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Energy Self-Sufficiency for the Cameroon Protestant College in Bali: feasibility study based on local renewable energies

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Sì come il ferro s'arruginisce sanza esercizio
e l'acqua si putrefà o nel freddo s'addiaccia,
così lo 'ngegno sanza esercizio si guasta.

Leonardo Da Vinci

Niente come tornare in un luogo rimasto immutato
ci fa scoprire quanto siamo cambiati.

Nelson Mandela

Acknowledgment

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Dario e Leonardo

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Nomenclature

Symbol	Description	Unit
Δh_{H2O}	Change in Specific Enthalpy of Water	[kJ/kg]
ρ_{water}	Density of Water	[kg/m^3]
Φ	Hour of Peak Wind Speed	[hr]
σ	Standard Deviation of Wind Speed	[m/s]
δ	Diurnal Pattern Strength	
η	General Efficiency	
η_{3SF}	Thermal efficiency of 3SF	
η_c	Collector Efficiency	
η_{syst}	System Efficiency	
$\eta_{thermal}$	Thermal Efficiency	
a,b	Regression Coefficients for River Flow	
A_{mean}	Average Area	[m^2]
C	Correction Factor	
c	Scale Factor	
c_j	Autocovariance of Wind Velocity at lag j	[m^2/s^2]
CO	Emissions of Carbon Monoxide	[kg/yr]
CO_2	Emissions of Carbon Dioxide	[kg/yr]
LCOE	Levelized Cost of Energy	[$/kWh]
$c_{p_{H2O}}$	Specific Heat of Water	[kJ/kg K]
EHV	Net Calorific Value of Wood	[MJ/kg]
E_{hw}	Energy to Heat Water	[MJ]
E_{ew}	Energy to Evaporate Water	[MJ]
FE	Final Energy	[MJ]
FE_{cook}	Final Energy for Cooking	[MJ]
$FE_{hot\ water\ domestic}$	Final Energy for Domestic Hot Water	[MJ]

Symbol	Description	Unit
$FE_{hot\ water\ public}$	Final Energy for Public Hot Water	[MJ]
FE_{KER}	Final Energy of Kerosene Using Technologies	[GJ]
FE_{LPG}	Final Energy of LPG Using Technologies	[GJ]
FE_{wh}	Final Energy for Hot Water	[MJ]
f_s	Solar Fraction	
$Fuel_{eq\_dry}$	Equivalent Dry Fuel Consumption	[kg]
g	Gravitational Acceleration	[m/s^2]
G	Monthly Sun Irradiation	[MJ/m^2]
H	Gravitational Head	[m]
I_{mean}	Mean Solar Irradiation	[kWh/m^2]
k	shape factor	
LHV	Lower Heating Value	[MJ/kg]
LHV_{biogas}	Lower Heating Value of Biogas	[MJ/m^3]
m,q	Regression Coefficient for wind speed	
MC_{wet}	Moisture Content on Wet Basis	[%]
m_{fuel}	Mass of Fuel	[kg]
m_{H2O}	Mass of Water	[kg]
$N°_{student}$	Number of Students	
NO_x	Emissions of Nitrogen Oxide	[kg/yr]
NPC	Net Present Cost	[$]
oDM	Organic Dry Matter	[%]
PE	Primary Energy	[GJ]
PE_{cook}	Primary Energy for Cooking	[GJ]
PE_{KER}	Primary Energy of Kerosene	[GJ]
PE_{LPG}	Primary Energy of LPG	[GJ]

Symbol	Description	Unit
PE_{wh}	Primary Energy for Hot Water	[GJ]
PE_{wood}	Primary Energy of Wood	[GJ]
P_{gross}	Gross Power	[kW]
PM	Emissions of Particulate Matter	[kg/yr]
P_{net}	Net Power	[kW]
pp	per capita	
$\dot{Q}$	Volumetric Flow Rate	[l/s]
$\dot{Q}_a$	Volumetric Flow Rate of Analogue Catchment	[l/s]
Q_{nov}	Volumetric Flow Rate of November	[l/s]
r,s	Exponential Regression Coefficients	
r_j	Autocorrelation Factor	
SO_2	Emissions of Sulfur Dioxide	[kg/yr]
$SWH_{capacity}$	Solar Water Heating Capacity	[m^2/pp]
T_{amb}	Ambient Temperature	[°C]
T_{boil}	Boiling Temperature	[°C]
T_{cold}	Cold Temperature	[°C]
T_{hot}	Hot Temperature	[°C]
T_{water}	Water Temperature	[°C]
UHC	Emissions of Unburned Hydrocarbon	[kg/yr]
V_{CPC}	Velocity of Wind at CPC	[m/s]
$V_{estimated}$	Estimated Wind Velocity	[m/s]
V_i	Hourly Average Wind Speed	[m/s]
V_m	Effective Mean Velocity	[m/s]
V_{mean}	Mean Velocity	[m/s]
V_{min}	Minimum Volume of Water	[l]
$V_{min, biogas}$	Minimum Volume of Biogas	[Nm^3/day]

Symbol	Description	Unit
$\mathbf{V_{NASA}}$	Wind velocity Measured by NASA	[m/s]
$\mathbf{V_{stud.potential,biogas}}$	Volume of Biogas from Students Waste	[Nm^3]
$\mathbf{V_t}$	Wind Speed at Time Step *t*	[m/s]
$\mathbf{V_{water}}$	Volume of Water	[l]

List of abbreviations

3SF	Three-Stone Fire
AC	Alternating Current
CCU	Cameroonian Catholic University
CFA	Financial Community of Africa (local currency)
LCOE	Levelized Cost of Energy
CPC	Cameroonian Protestant College
DC	Direct Current
EDI	Energy Development Index
FSTC	Food Service Technology Centre
GDP	Gross Domestic Product
HDI	Human Development Index
HOMER	Hybrid Optimization Model for Electric Renewables
ICS	Improved Cooking System
IEA	International Energy Agency
IRES	Integrated Renewable Energy Sources
KS	Kerosene Stove
LP	Linear Programming
LPG	Liquefied Petroleum Gas
MDGs	Millennium Development Goals
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organization
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
PCM	Project Cycle Management
RES	Renewable Energy Sources
RETs	Renewable Energy Technologies

SDGs	Sustainable Development Goals
SDP	Sawdust Pot
SWHS	Solar Water Heating System
UN	United Nations
UV	Ultra Violet
WBT	Water Boiling Test

Abstract

In this thesis the concept of the so-called *Sustainable Energisation* finds a field of application in the rural area represented by the Cameroon Protestant College of Bali, a boarding school in the North-West Region of Cameroon. Given the organization and composition of the college, CPC Bali is treated as a *micro-village*.

The purpose of the thesis is to assess the energy self-sufficiency of CPC, by meeting the increasing energy demand through the exploitation of locally available RES. Three specific goals are identified: energy balance assessment, energy resource assessment and energy solution planning.

The study was conducted in two phases. The first phase was a field survey during which direct measurements and investigations were conducted. The second phase involved desk and laboratory analyses of the results from the on field surveys.

In the energy balance assessment the current energy consumption within public and domestic drivers is investigated. The outcome is that firewood is the major primary source with 423.4 GJ consumed monthly, followed by LPG, diesel and kerosene; electrical energy consumption is 4.8 MWh/month. Thermal losses are huge, due to the poor technologies using firewood.

The resource assessment focuses on biogas, hydro, wind and solar potentials. Corn, animal and human waste are the available matter convertible to biogas through anaerobic digestion with an overall potential of 12088 Nm^3/month. Hydro is assessed in terms of head and stream flow of a river, for 13.2 kW of net power. Wind is measured by means of a cup anemometer; the yearly average speed results 3.3m/s. The annual sun radiation is 1909 kWh/m^2.

The energy solution planning consists in matching local needs and RES. The electrical solution planning is based on HOMER® simulations, reporting 18.3 kW of hydropower as the best solution in two different systems: off-grid and grid-RES hybrid. For the thermal planning, specific solutions are studied to unfold cooking, baking and hot water needs. For cooking and baking, the suggestion is to adopt more efficient stoves. Hot water can be provided by solar collector (0.41 m^2/pp) at domestic level and gas boilers at public level burning 90 Nm^3/day of biogas from students waste and cows manure.

Future scenarios are summarized by two energy flow diagrams in which new primary sources appear: hydro, solar and biogas. Of fundamental importance is the reduction of firewood primary energy supply (40% in the public and 38.6% in the domestic driver). Shifting from firewood and fossil fuel dependence towards diversified RES based supply is an extremely relevant enabler for the final goal of this thesis.

Keywords: Sustainable Energization, Rural Energy Balance, Rural Energy Planning, Rural Micro-Village, Grid-RES Hybrid System, Off-Grid System

Sommario

In questa tesi il concetto della c.d. *Energizzazione Sostenibile* trova campo di applicazione nel contesto rurale del Cameroon Protestant College di Bali, nel Nord Ovest del Cameroon. Considerata l'organizzazione e la composizione del campus, il CPC Bali è trattato come un *micro-villaggio*.

Lo scopo della tesi è valutare l'auto-sufficienza energetica del CPC, in modo da soddisfare la crescente domanda energetica attraverso lo sfruttamento delle fonti rinnovabili disponibili in loco. Tre sono gli obiettivi specifici individuati: valutazione del bilancio energetico, valutazione delle fonti rinnovabili e pianificazione energetica.

Il lavoro di ricerca è stato condotto in due fasi. La prima ha riguardato uno studio sul campo, in cui è stata svolta un'attenta indagine dell'ambiente sociale e fisico tramite sondaggi e misure dirette. La seconda fase ha riguardato un'analisi di laboratorio dei risultati acquisiti sul campo.

Nella valutazione del bilancio energetico è stato studiato l'attuale consumo energetico nel settore pubblico e privato. Il bilancio energetico complessivo mostra che il legname è la maggiore risorsa primaria con un consumo mensile di 423,4 GJ, seguito da GPL, diesel e cherosene; il consumo elettrico ammonta a 4,8 MWh/mese. Le perdite termiche sono ingenti in ragione della scarsa efficienza dei sistemi di conversione che bruciano legna.

Nel valutare le risorse l'attenzione si è focalizzata sui potenziali di biogas e di risorse idrica, eolica e solare. Mais, letame e liquami umani rappresentano la materia prima convertibile in biogas attraverso una digestione anaerobica con un potenziale complessivo di 12'088 Nm^3/mese di biogas. Il potenziale idrico è stato valutato in termini di prevalenza e portata disponibile, per una potenza netta complessiva di 13,2 kW. Il potenziale eolico è stato misurato grazie a un anemometro; la velocità media annuale risulta di 3,3 m/s. L'irraggiamento annuale è di 1'909 kWh/m^2.

La conseguente pianificazione energetica consiste nel soddisfare i fabbisogni con le fonti rinnovabili locali. In particolare, quella elettrica si basa sull'utilizzo di HOMER®, le cui simulazioni riportano 18,3 kW di micro-idro come miglior soluzione in due diversi schemi: off-grid e ibrido. Per quella termica sono studiate soluzioni specifiche per soddisfare i bisogni di cottura dei cibi e acqua calda. Nello specifico, per la cottura dei cibi, è suggerita l'adozione di sistemi di conversione più efficienti rispetto agli attuali. L'acqua sanitaria

può essere invece fornita da collettori solari (0,41 m^2/pp) a livello domestico e caldaie a biogas a livello pubblico, che bruciano 90 Nm^3/giorno di biogas digesto a partire da liquami degli studenti o da letame bovino.
Gli scenari futuri sono riassunti in due diagrammi di Sankey nel quale appaiono tre nuove risorse: idrica, solare e biogas. Di fondamentale importanza è la riduzione nel consumo primario di legname (40% nel settore pubblico e 38,6% nel privato) che ne può derivare. Il passaggio da una dipendenza basata sul consumo di legna e combustibili fossili ad una fornitura diversificata, basata su fonti rinnovabili, funge da catalizzatore di estrema rilevanza per il fine ultimo di questa tesi.

Parole chiave: Energizzazione Sostenibile, Valutazione del bilancio energetico, Pianificazione energetica rurale, Micro-villaggio rurale, Grid-RES sistema ibrido, Sistema off-grid

Executive summary

The availability of energy is a necessary pre-requisite to enable development, although it should be regarded as a tool for people to achieve improved living conditions. The worldwide consensus on the urgent action to be taken to face such issue has been indirectly addressed by the United Nations in the redaction of the Millennium Development Goals (MDGs) as initial step. Recently, MDGs have been revised and updated to the Sustainable Development Goals (SDGs) in which a proper statement on energy has been inserted. In fact, the seventh goal establishes to "*Ensure access to affordable, reliable, sustainable and modern energy for all"*, implying the enabling of a true sustainable development.

The concept of energy access could be translated into the theme of energisation. Energisation can be considered as the supply and planning of complete energy solutions to meet electrical and thermal demand, focusing on the short-term improvement of rural communities. Nevertheless, the concept of sustainable development has to be associated to that of energisation in order to highlight relevant features of energy services: diversified nature; accessibility and affordability; enhanced quality, quantity and variety to choose from. A further relevant aspect within the concept of energisation is the matching between needs and local resources. The satisfaction of the energy request of a confined area with its own peculiarities through what is available in site is fundamental and strongly beneficial for end users. In addition, ad-hoc solutions usually accomplish the task of covering the energy demand in a better manner than standardized procedures, since they aim at maximizing the system efficiency while minimizing costs, while accounting for social and cultural context. With this approach, the role of principal actors is played by renewable energy sources (RES). RES can be considered as the default selection for off-grids application, especially in developing countries where transmission and distribution grids, as well as firewood represent a serious limitation to a reliable and clean energy supply, respectively.

The issue of energisation finds particular relevance in Africa, as expressed by the extremely low value of the Energy Development Index (EDI) of its countries. This index summarizes the level of energy access. The ranking lists all developing countries according to their EDI (from 0 to 1) and the highest value in the Sub-Saharan region is 0.23. In this context, Cameroon is found with an EDI of 0.13. Access to electricity in Cameroon reaches 54% rate, with a deep discrepancy between urban (88%) and rural (17%) areas, while for what concerns the use of traditional biomass as cooking fuel, the share is 75% among the whole population. These values show the urgent and imminent need of *Sustainable Energisation* in the Country, focusing the attention on rural areas where the exploitation of indigenous sources is likely to create a desirable synergy between population and renewable energy technologies (RETs).

The present thesis is aligned with the perspective of rural areas energisation in developing countries, where the largest portion of population affected by a lack or a remarkably unreliable supply of energy is concentrated, by applying a need-resource matching approach. The rural area of interest is represented by the Cameroon Protestant College (CPC) in Bali, situated in the North-West Region of Cameroon. The school is part and under the formal administrative competence of the Protestant Church in Cameroon. It is a private boarding school offering secondary and high education to 1008 students. The school environment is composed by dormitories, classrooms, laboratories, administrative offices, dispensary, church, library, refectory, kitchen, bakery, canteen, furniture repair workshop and sport facilities. The school population is enriched by the presence of the personnel and related families living inside the campus in 47 households for a total of 179 people. From the energy point of view, the school is supplied with electricity by the national utility grid AES-SONEL. The thermal energy supply is composed mainly by firewood, LPG and kerosene. Fresh water for all purposes is taken from a stream running at approximately 3 km from the school. Three biogas systems are present in the campus. Their function is the disposal of student toilet waste producing biogas; unfortunately, only one of the system is working without a proper exploitation of the obtained biogas. Given the organization and composition of the college campus it is unequivocally simple to recognize services such as education, healthcare, craftsmanship and "public" administration. Indeed, they represent the characterizing features of an independent organization at economic, social and environmental level. Therefore, under the circumstances of this work, CPC Bali is treated as a *micro-village*.

The purpose of this thesis is to assess the energy self-sufficiency of the CPC. The study was conducted at a pre-feasibility level. The general objective of this work is the improvement of energy access of CPC Bali, by meeting the increasing energy demand through the exploitation of locally available RES. It would enhance the current school facilities and favour the long-term sustainable development of the rural area. In order to attain this task, three specific objectives have been derived:

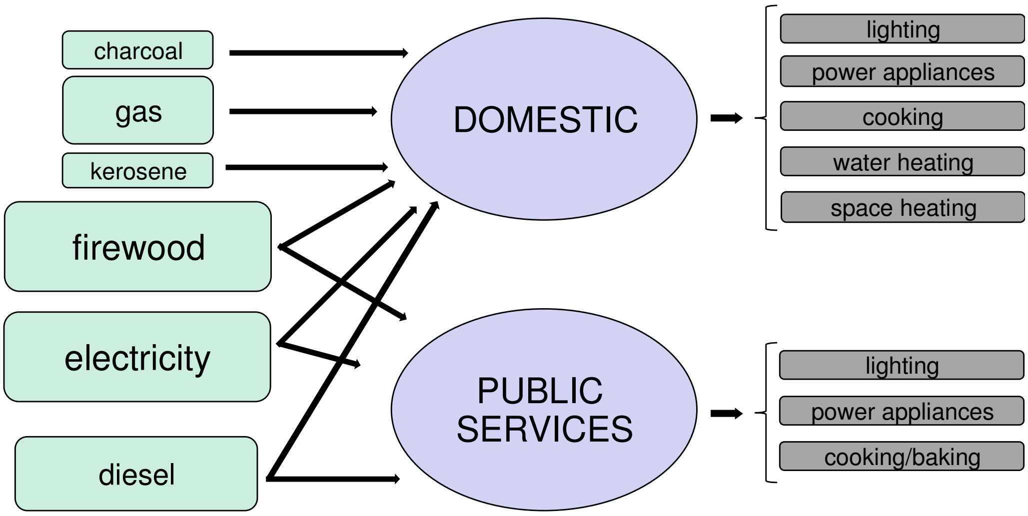
I. Assessment of the current consumption pattern through a comprehensive energy balance of CPC Bali, specifying sources, drivers and energy uses;
II. Assessment of the technical potential of the presently available renewable sources in site, focusing on biogas, hydro, wind and solar;
III. Energy solution planning through need-resource matching approach, identifying the most suitable combination of RETs to meet the electric and thermal demand according to the social and cultural context while drawing future scenarios of energy consumption.

The analyses to achieve the three specific objectives were conducted in two periods. The first period was spent in field at CPC Bali for three months. During the stay in Cameroon, main activities were to get to know the place subject of the study and collect all necessary primary data for the purpose of the work. Through a deep investigation of the social and physical environment, it was possible to recognize habits on energy consumption, technologies used at domestic and public level, local energy needs, presence and potential of RES. The research was carried out by means of surveys, observations, questionnaire, direct measurements, tests and interviews with local people. At the end of this period, a phase of revision and refining of collected data was needed in order to accomplish the first and second objective of the thesis. The second period was spent at Politecnico di Milano for desktop and laboratory analysis. First, a careful study and analysis of data concerning the energy consumption and the RES potential was done. Subsequently, the question of how the locally available sources could meet and satisfy the current demand was investigated through the energy solution planning. The matching of local needs and resources represents the driving force and the criterion for the energy planning phase.

The thesis is structured in five chapters. The first chapter is the introduction of the thesis. In the second chapter all the methods to achieve the specific objectives of the thesis are described. Then, the results of the energy balance assessment (*specific objective I*) and resource assessment (*specific objective II*) are presented in the third chapter. In the fourth chapter the results of the energy planning (*specific objective III*) are shown. Eventually, conclusions are drawn in the fifth chapter. In this executive summary, methods and results are summarized together according to the different objectives, in order to give a straightforward view of the work to the reader.

