp. 459–466, 2011.

[132] R. Tchinda and E. Kaptouom, "Situation des energies nouvelles et renouvelables au Cameroun," *Revue de l'Energie*, vol. 10, pp. 653–658, 1999.

[133] B. Tansi, *An assessment of Cameroon's renewable energy resource and prospect for a sustainable economic development.*, m.sc thesis ed., 2011, germany:Brandenburg Technical University.

[134] J. Kendjio, E. Kaptouom, and D. Njomo, "Estimation of mean wind energy available in far north Cameroon," *Energy Conversion and Management*, vol. 41, 2000.

[135] R. Tchinda and E. Kaptouom, "Wind energy in Adamaoua and North Cameroon provinces," *Energy Conversion and Management*, vol. 44, pp. 845–857, 2003.

[136] J. Ngundam and E. Nfah, "Modelling of wind/Diesel/battery hybrid power systems for far North Cameroon," *Energy Conversion and management*, vol. 49, p. 12951301, 2008.

[137] M. Elhadidy, "Performance evaluation of hybrid (wind/solar/diesel) power Systems," *Renewable Energy*, vol. 18, pp. 401–413, 2002.

[138] D. K. Lal, B. B. Dash, and A. K. Akella, "Optimization of PV / Wind / Micro-Hydro / Diesel Hybrid Power System in HOMER for the Study Area," *International Journal on Electrical Engineering and Informatics*, vol. 3, no. 3, pp. 307–326, 2011.

[139] O. A. . Jaramillo, M. A. Borja, and J. M. Huacuz, "Using hydropower to complement wind energy : a hybrid system to provide firm power," *Renewable Energy*, vol. 29, pp. 1887–1909, 2004.

[140] C. Belanger and L. Gagnon, " Adding wind energy to hydropowe," *Energy Policy*, vol. 30, p. 12791284, 2002.

[141] R. M. Dutra and A. S. Szklo, " Hydro-Wind Power Complementarity : A Way to Implementing Wind Power in Brazil," *World Renewable Energy Congress*, pp. 2344–2349, 2008.

[142] W. Pereira, B. Filho, and M. Vinicius, " Study of complementarity between wind and hydropower schemes for the state of Minas Gerais," *Latin American Meeting*, pp. 1–18, 2015.

[143] W. Pereira, A. Cesar, R. Garcia, A. Lombardi, R. Pinheiro, and W. Uturbey, "ESTIMATION OF COMPLEMENTARITIES BETWEEN SOLAR WIND AND HYDRO ENERGY SOURCES FOR THE PLANNING REGIONS OF THE STATE OF MINAS GERAIS," *Latin American Meeting*, pp. 1–15, 2015.

[144] O. A. C. Amarante, D. J. Schultz, R. M. Bittencourt, and N. A. R. Camargo, "Wind / Hydro Complementary Seasonal Regimes in Brazil," *DEWI Magazin*, no. 19, pp. 79–86, 2001.

[145] G. C. Bakos, "Feasibility study of a hybrid wind/hydro power-system for low-cost electricity production," *Applied Energy*, vol. 72, pp. 599–608, 2002.

[146] J. K. Kaldellis and K. A. Kavadias, "Optimal wind-hydro solution for Aegean Sea islands electricity-demand fulfilment," *Applied Energy*, vol. 70, pp. 333–354, 2001.

[147] M. R. Nouni, S. C. Mullick, and T. C. Kandpal, "Techno-economics of micro-hydro projects for decentralized power supply in India," *Energy Policy*, vol. 34, pp. 1161–1174, 2006.

[148] O. Paish, "Small hydro power: technology and current status," *Renewable and Sustainable Energy Reviews*, vol. 6, p. 537556, 2002.

[149] H. Tchouate, *Contribution des energies renouvelables au développement durable du secteur de l'électricité : Le cas du Cameroun.* Université Catholique de Louvain, 2003, these de Doctorat.

[150] R. Chedid, H. Akiki, and S. Rahman, "A decision support technique for the design of hybrid solar-wind power systems," *IEEE Transactions on Energy Conversion*, vol. 3, no. 1, pp. 76–83, 1998.

[151] M. Deshmukh and S. Deshmukh, "Unit Sizing and Cost Analysis of Stand-alone hybrid Wind/PV/Fuel generation system," *Renewable Sustainable Energy*, vol. 1, pp. 235–249, 2008.

[152] K. Pendieu, J. Bendfeld, and N. Anglani, "Assessment of Renewable Energy Resources in Cameroon and Special Regards on Energy Supply," *IEEE 5th International Youth Conference on Energy (IYCE)*, pp. 1–7, 2015.

[153] ——, "Assessment of Renewable Energy Resources and the use of Hydro Power for Fluctuation Compensation in Cameroon," *IEEE 5th International Youth Conference on Energy (IYCE)*, pp. 1–5, 2015.

[154] T. Westra and R. R. D. E. Wulf, "Modelling yearly flooding extent of the Waza-Logone floodplain in northern Cameroon based on MODIS and rainfall data," *International Journal of Remote Sensing*, vol. 30, no. 21, pp. 5527–5548, 2009.

[155] L. Zhang, G. Barakat, and A. Yassine, "Design and optimal sizing of hybrid PV / wind / diesel system with battery storage by using DIRECT search algorithm," *IEEE 15th International Power Electronics and Motion Control Conference (EPE-PEMC)*, pp. 1–7, 2012.

[156] J. K. Kaldellis, E. Kondili, and A. Filios, "Sizing a hybrid wind-diesel stand-alone system on the basis of minimum long-term electricity production cost," *Applied Energy*, vol. 83, pp. 1384–1403, 2006.

[157] J. Li, W. Wei, and J. Xiang, " A simple sizing algorithm for stand-alone PV/Wind/Battery hybrid microgrids," *Energies*, vol. 5, pp. 5307–5323, 2012.

[158] A. V. Anayochukwu, " Optimal Energy Management System for PV / Wind / Diesel-Battery Power Systems for Rural Health Clinic," *Intelligent Systems and Applications in Engineering*, vol. 2, pp. 64–70, 2014.

[159] M. Dahmane, J. Bosche, and M. Dafarivar, " Renewable Energy Management Algorithm for Stand alone System," *International Conference on Renewable EnergyResearch and Applications*, pp. 20–23, 2013.

[160] B. Ai, H. Yang, H. Shen, and X. Liao, "Computer-aided design of PV / wind hybrid system," *Renewable Energy*, vol. 28, pp. 1491–1512, 2003.

[161] P. A. Costa Rocha, R. C. de Sousa, C. F. de Andrade, and M. E. V. da Silva, "Comparison of seven numerical methods for determining Weibull parameters for wind energy generation in the northeast region of Brazil," *Applied Energy*, vol. 89, pp. 395–400, 2012.

[162] M. Miner, "Cumulative damage in fatigue," *Journal of Applied Mechanics*, vol. 67, pp. A159–A164, 1945.

[163] S. D. Downing and D. F. Socie., "Simple rainflow counting algorithms," *International Journal of Fatigue*, vol. 67, pp. 31–40, 1982.

[164] O. Sundstrom and L. Guzzella, "A Generic Dynamic Programming Matlab Function," *18th IEEE International Conference on Control Applications*, pp. 1625–1630, 2009.

[165] O. Sundstrm, D. Ambhl, and L. Guzzella, "On Implementation of Dynamic Programming for Optimal Control Problems with Final State Constraints," *Oil and Gas Science and Technology*, vol. 65, no. 1, pp. 91–102, 2010.

[166] B.-c. Chen, Y.-y. Wu, and H.-c. Tsai, "Design and analysis of power management strategy for range extended electric vehicle using dynamic programming," *Applied Energy*, vol. 113, pp. 1764–1774, 2014.

[167] H. He, H. Tang, and X. Wang, "Research for a Plug-In Series-Parallel Hybrid Electric Bus by Using Dynamic Programming," *Hindawi Publishing Corporation*, vol. 2013, pp. 1–11, 2013.

[168] D. K. Maly and K. S. Kwan, "Optimal battery energy storage system (BESS) charge scheduling with dynamic programming," *IEE Procedings Science Measurement Technology*, vol. 142, no. 6, pp. 453–458, 1995.

[169] H. Tischer and G. Verbic, "Towards a Smart Home Energy Management System - A Dynamic Programming Approach," *IEEE Innovative Smart Grid Technologies*, pp. 1–6, 2011.

[170] Y. Riffonneau, S. Bacha, F. Barruel, and S. Ploix, “Optimal Power Flow Management for Grid Connected PV Systems With Batteries,” *EEE TRANSACTIONS ON SUSTAINABLE ENERGY*, vol. 2, no. 3, pp. 309–320, 2011, publisher=IEEE.

[171] A. T. Tharakan, K. Asheesh, and P. Kumar, “Dynamic Programming Energy Management Algorithm for SNC Battery Based Hybrid Renewable Source,” *IEEE International Conference on Industrial Technology*, pp. 400–405, 2016.

[172] T. A. Nguyen and M. L. Crow, “Power Management for Renewable-Diesel Microgrids Using Dynamic Programming Algorithm,” *IEEE International Conference on Cyber Technology in Automation, Control and Intelligent Systems*, pp. 11–16, 2012.

[173] C. W. Ajan, S. S. Ahmed, H. B. Ahmad, F. Taha, A. Asuhaimi, and B. M. Zin, “On the policy of photovoltaic and diesel generation mix for an off-grid site : East Malaysian perspectives,” *Solar Energy*, vol. 74, pp. 453–467, 2003.

[174] Aeep., “Contry Power Market Brief: Cameroon,” *Africa Europe Energy Partnership*, pp. 1–5, 2012.