I. Energy balance assessment

The energy balance assessment consisted on first identifying the rural energy system of CPC Bali, which represents the boundary of the analysis, in terms of primary energy sources, energy drivers and final uses of energy, adopting the approach proposed in Johnson (2012). The scheme below gives the framework of CPC current energy system:



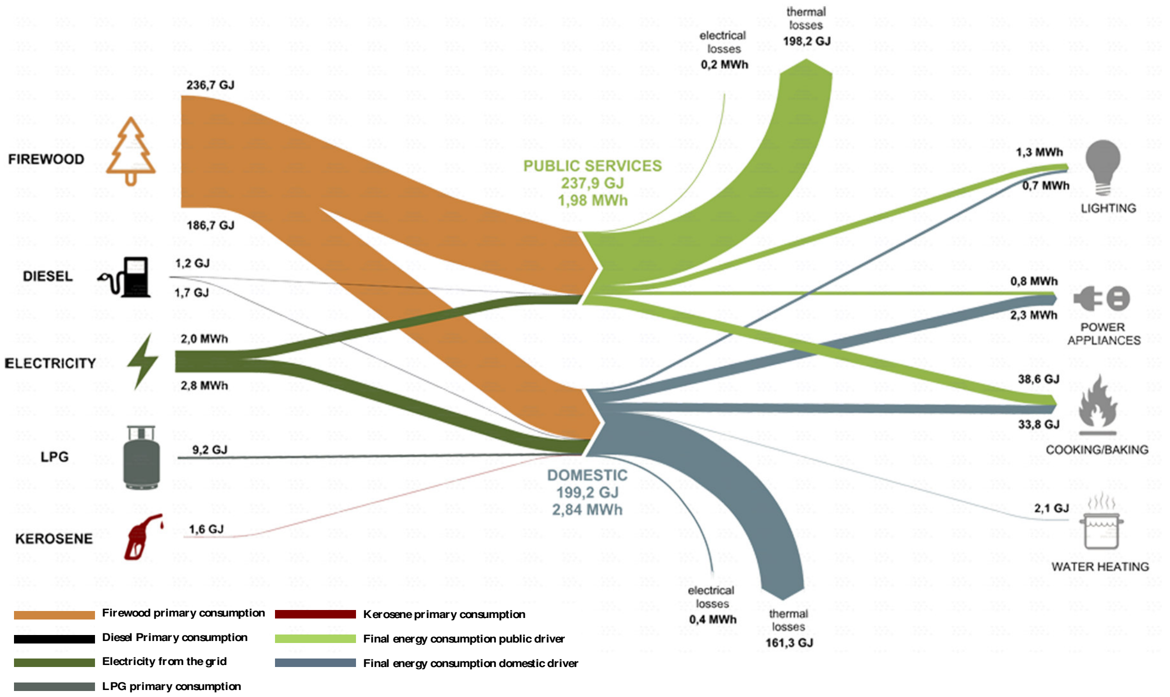
CPC Bali energy system

The energy sources currently exploited are charcoal, gas, kerosene, firewood, electricity and diesel. These sources are consumed by two energy drivers: domestic and public. For each energy drivers, final uses of energy can be distinguished. For every energy use, a specific technology undertakes the conversion from primary to secondary source of energy, as thermal or electrical energy. All the conversion processes occurring outside the campus were not taken into account and all the energy sources going into the system from outside were considered primary sources. For instance, electricity, provided to the campus by the national utility grid, is considered at the same level of other primary energy sources being all the conversions occurring outside the system boundary. During the period abroad, activities were conducted in order to quantify the consumption of primary and final source of energy within the two energy drivers.

The energy consumption patterns at domestic level were assessed by means of a questionnaire. It was administered in the form of peer-to-peer interview. The questionnaire (fully reported in Appendix A) included six sections: *general information*, *electricity use and supply*, *firewood use and supply*, *gas use and supply*, *other sources of energy and domestic waste production*. The main outcomes of the questionnaire were power consumption at domestic level shared by lighting and powering appliances, consumption of primary and final energy for cooking and water heating.

The energy balance assessment of the public driver was more encompassing than the domestic as the activities were many. Electricity was analysed through observations. The final power consumption was obtained as the share between the final uses, lighting and powering appliances respectively. For this purpose, the central meter of CPC was monitored in order to obtain the load profile of the campus and the power consumption and to confirm the validity of the findings of previous analyses. The data to build the real load curve were gathered through daily observation of the central meter. In particular, a smartphone was used to snapshot the reading of the meter and to record the data for a total duration of 5 days. Then, the data were elaborated with an Excel spreadsheet. Thermal energy needs were assessed through direct measurements of wood in the kitchen and bakery of CPC. Moreover, the efficiency of the improved cooking stoves of the kitchen was investigated by applying a Water Boiling Test (WBT).

Based on the results obtained from the energy balance assessment, a Sankey diagram was built on the model of the International Energy Agency (IEA), displaying the most important features of the energy consumption. Among the primary sources, firewood is the predominant with 423.4 GJ monthly consumed, followed by LPG (9.2 GJ), diesel (2.9 GJ) and kerosene (1.6 GJ). The electricity consumption is 4.8 MWh per month. Apart from kerosene and LPG consumed only at domestic level, the other sources are split amongst both energy drivers. The public driver consumes more primary energy (237.9 GJ) but less electricity (1.98 MWh) than the domestic driver (199.2 GJ, 2.84 MWh). The monthly consumption per capita of primary energy is 0.37 GJ/pp while electricity consumption is 4 kWh/pp. The final electric consumption is shared between lighting and power appliances uses: the former is greater in the public driver, while the latter in the domestic. The final uses of energy for cooking is larger in the domestic driver. Finally, water heating is only a domestic need. Visibly, thermal losses are huge, mostly due to the poor technologies that used firewood, as three stones fire and local stoves, characterized by low conversion efficiencies. The electrical losses are only those referred to the diesel generator providing electricity during period of power shortages, since grid losses are not quantified in this analysis. The current energy flow of CPC is shown herein below.



Energy flow diagram of CPC Bali

II. Renewable energy resource (RES) assessment

Biogas

In the analysis of biogas potential, the sources convertible to biogas considered were corn waste, human and animal waste. The strategy was to quantify the theoretical increment to the actual biogas production, which was assessed by taking periodically readings from the meter installed in the campus and resulted to be 295.2 Nm^3/month. The biogas potentially coming from corn waste was assessed considering the tonnes of corns produced on a monthly basis resulted from the questionnaire administrated at domestic level and the average quantity that could be extract from a fixed amount of harvested products. The biogas potential from animal waste was assessed in relation with average yield per tonnes of dry matter of animal dung. The mass of manure produced from animals was also assessed in the questionnaire within the *domestic waste production* section. A similar approach was followed for human waste, considering a different average daily production of faeces and urines, dry organic matter and biogas yield. The results are summarized in the table herein.

	Nm^3/month	GJ/month
Corn	9960	291.8
Animal waste	1225	35.9
Human waste	903	26.5
Total	12088	354.2

Potential of biogas from corn, animal and human waste

Hydro

Hydro potential was assessed in terms of water flow and head of the river. The river flow rate was evaluated on the field by applying the Floating Object Test in October and November. Then the results were extended to the whole year by regressing the short records against the known flows of a gauged river (Mewou) by overlapping the period and then predicting a relationship between the two-flow series. Half of the minimum flow rate, 54.4 l/s, occurring in March, was taken as maximum flow rate for future exploitations, in order to guarantee an acceptable residual flow rate. The head was assessed by means of an altimeter. After having identified possible locations for water catchment and power room, those spots were located on Google Earth computing the height (55 m) as well as the land distance between the two spots (1 km). With these values of river flow rate and head, a micro hydro scheme with an overall efficiency of 45% would produce a net power of 13.21 kW. Thus, considering a capacity factor of 70%, it meant an annual energy production of 81 MWh or 6.8 MWh per month.

Wind

The potential of the wind blowing in the study area was assessed by means of direct measurements taken by a cup anemometer placed at height of approximately 11 metres. Data collected included wind speed, direction, temperature and pressure for every minute, for seven months. In order to outline a thorough wind regime considering also seasonal and yearly fluctuations, a linear and exponential regression was applied taking the data of the NASA referred to the city of Bamenda, as reference values. The trend of the wind speed was then scaled along the year. The main parameters are reported in the table below.

Average wind speed	3.297 m/s
Standard deviation	1.865 m/s
Hour of peak wind speed	14
Diurnal pattern strength	0.329

Main parameters of wind source

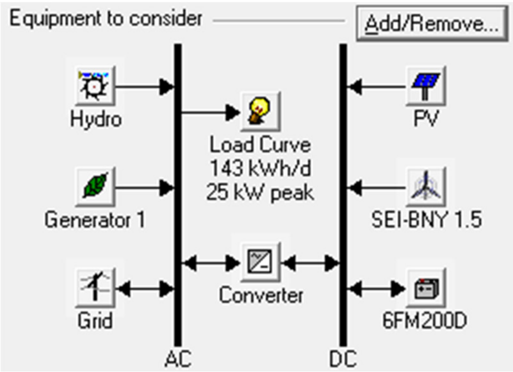
The frequency distribution of the wind speed was built, showing similarity with a Weibull distribution considering shape factor of 1.850 and scale factor of 3.713. Finally, to estimate the wind potential in terms of energy production, first the power per unit swept area was found equal to 11.25 W/m^2 [1]. Then, considering a capacity factor of 7%, it meant an annual energy production of 6.9 kWh/m^2, or 0.575 kWh/m^2 in a month.

Solar

The last RES studied in the research was the solar energy. Since the on field study was performed during a time window coincident with the rainy seasons and considering also the absence of adequate measuring instruments, direct measurements of the sun irradiation were impossible to take. Therefore, the potential of solar energy was estimated only through literature research. Due to the proximity to city of Bamenda, data of average monthly irradiation concerning this place was taken as reference. The data taken from the NASA and solar map provided by SolarGIS® suggested an annual sun radiation of 1908.84 kWh/m^2 with daily average on yearly basis of 5.23 kWh/m^2/day.

III. Energy solution planning

The energy solution planning consists in matching local needs and RES with the installation of alternative technologies or modifying the current energy asset of the system. Since electrical and thermal demands are rather different, they are investigated separately. The electrical solution planning was based on the use of HOMER®, a software that simulates and optimizes off-grids or hybrid micro power systems finding the most techno-economically feasible configuration according to the lowest Net Present Cost (NPC). Thus, the modelling of CPC Bali consisted in the RETs shown herein. The input parameters were taken from surveys at local level, literature review and market research. Both off-grid and hybrid RES-based systems were simulated.



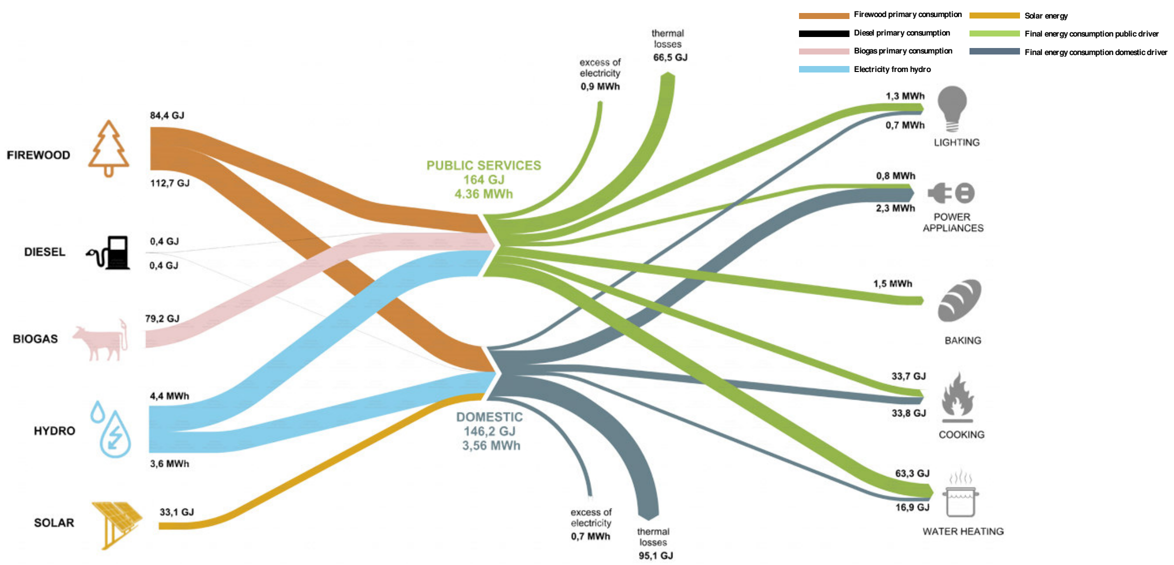
Structure of CPC energy system through HOMER®

The results reports hydropower as the best solution in the two different systems. In the case of off-grid application, the nominal power amounts to 15kW with 20 Vision batteries and back-up diesel generator as support, for 0.178 $/kWh as levelized cost of energy (LCOE), approximately equal to the actual electricity unit price of 0.17 $/kWh, and 163088 $ as NPC. The optimized hybrid solution includes a smaller cross-flow water turbine (8.33kW rated power), with 27% of annual electricity purchased from the grid. The comparison with the off-grid configuration show lower NPC (132791 $) and LCOE (0.123 $/kWh). Sensitivity analyses on capital costs of water turbine, PV panels and wind turbine assess the convenience of the first RET, while the exclusion of the other technologies even in case of 90% investment reduction. Sensitivity analyses on diesel and electricity unit price proved the solution robustness.

For the thermal solution planning specific solutions were studied upon unfolding cooking, baking and water heating needs. It is worth stating that cooking and baking were considered satisfied need both at public and domestic level. Thus, the aim was to reduce the primary energy consumption adopting more efficient cooking stoves, in particular the 40% efficient ASTRA stove for public and the 30% efficient Envirofit G3300 for domestic. For what concerns the bakery firewood oven, a replacement with the electric oven Moffat E32D5 was proposed. The strategy adopted was to simulate again with HOMER® the two configurations, increasing the load demand by the power consumption of the oven (6.3 kW) between morning and evening peaks, filling the load "valley". The outcome is meaningful since hydropower remains the best solution with a rated power of 18.3kW, slightly increased, equal for off-grid and hybrid systems. Thus, the hybrid solution could be regarded as a first step towards a purely autonomous power system. If cooking was at an acceptable level, water heating represents an unmet need. Therefore, the thermal analysis is completed with ad-hoc solutions in order to provide hot water to students (20lt/day/capita) and personnel with families (30lt/day/capita). In the public sector, the biogas might be fired through a boiler to produce hot water. However, this solution covers only 11% of the thermal request, clearly needing an additional quantity of biogas likely to be supplied by fully exploiting the available human potential and cows to be bought or corn wastes from farms. A different approach might be the application of solar water heating system with a total surface 216.6 m^2 needed, an extremely large extension. At domestic level, water heating could be satisfied with 0.41 m^2 per person thermal solar collectors.

Eventually, the electricity and thermal solution planning are summarized in future scenario energy flow diagram reporting the key aspects for the achievement of the CPC Bali energy self-sufficiency. Compared to the first diagram, three new primary sources appear: hydro, solar and biogas. Diesel remains only as back-up support but its consumption is negligible. Of fundamental importance is the reduction of firewood primary energy supply (40% in the public driver and 38.6% in the domestic driver). The shifting from a firewood and fossil fuel dependence towards a diversified and RES based supply is an extremely relevant enabler for the ultimate goal of this thesis. The energy end uses show enhanced level of supply and newly met needs.

Upon completing this pre-feasibility study, it could be affirmed that the energy self-sufficiency of CPC Bali could be attended. This implies that a truly sustainable development could be reached under the economic, social and environmental points of view in case a long-term perspective is adopted. The definition of *Sustainable Energisation* might find its complete fulfilment in this context. Due to the natural resources locally available and the disposition of the social tissue welcoming the presence of RETs, the improvement of the current energy supply and use levels is possible and desirable, with a setting towards the future. After considering the various approach for the CPC to be energy self-sufficient, the energy flow diagram was revisited and revised to show the resulting flow as shown herein below.



Future energy flow for off-grid system including thermal solutions

Riassunto Esteso

L’accesso all’energia è un pre-requisito necessario per consentire lo sviluppo, nonostante debba essere considerato solo come uno strumento per le persone al fine di raggiungere uno standard di vita più elevato. Il consenso a livello mondiale sull’urgente bisogno di azione per risolvere tale situazione è stato tradotto dalle Nazioni Unite con la redazione dei Millenium Development Goals (MDGs), che solo in maniera indiretta hanno toccato la problematica energetica. Infatti, recentemente sono stati aggiornati e superati dai Sustainable Development Goals (SDGs) in cui è stata fatta un’asserzione diretta sul tema energetico. A questo proposito il settimo obiettivo stabilisce di “*Assicurare un accesso all’energia per tutti che sia affidabile, sostenibile e moderno*”, che conduca implicitamente a un vero sviluppo sostenibile.

Il concetto di accesso all’energia rientra nel tema della cosiddetta energizzazione, ovvero la fornitura e la pianificazione di soluzioni energetiche complete per venire incontro alle domande elettrica e termica delle comunità rurali, in termini di miglioramento nel breve periodo. Tuttavia, risulta necessario associare il concetto di sviluppo sostenibile a quello di energizzazione in modo da evidenziare caratteristiche rilevanti ai fini della fornitura di servizi energetici: natura diversificata; accessibilità e costo contenuto; qualità, quantità e varietà di scelta migliorate. Un aspetto fondamentale nel quadro dell’energizzazione è la soddisfazione dei bisogni tramite lo sfruttamento di risorse presenti a livello locale, con il conseguente tangibile beneficio per gli utenti finali. Inoltre, va sottolineato come soluzioni *ad-hoc* sono in grado di coprire la richiesta energetica in maniera migliore e più precisa rispetto a sistemi standardizzati, poiché mirano a massimizzare l’efficienza del sistema stesso minimizzando i costi associati, racchiudendo nel proprio orizzonte il contesto socio-culturale d’implementazione. In questo approccio il ruolo fondamentale viene ricoperto dalle fonti rinnovabili, che si stanno affermando sempre maggiormente come la scelta di default per applicazioni off-grid. Ciò è particolarmente vero nei Paesi in Via di Sviluppo (PVS), in cui le reti di trasmissione e distribuzione da un lato, il legname dall’altro pongono seri limiti a una fornitura rispettivamente affidabile e pulita.

La problematica dell'energizzazione dei PVS trova rilevanza particolare nel contesto africano, come viene suggerito dai valori estremamente bassi dell'Indice di Sviluppo Energetico (EDI) dei Paesi ivi presenti. Tale indice riassume il livello di accesso all'energia di una stato. La classifica riporta una lista di tutti i PSV del mondo con valori di EDI (da 0 a 1), con il valore più alto di un Paese dell'Africa sub-sahariana pari a 0,23. Fra questi Paesi non si differenzia il Cameroon che è presente con EDI di 0,13. Il livello di elettrificazione è del 54%, con una netta discrepanza tra aree urbane (88%) e zone rurali (17%); per quanto concerne l'uso di biomassa tradizionale per fini domestici la diffusione raggiunge un tasso del 75% su tutto il territorio nazionale. I valori qui presentati evidenziano un bisogno urgente e imminente di *Energizzazione Sostenibile* in Cameroon, con particolare riferimento alle aree rurali in cui lo sfruttamento delle risorse indigene non può che creare una sinergia desiderata tra la popolazione locale e l'adozione di tecnologie energetiche rinnovabili.

La presente tesi si allinea con l'illustrata prospettiva di energizzazione delle aree rurali in PVS, in cui la maggioranza della popolazione soffre di una mancanza totale o parziale di fornitura energetica, attraverso l'implementazione di un approccio mirato a soddisfare i bisogni con le risorse disponibili in loco. L'area di interesse è rappresentata dal Cameroon Protestant College (CPC) di Bali, situato nella regione Nord-Occidentale del Cameroon. La scuola è parte e sotto la formale giurisdizione della Chiesa Protestante camerunense. È un convitto e collegio privato che offre istruzione secondaria e superiore a 1'008 studenti, secondo il modello di istruzione britannico. L'ambiente scolastico è composto da dormitori, aule, laboratori, uffici amministrativi, infermeria, chiesa, biblioteca, refettorio, cucina, panetteria, bottega, officina per riparazioni e campi sportivi. Il contesto è arricchito dalla presenza del personale scolastico e dalle relative famiglie che vivono in 47 abitazioni, per un totale di 179 persone. Dal punto di vista energetico, la scuola è collegata alla rete di distribuzione elettrica gestita dall'ente monopolista nazionale AES-SONEL. La fornitura di energia termica è invece soddisfatta da legna, GPL e cherosene. L'acqua corrente, utilizzata per tutti i fini, è disponibile grazie a un torrente che scorre a circa 3 km di distanza al di fuori delle mura che delimitano la proprietà del collegio. Ai fini della presente analisi, è da notare la presenza di tre sistemi biogas, adibiti alla digestione di feci e urine degli studenti; purtroppo, al momento solo un sistema è in funzione senza però uno sfruttamento appropriato del biogas prodotto. Data la composizione e la struttura della scuola è inequivocabile che il riconoscimento di servizi come educazione, sanità, artigianato e amministrazione pubblica consenta di considerare il CPC Bali nell'ambito di questo lavoro un *micro-villaggio* a tutti gli effetti. Concretamente, essi rappresentano gli elementi caratterizzanti un'organizzazione indipendente dal punto di vista economico, sociale e ambientale.

Scopo del presente lavoro è stabilire l'autosufficienza energetica del CPC al fine di realizzare un'analisi di pre-fattibilità. Obiettivo generale della tesi è quello di migliorare l'accesso all'energia del sistema in studio, coprendo la crescente domanda attraverso lo sfruttamento di risorse rinnovabili indigene. Ciò permetterebbe un innalzamento del livello delle strutture scolastiche favorendo lo sviluppo sostenibile della zona rurale di interesse, nell'ottica di Energizzazione Sostenibile. A tal fine sono stati stabiliti tre obiettivi specifici:

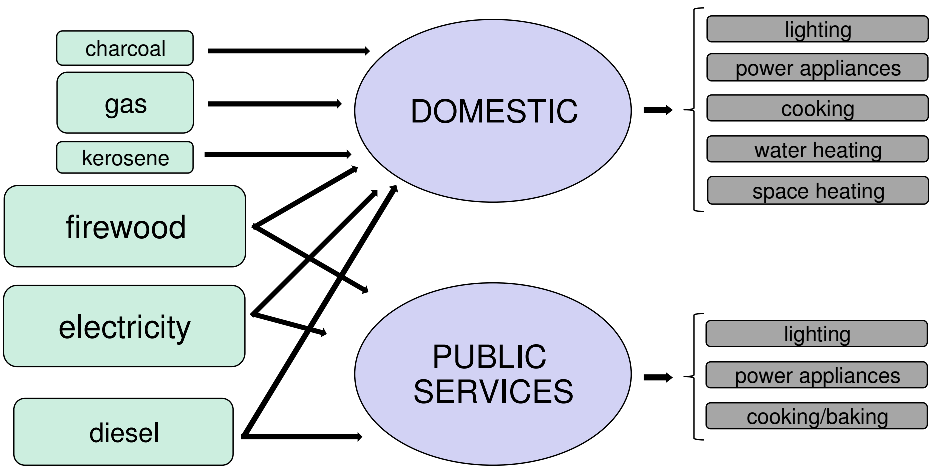
I. Valutazione dei consumi energetici attuali del CPC Bali, specificando risorse, settori e utilizzi finali;
II. Stima del potenziale tecnico delle fonti rinnovabili presenti, focalizzata su biogas, idrico, eolico e solare;
III. Pianificazione energetica tramite un approccio che soddisfi la domanda con le risorse locali, identificando la miglior combinazione di tecnologie per coprire le domande elettrica e termica, nel rispetto del contesto socio-culturale nonché delineando possibili scenari futuri.

L'analisi per il raggiungimento dei tre obiettivi qui riportati è stata condotta in due momenti differenti. Nel primo periodo è stato svolto uno studio sul campo per tre mesi. Durante la permanenza presso il CPC Bali sono state svolte attività di conoscenza approfondita del contesto e rilevamento di tutti i dati necessari. Attraverso un'attenta indagine dell'ambiente sociale e fisico è stato possibile discernere abitudini sui consumi energetici, bisogni locali, tecnologie utilizzate a livello domestico e pubblico, nonché rilevare e misurare il potenziale delle fonti rinnovabili. La ricerca è stata condotta tramite sondaggi, osservazioni, questionari, misure dirette, test e interviste. A conclusione della prima fase si è proceduto ad una revisione dei dati raccolti onde concludere i primi due obiettivi specifici prefissati. Durante il secondo periodo è stato svolto un lavoro di laboratorio presso il Politecnico di Milano. Dapprima è stata elaborata un'analisi accurata dei dati sul consumo elettrico e il potenziale delle fonti rinnovabili. In seconda istanza è stata risolta la questione di come le risorse disponibili nell'area di studio potessero soddisfare la domanda energetica, in riferimento al terzo obiettivo specifico.

La tesi si struttura in cinque capitoli. Il primo è di introduzione ai temi di accesso all'energia e all'area di studio. Il secondo descrive la metodologia adottata per raggiungere gli obiettivi. Nel terzo sono riportati i risultati inerenti la valutazione dei consumi energetici (I obiettivo specifico) e la stima del potenziale delle fonti rinnovabili (II obiettivo specifico). Nel quarto sono mostrati i risultati relativi alla pianificazione energetica (III obiettivo specifico). Il quinto include le conclusioni dell'intero lavoro. Nel presente riassunto esteso, metodi e risultati sono combinati a seconda dei vari obiettivi specifici, in modo da fornire al lettore una visione completa del lavoro in maniera sintetica.

I. Valutazione consumi energetici

La valutazione del bilancio energetico consiste nell'identificare il sistema rurale del CPC Bali, il quale rappresenta il campo di studio dell'analisi, in termini di fonti primarie, settori energetici e utilizzi finali. A tale scopo è stato adottato l'approccio proposto da Johnson (2012). Lo schema sotto riportato presenta la struttura del sistema energico del CPC Bali:



Sistema energetico del CPC Bali

Le fonti energetiche attualmente utilizzate sono carbone, gas, cherosene, legname, elettricità e diesel che vengono sfruttate in due settori: domestico e pubblico. Per ogni settore energetico possono essere distinti degli utilizzi finali, per ognuno dei quali è adottata una specifica tecnologia per le conversione da sorgente primaria a finale, come termica o elettrica. Tutte le conversioni che avvengono fuori del CPC non sono state prese in considerazione e tutte le risorse entranti nel sistema sono state considerate come fonti primarie. Per esempio, l'elettricità, che è fornita al campus tramite la rete di distribuzione nazionale, è stata trattata al pari di altri fonti primarie. Durante il periodo sul campo, come già detto, sono state condotte molteplici attività al fine di quantificare il consumo primario e finale di energia.

I fabbisogni energetici a livello domestico sono stati valutati tramite un questionario somministrato in forma di intervista personale. Il questionario (interamente riportato nell' Appendice A) è composto da sei sezioni: *informazioni generali, uso e fornitura di elettricità, uso e fornitura di legname, uso e fornitura di gas, altre fonti* e *produzione di residui domestici.* Il consumo di potenza a livello domestico diviso tra illuminazione e dispositivi e il consumo primario e finale per la cottura di cibi e la fornitura di acqua sanitaria rappresentano i risultati principali del questionario.

La valutazione del fabbisogno energetico per il settore pubblico ha compreso un maggior numero di attività rispetto al settore domestico. Il consumo elettrico è stato analizzato tramite osservazioni dirette che hanno permesso di stimare il consumo ripartito tra gli utilizzi finali, ovvero illuminazione e dispositivi di potenza. A tale proposito il contatore elettrico centrale del CPC è stato monitorato al fine di ottenere la curva di carico giornaliera dell'intero sistema considerato, confermando la validità dei dati raccolti. I valori sono stati ottenuti tramite uno smartphone posto su un apposito supporto che scattava uno foto ogni 10 secondi per la durata complessiva di 5 giorni in due diversi mesi (settembre e ottobre). Successivamente, i dati sono stati elaborati su un foglio di lavoro Excel. Il fabbisogno termico è stato ricavato tramite misure dirette della quantità di legna consumate nei forni migliorati della cucina e del forno nella panetteria. Inoltre, l'efficienza dei forni migliorati è stata misurata tramite l'applicazione del Water Boiling Test (WBT).

In riferimento ai risultati ottenuti è stato costruito un bilancio energetico totale sul modello fornito dalla Agenzia Internazionale per l'Energia (IEA), mostrando le caratteristiche più importanti del sistema energetico. Tra le fonti primarie il legname è predominante con 423,4 GJ consumati mensilmente, seguito da GPL (9,2 GJ), diesel (2,9 GJ) e cherosene (1,6 GJ). Il consumo elettrico ammonta a 4,8 MWh al mese. Ad eccezione di GPL e cherosene utilizzati solo a livello domestico, le fonti vengono condivise da entrambi i settori. Il settore pubblico consuma più energia primaria (237,9 GJ), ma meno elettricità (1,98 MWh) del settore domestico (199,2 GJ, 2,84 MWh). Il fabbisogno energetico mensile pro capite di fonti primarie è di 0,37 GJ, mentre quello elettrico è di 4 kWh. Il consumo finale elettrico è diviso tra illuminazione e dispositivi: il primo uso è maggiore nel settore pubblico, mentre il secondo nel privato. L'utilizzo finale per cucinare è maggiore nel settore domestico, per il quale si registra l'unica presenza di bisogno di acqua sanitaria. Dal grafico riportato si evidenziano ingenti perdite termiche, principalmente causate dalle basse efficienze di conversione dei forni (a legna). Le perdite elettriche sono di entità molto minore e si riferiscono solamente al generatore diesel, mentre quelle relative alla linea di distribuzione interna al campus scolastico non sono state valutate. L'attuale bilancio energetico del CPC è rappresentato nel diagramma di Sankey:

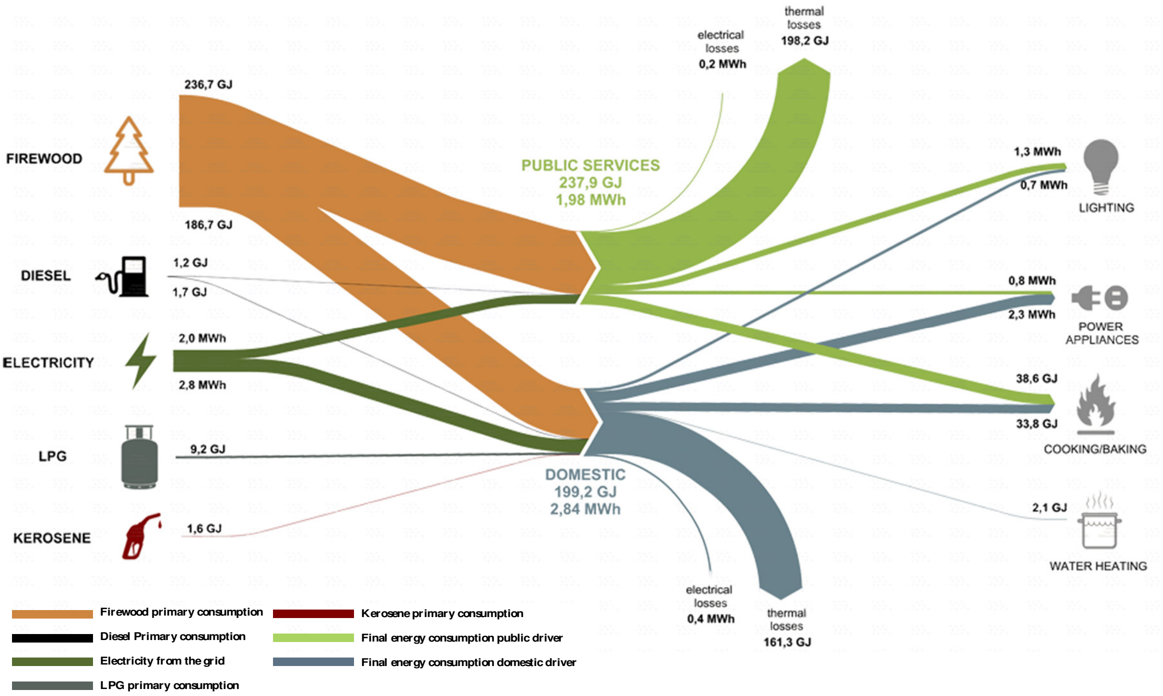


Diagramma di flusso energetico del CPC Bali

II. Stima potenziale delle fonti rinnovabili

Biogas

Nell'analisi del potenziale del biogas sono state prese in considerazioni fonti convertibili a biogas, tra cui mais, reflui umani e animali. La strategia è stata quella di quantificare l'incremento teorico rispetto all'attuale produzione di gas digesto, rilevata tramite letture periodiche del contatore installato nel sistema in loco, che ha mostrato una produzione mensile di 295,2 Nm^3. Il potenziale relativo agli scarti del mais è stato valutato con riferimento alle tonnellate di prodotto disponibili su base mensile, come risulta dal questionario, di cui una determinata quantità può essere utilizzata. Relativamente ai residui animali, il potenziale è stato derivato dalla loro digestione a partire da materia solida prodotta, anch'essa investigata con il questionario. Un approccio analogo è stato adottato per la stima della produzione aggiuntiva di biogas da feci e urine umane. I risultati sono riportati nella tabella seguente:

	Nm^3/mese	GJ/mese
Scarti da mais	9'960	291,8
Residui animali	1'225	35,9
Residui umani	903	26,5
Totali	12'088	354,2

Produzione potenziale di biogas da scarti di mais, residui animali e umani

Idrico

Il potenziale idrico è stato valutato a partire dai parametri di portata d'acqua e prevalenza del torrente. Tramite l'applicazione del Floating Object Test nei mesi di ottobre e novembre è stato possibile stimare la portata volumetrica. I risultati riguardanti i mesi di ottobre e novembre sono stati estesi in un secondo momento a tutto l'anno solare facendo una regressione lineare con i dati di un fiume noto (Mewou), sovrapponendo i dati ottenuti nel periodo di misurazione e proiettandoli per tutto l'anno. La portata di 54,4 l/s, pari a metà della portata disponibile durante il mese più secco (marzo) è stata impostata come portata massima al fine di garantire una portata residua accettabile dal punto di vista ambientale. La prevalenza, invece, è stata stimata tramite l'utilizzo di un altimetro tascabile. Dopo aver identificato i luoghi potenzialmente sfruttabili per il bacino di raccolta e la sala turbina, gli stessi sono stati localizzati su Google Earth; quindi è stata calcolata la prevalenza (55m) e la distanza via terra della condotta forzata (1 km). Con i valori ricavati di portata e prevalenza, un sistema di generazione di potenza con efficienza totale pari al 45% produrrebbe 13,21 kW. Considerando quindi un fattore di capacità del 70%, la produzione annuale sarebbe di 81 MWh, mentre quella mensile di 6,8 MWh.

Eolico

Il potenziale del vento presente nell'area di studio è stato valutato attraverso misure dirette di un anemometro a coppette posizionato ad un'altezza di circa 11 m da terra. I dati raccolti riguardano velocità del vento, direzione, temperatura e pressione per ogni minuto, per un periodo complessivo di sette mesi. Al fine di delineare un regime ventoso che assorba le fluttuazioni stagionali e annuali, sono state applicate una regressione lineare ed una esponenziale prendendo come riferimento i dati forniti dalla NASA, riferiti alla città di Bamenda (14 km distante dall'area di studio). L'andamento del vento è stato quindi esteso ad un intero anno. I risultati principali sono riportati nella tabella seguente:

Velocità media vento	3,297 m/s
Deviazione standard	1,865 m/s
Ora di vento massimo	14
Correlazione giornaliera	0,329

Principali parametri della fonte eolica

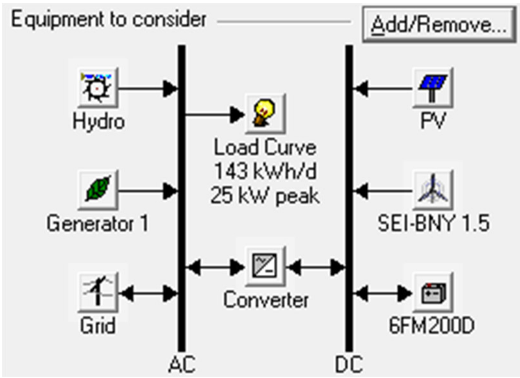
È stata anche ricavata la distribuzione di frequenza, simile a una distribuzione di Weibull con fattore di forma pari a 1,850 e di scala pari a 3,713. Al fine di stimare il potenziale eolico in forma di produzione energetica, dapprima è stata trovata la potenza per unità di area spazzata, pari a 11,25 W/m^2, poi, considerando un fattore di capacità del 7%, è stata calcolata la produzione annuale pari a 6,9 kWh/m^2 (0,575 kWh/m^2 /mese).

Solare

L'ultima fonte rinnovabile analizzata è quella solare. Considerando che lo studio è stato eseguito durante una finestra temporale coincidente con la stagione delle piogge e data la mancanza di strumentazione adeguata, non è stato possibile effettuare misure dirette dell'irradiazione solare. Per questo motivo il potenziale solare è stato stimato solo attraverso una ricerca bibliografica. Per la prossimità con la città di Bamenda i dati dell'irradiazione media mensile relativi a questo luogo sono stati usati come riferimento. I dati forniti dalla NASA e dalla mappa solare SolarGIS® indicano un'irradiazione solare di 1908,84 kWh/m^2 con una media giornaliera di 5,23 kWh/m^2.

III. Pianificazione energetica

La pianificazione consiste nella soddisfazione dei bisogni energetici tramite lo sfruttamento delle fonti rinnovabili disponibili in loco, con l'installazione di tecnologie alternative o la modifica dell'asset attuale. Data la diversa natura delle domande elettrica e termica, lo studio è stato condotto separatamente. La pianificazione elettrica si è basata sull'utilizzo del software HOMER®, che simula e ottimizza micro-sistemi di produzione di potenza off-grid o ibridi, ricercando la configurazione tecno-economica più fattibile a seconda del Net Present Cost (NPC). La modellizzazione del sistema CPC Bali è stata fatta con le tecnologie riportate nella figura sottostante. I parametri di input sono stati acquisiti tramite sondaggi a livello locale, ricerca bibliografica e ricerca di mercato. I sistemi simulati con il software sono due: off-grid e ibrido basato sulle fonti rinnovabili. Lo schema rappresenta la configurazione ibrida che include la rete come mostra l'icona in basso a sinistra. La configurazione off-grid è identica, ma senza rete.



Configurazione del sistema elettrico del CPC con HOMER®

I risultati ottenuti suggeriscono che la fonte idrica rappresenta la migliore soluzione per entrambe le configurazioni. Nel caso di applicazione off-grid, la potenza nominale è di 15kW con 20 batterie Vision e generatore diesel di back-up, per 0,178 $/kWh di costo dell'energia (LCOE), pressoché uguale all'attuale costo dell'energia elettrica (0,17 $), e NPC pari a 163'088$. La soluzione ibrida ottimizzata prevede una turbina idrica a flusso incrociato più piccola del caso precedente (8,33kW di potenza nominale), con 27% dell'energia elettrica annuale acquistata dalla rete. Il confronto con la soluzione off-grid mostra minori NPC (132'791$) e LCOE (0,123 $/kWh). Le analisi di sensibilità rispetto ai costi di turbina idraulica, pannelli solari e turbina eolica confermano la convenienza della prima tecnologia e l'esclusione delle restanti, anche in caso di riduzione fino al 90% dell'investimento relativo a pannelli solari e turbina eolica. Ulteriori analisi di sensibilità rispetto ai costi del diesel e dell'elettricità acquistata dalla rete mostrano la robustezza della soluzione trovata.

La pianificazione termica è stata impostata cercando soluzioni specifiche al fine di soddisfare i bisogni energetici analizzati in precedenza: cucinare, produrre il pane e fornire acqua calda. I bisogni inerenti la cottura dei cibi e del pane sono stati considerati attualmente soddisfatti in entrambi i settori, domestico e pubblico. L'obiettivo è stato quello di ridurre il consumo di energia primaria attraverso l'adozione di tecnologie più efficienti, in particolare il forno ASTRA con efficienza del 40% per il settore pubblico e l'Envirofit G3300 con efficienza pari a 30% per quello privato. Per quanto riguarda il forno della panetteria è stata proposta la sostituzione con il forno elettrico Moffat E32D5. La strategia adottata ha previsto una nuova simulazione delle configurazioni precedentemente analizzate con HOMER®, con aumento della curva di carico pari alla potenza del forno (6,3 kW) tra il picco mattutino e serale, riempendo la "valle". Il risultato è significativo in quanto la turbina idraulica rimane la soluzione migliore anche con riferimento al carico aggiuntivo, ma in questo caso presenta 18,3 kW di potenza nominale sia per il sistema off-grid che per quello ibrido. In tale prospettiva il sistema ibrido può essere visto come un primo passo importante verso un sistema di generazione elettrica completamente indipendente.

Se la cottura dei cibi è stata considerata a un livello accettabile, la fornitura di acqua calda rimane un bisogno non ancora soddisfatto. A tale proposito l'analisi termica è stata completata con soluzioni personalizzate in modo da fornire acqua sanitaria a studenti (20 lt/giorno pro capite) e popolazione (30 lt/giorno pro capite). Nel settore pubblico il biogas attualmente prodotto potrebbe essere utilizzato tramite l'impiego di caldaie a biogas. Purtroppo, tale soluzione coprirebbe solo l'11% della richiesta termica, necessitando chiaramente di una quantità aggiuntiva di gas digesto fornibile sfruttando appieno il potenziale umano degli studenti, animale delle mucche e gli scarti di granoturco dalle coltivazioni. Un approccio differente può essere l'implementazione di 216,6 m^2 di collettori solari. Per il settore domestico, invece, la fornitura di acqua calda può essere soddisfatta con 0,41m^2 a persona di collettore solare piano.