7 Annexes

DONNEES METEOROLOGIQUES ET ENERGIE SOLAIRE DES VILLES CAMEROUNAIRES

VILLES	LATITUDES	LONGITUDES	IRRADIATION SOLAIRE ANNUELLE (KWH/M² /J)	FORTE IRRADIATION SOLAIRE	FAIBLE IRRADIATION SOLAIRE	VITESSE DU VENT (M/S) ANNUELLE
ABONG MBANG	13.183	3.989	6.32	7.15 (AVRIL)	5.40 (DECEMBRE)	2.3
AKOM	10	2.783	5.59	6.22 (AVRIL)	4.61 (AOUT)	2.3
AKONOLINGA	12	3.767	5.85	6.6 (AVRIL)	5.16 (DECEMBRE)	2.3
AMBAM	11	2.383	5.68	6.30 (AVRIL)	4.89 (AOUT)	2.3
BAFAN	10	5.15	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
BAFIA	11	4.75	5.62	6.30 (AVRIL)	4.86 (AOUT)	2.3
BAFOUSSAM	10	5.467	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
BAFUT	10	6.083	5.59	6.31 (MARS)	4.34 (AOUT)	2.4
BALI	10	5.883	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
BAMENDA	10	5.933	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
BANA	10	5.15	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
BANGANTE	10	5.15	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
BANYO	11	6.75	5.71	6.40 (AVRIL)	4.80 (AOUT)	2.7
BATOURI	14	4.433	6.57	7.36 (AVRIL)	5.48 (DECEMBRE)	2.8
BERTOUA	13	4.583	6.30	7.13 (AVRIL)	5.36 (DECEMBRE)	2.3
BETARE	14	0.093	6.25	7.12 (AVRIL)	5.19 (DECEMBRE)	2.7
BOGO	14	10.736	6.55	7.47 (AVRIL)	5.36 (DECEMBRE)	4.4
BONABERI	9	4.084	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
BUEA	9	0.069	5.42	6.10 (MARS)	4.46 (AOUT)	2.3
DIBOMBARI	9	4.182	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
DJANG	10	5.45	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
DOUALA	9	4.05	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
DOUME	13	4.233	6.30	7.13 (AVRIL)	5.36 (DECEMBRE)	2.3
EBOLOWA	11	2.9	5.68	6.30 (AVRIL)	4.89 (AOUT)	2.3
EDEA	10	3.8	5.62	6.28 (MARS-AVRIL)	4.62 (AOUT)	2.3
ESEKA	10	3.65	5.62	6.28 (AVRIL)	4.62 (AOUT)	2.3
FONTEM	9	5.467	5.51	6.26 (MARS)	4.43 (AOUT)	2.3
FOUMBAN	10	5.717	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
FOUMBOT	10	5.5	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3

DONNEES METEOROLOGIQUES ET ENERGIE SOLAIRE DES VILLES CAMEROUNAIRES

FOUNDONG	10	6.25	5.59	6.31 (MARS)	4.34 (AOUT)	2.4
GAROUA BOULAÏ	14	5.883	6.46	7.34 (AVRIL)	5.29 (DECEMBRE)	3.0
GAROUA	13	9.3	6.37	7.24 (AVRIL)	5.30 (DECEMBRE)	3.9
GUIDER	13	9.934	6.37	7.24 (AVRIL)	5.30 (DECEMBRE)	3.9
IDENAO	9	0.071	5.42	6.10 (MARS)	4.46 (AOUT)	2.3
KAELE	14	10.109	6.55	7.47 (AVRIL)	5.39 (DECEMBRE)	4.4
KOUSSERI	15	12.078	6.77	7.66 (MAI)	5.44 (DECEMBRE)	4.5
KRIBI	9	2.95	5.42	6.17 (MARS)	4.32 (AOUT)	2.4
KUMBA	0.157	4.644	5.39	5.73 (FEVRIER)	5.06 (DECEMBRE)	3.4
KUMBO	10	6.2	5.59	6.31 (MARS)	4.34 (AOUT)	2.4
LAGDO	13	9.05	6.37	7.24 (AVRIL)	5.30 (DECEMBRE)	3.9
LIMBE	9	4.013	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
LOLODORF	10	3.233	5.62	6.28 (MARS-AVRIL)	4.62 (AOUT)	2.3
LOUM	9	4.716	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
MANJO	9	4.845	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
MAROUA	14	10.596	6.55	7.47 (AVRIL)	5.39 (DECEMBRE)	4.4
MBALMAYO	11	3.517	5.69	6.28 (AVRIL)	4.82 (AOUT)	2.3
MBENGWI	10	6.017	5.59	6.31 (MARS)	4.34 (AOUT)	2.4
MBOUDA	10	5.633	5.60	6.31 (AVRIL)	4.52 (AOUT)	2.3
MEIGANGA	14	6.517	6.14	7.11 (AVRIL)	4.96 (DECEMBRE)	3.3
MELONG	9	5.117	5.51	6.26 (MARS)	4.43 (AOUT)	2.3
MFOU	11	3.967	5.69	6.28 (AVRIL)	4.82 (AOUT)	2.3
MINDIF	14	10.403	6.55	7.47 (AVRIL)	5.39 (DECEMBRE)	4.4
MME	10	6.333	5.59	6.31 (MARS)	4.34 (AOUT)	2.4
MOKOLO	13	10.74	6.27	7.17 (AVRIL)	5.23 (DECEMBRE)	4.1
MONATELE	11	0.071	5.62	6.23 (AVRIL)	4.88 (AOUT)	2.4
MORA	14	11.043	6.61	7.45 (AVRIL)	5.45 (DECEMBRE)	4.4
MUTENGUENE	9	4.099	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
MUYUKA	9	4.297	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
MVANGUE	11	2.967	5.68	6.30 (AVRIL)	4.89 (AOUT)	2.3
NANGA	12	4.683	5.98	6.76 (AVRIL)	5.29 (AOUT)	2.3

Figure 7.1: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

DONNEES METEOROLOGIQUES ET ENERGIE SOLAIRE DES VILLES CAMEROUNAIRES

EBOKO						
NGAOUNDERE	13	7.317	6.28	7.21 (AVRIL)	5.23 (DECEMBRE)	3.2
NJINIKOM	10	6.233	5.59	6.31 (MARS)	4.34 (AOUT)	2.4
NKONGSAMBA	9	4.953	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
NKOTENG	12	4.517	5.98	6.76 (AVRIL)	5.25 (DECEMBRE)	2.3
OBALA	11	4.167	5.62	6.30 (AVRIL)	4.86 (AOUT)	2.3
OMBESSA	11	4.6	5.62	6.30 (AVRIL)	4.86 (AOUT)	2.3
REY BOUBA	14	8.4	6.56	7.44 (AVRIL)	5.34 (DECEMBRE)	3.9
SA'A	11	4.367	5.62	6.30 (AVRIL)	4.86 (AOUT)	2.3
SANGMELIMA	11	2.933	5.68	6.30 (AVRIL)	4.89 (AOUT)	2.3
TCHOLLIRE	14	8.4	6.56	7.44 (AVRIL)	5.34 (DECEMBRE)	3.9
TIBATI	12	6.467	6.01	6.84 (AVRIL)	5.25 (DECEMBRE)	2.8
TIGNERE	12	7.367	5.94	6.82 (AVRIL)	5.19 (DECMBRE)	3.2
TIKO	9	4.079	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
WUM	10	6.383	5.59	6.31 (MARS)	4.34 (AOUT)	2.4
YABASSI	9	4.454	5.48	6.27 (MARS)	4.38 (AOUT)	2.3
YAGOUA	15	10.343	6.76	7.60 (MAI)	5.45 (DECEMBRE)	4.5
YAOUNDE	11	3.867	5.69	4.82 (AOUT)	6.28 (AVRIL)	2.3
YOKADOUMA	15	3.517	5.94	6.94 (MAI)	4.59 (DECEMBRE)	3.8

Table 1: Mean monthly insolation in Maroua from 2000 to 2010 (Source: Meteorological Service of the Airport of Maroua-Salak)

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Average**
Insolation	5.61	6.24	6.56	6.31	5.96	5.50	5.03	4.85	5.34	5.70	5.85	5.56	5.70

Table 5: Evolution temperatures (in °C) of April and August in the town of Maroua in 2012.

Hours	**April**	**August**
0	33,2	22
3	31,8	22
6	32,4	20
7	34,3	21
8	35,9	23,5
9	38,3	24,5
10	40,6	25,7
11	41,7	27
12	42,3	28
13	42,3	28,8
14	42,2	29,8
15	41,2	29,8
16	41,8	28
17	41,8	26,5
18	37	25
21	33,2	23,5
Average	**38,125**	**25,3188**

Figure 7.2: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

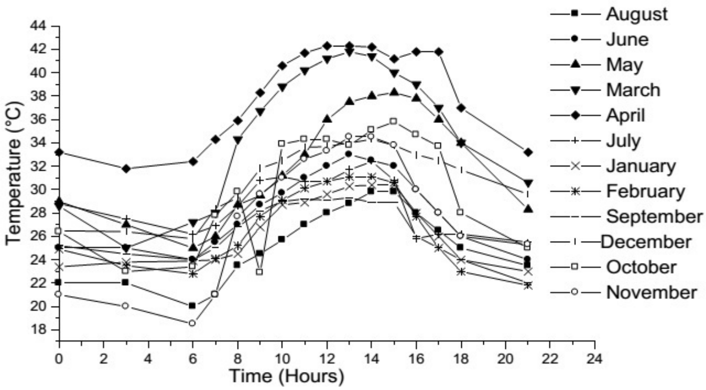

Figure 3: Mean hourly variation of outdoor temperature for the year 2012 in Maroua.

Figure 7.3: Means hourly variation of outdoor temperature of the year 2012 in Maroua (Data received from ISS Maroua)

NOMENCLATURE

δ : déclinaison solaire
h : humidité relative de l'air ambiant
H : rayonnement solaire global
H_d : rayonnement solaire diffus
H_D : rayonnement solaire direct
H_0 : rayonnement solaire extra-atmosphérique
I_{cs} : constance solaire
ϕ : latitude
n : durée d'insolation journalière mesurée
N : durée théorique du jour
Pr : précipitations
x : numéro d'ordre du jour dans l'année
ω_s : angle horaire au coucher du soleil.

Figure 7.4: Nomenclature of the following tables (Data received from ISS Maroua)

Tableau 1 – Stations de type I

Station		Janv.	Fev.	Mars	Avril	Mai	Juin	Juil.	Août	Sept.	Oct.	Nov.	Déc.	Moy. Ann.	Total des Pr.
AMBAM 2°23'N ;11°17'E Alt. : 602 m	n/N	0,33	0,42	0,36	0,52	0,57	0,43	0,16	0,12	0,30	0,31	0,34	0,33	0,35	
	(.)	(5)	(4)	(7)	(4)	(5)	(5)	(5)	(5)	(5)	(5)	(6)	(6)		
	Pr	40,7	76,5	157,6	187,9	204,4	123,7	44,3	48	209,2	307,1	180,6	79		1659
	h	-	-	-	-	-	-	-	-	-	-	-	-	-	
YAOUNDE 3°52'N ;11°32'E Alt. : 753 m	n/N	0,56	0,55	0,43	0,45	0,51	0,31	0,22	0,17	0,31	0,26	0,48	0,52	0,40	
	(.)	(22)	(22)	(23)	(22)	(22)	(22)	(23)	(23)	(23)	(22)	(24)	(24)		
	Pr	28	59,4	149	195	208,3	147,2	57,3	83,1	230,5	295,3	139,4	22,7		1615,2
	h	74	73	78,5	81,5	81	83	83	83,5	80,5	81,5	79	78	80	
DOUALA 4°01'N ;9°44'E Alt. : 5 m	n/N	0,56	0,54	0,41	0,50	0,49	0,26	0,12	0,10	0,23	0,32	0,52	0,48	0,38	
	(.)	(22)	(22)	(23)	(22)	(22)	(22)	(23)	(23)	(23)	(22)	(24)	(24)		
	Pr	51,6	81,6	198,9	239,5	321,1	520,2	740,9	782,8	649	385,1	151,3	151,3		4169,6
	h	77	78	80,5	81	81,5	83,5	86,5	88	86	84	82,5	80	82	
BATOURI 4°25'N ;14°24'E Alt. : 650 m	n/N	0,45	0,53	0,47	0,46	0,65	0,38	0,21	0,27	0,35	0,33	0,58	0,49	0,43	
	(.)	(22)	(22)	(23)	(22)	(22)	(22)	(23)	(23)	(23)	(22)	(24)	(24)		
	Pr	25	46,3	119,1	150,7	179,3	175,8	118	164	225,8	270	113,6	36,5		1624,1
	h	72	71	75,5	80	80	82	83,5	84	82,5	80,5	77,5	75	79	
MAMFE 5°43'N ;9°17'E Alt. : 126 m	n/N	0,58	0,59	0,45	0,51	0,49	0,37	0,24	0,21	0,27	0,34	0,54	0,59	0,43	
	(.)	(8)	(8)	(10)	(9)	(9)	(9)	(10)	(10)	(10)	(8)	(10)	(10)		
	Pr	30,2	69,2	175,5	239,9	339,6	421,2	476,6	460,3	522,2	441,5	152,6	38,3		3367,1
	h	74	73	77	79	80	82	84,5	81	81,5	82	79,5	78	79	

Figure 7.5: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

Tableau 2 – Stations de type II

		Janv.	Fev.	Mars	Avril	Mai	Juin	Juil.	Août	Sept.	Oct.	Nov.	Déc.	Moy. Ann.	Total des Pr.
YOKO	n/N	0,72	0,67	0,54	0,57	0,67	0,47	0,34	0,34	0,40	0,49	0,76	0,73	0,56	
5°33'N ;12°22'E	(.)	(21)	(22)	(23)	(22)	(22)	(22)	(23)	(23)	(23)	(21)	(24)	(23)		
Alt. : 1027 m	Pr	11,5	24,4	83,7	133,7	192,1	170,3	166,3	188,8	297	311,9	77,6	7,9		1665,2
	h	51	62	74	82,5	83,5	85,5	88	88	85,5	83	70	60	76	
NKOUNDJA	n/N	0,73	0,76	0,58	0,58	0,59	0,50	0,33	0,33	0,44	0,42	0,73	0,77	0,56	
5°37'N ;10°45'E	(.)	(22)	(22)	(23)	(22)	(22)	(22)	(23)	(23)	(23)	(22)	(24)	(24)		
Alt. : 753 m	Pr	3,3	28,7	114,2	169	197,9	203	326,6	315,4	369,2	269,1	62,2	10,5		2069,1
	H	55	54	66	76,5	79,5	81,5	81,5	82,5	81,5	78,5	69,5	61	72	
NGAOUNDERE	n/N	0,78	0,79	0,61	0,46	0,58	0,41	0,34	0,32	0,45	0,40	0,74	0,82	0,56	
7°17'N ;13°19'E	(.)	(22)	(22)	(23)	(22)	(22)	(22)	(23)	(23)	(23)	(22)	(24)	(24)		
Alt. : 1115 m	Pr	3	1,6	39,7	148,3	203,3	227,2	250,4	281	236,9	138,7	11,7	1,4		1543,2
	H	49	44	54,5	74	80,5	83,5	84	83	-81	75,5	67,5	54,5	69	
GAROUA	n/N	0,79	0,86	0,69	0,66	0,72	0,52	0,58	0,47	0,64	0,72	0,86	0,82	0,69	
9°20'N ;13°23'E	(.)	(22)	(22)	(21)	(22)	(22)	(22)	(23)	(23)	(23)	(22)	(24)	(24)		
Alt. : 241 m	Pr	0	0,3	4,3	42,4	125,5	154,2	178,6	223,5	211	70,3	1,5	0		1011,6
	h	30	24	28	52	71	75	78	80	78,5	74,5	53	38	57	
MAROUA-SALACK	n/N	0,81	0,86	0,71	0,65	0,63	0,55	0,58	0,52	0,64	0,73	0,85	0,86	0,70	
10°28'N;	(.)	(21)	(21)	(22)	(21)	(22)	(22)	(23)	(23)	(23)	(21)	(24)	(24)		
14°16'E Alt. :	Pr	0	0	2,0	15,7	66	115	190	259	152,1	33,4	0	0		833,2
423 m	h	23	27	19	35,5	58,5	67	75	76	71	59,5	34,5	26	48	

Figure 7.6: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

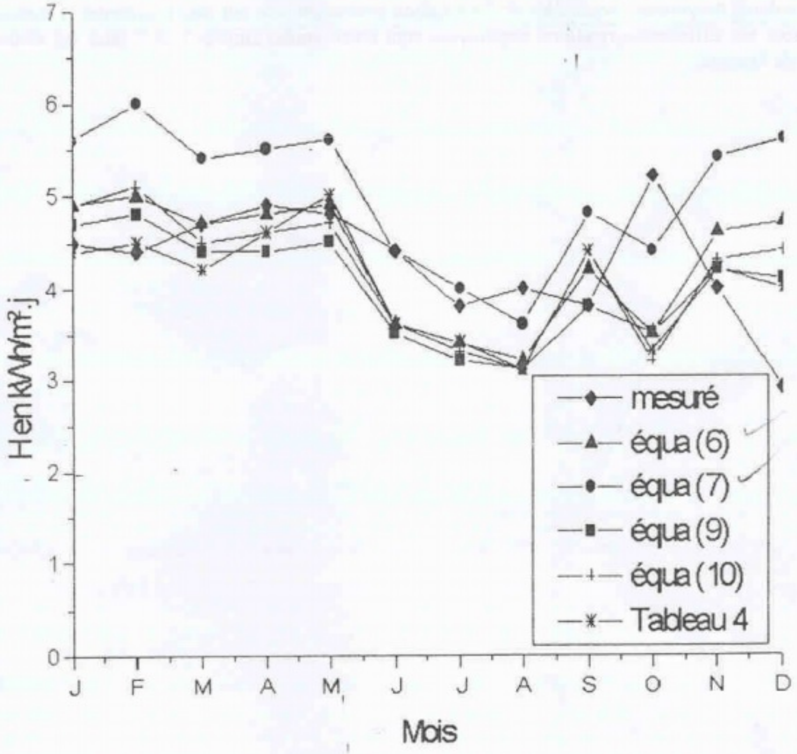

Fig. 2 - Comparaison à Yaoundé entre les valeurs du rayonnement global H en kWh/m².j mesurées et estimées par différentes relations.

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Figure 7.7: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

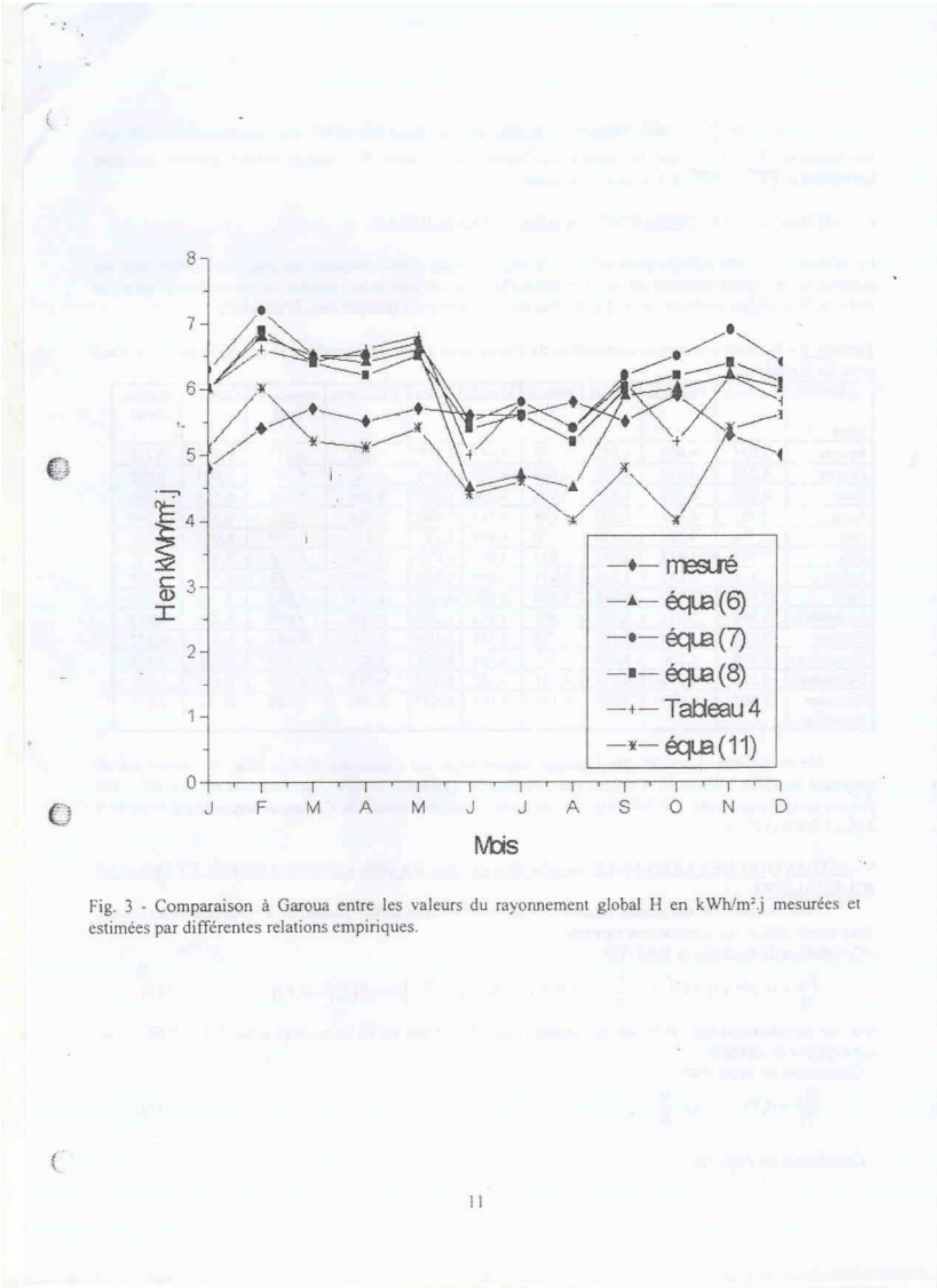

Fig. 3 - Comparaison à Garoua entre les valeurs du rayonnement global H en kWh/m².j mesurées et estimées par différentes relations empiriques.

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Figure 7.8: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

Tableau 5 - Valeurs moyennes mensuelles de l'irradiation globale journalière H (en $kWh.m^{-2}/j$) estimé pour les dix stations.

Stations / Mois	Ambam	Yaoundé	Douala	Batour - i	Mamfe	Yoko	Nkoundja	Ngaoun-déré	Garoua	Maroua Salak
Janvier	3,651	4,657	4,645	4,143	4,647	6,079	6,170	6,312	6,140	6,126
Février	4,230	4,793	4,788	4,669	4,923	6,141	6,742	6,742	7,008	6,926
Mars	4,012	4,422	4,316	4,625	4,504	5,657	5,866	6,045	6,518	6,586
Avril	4,782	4,491	4,703	4,498	4,725	5,882	5,884	5,272	6,460	6,368
Mai	4,770	4,525	4,430	5,250	4,487	6,217	5,813	5,776	6,694	6,211
Juin	4,042	3,518	3,230	3,835	3,881	4,971	5,174	4,748	5,449	5,712
Juillet	2,818	3,155	2,666	3,071	3,207	4,303	4,205	4,368	5,777	5,829
Août	2,726	2,950	2,648	3,468	3,182	4,414	4,313	4,343	5,213	5,545
Septembre	3,648	3,755	3,338	3,962	3,543	4,792	5,105	5,098	6,226	6,214
Octobre	3,716	3,379	3,680	3,775	3,745	5,166	4,759	4,607	6,315	6,352
Novembre	3,676	4,306	4,490	4,765	4,504	6,431	6,235	6,110	6,598	6,496
Décembre	3,583	4,373	4,171	4,151	4,582	6,036	6,218	6,339	6,149	6,209
Moyenne Annuelle	3,804	4,027	3,925	4,184	4,161	5,507	5,540	5,480	6,212	6,214

Tableau 6 - Moyennes mensuelles du global H et du diffus H_d mesurés et des indices de clarté K_T estimés.