Infine, i risultati della pianificazione energetica elettrica e termica sono riassunti in un nuovo diagramma di Sankey per un possibile scenario futuro, che riporta gli aspetti chiave per il raggiungimento dell'autosufficienza energetica del CPC Bali. Comparato al diagramma dei consumi attuali, appaiono tre nuove fonti primarie: idrico, solar e biogas. Il diesel rimane solo come supporto di generazione, ma il suo consumo è trascurabile. Di fondamentale importanza è la riduzione nel consumo primario di legname (40% nel settore pubblico e 38.6% nel privato) che ne deriva. Il passaggio da una dipendenza basata sul consumo di legna e combustibili fossili ad una fornitura diversificata, basata su fonti rinnovabili, funge da catalizzatore di estrema rilevanza per il fine ultimo di questa tesi. Inoltre, gli utilizzi finali di energia mostrano un livello più elevato e la possibilità di soddisfare nuovi bisogni.

A completamento di questo studio di pre-fattibilità, si può affermare positivamente di poter raggiungere l’autosufficienza energetica del CPC Bali. Ciò implica che un vero sviluppo sostenibile possa essere conseguito dal punto di vista economico, sociale e ambientale nel caso venga adottata una prospettiva di lungo termine. L’*Energizzazione Sostenibile* può quindi trovare una completa attuazione in questo contesto. Grazie alla disponibilità di fonti rinnovabili a livello locale e alla disposizione del tessuto sociale nell’adottare le relative tecnologie, il miglioramento dell’attuale situazione energetica è possibile oltre che desiderato, con un’impostazione improntata al futuro. Tenendo in considerazione i vari approcci seguiti per il fine ultimo della tesi, è stato delineato un nuovo bilancio energetico futuro per il CPC Bali, come mostre il diagramma di Sankey.

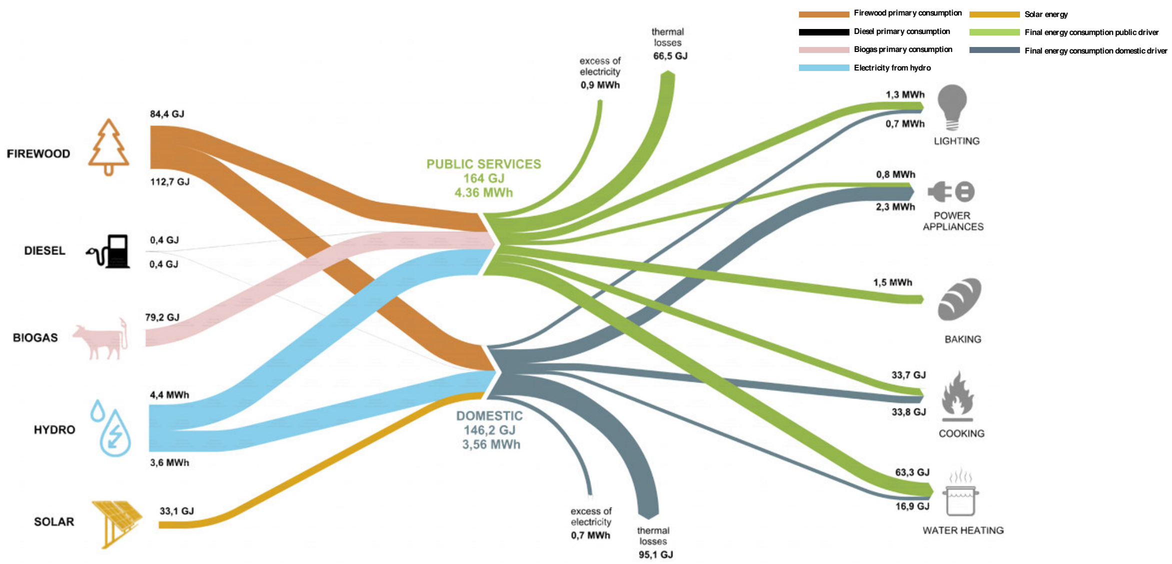


Diagramma di flusso energetico del sistema off-grid incluse le soluzione termiche

1 Introduction

1.1 Context and background

It is widely recognized that energy has always been a major factor for the development, growth and progress of a country, a region or a population: without energy no activities could be carried. It is of global concern that energy access should be provided for all those who lack in the world. Thus, the attention is placed onto developing countries which are in the process of rising from a poverty situation that has endured for a consistently long period in their history and persists nowadays.

The availability of energy is a necessary pre-requisite to enable development [2], although it should be regarded as a tool for people to achieve improved living conditions. The worldwide consensus on the urgent action to be taken to face such issue has been indirectly addressed by the United Nations in the redaction of the Millennium Development Goals (MDGs) as initial step. Subsequently, energy access and modern energy services have been placed as a primary key goal to satisfy basic human needs, according to the UN Secretary General's Advisory Group on Energy and Climate Change [3]. Only recently the MDGs have been revised and overcome by the Sustainable Development Goals (SDGs) in which a proper statement on energy has been inserted [4]. In fact, the seventh goal establishes to "*Ensure access to affordable, reliable, sustainable and modern energy for all*", implying the enabling of a true sustainable development.

The concept of energy access could be translated into the theme of energisation. Frequently, providing energy, which has a multiple nature of forms, is simply related to electrify areas without energy services. As a matter of fact, a wider and more comprehensive approach is required going beyond, or in contrast to, electrification [5]. Thus, energisation could be considered as the supply and planning of complete energy solutions to meet electrical and thermal demand, focusing on the short-term improvement of rural communities [6]. Nevertheless, this definition omits the perspectives in the further future, obstructing the path towards a sustainable development, as described in the Brundtland Report. On these premises, Nissing and von Blottnitz have sought harmony between energisation and sustainable development, deriving from such combination important characteristics that energy services should feature: diversified nature; accessibility and affordability; enhanced quality, quantity and variety to choose from [7]. The third aspect is of particular relevance so that it could be brought upfront as the final objective of energisation, together with the matching between needs and local resources. The satisfaction of the energy request of a confined area with its own peculiarities through what is available in site is fundamental and strongly beneficial for end users [8]. In addition, ad-hoc solutions usually accomplish the task of covering the energy demand in a better manner than standardized procedures, since they aim at maximizing the system efficiency while minimizing costs [9], while accounting for social and cultural context. With this approach, the role of principal actors is played by renewable energy sources (RES), present everywhere under one of their uncountable forms at least. Exploiting the locally available RES is possible today as the conversion technologies have reached a sufficient level of maturity with a significant cost reduction comparing to the past [2]. It resulted that RES could be considered as the default selection for off-grids application, especially in developing countries where transmission and distribution grids, as well as firewood represent a serious limitation to a reliable and clean energy supply, respectively [10].

The issue of energisation finds particular relevance in the African continent, as expressed by the extremely low value of the Energy Development Index (EDI) of its countries. This index summarizes the level of energy access and uses through four sub-indices, whose explanation is redirected to appropriate publications. The ranking lists all the developing countries of the world according to their EDI (from 0 to 1) and the highest value in the Sub-Saharan region is 0.23, while the electrification index is below 0.44 and the modern fuel for cooking index well below 0.1 in the majority of cases. In this context, Cameroon is found with an EDI of 0.13, ranking it to the 48th position on 64 countries reported [11]. Scarce utilization rate of energy always comes along with a general background of poverty and underdevelopment, as described by the Human Development Index (HDI). Also in this classification, African countries are present only in the last positions. For Cameroon the HDI is equal to 0.504 [12]. It has a population of 22.25 millions of people [13] living on a land of approximately 475.4 thousands of square kilometres, with a latitude from 6° to 12° North of the Equator, confining with Nigeria, Chad, Central African Republic, Republic of Congo, Gabon and Equatorial Guinea [14]. The poverty rate reaches almost the level of 40% across the entire population with a yearly GDP (PPP) of 2625 USD [13].

From an energetic perspective, the most relevant data worth reporting is the total primary energy supply of 6986 ktoe, with a 66.5% of share of biofuels and waste. For the electricity production, the total accounts for 6.3 TWh, with the predominance of hydropower (72%), followed by oil (20%), gas (7%) and biofuels (1%) [15]. From the end user point of view, only 54% of the population has access to electricity, with a deep discrepancy between urban and rural electrification rates, 88% and 17% respectively. For what concerns the use of traditional biomass as cooking fuel, the share is 75% of all Cameroonians [16]. These values show the urgent and imminent need of *Sustainable Energisation* in the whole country, focusing the attention on rural areas where the exploitation of indigenous sources is likely to create a desirable synergy between population and renewable energy technologies (RETs).

1.2 Purpose of the thesis

The centrality of the energisation concept to alleviate poverty finds its complete fulfilment through a need-resource matching approach, as previously described. In particular, the largest portion of population affected by a lack or a remarkably unreliable supply of energy is concentrated in rural areas within the context of developing countries. Therefore, the redaction of the present thesis has been aligned to this point of view. The ultimate goal was to assess the energy self-sufficiency of the Cameroonian Protestant College (CPC) in Bali, situated in the North-West Region of Cameroon. The study was conducted at a pre-feasibility level with a focus on the RES application in order to accomplish the main target. In addition, the capability of producing enough energy to become autonomous from external suppliers could be achieved only through site specific solutions intended to accommodate the peculiar energy needs, enabling a long-term sustainable development of the considered school.

1.3 Problem statement

In Cameroon the electricity supply from the national utility grid is extremely unreliable, resulting in several days of outages interrupting or preventing the attendance of school and productive activities, limiting the development of the affected population. On a yearly basis, the blackout period can be up to 50 days [17]. In addition, under the current policy, consumers are not rewarded for the lack of supply, causing untrustworthiness and high bills compared to the service provided. Thus, there is a felt need of a more stable electricity supply. In addition, the heavy reliance on biomass through inefficient traditional stoves leads to unhealthy cooking and living conditions, worsening the already critical situation of the people living in CPC Bali.

The proved unsustainability of the current situation has pushed towards researching for alternative and innovative solutions with a view in the long run.

1.4 Objectives

The present work has been organized with a proper structure followed throughout the research period, during the work on the field of study and the laboratory development. The guidelines have been taken from the Project Cycle Management (PCM), representing the framework used [18]. Although the PCM includes an organic and integral sequence of steps from the inception to the completion of a project, while the present work deals with the preliminary phases, its selection is based on the long-term perspective adopted and the need of continuity with follow-up studies. In fact, this research is set to provide a pre-feasibility study of CPC Bali energy self-sufficiency, covering the PCM steps of Programming and Identification.

The general objective of this work was the improvement of energy access of CPC Bali, by meeting the increasing energy demand through the exploitation of locally available RES. It would enhance the current school facilities and favour the long-term sustainable development of the rural area, with the final goal of turning the school energetically self-sufficient. In order to attain this task, three specific objectives have been derived:

I. Assessment of the current consumption pattern through a comprehensive energy balance of CPC Bali, specifying sources, drivers and energy uses;
II. Assessment of the technical potential of the presently available renewable sources in site, focusing on biogas, hydro, wind and solar;
III. Energy solution planning through need-resource matching approach, identifying the most suitable combination of RETs to meet the electric and thermal demand according to the social and cultural context while drawing future scenarios of energy consumption.

The general objective as well as the specific objectives have been achieved by means of a multiplicity of activities addressed in the following chapters.

1.5 Study area

Geographically, Cameroon has 10 regions. The school of CPC Bali is found in the North-West Region, one of the two Anglophone areas among all the country, within the Mezam Division, in the Sub-Division of Bali itself (as shown in Figure 1.1). The studied area of interest is found within the context of tropical and eucalyptus forest environment surrounded by mountains and manure fields. CPC Bali is part and under the formal administrative competence of the Protestant Church in Cameroon, being one of the 23 Presbyterian Church schools. Practically, every school is independent from each other, although there exists a partnership aimed at creating collaboration and reciprocal aid. The finances are controlled at the school level by two bookkeepers, while the proprietor Presbyterian Church has its own financial office which manages and checks the regularity of each school. In addition, the role of this body is also to approve or dismiss projects proposed by the schools, concerning any kind of activity. However, this results of marginal importance as the procedure is a merely pro-forma step. The decisions within the school are taken by the Principal, who is the leader and the most important figure, with an advisory group of teachers, staff members and students’ parents.

CPC Bali is a secondary and high private boarding school with 1008 students ranging from 10 years old to 19 years old, according to the English teaching system, with a slight dominance of male presence (54%) comparing to the female (46%). The school environment was composed by 60 dormitories, 6 toilettes (considering one shower room for each toilette), 14 classrooms, 4 laboratories, 7 administrative offices, staff room, dispensary, church, library, refectory, kitchen, bakery, canteen (a small store for students managed by the school direction), workshop and sport facilities.

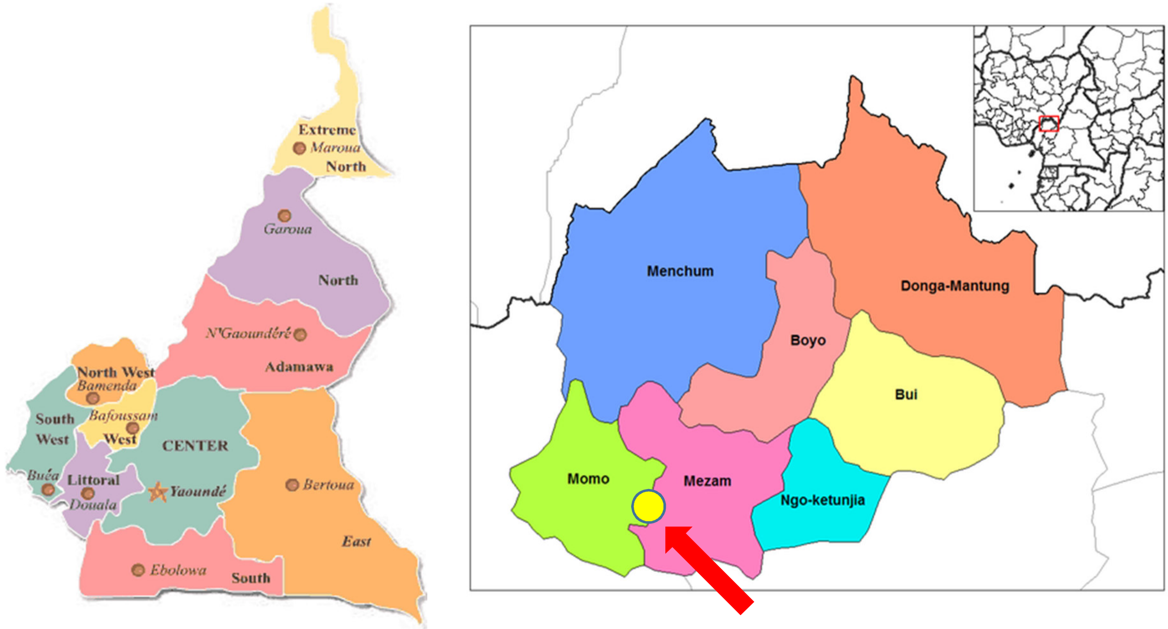


Figure 1.1 Location of CPC Bali. Source: [19] [20]

The school population is enriched by the presence of the personnel and related families living inside the campus in 42 households for a total of 179 people. An additional end user, treated as a whole aggregate, is represented by the Cameroonian Catholic University (CCU), which is not of direct interest for this work, but necessary to consider being inside the system boundaries. Thus, all its facilities will be summarized only under the name of CCU with the corresponding energy consumption. Also, there exists a sort of artisan or trading network within the campus since several families produce certain goods sold in the canteen with a resulting income. The revenues of the small store increases the school funds.

From the energy point of view, the school is supplied with electricity by the national utility grid AES-SONEL through a central meter in 220V. Here, all the consumed electricity passes and from which it is transported to each dwelling or building with an internal distribution grid. The thermal energy supply is composed by firewood, LPG and kerosene. However, a more detailed description is given in the following sections. Fresh water for all purposes is taken from a stream running at approximately 3 km from the school, deviating through a sand filtering system. It works only with the principle of gravitational force, without the application of any pump, supplying in sufficient quantity all the inhabitants of the college campus. It is worth noting the presence of three biogas systems built in different periods with the same procedure. Their function is the disposal of student toilet waste producing biogas; unfortunately, only one of the system is working at the moment without a proper exploitation of the obtained biogas. Further details and possible improvement of these systems are partly subject of the thesis.

Given the organization and composition of the college campus it is unequivocally simple to recognize services such as education, healthcare, craftsmanship and "public" administration. Indeed, they represent the characterizing features of an independent organization at economic, social and environmental level. Therefore, under the circumstances of this work, CPC Bali is treated as a *micro-village*.

1.6 Rural energy planning

The objective of transforming the college campus in an energetically autonomous entity implies a review of past studies. In fact, the consumption-resource matching concept is not introduced in this thesis as a novel concept, instead is borrowed from the literature and applied to the treated system. In addition, the definition of CPC Bali as a *micro-village* allows an insight into the topic of rural energy planning, a necessary phase to step into in order to achieve the energy self-sufficiency. A similar study case in terms of system and type of study is provided by Kayungilo [21], in which the performance of an Indian school have been analysed with the main goal to achieve energetic autonomy. Following in this section, a brief literature review is presented for each specific objective.

The current energy balance represents the first specific objective. Previous studies have been found in the literature concerning the analysis of energy consumption in rural areas of developing countries. Johnson [22] provides a comprehensive approach when an energy assessment is conducted in field. He carried out four visits to an isolated rural village in Mali with his team. During the initial planning visit he identified all the energy use activities and organized them into *energy drivers* that are the sectors where energy is consumed. The other visits consisted on field studies where he conducted surveys to the households of the village with the aim to identify type and quantity of energy consumption, locations of energy use activities and to collect demographic information. Moreover, quantitative analyses have been conducted by Johnson in order to measure the energy supply and use for each source of energy, in the specific case wood, charcoal, electricity and petroleum fuels. The relevance of the study lies on the global approach adopted, assessing the entire energy layout of the village and the measuring activities occurred during three different periods of the year that gave additional quantitative information on the seasonal variations of habits in energy consumption. However, the research at household level focused mostly on firewood consumption. Power consumption has been calculated at the level of supply, in the specific case PV and batteries. On the other hand, Bhattacharyya [23] has set a well-rounded analytical approach. It consisted in a precise energy balance matrix in which the considered system has been detailed with all the possible entries for primary and secondary/final forms of energy supply. A source is treated as primary when directly extracted by a natural stock without having undergone any conversion process before entering the system, while a form of energy is considered secondary after a conversion process that has made it available for the final consumer. The energy flow diagrams of the International Energy Agency (IEA) are based on the same concepts and are largely diffused in the literature [24]. The adoption of this diagram comes from its schematic representation summarizing the most important characteristics of the system, reporting sources, drivers and uses. Also many examples are present in literature, as the energy balance of Cameroon (see Figure A.1 in Appendix A). Aside the global approach, in the literature it is recurrent the use of questionnaire as a tool to make analysis of domestic consumption specifically. Some studies focused on the domestic consumption of electricity. Murthy [25] in his article analyses the power consumption at domestic level in the Indian state of Karnataka, providing a methodology to assess the total electricity consumed. In this case a questionnaire had been tested and then used: rated power, number of appliances and number of hours of usage were asked to more than one thousand households. Alternatively, in the work it was presented the appliance census approach using of regression analysis to determine the contribution of various categories of appliances to the total electricity consumption. Other studies on firewood consumption in the Sub-Saharan Africa applied questionnaires as instrument of analysis. For instance, Njiti investigated the firewood consumption in the rural area around the Cameroonian city of

Garoua [26]. His study consisted in collection of data through the use of appropriate questionnaires addressed to wood consumers, vendors and producers. Beside the quantity of firewood, also the way of production, transportation, use, alternative energy sources and precautions taken to economize energy consumption had been included in the questionnaire.

The second specific objective, assessing the technical potential of the locally available RES, involved a diversified approach due to the different nature of sources to study. Thus, a proper literature review is inappropriate in this case. Nevertheless, each of the resource has been measured or estimated by applying a specific methodology based on past experience. This is reported in the following chapter prior to the description of the adopted method in this work.

Following from the consumption-resource approach, the third specific objective concerns the energy solution planning based on the consumption patterns found and the exploitable RES. At first, the electricity solution planning is presented. In literature it is possible to find uncountable studies of Integrated Renewable Energy Sources (IRES) with diverse methods applied and resolution software used. A Linear Programming (LP) approach was proposed by Ramakumar [27] according to whom the total annual cost of the systems is minimized. Another method is the Dynamic Programming [28]. A further approach, the Goal Programming [29], was used for solving the lighting problem in households in India. There exist several software for optimization such as LINDO [30], LINGO [31], HOMER® [32] and many others. A more comprehensive and exhaustive review of methods and programs is provided by Akella [33] and Kanase [34]. Past experiences have shown a certain diversification in countries where energy solution planning studies have been conducted. In fact, in developed countries it is of common worry the integration and exploitation of RES in the production mix. For instance, Dalton highlights the possibility to supply electricity to a large hotel in Australia [35], or Khan has researched possible hybrid systems configuration also using hydrogen energy storage in Newfoundland, Canada [36]. In the case of developing countries, where RES are desirable to be used in order to electrify rural and remote areas or to improve the unreliable grid supply, cases were found worldwide. In Saudi Arabia, the inclusion of wind turbines to a diesel generator has been studied [37] for a remote village. Also, a system based on solar PV panels has been simulated for households in Sri Lanka [38]. In the African context, a well-rounded analysis is provided for a case of electrification of a village in northern Ghana [39]. Besides, some noticeable attempts to conduct a feasibility study in Cameroon have been found, with a great relevance for this work [40] as the context is similar. For this work, HOMER® was selected as modelling software due to its specificity for the simulation of micro power systems based on RETs. The choice was also based on the vast series of examples found in literature above reported about pre-feasibility and feasibility studies, as this thesis.

The latter part of energy solution planning concerns the thermal demand. For this purpose the LP approach proposed by Ramakumar [27] is similar to the one used with HOMER®, but it comprises all kinds of energy loads, electrical and thermal. The design of IRES is achieved by minimizing an objective function, the total annual cost, under certain energy and power constraints.

The literature review reveals the gap of a comprehensive study from the assessment of energy consumption to the forecast of future scenarios, passing through the analytical and software-based energy solution planning. The aim of this thesis is to bridge the highlighted void taking example from the proposed approaches combining them in a unique manner.

1.7 Structure of the thesis

The thesis is divided in five chapters. The first introductory part is the current one, where background information on energy access, context of the study and research design are reported. Chapter 2 describes in detail the followed methodology of each single activity, explaining the shape of the thesis, respecting the order of the three specific objectives. In Chapter 3 the results on the current situation are given, with a comprehensive overview of all aspects related to energy balance and RES potential. Future scenarios based on the energy solution planning are found in Chapter 4 where the energy self-sufficiency of CPC Bali is investigated, whilst Chapter 5 involves conclusive remarks and suggestions for further research.

2 Methodology

In this chapter the methodology of the study adopted is presented. The general structure of the methodology follows the three specific objectives of the thesis stated in the first chapter. Two periods of analyses can be distinguished: the first period spent in field at CPC Bali for a total of three months; the second period spent at the home university of Politecnico di Milano for the desktop and laboratory analysis.

During the period abroad, main activities were to get to know the place subject of the study and collect all necessary primary data for the purpose of the work. Through a deep investigation of the social and physical environment, it was possible to recognize habits on energy consumption, technologies used at domestic and public level, unmet energy needs, presence and potential of RES. The research was carried out by means of surveys, observations, questionnaire, direct measurements, tests and interviews to local people. At the end of this period, a phase of revision and refining of data collected in field was needed in order to accomplish the first and second objective of the thesis.

The work on the field was followed by a careful study and analysis of data in Milan concerning the energy consumption and the resource assessment. Thus, the question of how the locally available RES could meet and satisfy the current demand was tried to be solved. This issue represents the driving force and the basement of a truly sustainable development of the school community in the long-term. In addition, energizing a rural context or, as in this case, improving the on-going insecure situation through a resource-need matching is a more suitable method than a standard electrification process [9]. At the end of this part, the feasibility of energy self-sufficiency of CPC Bali based on RES is the achieved objective.

The chapter is below sub-divided into three paragraphs: energy balance assessment, energy resource assessment and energy solution planning focusing on electricity and thermal demands separately. For each paragraph, the specific adopted methodology to drive the analysis and the activities to reach the results is explained, by reviewing the literature and gathering examples to adapt and apply to the context of CPC Bali.

2.1 Energy balance assessment

In this thesis the approach of Johnson [22] together with the method proposed by Bhattacharyya [23] was used to define a framework for the energy balance assessment of a rural area. In this framework, energy sources, energy drivers and final uses are allocated as the diagram shows below:

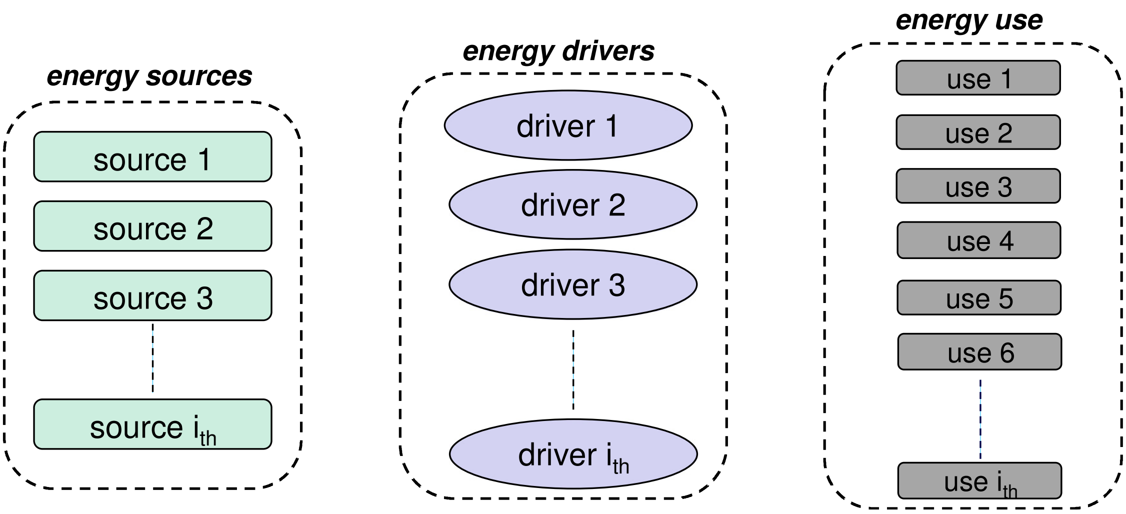


Figure 2.1 General diagram of an energy system. Source: Authors

While energy sources can be various, Johnson identified specific energy drivers in a rural village that can be *domestic*, *public services*, *transport* and *artisan*. For the specific area dealt by this work, the concept of rural village is applied to CPC, a school campus which includes different services as education, healthcare, craftsmanship and "public" administration, and that is then considered a *micro village* as explained in paragraph 1.5. Being CPC a boarding school where students and staff live, the public energy driver includes the school itself, dormitories, administration buildings, church and library, while the domestic energy driver is referred to the households of the staff. Transport is neglected as well as the artisan driver since no activities of this kind are present in the school. However, if some artisan activities are conducted at household level, then they are included in the domestic driver. Finally, within every energy driver, different energy uses can be distinguished. For each energy use, a specific technology undertakes the conversion from primary to secondary source of energy, as thermal or electrical energy. Activities have been conducted in order to quantify the consumption of primary and secondary source of energy as questionnaire, surveys, interviews, observations and direct measurements that are thoroughly explained in the next sub-paragraphs.

For the specific case dealt by the thesis, the rural energy system represented by CPC Bali is the boundary of the analysis. This means that all the conversion processes occurring outside the campus are not taken into account and all the energy sources going into the system from outside are considered primary sources. For instance, electricity, provided to the campus by the national utility grid, is considered at the same level of other primary energy sources being all the conversions occurring outside the system boundaries.

For domestic and public energy drivers, activities were planned before the arrival at CPC Bali, while some others were included during the stay abroad, with the aim to quantify the total amount of primary and secondary energy consumption on a monthly basis. Depending on the accessibility and the easiness of getting quantitative data, primary and final energy consumptions were assessed for each final use of energy.

Based on the results obtained from the energy balance, a Sankey diagram was built following the same guidelines that the IEA sets. The diagram gives additional information about conversion technologies and relative efficiencies; but also various indicators as energy supply mix, shares of renewable in supply, per capita consumption of primary and final energy can be derived from it.

In the following paragraphs, specific methodologies adopted to assess the consumption of primary and final energy for each energy driver are described in detail. In addition, the methods to measure the real load curve is reported to gain proper insights on the load profile. Eventually, the energy consumption analysis is summarized by means of an energy flow diagram with the IEA footprint.

2.1.1 Domestic energy driver

For the purpose of this part, the questionnaire was chosen to conduct the investigation of domestic energy consumption assessment. A draft was sketched before the arrival in Cameroon and subsequently refined after having familiarized with local environment and people. In this way an ad-hoc questionnaire could be formulated, tested with 5 households during the fourth week and finally submitted to the remaining families until the end of the period abroad. The questionnaire was administered in the form of peer-to-peer interview (Figure 2.2), in order to explain directly the importance of the research and the information coming from the questionnaire and to make people interested and somehow involved in the research. In addition, while interviewing it was possible to explain some questions and clarify any arisen doubt. Most of the times the questionnaire was filled by the family heads, because of their usual habit of welcoming guests in the house. Family heads were also responsible for the house expenses; in case they were unable to answer some questions other members of the family came to help. The questionnaire entirely covered the domestic energy consumption and supply of CPC, including final use of thermal and electric energy.

Figure 2.2 Questionnaire to Chief Cook (left) and to staff at home (right). Source: Authors.

In the next subparagraphs first the questionnaire is explained in detail, secondly the methods used to analyse the answers are outlined.

Questionnaire

The whole questionnaire is reported in Appendix A, while herein only the major information are described. The questionnaire has been divided into six sections.

The first section includes general information about number, gender, age and role inside CPC of the family members, for a total of 4 questions.

From the second to the fifth section the questionnaire was organized according to the different energy sources consumed in the households. In *electricity use and supply* type and number of power appliances and daily average use were asked. Also, the number of shortages occurring on a monthly base was asked. Finally, qualitative questions about damages due to voltage fluctuations and comments about the electricity supply concluded the electricity section of the questionnaire.

The third part of the questionnaire concerned the *firewood consumption and supply*. It was subdivided into further parts, according to the final use and the supply of the wood source. After the identification of final use of firewood, the supply of the source was investigated in terms of transportation mean, frequency of supply, quantity purchased and costs. In order to adopt common unit of measure, two samples of wood were used as reference for the interviewed people to indicate the amount of wood consumed: the first was a bundle of eucalyptus logs cut in small pieces that local people used to buy on the road outside the campus, with fixed price and weight; the latter was the quantity that could fit in a pick-up they used to transport firewood, usually loaded of the same amount of eucalyptus logs each time. Further, for each final use technologies using firewood and occurrence of use were asked.

An additional annex to the *firewood consumption and supply* has been added afterwards. This annex concerned the consumption of wooden sawdust in local pot (see Appendix A) for cooking purposes. The weekly use of the sawdust pot and the type of food cooked there were subjects of this section.

The fourth part of the questionnaire covered the *gas use and supply*. Final use, type of bottle, cost and consumption rate were asked. The quantity was measured in terms of bottles, with a known mass of LPG contained.

In the *other sources of energy* section, the consumption of kerosene and charcoal was asked and also the final use, quantity and cost of each source. For kerosene the quantity was expressed in terms of litres.

The sixth and final section was about the *domestic waste production*. All the four questions were about the farm owned by each family. Type and approximated extension of plantations were asked; finally, animals were investigated in terms of unit number and feeding.

Analysis of the answers

The analysis of data coming from the questionnaire is determinant to draw statistics and obtain relevant indicators from the information collected. Since the questionnaire was adopted to investigate the domestic energy driver, the expected results are the primary and final consumption of energy within the domestic driver of CPC.

First of all, all the answers of the questionnaire were organized in working tables of Excel. Then, the data were processed in order to obtained results with common unit of measure. Except for electricity for which the unit of measure adopted was the kWh, data on energy consumption related to other sources were expressed in GJ. Below, further analyses of data coming from each section of the questionnaire are explained.

For the *electricity supply and use* section, the electrical energy consumed by each household was computed as the sum of the products between each appliance rated power (kW) and the daily use (hr); the result was multiplied by 30 days to obtain the monthly consumption. Efficiencies of every single power appliance were not considered (as the approach of the IEA in its energy diagram flows). Therefore, in this case, supply and final use of energy coincide.

Consumption of firewood asked in the questionnaire was quantified in terms of mass (kg). To simplify the analysis of wood consumption, an equivalent lower heating value (LHV) was used and mass converted into MJ. The equivalent heating value adopted for this analysis is that of the Eucalyptus Grandis (Rose Gum, Grand Eucalyptus), the most available and used wooden source in the zone. Its properties are assumed considering a wet wood sample, implying a considerable moisture content. During the period in Cameroon the rainy season was ongoing and dry wood was inaccessible. The moisture content of wood could have been easily gauged with a moisture meter, but the instrument was unavailable in site. From the study of Crafford [41], average moisture content of wet Eucalyptus Grandis of 40% was found out of two samples of different size and three samples of different age. It was observed that the moisture content was constant to 40% for every age of tree and reduced to 33.4% only for a 5 years old organism. However, since young wood is not cut at CPC, average moisture content of 40% has been picked as reference. The LHV of Eucalyptus Grandis is 18.43 MJ/kg; for the calculation the net calorific value that takes into account the energy to heat and evaporate the moisture, the following equation is applied [42]:

$$EHV = LHV * (1 - MC_{wet}) - MC_{wet} * \Delta h_{H_2O} \qquad \text{Eq 2.1}$$

where EHV is the net calorific value, LHV the lower calorific value MC_{wet} the moisture content on wet basis, Δh_{H_2O} the change in specific enthalpy of water. The computation follows the protocol of the water boiling test (WBT) and the results are showed later.

The consumption of primary energy coming from the wood source was computed subsequently to the calculation of the net calorific value, by applying *Eq 2.2*:

$$PE = m_{fuel} \times EHV \qquad \text{Eq 2.2}$$

where PE is the primary energy relative to the mass of fuel m_{fuel}.

For the final thermal consumption, efficiencies of the burning wood systems had to be unfolded. For this reason, the water boiling test (WBT) or referenced data were used to obtain the thermal efficiency. At domestic level two systems were analysed:

- three-stone fire
- sawdust pot

The three-stone fire (3SF) is the most simple and most common cooking stove in rural areas of developing countries, where gas facilities are not contemplated or families cannot afford highly expensive alternatives. This basic method to burn biomass consists of an open fire where three stones are placed to hold a pot or a pan over the fire; in this stove sticks of wood are burned directly under the pot. The absence of combustion chamber and chimney leads to a very low efficiency of combustion [43]. The work of Santachiara investigates, among the others, the efficiency of the 3SF stove. He found experimentally that the thermal efficiency of a 3SF system reaches 11% when the external temperature is at 12°C, so the 89% of the heat content of the biomass source is lost in the environment [44]. The efficiency is dependent on the external conditions when experiments are conducted; in the literature various values of efficiency are found, as 15% with outside temperature of 30°C [45]. For the purpose of this thesis the value of 15% as thermal efficiency is taken to compute final energy consumption with 3SF.

The sawdust pot is an improved system that burns wooden dust generated from sawing activities outside the campus. Local people used to go to the place where wood had been sawed previously and collect sawdust in bags for free. Children were often sent to do this work. The system is constituted by a metal pot where inside wooden sawdust is pounded and pressed until complete filling; two empty channels, one at the bottom and the other in correspondence of the vertical axis, are left so that air and flue gas can flow (see Figure A.2 in Appendix A). The fire is lit from the bottom, while combustion of sawdust occurs in axial direction from inside towards outside the pot. Local people used to like this system and generally it is preferred because it has some advantages. First, the wooden fuel is for free. In second instance, the sawdust burns slower than firewood and the thermal efficiency is higher, so less heat is lost. Finally, sawdust is a cleaner fuel since less smoke is produced during the combustion. Unfortunately, the sawdust is available only occasionally. To compute the efficiency and then the final consumption, the WBT was performed on the sawdust pot by following the international protocol adapted to local conditions [42].

Eventually, the consumption of primary and final energy of the firewood source was differentiated according to final uses. Among these, the consumption of final energy for hot water at 60 °C was computed applying the following equation:

$$FE_{wh} = m_{H_2O}\, cp_{H_2O} * (60 - T_{amb}) \qquad \textit{Eq 2.3}$$

where FE_{wh} is the final energy consumption for hot water, m_{H2O} the mass of water, cp_{H2O} the specific heat of water and T_{amb} ambient temperature.
Then, the related consumption of primary energy was obtained thanks to the efficiency of the system used to heat water according to *Eq 2.4*:

$$PE_{wh} = FE_{wh} / \eta_{3SF} \qquad \textit{Eq 2.4}$$

where PE_{wh} is the primary energy consumption for hot water and η_{3SF} the thermal efficiency of the 3SF cooking system.

Eventually, primary energy for cooking was found as difference between total consumption of primary energy and consumption of primary energy for water heating:

$$PE_{cook} = PE_{wood} - PE_{wh} \qquad \textit{Eq 2.5}$$

where PE_{cook} is the primary energy consumption for cooking and PE_{wood} the overall primary energy of wood.

In the *gas use and supply* section of the questionnaire, the quantity of gas consumed is expressed in terms of kg of LPG. The fuel is liquefied under high pressure and stored in metal bottles of standard size. The average consumption of the primary source of LPG is expressed in GJ by taking the net calorific value of 46.15 MJ/kg [24]. The consumption of secondary energy is computed by considering the thermal efficiency of LPG stoves being 63% [46].

In the *other sources of energy* section of the questionnaire the use of alternative sources of energy was investigated. The final use of kerosene had been asked in the questionnaire as well as the average consumption in litres per month. This quantity was then converted into primary energy thanks to the LHV of kerosene of 43.92 MJ/kg and a density of 802.6 kg/m^3 [24]. The efficiency of kerosene stoves of 51% was taken from past experience [46]. Charcoal was another source of energy was another source investigated. Basically charcoal came from the firewood burnt in 3SF. Due to the difficulty to measure the quantity of charcoal left by firewood burnt, collected and recycled for other aims, the average consumption of charcoal has not been quantified. This leaves practically unaffected the energy balance since only few households used this source of energy and on limited occasions.

In the *domestic waste production* the goal was to approximately quantify the residues coming from the farm of each family living inside the campus in order to compute the theoretical potential of biogas. Biogas can be mainly produced from corn silage and animal dung. The attention was then focused on these domestic wastes. All the types of plantations cultivated by each family were asked as well as the extension of the land. The number and type of animals owned by each family was demanded, in particular pigs, goats, cows and fowls. The potential of biogas coming from these sources is computed in the next chapter. In order to quantify the source of corn, the yield in terms of tonnes dry matter produced per hectares of cultivated land had to be assumed. From the World Bank, the production of corn dry grain per hectare of harvested land in Cameroon between 2010 and 2014 has been of 1.65 tonnes [47]. However, in case of corn harvested to produce biogas the yield is much higher, since more parts of the plant can be used. According to the IEA Bioenergy, corn used as energy crops yields between 9 and 30 tonnes of dry matter per hectare [48].

For what concerns the potential of biogas coming from animal waste, average tonnes of manure per head were considered for each species [49]. The results are presented in the next chapter.

2.1.2 Public energy driver

The public sector represents the second energy driver of CPC Bali analysed during the period in Cameroon. Comparing to the domestic energy driver, the public assessment was more encompassing as the activities directly related were many. Electricity was analysed through observations, whilst thermal energy with the help of direct measurements of wood, being the only primary source used to cook and boil water. In the following subsections, such activities are extensively explained with the related focuses.

Surveys and observations

During the whole period of stay on the field of study, surveys were conducted in order to gather information on the school, treated as public service unit with different energy consumption patterns. The collected information concerned cooking habits, timing and technologies adopted in the kitchen and in the bakery. In addition, number, model, rated power and time of use of electrical appliances in dormitories, classrooms, laboratories, offices and church were taken.

Observations regarded the electrical consumption of the entire school campus from the installed central electricity meter were taken. In order to obtain the load curve, the procedure described in paragraph 2.1.3 was followed.

Direct Measurements

The energy balance assessment implies the acknowledgement of resource consumption of the people living inside the school campus area. Thus, direct measurements were necessary in order to acquire an insight of wood utilization rate in kitchen and bakery. Wood had been cut in logs and branches, carefully weighted with an industrial scale recalibrated for this purpose and grouped in hips of 400kg and 150kg, respectively (Figure 2.3). It was estimated in advance that such hips were in sufficient quantity to meet the wood demand of both facilities, with the help of the Chief Cook and the Board Master. At the end of every single day for a total of one week, the remaining quantity was measured obtaining the average consumption of firewood.

Figure 2.3 Weighting wood with industrial scale (left), wood bundles (right.) Source: Authors

Bridging the gap between need and consumption of wood fuel required the understanding of working principles and performances of the kitchen stoves. Therefore, a reviewed version of the WBT was performed on them. The attended procedure will be extensively explained in the following section.