	Mois	J	F	M	A	M	J	J	A	S	O	N	D
YAOUNDE	H	4,46	4,38	4,62	4,93	4,81	4,29	3,82	3,97	3,76	5,04	4,02	2,71
	H_d	2,40	2,75	2,83	2,74	2,48	2,43	2,70	2,76	3,08	3,20	1,07	0,95
	K_T	0,48	0,47	0,42	0,43	0,45	0,36	0,32	0,29	0,36	0,33	0,44	0,46
	n/N	0,56	0,55	0,43	0,45	0,51	0,31	0,22	0,17	0,31	0,26	0,48	0,52
GAROUA	H	4,85	5,39	5,70	5,52	5,69	5,61	5,62	5,77	5,55	5,92	5,31	4,96
	H_d	2,56	3,17	3,29	3,12	2,55	2,54	2,63	2,76	2,77	2,59	2,42	2,32
	K_T	0,68	0,72	0,63	0,61	0,64	0,53	0,56	0,50	0,60	0,64	0,72	0,70
	n/N	0,79	0,86	0,69	0,66	0,72	0,52	0,58	0,47	0,64	0,72	0,86	0,82

Figure 7.9: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

Tableau 7 - Valeurs moyennes calculées du rayonnement global journalier H en $kWh/m^2.j$ et des fractions journalières des rayonnements diffus H_d/H et direct H_D/H pour les dix stations.

	Mois	J	F	M	A	M	J	J	A	S	O	N	D	Moyenne annuelle
AMBAM	H	3,65	4,23	4,01	4,78	4,77	4,04	2,82	2,73	3,65	3,72	3,68	3,58	3,80
	H_d/H	0,52	0,49	0,52	0,45	0,44	0,49	0,61	0,62	0,55	0,53	0,52	0,52	0,52
	H_D/H	0,48	0,51	0,48	0,55	0,56	0,51	0,39	0,38	0,45	0,47	0,48	0,48	0,48
YAOUNDE	H	4,66	4,79	4,42	4,49	4,52	3,52	3,15	2,95	3,75	3,38	4,31	4,37	4,03
	H_d/H	0,43	0,44	0,48	0,48	0,46	0,54	0,58	0,61	0,54	0,56	0,46	0,45	0,50
	H_D/H	0,57	0,56	0,52	0,52	0,54	0,46	0,42	0,39	0,46	0,44	0,54	0,55	0,50
DOUALA	H	4,64	4,79	4,32	4,70	4,43	3,23	2,67	2,65	3,34	3,68	4,49	4,17	3,92
	H_d/H	0,43	0,44	0,49	0,46	0,47	0,57	0,63	0,63	0,57	0,53	0,45	0,46	0,51
	H_D/H	0,57	0,56	0,51	0,54	0,53	0,43	0,37	0,37	0,43	0,47	0,55	0,54	0,49
BATOURI	H	4,14	4,67	4,62	4,50	5,25	3,83	3,07	3,47	3,96	3,77	4,76	4,15	4,18
	H_d/H	0,47	0,45	0,47	0,48	0,41	0,52	0,59	0,56	0,52	0,52	0,43	0,46	0,49
	H_D/H	0,53	0,55	0,53	0,52	0,59	0,48	0,41	0,44	0,48	0,48	0,57	0,54	0,51
MAMFE	H	4,65	4,92	4,50	4,72	4,49	3,88	3,21	3,18	3,54	3,74	4,50	4,58	4,16
	H_d/H	0,42	0,43	0,48	0,46	0,47	0,52	0,58	0,59	0,56	0,52	0,44	0,42	0,49
	H_D/H	0,58	0,57	0,52	0,54	0,53	0,48	0,42	0,41	0,44	0,48	0,56	0,58	0,51
YOKO	H	6,08	6,14	5,66	5,88	6,22	4,97	4,30	4,41	4,79	5,17	6,43	6,04	5,51
	H_d/H	0,33	0,38	0,50	0,46	0,38	0,56	0,68	0,68	0,63	0,55	0,27	0,31	0,48
	H_D/H	0,67	0,62	0,50	0,54	0,62	0,44	0,32	0,32	0,37	0,45	0,73	0,69	0,52
NKOUNDJA	H	6,17	6,74	5,87	5,88	5,81	5,17	4,20	4,31	5,10	4,76	6,23	6,22	5,54
	H_d/H	0,31	0,27	0,46	0,46	0,44	0,53	0,70	0,70	0,58	0,61	0,31	0,27	0,47
	H_D/H	0,69	0,73	0,54	0,54	0,56	0,47	0,30	0,30	0,42	0,39	0,69	0,73	0,53
NGAOUN DERE	H	6,31	6,74	6,04	5,27	5,78	4,75	4,37	4,34	5,10	4,61	6,11	6,34	5,48
	H_d/H	0,26	0,26	0,43	0,56	0,46	0,61	0,68	0,70	0,58	0,63	0,31	0,22	0,47
	H_D/H	0,74	0,74	0,57	0,44	0,54	0,39	0,32	0,30	0,42	0,37	0,69	0,78	0,53
GAROUA	H	6,14	7,01	6,52	6,46	6,69	5,45	5,78	5,21	6,23	6,31	6,60	6,15	6,21
	H_d/H	0,26	0,19	0,34	0,38	0,33	0,51	0,46	0,56	0,39	0,33	0,19	0,22	0,35
	H_D/H	0,74	0,81	0,66	0,62	0,67	0,49	0,54	0,44	0,61	0,67	0,81	0,78	0,65
MAROUA SALAK	H	6,13	6,93	6,59	6,37	6,21	5,71	5,83	5,54	6,21	6,35	6,50	6,21	6,21
	H_d/H	0,24	0,19	0,33	0,39	0,41	0,48	0,46	0,51	0,39	0,31	0,19	0,19	0,34
	H_D/H	0,76	0,81	0,67	0,61	0,59	0,52	0,54	0,49	0,61	0,69	0,81	0,81	0,66

Figure 7.10: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

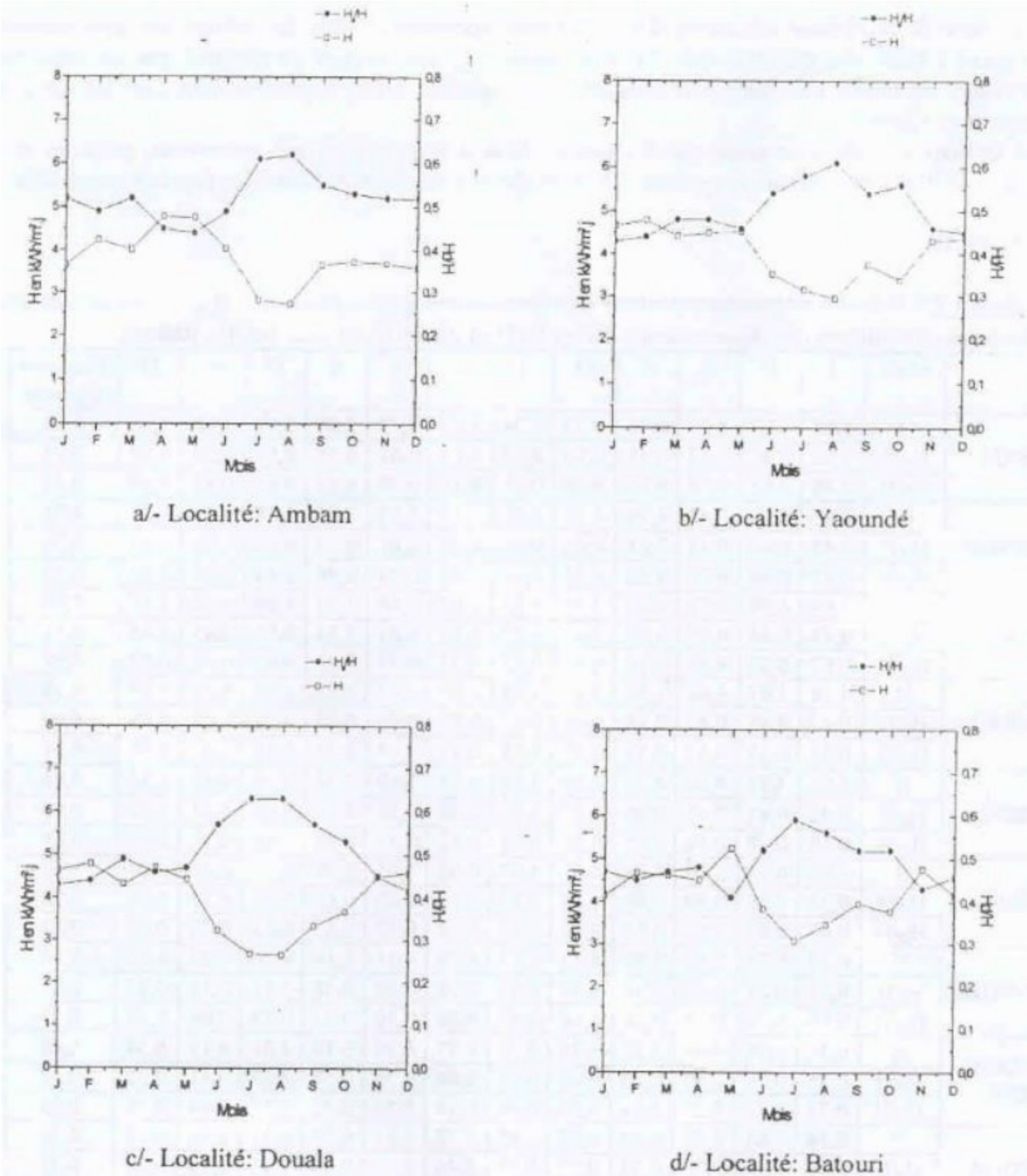


Figure 7.11: Meteorological data of some cities in Cameroon (Data assessed from ISS Maroua)