For what concerns the efficiency of the oven of the bakery, a tailored test was not feasible. In the literature, the energy efficiency index for baking processes is defined as the ratio of the energy used by the product during the process (enthalpy change of dough from the initial temperature to the final temperature plus the energy due to the moisture loss of the bread during baking) to the energy demand of the equipment (primary energy of firewood) [50]. From the literature, the mean specific energy demand for bread baking is

3.7 MJ per kg of dough of which around 37% due to heat the dough and moisture loss. Eventually, 1.37 MJ/kg is considered to compute the final energy consumption to bake bread.

Interviews

Several interviews were carried out inside the school campus. The Principal has been interviewed concerning the availability of wood resources, the management of the school and the organizational structure of the Presbyterian School in Cameroon administered by the Protestant Church. In addition, the school plumber was consulted to know the water resources used by the school and those possible to be exploited for energy purposes.

Water Boiling Test

Due to the nature of the information gathered about thermal energy consumption covering the primary energy supply without any hint on the real need of such energy type, the WBT was performed on two cooking facilities: the improved cooking stove in the kitchen and the sawdust pot for domestic users. The methodology is reported here since the WBT interests both domestic and public sectors. The relevance to mention how the WBT was conducted is due to its adaptation to the contingent context.

The WBT is a controlled test to measure the efficiency of a stove at converting fuel into heat to boil a certain amount of water. Since it is performed under the control of a technician it might not be representative of actual cooking conditions or habits. However, for the aim of this thesis and the available equipment during the study on the field, the WBT gives a rather reliable indicator of efficiency. In addition, it was performed by a local operator, which somehow should align the results with the real cooking behaviour. As an internationally recognized and standardized procedure [42], it establishes the conduction of three steps consequent to each other. The first (cold start) and the second (hot start) are meant to bring water at boiling temperature as shown in Figure 2.4, entailing a great amount of firewood to be inserted in order to develop a great thermal power. After each of these two steps, the pot has to be removed from the cooking facility and weighted together with the water, without the evaporating quantity. The third part is supposed to simulate the cooking of meals requiring long time (e.g. beans, cereals), so it is sufficient to have water approximately at boiling condition ($T_{water} \geq T_{boil}$-6°C) and a moderate thermal power.

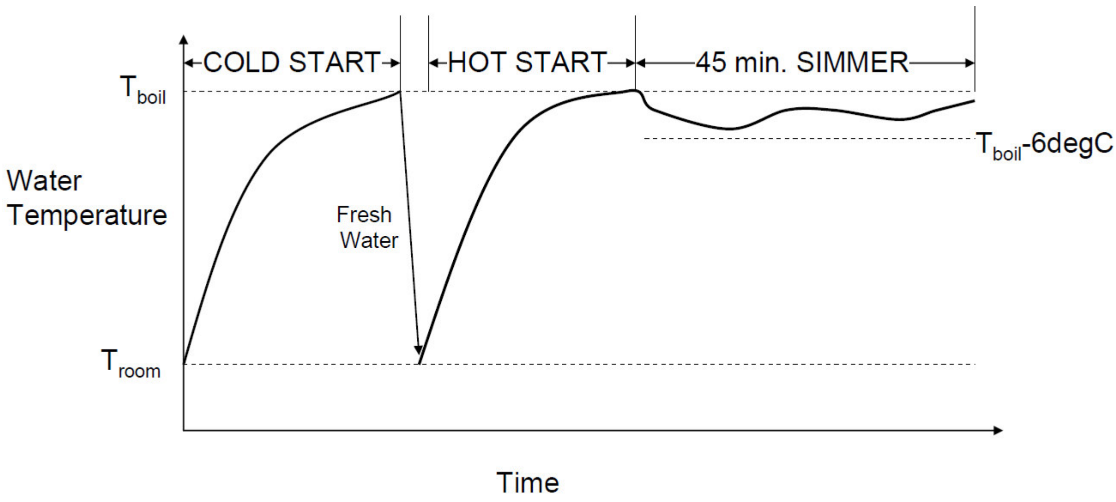


Figure 2.4 Temperature profile of the three phases of the WBT

Unfortunately, in the case of CPC Bali, the third phase could not be attended due to the long lasting of the test as a whole, including its preparation, which impeded the utilization of one of the seven cooking stoves. Being the kitchen of the school, the primary function was to provide meals for the students and it was impossible to have a time window satisfying all the parties; therefore, a compromise was found and only the first two steps were carried out. For what concerns the sawdust pot the encountered problem was similar, but applied to a private family.

A second differentiation from the standard protocol was the impossibility of pot removal in the kitchen upon completion of the first two steps. In fact, the pot was fixed in the wall of the stove. This was not the case of the sawdust pot where the pot could be easily removed due to its modest size (approximately 12 litres). On this type of pot, a last diversity from the standardized method to perform the WBT was registered. Due to its current and usual manner of use, the dust pressed into the pot is ignited only once until it burns completely. Following this path, the modified WBT consisted only in one step with cold start. In fact it was impractical to extinguish the fire, separating the charcoal from the unburnt wood. It is important that for the aim of this work a reference value of the efficiency was researched considering the feasibility of such measurement.

The equation to compute the thermal efficiency is taken from [42]

$$\eta_{thermal} = \frac{E_{hw}+E_{ew}}{Fuel_{eq\_dry}*LHV} \qquad \textit{Eq 2.6}$$

where E_{hw} is the energy to heat water from ambient temperature to boiling temperature, E_{ew} is the energy to evaporate water in the pot, $Fuel_{eq\_dry}$ is the equivalent dry fuel consumption. The equipment used for both tests was composed by:

- One thermocouple to measure water temperature;
- One quicksilver thermometer to measure ambient temperature;
- One scale with maximum weight of 20kg and sensibility of 20g;
- One plastic bucket to collect the unburnt firewood and the coal;
- One scraper to separate coal from unburnt wood;
- One chronometer to measure time.

Peculiarities and specifications of each test are reported in Appendix A; while efficiency and principal parameters in the next chapter.

2.1.3 Load curve and electrical energy consumption

Although in the previous paragraphs power consumption of CPC is computed by investigating separately the domestic and public energy driver, additional information was gained by looking at the central meter of the whole campus. The central meter counted the kWh that CPC consumed from the national grid, currently the only supply of electricity. The monitoring of the central meter was done in order to obtain the load profile of the campus and the power consumption. These results were also used to confirm the validity of the findings of the previous analysis.

The data to build the real load curve was gathered through daily observation of the central meter. In particular, a smartphone was used to snapshot the reading of the meter every 10 seconds (see the set-up in Figure 2.5) and to record the data for a total duration of 5 days. Then, the data was elaborated with an Excel spreadsheet. The choice of a time step of 10 seconds had been taken after some trials in order to have a compromise between the error and the quantity of data to process. Beside the typical load curve of the school, the overall daily consumption of electricity in the school was assessed. This kind of analysis gives relevant insights when future systems are considered to replace the current electricity supply. Indeed, both the total electrical energy consumption and the power load have to be always assured in order to provide a reliable and safe supply. The procedure was repeated for the months of September and October to observe differences of power load and energy consumption after the school has fully started.

Figure 2.5 Set up of smartphone for load profile measurements. Source: Authors

2.1.4 Energy flow diagram

The results of the energy balance assessment represent the basement for this work, thus a precise and well-organized structure is necessary. As described in paragraph 2.1, the reference is the article of Johnson [22], in which all the sources and uses are given with the corresponding percentage of occurrence. Nevertheless, a careful and more complete analysis of the energy consumption in CPC Bali is desired, so a different perspective is also adopted. According to the IEA energy flow diagrams [24], the conversion processes of sources are outlined though a step-by-step sequence from the primary energy supply to the final use. Therefore, such combination will result in a detailed representation of the data gathered on the field of study, quantitatively showing it in the singular and aggregate forms.

Although the IEA diagram is an extremely standardized method, it is fundamental to consider that its usual object of application is an entire country. This involves a natural adaptation to the studied context of a school campus, a micro-cosmos in this regard. Consequently, some entries are missing, for instance bunkers, exports, stock changes, even though the original layout is conserved: on the left the resources are found, moving to the right the conversion processes and final energy consumptions are outlined. Since the system of interest is CPC Bali, whichever energy conversion occurring outside these boundaries is not accounted within the redaction of the balance diagram. In addition, due to the difficulties encountered to measure the efficiencies of every single appliance, electricity is also considered directly as final energy supply. For what concerns other sources such as LPG, wood, diesel, kerosene and biodegradable waste, referenced and measured efficiencies are considered to link primary and secondary (or final) energy supply.

The energy flow diagram summarizes the first objective of this thesis work, displaying the most important features of the energy consumption of CPC Bali, without neglecting the details required by this kind of analysis. The overall flow diagram was drawn with the help of eSankey 3.0 software.

2.2 Renewable source assessment

The assessment of the RES potential of CPC Bali accomplishes the second specific objective of the thesis project. Among the RES those locally present and assessed are biogas, hydro, wind and solar energy. The methodology applied to compute the potential for each source is described below.

2.2.1 Biogas

The potential of biomass for the production of heat and electricity can assume multiple forms. Indeed, biomass comes from different sources and can be also converted into useable energy by means of several technologies. Above all, the firewood source needs to be addressed as renewable or not. Thus, the attempt of this paragraph is to confine the analysis of biomass potential within clear boundaries and to provide the methodology to assess it.

The current situation of CPC Bali presented a huge consumption of firewood as primary source of thermal energy; although trees were replanted frequently, the rate of cutting trees remained too high compared to the growth of newly planted units. This shall lead to deforestation and depletion of soil in the long run. Since its current over use makes the source scarce, firewood cannot be considered a RES in the short term. Despite the fact that firewood is undoubtedly a source of biomass, its potential was not explored in this paragraph, where only renewable sources of biomass were assessed.

Beside firewood, three biogas systems were installed inside the campus. Only one, fed by faeces and urines of male students, worked and produced biogas during the observation period. The system consisted of two digesters connected in series where the anaerobic digestion by means of bacteria takes place. Biogas was produced by both the digesters and was delivered from the system by means of a pipe.

In the analysis of biomass potential, those sources convertible to biogas were considered. The final result was then expressed in cubic meters of equivalent biogas having a LHV between 21 and 37.5 MJ/m^3 [2]. The idea was to quantify the theoretical increment to the actual biogas production. Three types of sources were included in the analysis: corn, human and animal waste. The other plantations of the local farms, such as banana, plantains, pineapple, tubers, cereals and vegetables were not considered because they were representative of potential crops for energy purposes. However, they still produced biodegradable wastes resulting from peeling or cleaning mainly in the kitchen of the school, but they were not quantified. This should have negligible effect on the analysis since the organic waste was already recycled inside the campus as animal feeding, so the quantity was consistently reduced.

The biogas potentially coming from corn was assessed considering the average quantity that could be extract from a fixed amount of harvested products. From a laboratory digester undertaking anaerobic digestion of maize, the biogas production resulted to be between 455 and 603 Nm^3 per tonnes of volatile solids that corresponded to a production of methane from 251 to 339 Nm^3/tonnes of corn (around 55% of methane content) [51]. The range stated by the IEA is wider, from 205 to 450 Nm^3 of methane per tonnes of volatile solids [48]. An average production of biogas of 530 Nm^3 per tonnes of volatile solids was assumed in this thesis. The tonnes of corns produced on a monthly basis resulted from the questionnaire administrated at domestic level to analyse the domestic waste production.

The biogas potential from animal waste was assessed in relation with average yield (Nm^3) per tonnes of dry matter of animal dung. This was done by selecting the potential of different animal dungs found in the literature [49]. The mass of manure produced from animals was also assessed in the questionnaire administrated at domestic level to analyse the domestic waste production.

A similar approach was followed for human faeces and urines. The average daily production of faeces and urines, dry organic matter and biogas yield were taken from the literature [52], expressed in terms of grams per capita. Being such values referred to adults, for people less than 16 years old half of average production was taken as approximation, while infants were not included in the analysis. Subsequently, knowing the total population of CPC, the overall production of human faeces and urines was computed. Moreover, a separate investigation was made for the current biogas system fed by the male students' faeces. Indeed, through direct observations of the gas meter installed, the average production of biogas was assessed in field.

Finally the production of the current system was analysed and compared to the overall potential of biogas. The quantity of biogas produced was assessed by taking periodically readings from the meter. During that period the breathing pipe connected to the digester was left open. At the end, the average production was obtained for a total of 43 days, starting from the 19th of September and ending on the 31st of October.

In the next chapter, the results are presented and the potential of the current working digester compared to the observations in field.

2.2.2 Hydro

The hydro source has been one of the most exploited RES around the world for more than a century. The kinetic and potential energy of flowing or falling water can be converted into mechanical energy of a rotating shaft by means of a turbine and subsequently into electricity through a generator. Hydropower is an interesting application when power units have to be installed in rural and isolated areas to locally supply electricity. In fact, if the hydro source is present on the field, micro hydropower is a valid solution to investigate as it uses proven and mature technologies, with relatively low operation costs while offering a stable supply of electricity [53].

Through the survey of the environment, it was found a stream around the school from which hydropower could be generated. Part of the stream was already caught and filtered in order to provide fresh water to all the facilities and households inside the campus. The current water system was constituted by a river catchment, a filtering system, a pipe where fresh water flew to reach the school and an internal grid in CPC. Thanks to the relevant head, water moved only by gravity and no pumping system was needed.

Micro hydropower could represent a renewable and sustainable source to supply power to CPC Bali. The gross potential of the hydro source is basically given by two parameters, water flow and head, as *Eq 2.7* shows:

$$P_{gross} = g * H * \rho_{water} * \dot{Q} \qquad \text{Eq 2.7}$$

where P_{gross} is the gross power, g the gravitational acceleration, H the head, ρ_{water} the water density and $\dot{Q}$ the volumetric flow rate of the river. Thus, flow rate and head between catchment and location had to be measured. The gross potential is the energy contained in a given quantity of water with a certain head. Instead, the net power P_{net} accounts for the losses along the conversion chain (penstock, turbine, generator, drive system) in the efficiency term η:

$$P_{net} = P_{gross} * \eta \qquad \text{Eq 2.8}$$

Since fresh water had to be always guaranteed to the school, the water to produce power should be taken downward the river catchment currently present; thus, for the assessment of the hydro potential, the water flow had to be computed downward the existent catchment for drinking water.

The activities to assess water flow and head are explained in detail in the next subparagraphs.

Water flow

Uncountable methods have been found in the literature when the water flow had to be assessed on the field [54]. Using electromagnetic current meter represents an option, but the instrument was not available during the inspections to the river. The weir method was impossible to apply because it required the presence of a structure such as a low wall across the river that was not in place. The container method implied the diversion of the whole and the use of a container that was filled by the water; unfortunately, even in this case, diverting the whole flow of the river was unfeasible. Eventually, the water flow was measured by undertaking the 'Floating Object Test'. This test represents an easy way to measure the approximate water flow of small rivers and consists in multiplying the cross sectional area of the river by the velocity of the water. First of all, a straight length of the river of around 10 meters had to be selected.

Figure 2.6 Depth measurement (left); 10m distance of the stream (right). Source: Authors

Then, in order to know the cross section of the river, the depth of the stream at equal intervals along the width was measured by using a meter stick. Three cross sections were measured along the picked length and the average of the three was used for the calculations (see Figure 2.7). Due to the relative fixed geometry of the river portion, along this length the velocity of the water was supposed to be constant. Figure 2.7 shows the measurements of depth and length of the river.

The velocity was assessed by throwing a floating object (an orange of 7.5 cm of diameter) upward the initial cross section and measuring the time it took to travel down the length of the stream with a stopwatch. This was repeated ten times in order to have a more accurate average velocity of the stream. *Eq 2.9* was then used to estimate the flow Q:

$$\dot{Q} = A_{mean} * V_{mean} * C \qquad \text{Eq 2.9}$$

where C is a correction factor that converts the measured mean surface velocity into the effective mean velocity V_m and A_{mean} is the mean river cross section. The correction factor depends on depth and riverbed type:

1) Concrete channel which cross section is uniform = 0.85
2) Small stream where a riverbed is smooth = 0.65
3) Shallow flow (about 0.5 m) = 0.45
4) Shallow and riverbed is not flat = 0.25

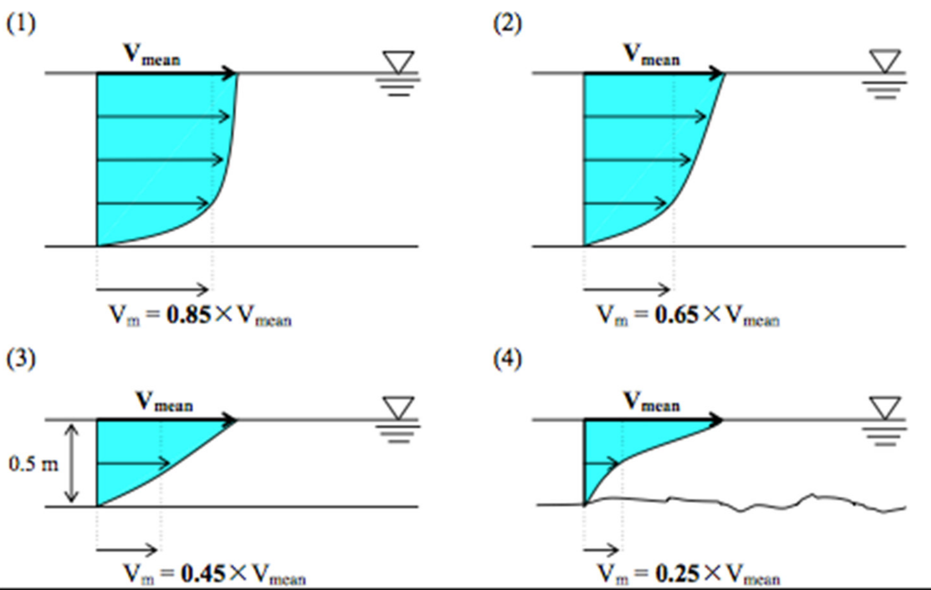


Figure 2.7 Correction coefficient for different riverbed types. Source: [54]

The test was conducted on two occasions: in the second week of October and after three weeks, to take into account the change of the water flow in November.

The average water flow of the river computed with the Floating Object Test gave an indicative idea of the size of the river. However, the approximate value previously computed had to be refined and extended to the whole year for the investigation of power production. Generally, when data on daily measurements of a water stream along one or more years is unavailable, three methods could be used for the trend estimation of the water flow: empirical, statistical and rainfall-runoff modelling. The empirical method evaluates stream flow indices with simple mathematical equations. Basically, it compares the river with another similar whose data is available. This method has been applied in different micro hydropower prefeasibility studies as the Bekele's [55], where a reference river was set to estimate the flow rate of the examined river comparing their catchment areas. The more complex statistical models derive the flow at ungauged sites with the aid of multiple regression techniques. The rainfall-runoff method models the stream flow representing hydrological processes such as catchment structure, rainfall inputs, evaporative outputs and stream flow, with mathematical equations [56]. Eventually, simple transposition technics exist when short records of the river flow are available, as the case of this thesis. It consists of regressing the short records against the known flows of a gauged river by overlapping the period and then predicting a relationship between the two-flow series. This method can be applied under the assumption that the river catchments are synchronous, i.e. when the reference river catchment is [56]:

1) geographically close to the ungauged catchment and hence has the same climatic regime;
2) hydrogeologically similar;
3) similar in size;
4) either a natural catchment or one that has a naturalized flow record.

The river Mewou was chosen as reference. It is a small river flowing in the West region of Cameroon, adjacent to the North West region, so conditions 1 and 2 are respected. The stream flow is one order of magnitude higher, acceptable for the purpose of this analysis. An additional but strong assumption made was that the flow rates measured with the Floating Object Test were considered as mean values of the month of October and November. In the reference found, the flow rate of the Mewou river is measured by means of a gauging float and data are available from July 2011 until January 2013 [57]. The data of the whole 2012 was used as reference. So the linear regression was built by applying the following equation:

$$\dot{Q} = a + b * \dot{Q}_a \qquad \textit{Eq 2.10}$$

where $\dot{Q}_a$ is the flow rate of the analogue catchment, a and b are the regression coefficients estimated from with the method illustrated above, so when the flow records $\dot{Q}$ are available. The lowest water level occurring during the driest period was then estimated and compared to the information coming from an interview with an employee of CPC in charge of maintenance and management of the filtering system, who gave a rough estimation of the yearly lowest volume flow rate of the river.