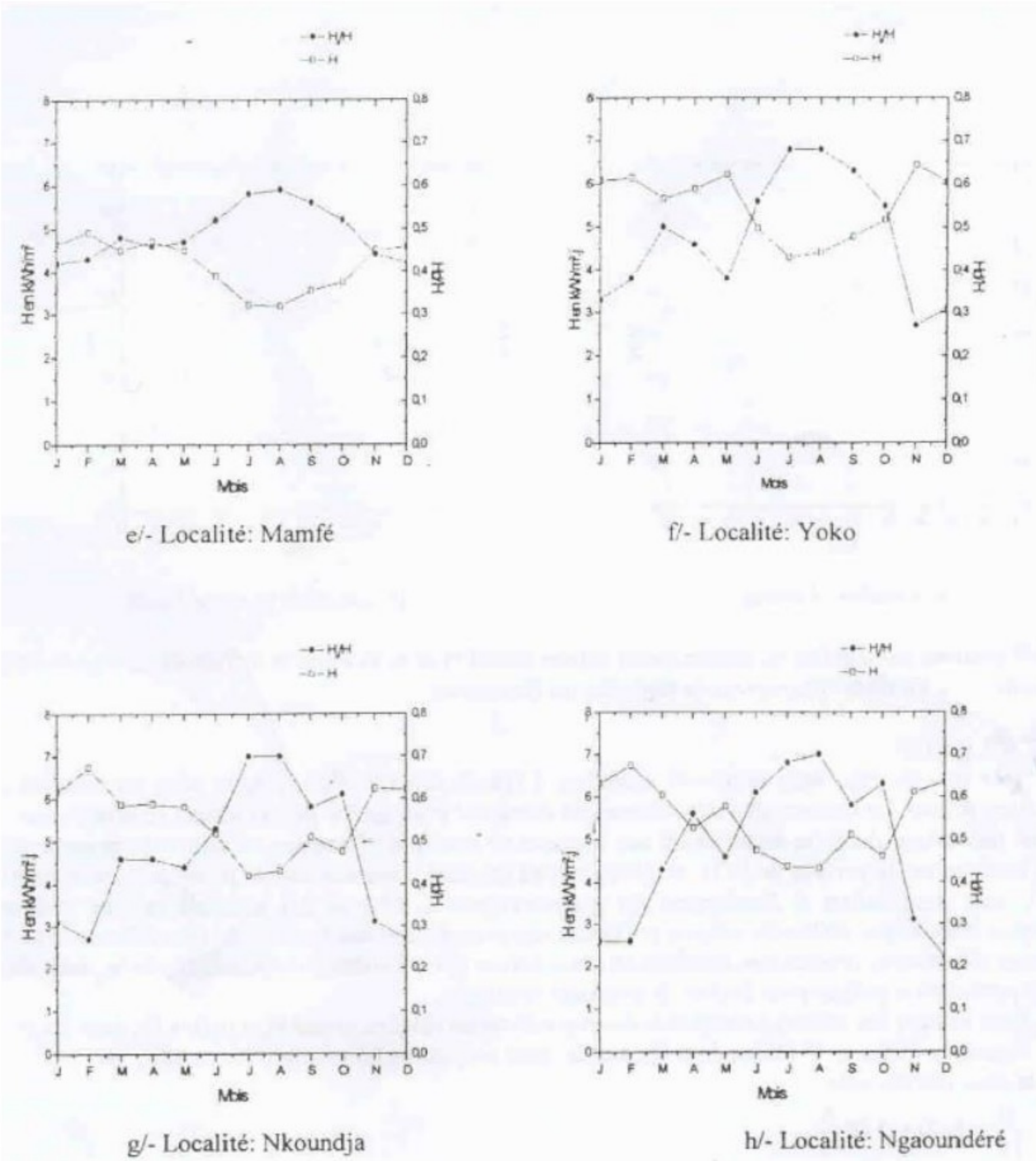


Figure 7.12: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

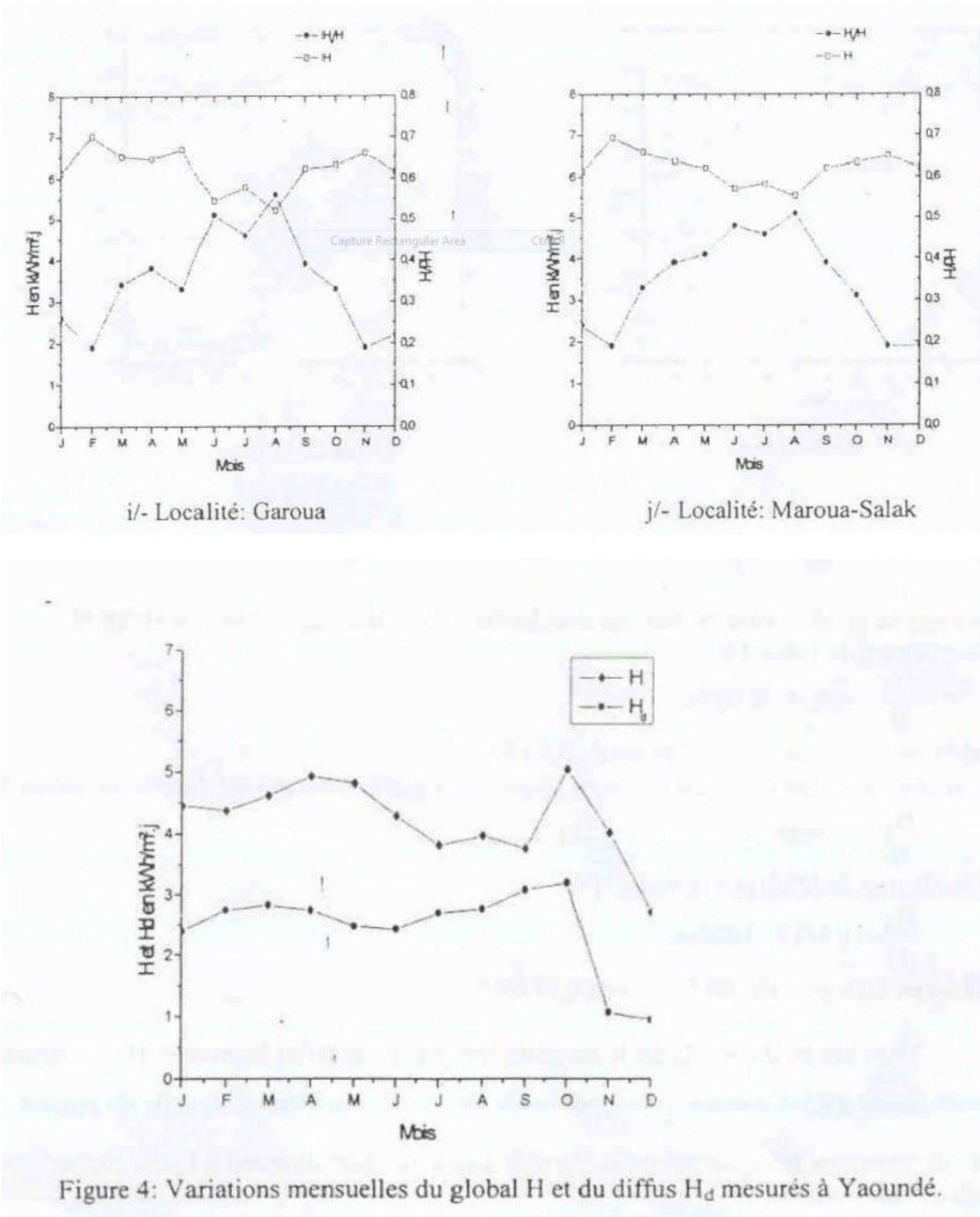


Figure 7.13: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

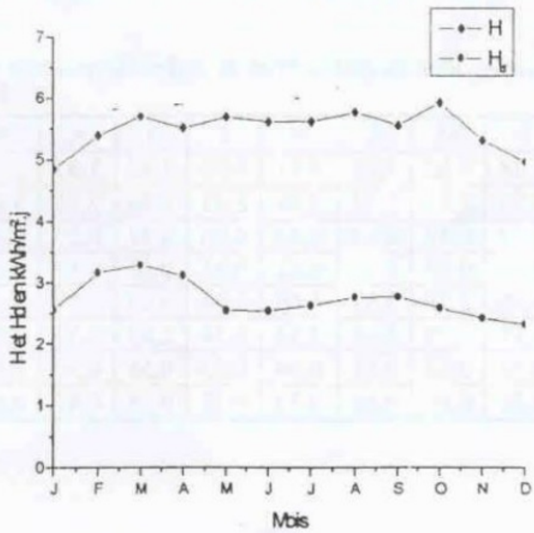


Figure 5: Variations mensuelles du global H et du diffus H_d mesurés à Garoua.

Figure 7.14: Meteorological data of some cities in Cameroon (Data received from ISS Maroua)

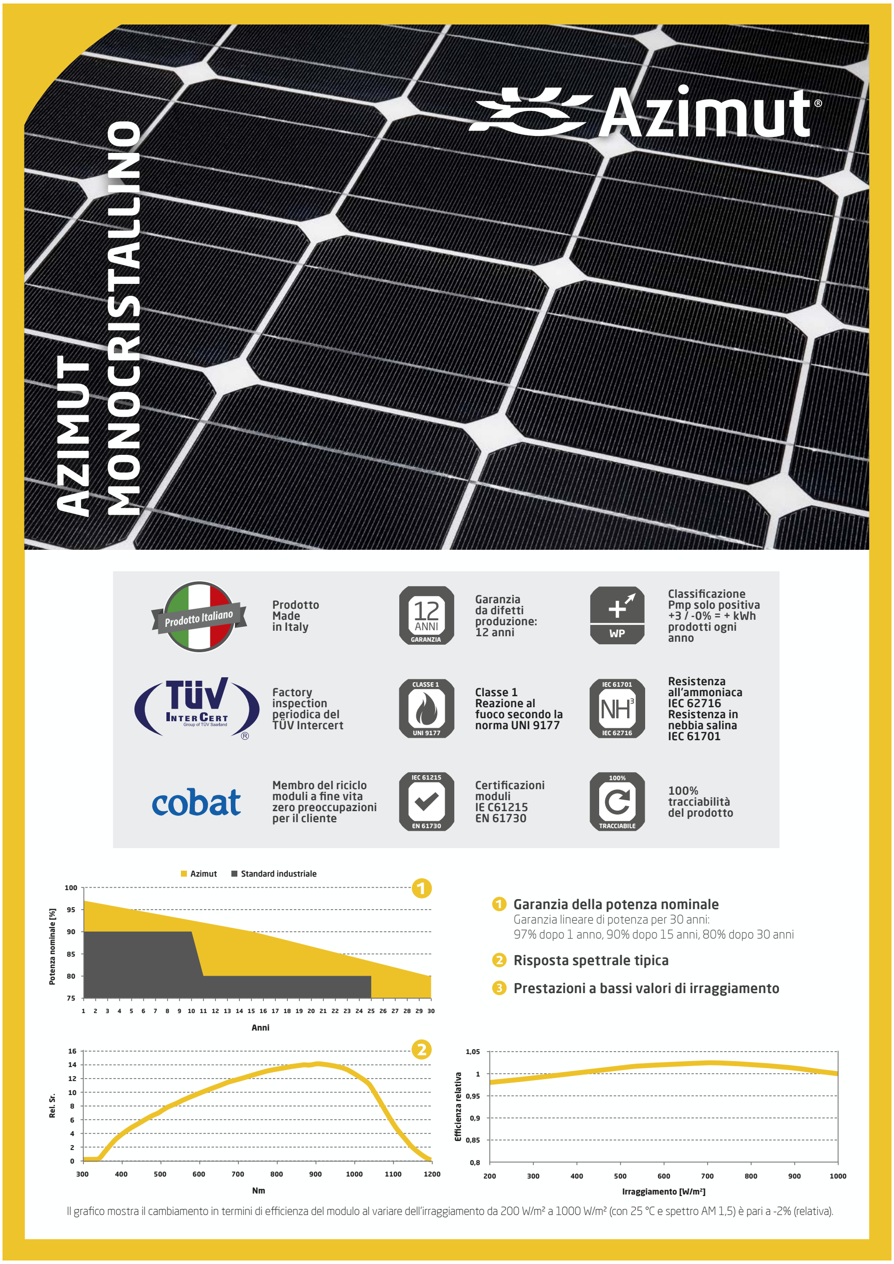
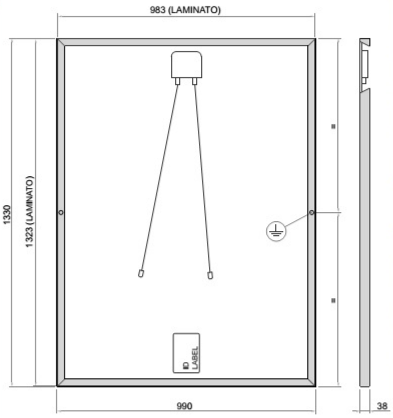


Figure 7.15: Datasheet of the photovoltaic module

AZM486M



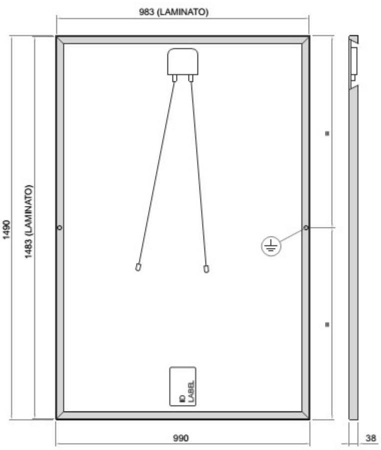
Dati elettrici in condizioni STC (AM 1,5, IRR 1000 w/m²; temperatura 25±2 °C)		
Modello		205
Potenza nominale P_{nom}	W	205
Classificazione in Potenza	%	0 / + 3
Tensione alla massima potenza Vmp	V	24,91
Corrente alla massima potenza Imp	A	8,23
Tensione di circuito aperto V_{oc}	V	29,55
Corrente di corto circuito I_{sc}	A	8,95
Efficienza modulo	%	15,57
Dati elettrici in condizioni NOCT (IRR 800 w/m²; t. amb = 20°c; t. celle = 44°C; vel. vento = 1 m/s, AM 1,5)		
Potenza nominale P_{nom}	W	150
Tensione alla massima potenza Vmp	V	22,81
Corrente alla massima potenza Imp	A	6,58
Tensione di circuito aperto V_{oc}	V	27,04
Corrente di corto circuito I_{sc}	A	7,11
Precisione di misura in STC: Pmp ≤ 3%; Voc, Vmp, Isc, Imp ≤ 10% Precisione di misura in NOCT: Pmp ≤ 5%; Voc, Vmp, Isc, Imp ≤ 10%		

Vetro	Temprato prismatico ad alta trasmittanza. Spessore 3,2 mm per modulo con cornice e 4 mm per modulo laminato.
Celle	48 (6x8) monocristalline, 156 x 156 mm
Scatola di giunzione	IP65, 3 diodi di bypass, cavi lunghezza 100 (+) / 100 (-) cm da 4 mm²
Connettori	IP68, connettori ad innesto rapido PV4.
Dimensioni	1330 x 990 mm +/- 1 mm (L=1642 x 982 mm)
Peso	16 +/- 1 kg
Versioni	Backsheet nero (N), backsheet trasparente (T), laminato (L), laminato nero (LN), laminato trasparente (LT).

AZM546M

Dati elettrici in condizioni STC (AM 1,5, IRR 1000 w/m²; temperatura 25±2 °C)		
Modello		225
Potenza nominale P_{nom}	W	225
Classificazione in Potenza	%	- 0 / + 3
Tensione alla massima potenza Vmp	V	27,57
Corrente alla massima potenza Imp	A	8,16
Tensione di circuito aperto V_{oc}	V	32,80
Corrente di corto circuito I_{sc}	A	8,85
Efficienza modulo	%	15,25
Dati elettrici in condizioni NOCT (IRR 800 w/m²; t. amb = 20°c; t. celle = 43°C; vel. vento = 1 m/s, AM 1,5)		
Potenza nominale P_{nom}	W	165
Tensione alla massima potenza Vmp	V	25,25
Corrente alla massima potenza Imp	A	6,52
Tensione di circuito aperto V_{oc}	V	30,02
Corrente di corto circuito I_{sc}	A	7,03
Precisione di misura in STC: Pmp ≤ 3%; Voc, Vmp, Isc, Imp ≤ 10% Precisione di misura in NOCT: Pmp ≤ 5%; Voc, Vmp, Isc, Imp ≤ 10%		

Vetro	Temprato prismatico ad alta trasmittanza. Spessore 3,2 mm per modulo con cornice e 4 mm per modulo laminato.
Celle	54 (6x9) monocristalline, 156 x 156 mm
Scatola di giunzione	IP65, 3 diodi di bypass, cavi lunghezza 100 (+) / 100 (-) cm da 4 mm²
Connettori	IP68, connettori ad innesto rapido PV4.
Dimensioni	1490 x 990 mm +/- 1 mm (L=1642 x 982 mm)
Peso	18 +/- 1 kg
Versioni	Backsheet nero (N), backsheet trasparente (T), laminato (L), laminato nero (LN), laminato trasparente (LT).



DC/AC Inverter system

The Industrial bulk feed (IBF) unit is designed for systems with 48, 60, 110, 125 & 220 VDC input. The Power Core is built around the INV 222 inverters, and designed for all type of applications where an uninterruptable AC power supply is needed, such as switchgear, telecom, emergency lighting and alarm systems.

Its compact design and simple installation make it a powerful 19" power supply package.

The IBF-INV can be fitted with an optional static switch, with uninterruptable switch between mains and inverter mode.

IBF DC/AC-INV (Inverter)

48 V_{DC}, 60 V_{DC}, 110 V_{DC}, 125 V_{DC} & 220 VDC Input

DOC. NO: CINV0306.000.DS3, v1

INDUSTRY APPLICATIONS

Power Utilities

- Low & High Voltage switchgear
- Transformer & SUB Stations
- Power Generation & Distribution
- Control & protection
- SCADA
- Communications equipment

Offshore and process industry

- Safety and Automation Systems (SAS)

Marine

- Communication onboard ships

Railway infrastructure

- Control & protection
- Signaling

Telecom – Mobile - Fixed / Wireless

- Radio Base stations/ Cell Sites
- LTE / 4G / WiMAX
- Distributed Antenna Systems
- Microwave
- Broadband

INV 222 inverters

STS 207 Static Switch

KEY FEATURES

- ✓ Compact design and simple installation
- ✓ 48, 60, 110, 125 & 220 VDC Input
- ✓ House up to 3 Inverter modules
- ✓ 2,25-6,75 kVA Output
- ✓ Built in manual bypass
- ✓ Option with static switch
- ✓ Input and output protections on each inverter by built in MCB
- ✓ Ethernet for remote or local monitoring and control via WEB Browser
- ✓ SNMP protocol with TRAP, SET and GET on Ethernet. Email of TRAP alarms
- ✓ 1 digital programmable relay output
- ✓ Option with 6 relay outputs

See reverse side for specifications

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48V DC/AC Inverter

The INV 222 inverters, and designed for all type of applications where an uninterruptable AC power supply is needed, such as switchgear, telecom, emergency lighting and alarm systems.

Applications

- Alarm systems
- PABX systems
- Emergency lighting
- Industrial control systems

48V DC INPUT				AVAILABLE 48V DC INPUT CONVERTERS			
Part Number	Description	Intput Voltage Range	Efficiency	Max Output Power			Output protection
				1 Module	2 Module	3 Module	
501-022-515.00	INV222-48/230-50	40,8-67,5 VDC	> 90%	2,25 kVA	4,5 kVA	6,75 kVA	In IBF DC/AC

60V DC/AC Inverter

The INV 222 inverters, and designed for all type of applications where an uninterruptable AC power supply is needed, such as switchgear, telecom, emergency lighting and alarm systems.

Applications

- Telecommunication systems; SCADA, GSM-R
- PABX systems
- Emergency lighting
- Industrial control systems

60V DC INPUT				AVAILABLE 60V DC INPUT CONVERTERS			
Part Number	Description	Input Voltage Range	Efficiency	Max Output Power			Output protection
				1 Module	2 Module	3 Module	
501-022-615.00	INV222-60/230-50	52-76 VDC	> 90%	2,25 kVA	4,5 kVA	6,75 kVA	In IBF DC/AC

110/125 V DC/AC Inverter

The INV 222 inverters, and designed for all type of applications where an uninterruptable AC power supply is needed, such as switchgear, telecom, emergency lighting and alarm systems.

Applications

- Low & High Voltage switchgear
- Transformer & SUB Stations
- Power Generation & Distribution

110V/125 V DC INPUT				AVAILABLE 110V/125 V DC INPUT CONVERTERS			
Part Number	Description	Input Voltage Range	Efficiency	Max Output Power			Output protection
				1 Module	2 Module	3 Module	
501-022-715.10	INV222-110/230-50 WIR	91,8-145 VDC	> 90%	2,25 kVA	4,5 kVA	6,75 kVA	In IBF DC/AC

220 V DC/AC Inverter

The INV 222 inverters, and designed for all type of applications where an uninterruptable AC power supply is needed, such as switchgear, telecom, emergency lighting and alarm systems.

Applications

- Low & High Voltage switchgear
- Transformer & SUB Stations
- Power Generation & Distribution

220V DC INPUT				AVAILABLE 220V DC INPUT CONVERTERS			
Part Number	Description	Output Voltage Range	Efficiency	Max Output Power			Output protection
				1 Module	2 Module	3 Module	
501-022-815.00	INV222-220/230-50	183,6-270 VDC	> 90%	2,25 kVA	4,5 kVA	6,75 kVA	In IBF DC/AC

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CINV0306.000.DS3, v1

IBF DC/AC-INV (Inverter)