Beside the lowest flow rate available, the compensation flow rate had to be defined. It represents the minimum flow of water to be maintained at any time in the natural channel in order to safeguard aquatic life and other activities that exploit the water source downward the catchment. No particular activities were found except washing and cattle drinking. In absence of a regional legislation and policy, the residual flow, that is the flow remaining in the river when abstraction is taking place, had to be set to the minimum level of the compensation flow. In literature, the most conservative approach expects a compensation flow rate equal to the 50% of the flow rate [58]. Average flow rate, mean flow rate and residual flow rate were then computed (section 3.2.2).

Hydraulic head

The hydraulic head between the river catchment and the campus was also assessed. The head can be measured with different methods: clear hose method, spirit level and plank method, altimeter method, sighting meter method [54]. The instrument used for the study was the altimeter since it represents the most suitable method to assess the head when distance between the possible river catchment and the location of the power room is very long. The altimeter is a gauge instrument that measures the height above the sea level by calculating first the atmospheric pressure. Several measurements should be taken since the accuracy of a single-day measurement can be low due to the influence of temperature, atmospheric pressure and humidity. Unfortunately, due to the difficulties to reach the river because of the bad conditions of the road only three records were taken during daily inspections to the river. The height difference between a reference position in the campus (biogas system) and four different places along the river was taken.

During the period abroad, the river site under investigation was identified in satellite images provided by Google Earth with the help of local people. The head previously measured by using the altimeter was then compared with the one found by using Google Earth. The results presented in the next chapter show only a small discrepancy among the values. However, due to the few records taken with the altimeter, the height difference from Google Earth was considered more accurate. With the same software, even the distance of the penstock was estimated. Figure 2.8 shows the layout of the hydropower scheme and it used as reference for the results in the next chapter.

Figure 2.8 Proposed layout of Micro hydropower scheme. Source: adapted by authors from Google Earth

2.2.3 Wind

A complete overview of the wind source potential requires the collection of data over a reasonably long period of time, such as one year in order to filtrate perturbation occurrence. Subsequently, data are processed to obtain the wind regime profile, evaluating the wind potential for possible hybrid generation systems embedding micro wind generation.

Measurements

The task of measuring the wind was eased by the presence of a cup anemometer already installed on an elevated area within the school. Generally, cup anemometers use their rotation, which varies in proportion to the wind speed, to generate a signal that is converted into data. The model installed was the LeWL Wind Speed Logger of the Logic Energy Ltd. The LeWL is an automatic stand-alone data logger charged by batteries, monitoring 2 digital inputs, 1 analogue input and a built-in temperature sensor. The cup anemometer was placed on a vertical shaft at height of approximately 11 metres. At the end of every month since its installation in May 2014, data was collected concerning wind speed, direction, temperature and pressure for every minute, saved on a CSV file on the SD Card provided with the anemometer. The data collection covered the period from June 2014 to October 2014 included. Wind data of November and January were sent later by the administration office of CPC. Figure 2.9 shows anemometer and data acquisition.

Figure 2.9 LeWL logger (left); anemometer installation (center); data acquisition (right). Source: Authors

Wind characteristics and Weibull distribution

Prior the presentation of the methods to visualize the wind speed distribution during the observation period, some characterizing parameters were calculated in order to obtain a well-rounded knowledge of the wind regime.

At first, the average wind speed was found together with the standard deviation by means of implemented functions in Excel. These two fundamental parameters represent the base upon which the Weibull distribution calculation methods are built. A further parameter is the autocorrelation factor, stating the influence of the wind speed at a certain time step over the wind speed in the next time step. Considering the measurements with a time step of one minute during five entire months, it was possible to compute the autocovariance c_j at lag *j*, according to [59]:

$$c_j = \frac{1}{n-j-1} \sum_{t=j+1}^{n} (V_t - V_{mean})(V_{t-j} - V_{mean}) \qquad \textit{Eq 2.11}$$

where V_{mean} is the average wind speed, V_t is the wind speed measurement at a determined time step *t* and V_{t-j} is the wind speed measurement occurring at a unit of time *j* in advance with respect to *t*. By dividing c_j for the variance c_0 of the data series, the autocorrelation factor r_j was found:

$$r_j = \frac{c_j}{c_0} \qquad \textit{Eq 2.12}$$

Another useful parameter is the hour of peak wind speed (Φ), which indicates the time of day with the greatest wind speed. Obviously, such time is not exactly the same for every day, consequently the largest occurrence was taken as reference time of peak wind speed. From this, the diurnal pattern strength could be obtained. Being a number between 0 and 1, it describes the strength of wind speed dependence on the time of the day. The diurnal pattern strength δ is derived from [1]:

$$\delta = (\frac{V_i}{V_{mean}} - 1)/\cos\left[\left(\frac{2\pi}{24}\right)(i - \Phi)\right] \qquad \textit{Eq 2.13}$$

for i=1,2,…,24, where V_i is the hourly average wind speed.

Due to its random nature, wind speed has a distribution over a range of values, usually set between 0 m/s and 25 m/s. The frequency distribution is described statistically by the Weibull distribution. The shaping of the Weibull frequency distribution resembling the real data frequency distribution is translated into the identification of the two characterizing parameters of the Weibull distribution itself, i.e. the shape factor (k) and the scale factor (c). The shape factor determines the wind speed regime of the region and whether there is a higher concentration of energy below or above the average value; the scale factor states the concentration of the distribution around the mean wind speed [60].

From real data there exist different paths to take in order to obtain such distribution. Three methods are reported in this work to highlight possible differences in the corresponding values. The analytical method [1] expresses the average wind speed and the standard deviation in terms of k and c embedded in gamma functions.

$$V_{mean} = c * \Gamma\left(1 + \frac{1}{k}\right) \qquad \textit{Eq 2.14}$$

$$\sigma = \sqrt{V_{mean}^2 * \left[\frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2\left(1+\frac{1}{k}\right)} - 1\right]} \qquad \textit{Eq 2.15}$$

The resulting parameters were computed iteratively setting as initial values k of 2 and c of 4. Few iterations were required to obtain the true values.

Beside the analytical calculation, also two empirical methods were applied. The first is suggested by Kaoga [61], according to which the shape factor is directly correlated, through an exponential law, to average velocity and standard deviation, as described in *Eq 2.16*; scale factor is then found with the help of the gamma function (*Eq 2.17*).

$$k = \left(\frac{\sigma}{V_{mean}}\right)^{-1.089} \qquad \textit{Eq 2.16}$$

$$c = \frac{V_{mean}}{\Gamma\left(1+\frac{1}{k}\right)} \qquad \textit{Eq 2.17}$$

A second method was selected to avoid the use of the gamma function, by applying a purely empirical correlation [62]. Nonetheless, the formulation to find the shape factor is rather similar to the previous, as seen in equation *Eq 2.18*:

$$k = \left(\frac{\sigma}{V_{mean}}\right)^{-1.086} \qquad \textit{Eq 2.18}$$

$$c = V_{mean}\left(0.568 + \frac{0.433}{k}\right)^{-\frac{1}{k}} \qquad \textit{Eq 2.19}$$

The values of average wind speed, standard deviation, shape and scale factors are reported in the section results.

Scaling wind data

The measurements taken in CPC Bali started only in June, allowing a data set of 7 months for the wind speed. A larger sample would be required in order to outline a thorough wind regime considering also seasonal and year fluctuations. However, due to the lack of such data, a scaling of the wind speed trend during the year was performed comparing to well-known and reliable measurements over a longer observation period.

The reference data set was taken from the NASA [63] for the location of the city of Bamenda, capital of the North-West region in Cameroon, at approximately 16 km from the field of study, thus a reasonable distance to be taken as reference. The methodology applied to scale wind speed data is a linear regression, as suggested by Rogers [64], in which V_{CPC} are the available CPC measurements while the independent variable V_{NASA} is the reference value. The coefficients m and q are computed through the known wind speed values:

$$V_{CPC} = m * V_{NASA} + q \qquad \textit{Eq 2.20}$$

A further method is to correlate data through an exponential interpolation, as proposed by [65]. The coefficients r and s are computed through the exponential interpolation:

$$V_{CPC} = r * {V_{NASA}}^{s} \qquad \textit{Eq 2.21}$$

The resulting wind regime and the corresponding values are presented in paragraph 3.2.3.

2.2.4 Solar

The last RES studied in the research was the solar energy. The motivation to insert this source was its great availability and the shared public consensus about the possibility to exploit it for electrical and thermal purposes. Unfortunately, the current study was performed during a time window of three months coincident with the rainy season. Thus, direct measurements of the sun irradiation on the field of study were impossible to take, also considering the absence of adequate measuring instruments. Therefore, the potential of solar energy was estimated only through literature research.

The methodology followed is straightforwardly simple. In fact, a reliable dataset is provided by the NASA [63], which Afungchui and Neba have used as benchmark in their article [66] concerning the estimation of solar radiation through several methods. Due to the proximity between CPC Bali and the city of Bamenda, capital of North-West Region in Cameroon, the data concerning the latter place was taken as reference. Only average monthly values were considered due to the limited availability. In addition, it was impossible to verify such values through the clearness indices since their calculation is based on the solar radiation [67], which is selected from the NASA in turns. The sole possible comparison was by means of solar map internationally recognized visualizing a range of yearly sun irradiation on the whole Cameroonian territory. The results are reported in paragraph 3.2.4.

2.3 Energy solution planning

The energy solution planning consists of matching local needs and RES with the installation of alternative technologies or modifying the current energy asset of the system. Since electrical and thermal demands are rather different they are investigated separately. The electrical solution planning was based on the use of HOMER®, a software that simulates off-grids or hybrid micro power systems. Renewable sources, technologies and power load were modelled with the software in terms of potentials, technical features and costs. For the thermal solution planning a different approach was used. Specific solutions were analysed for each thermal needs. In the following paragraphs 2.3.1 and 2.3.2 methods adopted for electrical and thermal energy solution planning are described.

2.3.1 Electricity solution planning

The modelling of the electric system at first, the simulation of a RES based micro power system in second instance were performed with the help of the software HOMER®, developed by the National Renewable Energy Laboratory (NREL). HOMER® is an optimization modelling program supporting the design of micro power systems, mainly based on RETs, performing simulation and allowing the comparison of several setups and technologies. It gives the possibility to model grid-connected and stand-alone systems [68]. The goal function is the minimization of the Net Present Cost (NPC) over the system lifecycle, while respecting constraints on availability of resources, meeting the load demand and other aside parameters set by the user. The software works on three subsequent levels of modelling:

i. *simulation*
ii. *optimization*
iii. *sensitivity analysis*

The simulation process involves only one specific configuration; whilst, the optimization phase aims at finding the best system among those possible, always under certain constraints. The last step is to verify the robustness of the optimal solution according to variations in some input variables, which may be affected by uncertainty [69].

In the modelling of the system with HOMER®, the base case scenario included the technologies to exploit the studied RES: water turbine, PV panel, wind turbine and hybrid diesel generator. Prior to their description, the load profile had to be set in order to establish the energy demand of CPC Bali to satisfy. Such task was fulfilled thanks to the collaborative work with Losa [70]. Through real data collected on electricity consumption, power appliances and their use windows during the three months of stay, it was possible to develop and test a model able to estimate and forecast load profile of a certain user. An additional option for randomness was included to obtain different load curves for any day of the year. The resource input was derived from the energy balance assessment.

A brief explanation is necessary for what concerns the technologies inputs. As preliminary consideration it is important to mention that all data reported was collected in field with surveys, observations and investigations. Whenever it resulted impossible, literature references were considered taking the most inherent to the CPC Bali context.

Hydropower turbine

For the hydropower turbine, the type selected was a cross-flow turbine for the relative simplicity of design, the high reliability and the availability in the local marketplace, as the characteristics of the surrounding system. The costs were found through surveys while the O&M costs taken from the IRENA report [71]. The flow rate was set below the upper limit represented by the residual flow rate as explained in the assessment of the hydro source. In this way a range of flow rates was simulated in order to find the best techno-economical solution.

PV solar panel

The capacity of PV panels is not a fixed parameter, but different sizes can be simulated with HOMER®; the maximum size considered was the one fulfilling the entire demand when the highest peak of the day occurs. The costs related to PV panels resulted from a compromise between local researches and the LAZARD report [72]; the reason lies on the wide range of $/kW. The PV derating factor (a scaling factor accounting for power losses due to different reasons) was taken from a similar case study in Nigeria [73].

Wind turbine

Although HOMER® provides a good selection of micro-wind turbines with few kW of power, further turbines (either HAWT or VAWT) were added from the work of Molina and Rostoni [17] to have a full insight into the market. For what concerns the size to consider, the same approach used for PV panels was followed.

Diesel generator

The production of biogas in the school campus unfolded the possibility to obtain a hybrid diesel generator running with a mixture of fossil fuel and biogas. The current production of biogas quantified through in field activities was then used as input in HOMER®. While the investment cost for the generator was null since it was already in place, the investment cost to make the system hybrid was found from an NGO working in this field [74]. The replacement cost was assessed from an interview with the bookkeeper of the school, documented with bills on the current generator, as well as other characteristics from the producer [75]. The cost relative to the fuel and the grid price were obtained from consultation of diesel and electricity invoices in the school archives.

Converter

The selection of the size and voltage of the converter playing the role of inverter (from DC to AC) and rectifier (from AC to DC) was fundamental to match the correspondence between alternate and direct current buses. In addition, it established the maximum power that could flow from one bus to the other, i.e. the maximum power PV panels, wind turbine and/or batteries can give instantaneously to cover the load profile. Information on costs, sizes and voltages were taken through local investigations and a market research.

Battery

A battery bank is always required whilst dealing with RETs in a micro power system. The type was chosen from the catalogue embedded in HOMER® and the costs were found relative to the Nigeria case study [73].

Simulation and results

After having reported the input parameters, the above mentioned three levels analysis were performed. In the first instance, a simulation of a complete set of RETs was done aimed at optimizing the system configuration satisfying the constraints, as stand-alone and grid-connected systems. Then a sensitivity analysis was performed, checking the resilience of the best solution dealing with uncertainties relative to PV capital costs, wind turbine capital costs, diesel price and grid electricity price.

2.3.2 Thermal solution planning

In this paragraph, the methodology for the thermal solution planning of CPC Bali is discussed. Although the approach by Ramakumar [27] is a valid alternative when thermal energy systems based on RES are to be designed together with electrification, in the case of this thesis a different approach was used. Due to the lack of economic data, the analysis of the thermal load was conducted only considering the potential of local resources to meet the thermal needs. A solution-focused approach was then followed for each thermal need.

The solution-focused methodology consisted of first looking at the specific thermal requirements of the local community and secondly investigate ad-hoc solutions for each need. The approach was then more specific than for the electrical energy solution planning, since it was based on the results coming from on field surveys and observations about the thermal energy consumptions of CPC community. Thermal energy consumptions are embedded into the domestic and public driver and they can be also schematically visualized in the energy flow diagram of CPC (Figure 3.4). The areas where thermal energy is needed are:

- public cooking
- public baking
- public water heating
- domestic cooking
- domestic water heating

The public need of hot water for the students of CPC has been added to the four final uses, because it is an energy requirement currently unmet. In fact in this analysis, solutions are provided to meet the needs that are currently unmet or only partially satisfied.

The current thermal consumptions for domestic and public cooking as well as for public baking were the only ones considered actually fully satisfied. Therefore the consumption coincides with the actual need. This assumption was rooted on the observations made during the period in Cameroon, where, thanks to the abundance of the firewood source, shortages of primary energy to supply school kitchen and oven and domestic kitchens were never experienced. However, energy losses for these uses were huge due to the poor conversion efficiency of cooking technologies. Further, cooking conditions proved to be very poor and far from minimum standards.

On the contrary, the energy need for water heating was partially met for the case of households, while totally unmet for students. At domestic level, mostly families with children used to heat water with 3SF; others preferred to save firewood and have bath or conduct other hygienic activities with cold water. This led to considering a minimum standard per capita of hot water to be supplied, regardless the current energy consumption for water heating. The reference is provided by the World Health Organization, which established an intermediate level of daily water access per capita, covering the need of bathing and laundry, unaccounted in the basic level. This level corresponds to daily quantity of 50 litres per capita in total, with 30 litres only for bathing and laundry, being the difference with the basic level of 20 litres [76] (see also Table C.5 in Appendix C). The computation of the thermal energy demand of hot water ($FE_{hot\ water\ domestic}$) is derived from the equation 2.22:

$$FE_{hot\ water\ domestic} = c_p\ \rho_{water}\ V_{water}\ (T_{hot} - T_{cold}) \qquad \textit{Eq 2.22}$$

where the water volume (V_{water}) is 30 litres, c_p is the specific heat of water, ρ_{water} the water density, T_{cold} is the initial water temperature set at 20°C as from the WBT, while T_{hot} is the final water temperature. This latter parameter is found to be in the range between 40°C and 50°C [77] [78]. An intermediate and reasonable value of 45°C was selected.

In the following sections, methods used to investigate the fulfilment of the thermal energy needs with local sources are explained. All the solutions provided have common guidelines. They have to be potentially feasible, thus satisfying the whole thermal demand, using local and available RES, reducing the monthly consumption of firewood and thermal losses, improving the current system in terms of reliability and quality of energy or fuel, permitting a sustainable development of the community by reaching minimum standard levels. Economic analyses are not included in this part. Further studies should be carried out in order to prove the economic feasibility of the proposed solutions.

Public cooking

The huge amount of firewood use in the school kitchen is caused by the consistent number of students to feed and the partial inefficiency of the improved cooking stoves (see figure 2.10).

Figure 2.10 ICS of school kitchen and cook during usual cooking operation. Source: Authors

In fact, upon several visits to the kitchen and various activities conducted there, some adjustments could be carried out in order to improve the current situation characterized by high concentration of smoke and considerable heat losses. A proper and regular maintenance should be attended. The focus should be placed on the integrity of the brick stoves, aimed at preventing any leakage of combustion gases, the cleaning of chimneys to allow a fluent exhaustion and the repair of stove closure doors. However, the estimation of the efficiency improvement according to these actions is rather difficult since no reference benchmark exists for a comparison with a “best practice” of the same kind of stove. Actually, a second prototype of the CPC Bali stove was under construction in another school, by the same engineer (see figure 2.11). The layout was slightly changed according to the available space while enhancing the heat conservation and transfer. From the picture below it might be possible to outline a compact structure with all the pot fittings next to each other. Unfortunately, it was impossible to conduct a WBT on site.

Figure 2.11 ICS of a public school of Bamenda. Source: Authors

The issue moved to the choice of a valid substitute to the kitchen stoves. Due to the large size for providing food to more than a thousand students, a comparable alternative should be found. Although delocalized in space, the ASTRA stove represented a good example of improved cooking stove of remarkable dimensions. It is widely used in India, where it has been developed. The layout is rather similar to the present stoves, with two pot fittings next to each other and a common chimney. In addition, it had the same application of the case of CPC Bali, being utilized in the kitchen of a tribal school in rural area in Karnataka [21]. The efficiency of the ASTRA stove was computed through the WBT, resulting equal to 37%. Further readings have shown a slightly higher efficiency in the range of 40%-45%, due to the optimized use comparing to a standard WBT, unlikely to describe the actual cooking habits [79] [80]. Thus, 40% was selected as the efficiency value.

The last step was to compute the primary energy supply in case the ASTRA stove was built to replace the kitchen cooking stove. It was achieved by considering the final energy consumption unchanged with the present situation as it proved a sufficient level of nutrition for all the students and the personnel.

Public baking

The current system to bake bread consisted in a firewood oven as described in section 2.1.2. In the results chapter the quantity of firewood consumed every day is computed. Figure 2.12 shows the current oven to bake bread. Together with the school kitchen, the bakery consumed the largest quantity of firewood in the school.

Figure 2.12 Bakery oven during operation (left); back-door for firewood inlet (right). Source: Authors

For this final use of energy the solution focused on the firewood substitution with another cleaner and more available fuel. In particular, the use of electricity was investigated. Electric oven is a rather developed technology, especially in Western countries. If electricity could be produced in larger quantities and from renewable sources, it would surely represent a more sustainable alternative to traditional wood oven; then, wood consumption would drastically decrease. Further, electric oven would guarantee better life standards for workers, no more forced to work closely with fire and to inhale black smoke, ashes and other combustion exhaust.