TECHNICAL SPECIFICATIONS

Model	IBF-DC/AC-48 VDC Input	IBF-DC/AC-60 VDC Input	IBF-DC/AC-110/125 VDC Input	IBF-DC/AC-220 VDC Input
Part number	CINV0306.xxx	CINV0306.xxx	CINV0306.xxx	CINV0306.xxx
INPUT DATA				
Voltage (range)	40,8-67,5 VDC	52-76 VDC	91,8-145 VDC	183,6-270 VDC
Nominal Input voltage	48 VDC	60 VDC	108 VDC	216 VDC
Nominal Input current (on each Inverter)	41,6 ADC @ 48VDC	33,3ADC @ 60VDC	18,4 ADC @ 108VDC	9,2 ADC @ 216 VDC
DC Input Protection (on each Inverter)	63 A MCB	63 A MCB	25 A MCB	16 A MCB
AC Input Protection	32 A MCB			
Connection AC Input	Individual screw terminal 6 mm2 PE screw terminal, max 6 mm2 and M5 cable lug directly to chassis			
Connection bulk DC input	M8 bolt			
OUTPUT DATA				
Voltage (default)	230 VAC			
Power (maximum)	5400 W/6750 VA @cos phi=0,8			
Current (maximum)	29,4 AAC @cos phi=0,8, 23,4 AAC @ cos phi=1 (resistive power)			
Frequency	50 Hz			
Output protection (on each Inverter)	10 A MCB			
AC Output protection	32 A MCB			
Connection AC Output	screw terminals 6mm2, PE screw terminal max 6 mm2			
CONTROL AND MONITORING				
Monitoring Unit	In STS 207			
Local Operation	Display and keys, WEB interface via standard browser			
Remote Operation	WebPower (WEB Interface & SNMP protocol)			
Alarm Relays (Connection: clamp ≤ 1.5 mm^2)	1 x Potential free contacts (NO, NC, C)			
Option: Relayboard DCC-RB6-STS	6 x Potential free contacts (NO, NC, C), 12-300 VDC, 0,1 A			
Monitoring functions	Voltage, Frequency, Synchronization, Over temperature, etc			
Alarms (from Web Interface or RB6 board)	Over temperature, STS outputcurrent too high, Source 1 & 2 failure, Collective failure STS, Load on Inverter etc			
OTHER SPECIFICATIONS				
Protection class	IP 20			
Operating temperature	-20 to +55℃, humidity 5 - 95% RH non-condensing			
Storage temperature	-40 to +85℃, humidity 0 - 99% RH non-condensing			
Dimensions[WxDxH]	482*432*267mm (6U)			
Weight (excluding Inverters & static switch)	17 kg			
DESIGN STANDARDS				
Electrical safety	EN 60950-1			
EMC	EN55011/22 class "B" EN 61000-4 T2-5			

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A Revolution in Wind Energy

Inverter

Type	Grid-tie
Input Power Rating	1350 W
Electrical Input	Three-phase
Rated Input Voltage	125 Vac peak/phase
Rated Input Current	3.6 Aac peak/phase
Output Voltage	120 Vrms True Sine Wave
Max Output Current	10 Arms True Sine Wave
Power Factor at Output	>0.99
Certifications	CSA 22.2 #107.1 and UL 1741
Enclosure Weight	9 kg
Size	300 mm x 300 mm x 100 mm

System Power Curve

Wind Speed (m/s)	Power Out (W): Grid-tie	Power Out (W): Battery Charger
4	58	74
5	127	155
6	241	279
7	429	472
8	673	713
9	914	965
10	1200	1289
11	1200	1500
12	1200	1500
13	1200	1500

Tower

Tower Type	Engineered free-standing steel truss
Installation Method	Gin pole; no crane required
Foundation	3 m³ reinforced concrete
Number of Sections	4 x 3 m (10') sections + 2m mast
Tower Height to Nacelle	14.5 m (48')
Tower Mass	165 kg
Max Lateral Load at Mast	2200 N (500 lbs)
Max Vertical Load at Mast	440 N (100 lbs)
Survival Wind Speed*	45 m/s (162 km/h)

*With 2200 N (500 lbs) loading at mast tip

Annual Energy Production

Wind Speed (m/s)	kWh/year: Grid-tie	kWh/year: Battery Charger*
4	1221	1393
4.5	1781	2016
5	2443	2813
5.5	2766	3365
6	3331	4205
6.5	3610	4859
7	3877	5413
7.5	4047	6068

* Does not include efficiency of off-grid inverter

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Canada

Regional Raum Certified Dealer

Figure 7.17: Datasheet of the wind turbine generator

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Slow-Turning 5 kW Kohler Diesel Generator

Our Reduced Price: $3475

Slow-Turning 5 kW Kohler Diesel Generator - Grab a 19 gallon fuel tank you'll have electricity for 79 hours. That's an entire weekend plus on only 19 gallons of diesel fuel! This slow-turning diesel generator is THE MOST FUEL EFFICIENT DIESEL GENERATOR WE HAVE EVER SEEN and is suitable for standby or continous use. The slow speed design enhances engine life and significantly decreases sound levels and fuel consumption. Add the two-wire auto feature and this unit would be *ideal* for a solar power application. This unit includes a slow-turning 10 HP Kohler Diesel engine, brushless generator end suitable for powering sensitive electronics, residential muffler, replaceable foam air filter elemant, steel skid base w/ vibration isolators (for smooth operation), compact design (LxWxH:29-3/4"x20"x26-1/4"), 2 year engine/generator warranty and is electric start. CALL FOR SHIPPING QUOTE.

55 GALLON DRUM FUEL TANK KIT

Options

Options	Price
Two-Wire Auto Start Control	+ $375
Deluxe Receptacle Panel w/ Hour Meter	+ $495
18 Gallon External Fuel Tank	+ $375

Features/Benefits

Generator

Generator	

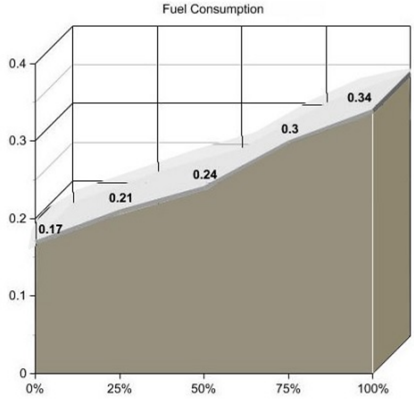
Figure 7.18: Datasheet of the 5 kW diesel generator

Power Single-Phase	---
Is this unit suitable for powering sensitive electronic equipment like a laptop computer?	Yes
Maximum Output	5,000 watts
Continous Output	4,500 watts
Load Amperage at 120 volts	---
Maximum Load	41 Amps
Continous Load	37.5 Amps
Load Amperage at 240 volts	---
Maximum Load	21 Amps
Continous Load	18.75 Amps

Engine

Engine	-
Make	Kohler KD440
Type	4 Stroke
Oil Capacity	1.6 qts
Cylinder Block	Aluminum w/ Cast Iron Sleeves
Bore & Stroke	3.38" x 2.95"
Cylinders	1
Exhaust Outlet	1" OD Mufler
Fuel	No. 2 Diesel
Starting System	Electric

Consumption



Consumption	
Consumption at 1/2 load	0.24 gallons/hour
Consumption at 3/4 load	0.30 gallons/hour
Consumption at full load	0.34 gallons/hour

Installation Data

Generator	
No. Power Lead Conductors	4
Minimum Power Lead Size	0-50 Feet: 12 AWG 51-100 Feet: No. 10 AWG 101-150 Feet: No. 8 AWG
Exhaust Outlet	1-1/2" OD Muffler Outlet
Service-Side Direction (Facing Engine)	Left-Side
Exhaust Direction (Facing Service Side)	Back-Side
Fuel Tank Location (Facing Service Side)	Front-Side
Power Output Direction (Facing Service Side)	Left-Side
Battery Type	12 VDC - 350 CCA
Engine Oil Type	10W-30

Warranty

Warranty	
Engine Warranty	2 Years
Generator Warranty	2 Years
100% Coverage for Parts & Labor	Standard

Dimensions

Dimesions	
Length	29-3/4"

Generator set data sheet

Power Generation

Model: C8 D5 (X-series)
Frequency: 50
Fuel type: Diesel

Spec sheet:	**SS25-CPGK**
Noise data sheet (open/enclosed):	**ND50-OS550/ND50-CS550**
Airflow data sheet:	**AF50-550**
Derate data sheet (open/enclosed):	**DD50-OS550/DD50-CS550**
Transient data sheet:	**TD50-550**

Fuel consumption

	Standby				Prime			
	kVA (kW)				kVA (kW)			
Ratings	8.3 (6.6)				7.5 (6)			
Load	**1/4**	**1/2**	**3/4**	**Full**	**1/4**	**1/2**	**3/4**	**Full**
gph	1.5	1.9	2.4	3	1.3	1.7	2.1	2.6
L/hr	0.4	0.5	0.6	0.8	0.3	0.5	0.6	0.7

Engine

	Standby rating	Prime rating
Engine manufacturer	Cummins	
Engine model	X1.3G2	
Configuration	4 cycle, in-line, 2 cylinder diesel	
Aspiration	Naturally aspirated	
Gross engine power output, kWm	11.8	10.6
BMEP at set rated load, kPa	711	672
Bore, mm	95	
Stroke, mm	91	
Rated speed, rpm	1500	
Piston speed, m/s	4.55	
Compression ratio	18.5:1	
Lube oil capacity, L	4.5	
Overspeed limit, rpm	2050	
Regenerative power, kW	2	
Governor type	Electronic	
Starting voltage	12 Volts DC	

Fuel flow

Maximum fuel flow, L/hr	40
Maximum fuel inlet restriction, mm Hg	73
Maximum fuel inlet temperature, °C	60

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Figure 7.19: Datasheet of the 6 kW diesel generator

Air

Air	Standby rating	Prime rating
Combustion air, m^3/min	11.60	11.60
Maximum air cleaner restriction, kPa	3.73 (HD clean element)	

Exhaust

Exhaust gas flow at set rated load, m^3/min	12.2	12.2
Exhaust gas temperature, °C	550	530
Maximum exhaust back pressure, kPa	4.133	

Standard set-mounted radiator cooling

Ambient design, °C	50	
Fan load, kW_m	<1	
Coolant capacity (with radiator), L	4.65	
Cooling system air flow, m^3/sec @ 12.7 mmH_2O	0.388	
Total heat rejection, Btu/min	7.5 (to coolant)	7.5 (to coolant)
Maximum cooling air flow static restriction mm H_2O	0.125	

Weights*

Weights*	Open	Enclosed
Unit dry weight kgs		RTF
Unit wet weight kgs		596

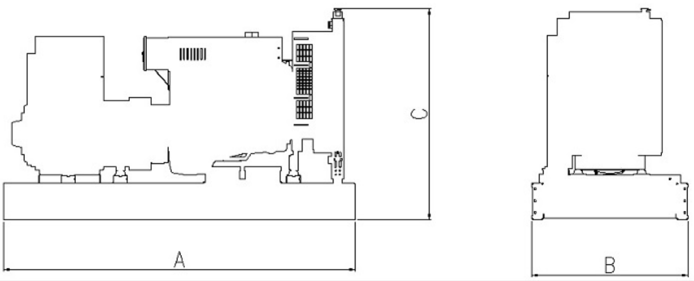
* Weights represent a set with standard features. See outline drawing for weights of other configurations.

Dimensions

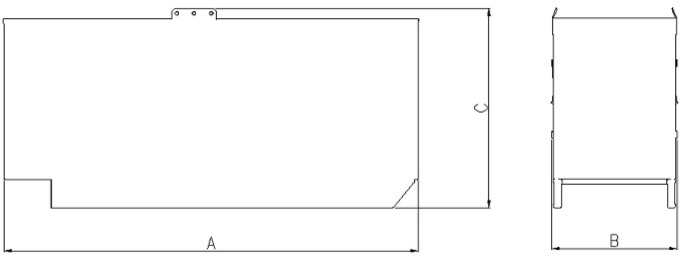
Dimensions	Length	Width	Height
Standard open set dimensions			
Standard enclosed set dimensions	1460	886	1140

Genset outline

Open set



Enclosed set



Outlines are for illustrative purposes only. Please refer to the genset outline drawing for an exact representation of this model.

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Alternator data

Connection[1]	Temp rise °C	Duty[2]	Alternator	Voltage
1 phase	125/105C	S/P	PI044F	230
3 phase	163/125C	S/P	PI044D	415

Ratings definitions

Emergency standby power (ESP):	Limited-time running power (LTP):	Prime power (PRP):	Base load (continuous) power (COP):
Applicable for supplying power to varying electrical load for the duration of power interruption of a reliable utility source. Emergency Standby Power (ESP) is in accordance with ISO 8528. Fuel Stop power in accordance with ISO 3046, AS 2789, DIN 6271 and BS 5514.	Applicable for supplying power to a constant electrical load for limited hours. Limited Time Running Power (LTP) is in accordance with ISO 8528.	Applicable for supplying power to varying electrical load for unlimited hours. Prime Power (PRP) is in accordance with ISO 8528. Ten percent overload capability is available in accordance with ISO 3046, AS 2789, DIN 6271 and BS 5514.	Applicable for supplying power continuously to a constant electrical load for unlimited hours. Continuous Power (COP) is in accordance with ISO 8528, ISO 3046, AS 2789, DIN 6271 and BS 5514.

Formulas for calculating full load currents:

Three phase output

$$\frac{\text{kW} \times 1000}{\text{Voltage} \times 1.73 \times 0.8}$$

Single phase output

$$\frac{\text{kW} \times \text{SinglePhaseFactor} \times 1000}{\text{Voltage}}$$

See your distributor for more information.
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Power Generation

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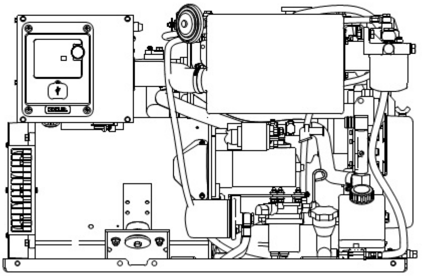
DS336-CPGK-RevE-7/8/2012

Model: 9EKOZD 60 Hz
7EFKOZD 50 Hz

KOHLER Power Systems

1-Phase Diesel



Marine Generator Set

Engine Features

- Diesel fueled
- Certified by the Environmental Protection Agency (EPA) to conform to Tier III marine auxiliary standards
- Three cylinder
- Four cycle
- Closed cooling system
- Heat exchanger
- Electric fuel lift pump
- Lifting eye

Generator Features

- Remote start 12-pin connector
- Class H insulation
- Multivoltage adjustability
- Voltage regulation of ±1.0%
- Radio suppression

ADC IId Advanced Digital Control Features

- Designed for today's most sophisticated electronics
- Easy to read 12 x 2 LCD alpha-numeric display
- Compact, integrally mounted control
- Sealed connectors for maximum corrosion protection
- SAE J1939, SmartCraft™, NMEA 2000 selectable CANbus outputs
- Remote monitoring of fault conditions
- Pushbutton dial for configuration and adjustment
- Programmed crank cycle

Optional Accessories

- Aluminum sound shield
- Remote digital gauge (2 or 3 inch)
- Siphon break
- Ignition protected starter
- Circuit breakers

Generator Weights and Dimensions

	Without Sound Shield	With Sound Shield
Weight, kg (lb.)		
Wet	211 (465)	249 (548)
Dry	207 (456)	245 (539)
Length, mm (in.)	827 (32.58)	865 (34.06)
Width, mm (in.)	448 (17.65)	528 (20.79)
Height, mm (in.)	536 (21.12)	559 (22.01)

Generator Ratings

Model Generator (Alternator)	Voltage	Hz	25°C (77°F) Amps	25°C (77°F) kW/kVA	Ph
9EKOZD (4H4)	120	60	70.8	8.5/8.5	1
	120/240	60	70.8/35.4	8.5/8.5	1
7EFKOZD (4H4)	115/230	50	60.8/30.4	7/7	1
	230	50	30.4	7/7	1
	240	50	29.2	7/7	1

RATINGS: Marine continuous ratings per ISO 3046, ISO 8528-1, and Kohler ISO rating guideline 2.14. Obtain technical information bulletin (TIB-101) on ratings guidelines for complete ratings definitions.

Availability is subject to change without notice. Kohler Co. reserves the right to change the design or specifications without notice and without any obligation or liability whatsoever. Contact your local Kohler generator distributor for availability.

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Figure 7.20: Datasheet of the 7 kW diesel generator

Application Data

Engine

Engine Specifications	60 Hz	50 Hz
Type	4 cycle, naturally aspirated	
Cylinder, quantity	3	
Displacement, L (cu. in.)	1.028 (62.7)	
Bore and stroke, mm (in.)	75 x 77.6 (2.95 x 3.05)	
Compression ratio	24.5:1	
Combustion system	Indirect injection	
Rated rpm	1800	1500
Max. power at rated rpm, HP	14.5	11.9
Governor, type	Mechanical	
Frequency regulation, mechanical governor		
No load to full load (droop)	5%	
Steady state	±0.7%	
Angular operation		
Instant (1 min.)	35°	
Intermittent (30 min.)	25°	

Engine Electrical

Engine Electrical System	60 Hz	50 Hz
Battery, voltage	12 volt	
Battery charging module	10-amp	
Battery, minimum recommendation	650 CCA @ 0°F	
Starter motor	2.5 kW, 12 V	

Cooling

Cooling System	60 Hz	50 Hz
Capacity, L (qt.), approx.	3 (3.2)	
Heat exchanger type	2.5 in. dia. x 2 pass	
Seawater pump type	Belt-driven, 10-blade impeller	
Heat rejected to cooling water at rated kW, wet exhaust, kW (Btu/min.)	12 (683)	11.1 (635)
Engine water pump flow, Lpm (gpm)	21.6 (5.7)	21.2 (5.6)
Seawater pump flow, Lpm (gpm)	28.4 (7.5)	24.6 (6.5)

Fuel

Fuel System	60 Hz	50 Hz
Fuel shutoff solenoid	Electric	
Fuel pump	Electric	
Maximum recommended fuel lift, m (ft.)	1.2 (4.0)	

Lubrication

Lubricating System	60 Hz	50 Hz
Oil pan capacity with filter, L (qt.)	2.5 (2.6)	
Oil pump type	Pressure, trochoid pump	

Operation Requirements

Air Requirements	60 Hz	50 Hz
Engine combustion air requirements, L/min. (cfm)	1132 (40)	934 (33)
Generator cooling requirements, L/min. (cfm)	4814 (170)	3964 (140)
Max. air intake restriction, in. (mm) H_2O	10 (250)	
Exhaust flow, m^3/min. (cfm)	2.5 (88)	2.0 (73)
Exhaust temp., °C (°F) at full load	398 (750)	398 (750)
Max. allowed exhaust back pressure, kPa (mm H_2O)	14.2 (1444)	

Fuel Consumption	60 Hz	50 Hz
Diesel, Lph (gph) at % load		
100%	3.4 (0.9)	2.6 (0.7)
75%	2.6 (0.7)	1.9 (0.5)
50%	1.9 (0.5)	1.5 (0.4)
25%	1.1 (0.3)	1.1 (0.3)

Note: The fuel consumption of the 60 Hz model is based on 9EKOZD and the fuel consumption of the 50 Hz model is based on 7EFKOZD.

Engine Features

- Low oil pressure shutdown
- High engine temperature shutdown
- Low seawater pressure shutdown
- Vibromount
- Belt guard
- Disposable oil filter
- Oil drain valve
- Programmed glow plug circuit for cold starting
- Disposable fuel filter

Alternator Features

- Brushless, rotating field design permits power to be obtained from stationary leads.
- Windings are vacuum impregnated with epoxy varnish for dependability and long life.
- Rotors are dynamically balanced to minimize vibration.
- Copper windings ensure minimal heat buildup. Insulation meets NEMA standards for class H insulation.
- Direct connected to the engine, the generator has sealed precision ball bearings with a precision-machined steel sleeve in the end bracket to prevent shaft misalignment and extend bearing life.
- Mounted on a drip-proof tray.
- Equipped with a four-lead reconnectable stator.

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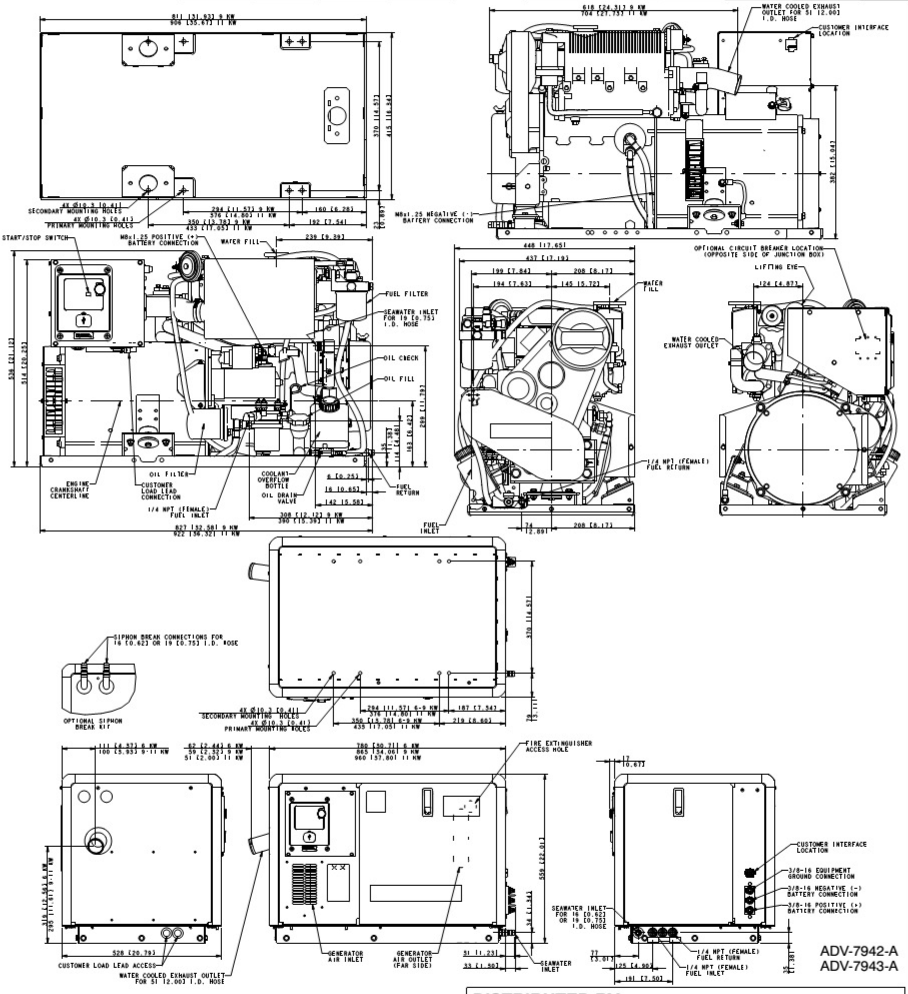
KOHLER.
Power Systems

KOHLER CO., Kohler, Wisconsin 53044 USA
Phone 920-457-4441, Fax 920-459-1646
For the nearest sales and service outlet in the US and Canada, phone 1-800-544-2444
KOHLERPower.com



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NOTE: Dimensions in [ ] are inch equivalents.

NOTE: This drawing is provided for reference only and is not intended for installation planning. Contact your local distributor for more detailed information.

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