The feasibility of this solution was based on the results coming from section 4.1 that suggested a reasonable availability of electricity from RES, especially from hydro source. The electric oven simulated was the model E32D5 manufactured by Moffat, found after a web research [81]. The oven was chosen for its suited dimensions and power rate. All the specifics of the convection oven, such as energy input rate, preheat time, heavy-load cooking efficiency and production capacity, were tested by applying the ASTM Standard Test Method F1496-13 [81]. The advantage of this solution lie on the flexibility with which the electric oven could work. A known quantity of bread is produced 6 days a week at CPC; since bread had to be supplied the day after, then the operation window was rather variable. The strategy adopted was to simulate again with HOMER® the same power system, increasing the load demand by the power consumption of the oven. The operation time chosen was during the daytime, between morning and evening peaks, in a time window where no particular loads were measured. The results provided by HOMER® were ranked in order of NPC as previously explained in section 2.3.1. The configurations simulated were both the off-grid system and the grid-RES hybrid system.

Public water heating

As previously explained, hot water at public level was currently unmet at CPC. The need of hot water comprised all the 1008 students of the school who on average used to the take two showers every day with a 10 litres bucket each time. Hot water for students is considered a high priority by the principal of the school since it is a need of great importance in order to improve the living and hygienic conditions of students. The strategy adopted herein is to investigate the feasibility of hot water for students by first exploiting the current biogas production, then the potential biogas by considering all the students, finally thinking alternative ways to fill the gap in case the biogas would be insufficient.

To calculate the final energy for water heating, 20 litres were taken as reference, while the temperature jump from 20°C to 45°C. The minimum quantity of water was lower than the 30 litres assumed for domestic uses because laundry activities were less recurrent and 20 litres corresponded to the current use for shower by students. The equation to calculate the final energy is the following, simply Eq 2.22 multiplied for the number of students $N°_{student}$:

$$FE_{hot\ water\ public} = N°_{student}\ c_p\ \rho_{H_2O}\ V_{min}\ (T_{hot} - T_{cold}) \qquad \textit{Eq 2.23}$$

The solution investigated was to exploit the current production of biogas by means of water boilers. In the literature this on-site heating solution is mentioned among the possible direct uses of biogas. Biogas boilers are simply re-adapted methane boilers; adjustments to the air-fuel mixture and enlargement of the burner jets are the precautions to take. Biogas boilers have sizes from 13 kW and larger, thermal conversion efficiencies between 75% to 85% and typical commercial control systems supplied with boilers [82]. The average thermal conversion efficiency used in this work was 80%. After having computed the final energy need, the conversion efficiency allowed to find the corresponding primary source. Eventually, the LHV of biogas (the average assumed here was 29.3 MJ/m^3) enabled to have the volume of biogas needed. This value was compared to the potential of biogas from students computed in section 3.2.1 and the alternatives were studied subsequently to fill the eventual gap, with particular attention to biogas from corn plantations wastes and from cows owned by the school or to solar collectors. The results are presented in section 4.2.

Domestic cooking

The investigation on the field of study revealed an extremely high diffusion of 3SF as main cooking technology. The heavy reliance of traditional biomass stove is not new in developing countries and this situation needs to be addressed immediately toward an improvement in both technology and habits [16]. In addition, ensuring access to modern cooking facilities is integrating part of the seventh SDG, driving force and basis of the whole research [4].

At domestic level, the selection of improved cooking stove was much wider comparing to the case of the school kitchen in which the dimensions played a determinant limiting role. Since the goal of this analysis is to suggest solutions to improve the situation either by reducing the primary energy supply or augmenting the final energy consumption, the choice is narrowed to only one type of improved stove. The selected model is the Envirofit G3300, as tested by Santachiara in comparison with the 3SF [44]. It also resulted to be very similar to the sawdust pot in the layout, a feature that should ease the adoption by local people. The resulting efficiency was of 30% as specified by the manufacturer [83], with a doubling of the 3SF value.

As for the public cooking, also for the domestic sector this end use is considered as fully satisfied at the moment. Therefore the future scenario will concern the reduction of primary energy use. In the perspective of energy self-sufficiency and sustainability, for this purpose also the LPG and kerosene primary energy supply for cooking are replaced by firewood. The use of firewood as fuel in the context of CPC Bali, where a policy of tree replanting is under action, is regarded as sustainable in the long-term more than the depletion of consumables.

Domestic water heating

If cooking was considered adequate in terms of final energy consumption, the situation of water heating is completely opposite. The need is only partially met in the domestic sector very limitedly, while in the public sector is even not contemplated.

The investigated technology was the Solar Water Heating System (SWHS) to exploit the great potential of solar energy through a device with a relatively simple layout. A typical SWHS is composed by a collector on the building roof, a storage tank for hot water usually of 100-300 litres and piping connections; the most common type is the flat plate collector [84]. The system is passive because water circulates thanks to natural convection caused by the heat provided by the sun. Since the thermal energy demand is known from the previous equation, the SWHS needed to be calculated as in *Eq 2.24* [85]:

$$SWH_{capacity} = \frac{f_s}{\eta_c \eta_{syst}} \frac{FE_{hot\,water}}{G} \qquad \text{Eq 2.24}$$

The terms in equation 2.24 are the solar fraction f_s, the efficiencies of collector η_c and of the whole system η_{syst}, the thermal energy demand per capita $FE_{hot\,water}$ and the sun irradiation G. The choice of each value will be given in the result section. The resulting capacity will give the square meter per capita of flat plate collector necessary to satisfy the need of water heating.

3 Results and analyses of the current state

In this chapter the results of the energy balance and resource assessment are presented. Initially, the analysis is focused on key issues such as domestic and public energy drivers, relevant to the first specific objective; the results are then summarized in an energy flow diagram. Secondly, the principal features of RES potential measurements and estimations are found, instrumental to evaluate the source available in CPC Bali.

3.1 Energy balance

The main two energy drivers at CPC were the domestic and public. Artisan and transportation were not included in the analysis since no relevant activities were present within the research area boundaries. The main sources of primary energy exploited were firewood, gas, charcoal, kerosene, diesel and electricity. The general energy framework discussed in the methodology (see Figure 2.1) is then applied to CPC Bali and graphically given below:

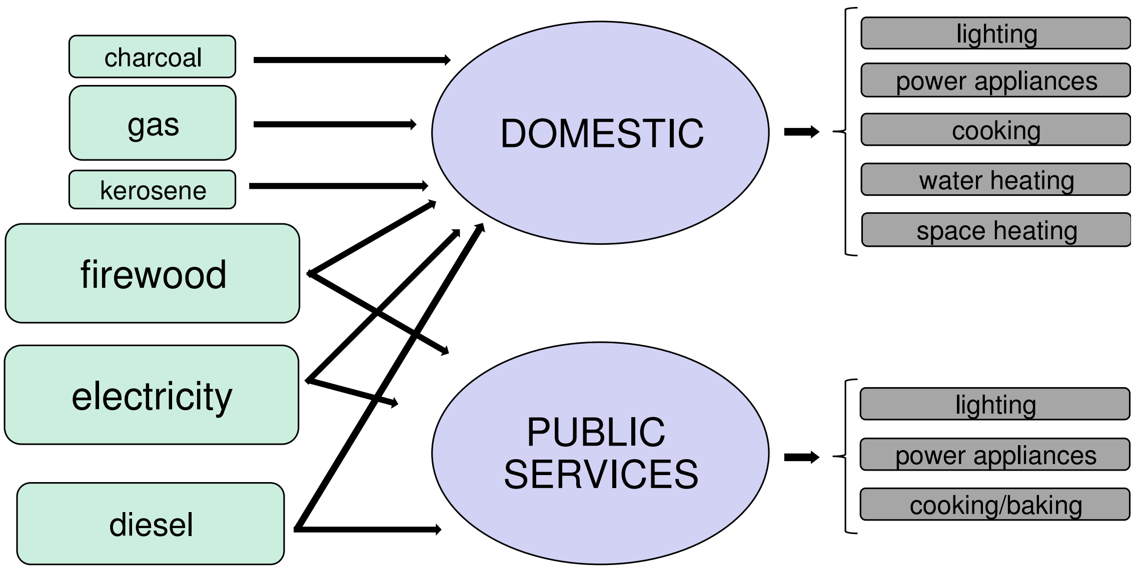


Figure 3.1 CPC Bali energy system. Source: Authors

In the following paragraphs the results within the domestic and the public driver are described; afterwards, all the results are combined together; lastly, the energy flow diagram of CPC is illustrated.

3.1.1 Domestic energy consumption

The domestic is one of the two energy drivers of CPC Bali. It consists of 47 households where the staff of the school lives with the respective family. The staff is composed by teachers, administrative personnel, cooks, bakers, technicians and shoppers. The resources exploited within this energy driver are firewood, gas, kerosene, charcoal and electricity. The main final uses are cooking, water heating, space heating, lighting and powering appliances (see Figure 3.1). The methodology chosen to investigate the domestic driver was a questionnaire, as described in the methodology.

A total of 45 households out of 47 were interviewed, so more than 95%. However, the two houses where it was impossible to conduct the questionnaire represent a rather negligible missing of data for the purpose of this analysis. One house was newly built and the family moved in three weeks before the end of the period in Cameroon; a single professor, who was often out of the campus for work, inhabited the second house. The results of the energy consumption should be read considering this shortage in the overall domestic energy consumptions accounting.

General information

The first section of the questionnaire helped to introduce the person interviewed and give information about people living in the house. Only in four cases the person interviewed was not the head of the family. Most of the times the head of the family was the man, but in absence of man for different reasons the woman had the role of family head. The results about the demography of the CPC domestic driver are summarized in Table 3.1 and Chart 3.1.

total population	179
max people per house	9
min people per house	1
average people per house	4

Table 3.1 Demographic data of CPC staff and family members

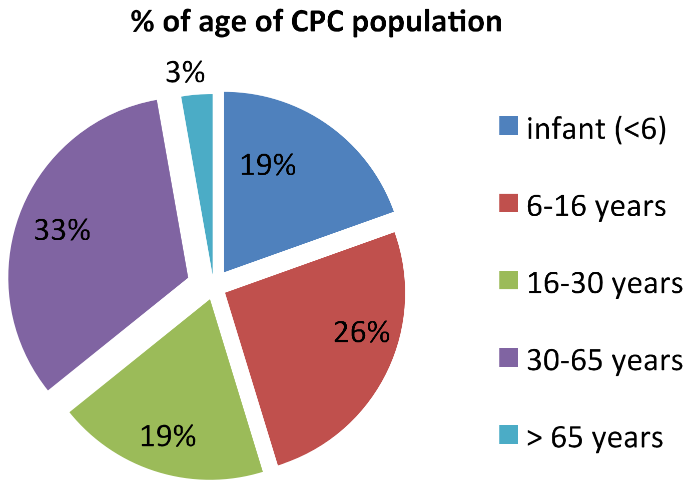


Chart 3.1 Age distribution of CPC staff and family members

People living inside the campus had a role in the school. They were mainly part of the teaching staff (51%), but also non-teaching staff (31%) and administration (18%). Among the non-teaching staff cooks, bakers, technicians, gardener and nurse were included. In some cases more family members used to work in the campus.

Electricity use and supply

All the 45 households interviewed were connected to the grid. Energy consumers within the households were surveyed in terms of type of appliances, quantities and daily/weekly use in order to estimate the average power consumption. For the power rates an average value was picked for each item out of a sample because of the difficulty of people to answer this question and also the discomfort of annotating the power rates inside every house. The devices present in the houses were: TV and decoder, stereo, small radio, phone charger, laptop, pc, iron, fridge and water boiler. Since the use of a device had often a weekly routine, the hours of use in a week was annotated for each device. Besides, a factor of use, taking into account when not all the devices of the same type were functioning, was included in the tables. The factor of use enables to consider those cases when not all the devices of the same type are used simultaneously. Indeed, if one neglected this aspect, the total power consumption would be overestimated. A typical example of the factor of use is for the light bulbs that were rarely on at the same time. The overall results of domestic power consumption are shown in Table 3.2 and Table 3.3, respectively power consumption for lighting use and for powering appliances:

	Indoor bulbs	Outdoor bulbs
Houses with the appliance	45	22
Max power consumption per hh [kWh/week]	9.1	4.4
Min power consumption per hh [kWh/week]	0.2	0.2
Mean power consumption per hh [kWh/week]	2.8	1.3
Total consumption [kWh/week]	126.3	29.7

Table 3.2 Power consumption for lighting use

	TV and dec	stereo	radio	phone charger	laptop	PC	iron	fridge	Water boiler
houses with the appliance	37	22	16	44	11	11	36	26	4
Max power consumption per hh [kWh/week]	17.6	4.2	0.8	1.4	7.8	16.4	11.2	11.3	5.6
Min power consumption per hh [kWh/week]	0.7	0.1	0.1	0.1	0.1	0.8	0.4	5.6	5.6
Mean power consumption per hh [kWh/week]	5.3	2.0	0.3	0.4	2.5	3.8	2.4	5.8	5.6
Total consumption [kWh/week]	194.9	31.4	2.9	15.4	22.7	30.7	83.0	152	22.5

Table 3.3 Power consumption for power appliances

The obtained weekly power consumption was extended to a period of one month, with the aim to have all the results of the energy balance assessment referred to the same temporal distance. In the following pie charts the share of different appliances and the share of the final uses of power are shown:

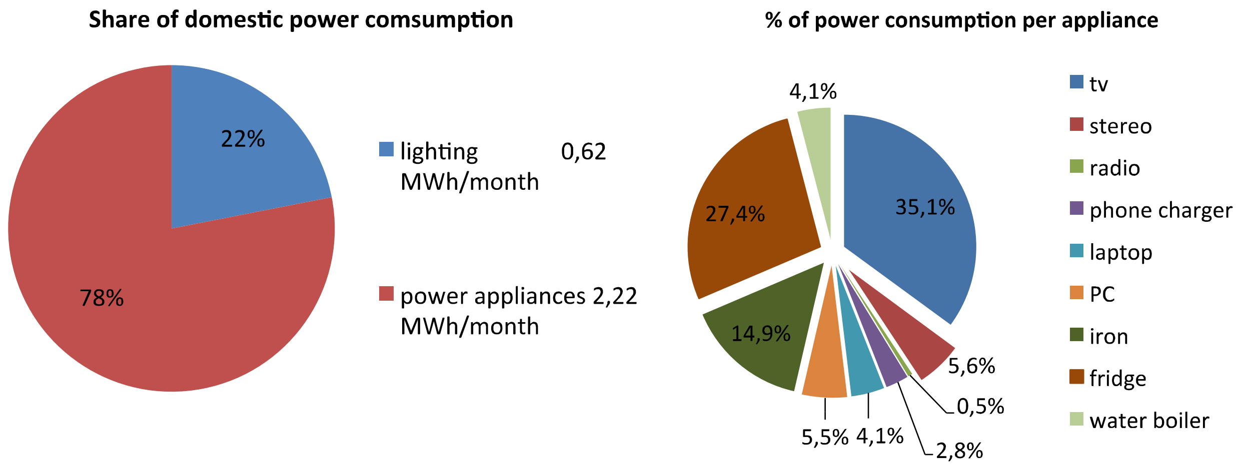


Chart 3.2 Share of domestic power consumption by final uses (left) and power appliances (right)

The total power consumption within the domestic driver was of 2.84 MWh/month, which corresponds to 10.224 GJ/month of electricity. The domestic consumption per capita of power was 16 kWh/pp. The mean power consumption per households was of about 63 kWh/month. As previously said, electricity was completely supplied by the national and had a current unit cost of 99 CFA/kWh for the school. However, the electricity was paid by the households at the subsidized price of 70 CFA/kWh. The average bill paid by each household is shown in the in Table 3.4:

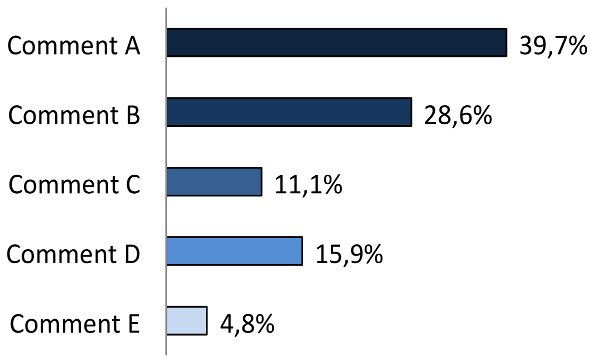
	CFA/month	kWh/month
Maximum electricity bill	11000	157
Minimum electricity bill	1000	14
Mean electricity bill	3015	43

Table 3.4 Domestic power bills at CPC

It can be noted that the mean value of monthly consumption of 43 kWh per household is lower than 63 kWh previously computed. Two aspects can explain this. First, people overestimated the use of some appliances, for example TV or stereo were estimated to be in use for up to 18 hours per day. Secondly, the monthly bill paid by the household was affected by periods of power-cut that were very recurrent (they could occur for whole days in a month) aspect that was been included in the computation of the average monthly consumption.

Quality and reliability of power supply

The reliability of power service was asked within the *electricity use and supply* section of the questionnaire in order to get the feelings of local people respect to the electricity supply and to quantify the monthly shortages. The question about power shortages has encountered the true difficulty of people to estimate a mean duration of power-cut in a month. The qualitative information coming from this question was that periods of black out could vary from couple of days at best, up to the worst case of whole weeks in a month. A better analysis of power shortages is conducted later in paragraph 3.1.4. Finally, the quality of the electricity supply was investigated. Generally, all the households had damages to any kind of appliances due to frequent voltage fluctuations in the power grid and a common dissatisfaction emerged from the questionnaire. The comments about the power supply were grouped in five types:



A. The supply is irregular. Blackouts are frequent and availability of the supply is limited.

B. Instability of supply. The voltage fluctuates, leading to damage or breaking of appliances.

C. There is no compensation for damages and interruption of supply. The cost of electricity is too high compared to the (poor) service offered.

D. The AES-SONEL equipment is too old to work properly. Maintenance should be carried more regularly.

E. General satisfaction or at least feeling of improvement from AES-SONEL

Chart 3.3 Quality energy supply for people of CPC

Firewood use and supply

The majority of the 45 households interviewed used firewood, only 6 didn't use it. In that case, LPG and kerosene were used in place of firewood and their consumption is analysed in following paragraphs. The main purpose was for cooking and water heating.

Instead 5 households used firewood for space heating too. However, the employment of firewood for space heating was limited to some days during the rainy season and, according to some answers, the same firewood burnt for cooking purposes was exploited for heating the environment. Due to the complexity of splitting the consumption between cooking and space heating and of quantifying the wood used for space heating, the final use of space heating was not analysed quantitatively. This slightly affects the analysis of domestic firewood consumption, but the mistake presumably is not relevant since the percentage of households burning wood for space heating is small. Chart 3.4 shows the end-use of firewood by the households.

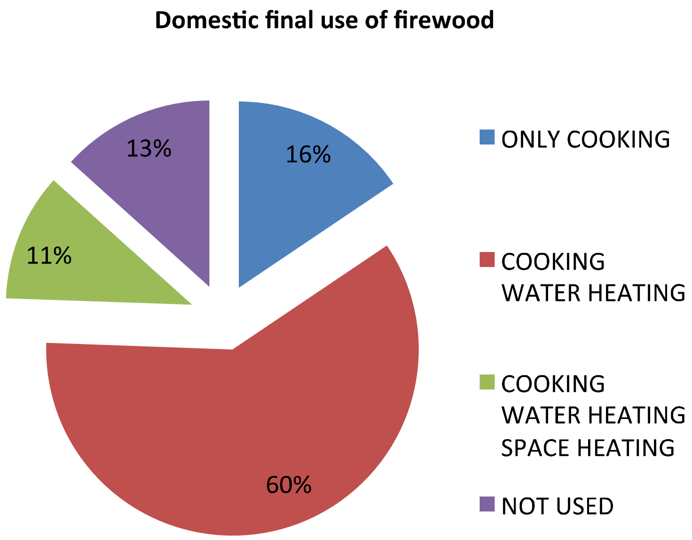


Chart 3.4 Domestic final uses of firewood

The households use three main technologies for firewood conversion, namely: 3 stones fire (3SF), sawdust pot (SDP) and improved cooking system (ICS) that generally consisted of a wood oven. The share of these technologies is shown in Chart 3.5.

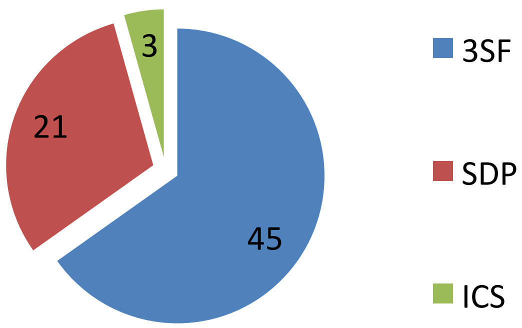


Chart 3.5 Share of firewood conversion technologies among households

The common practice for families was to cook heavy meals for several people, sometimes just one big meal in a day. The kitchen was usually placed in a different environment from the bedrooms, outside the house. Traditional meals were cooked only with the 3 stone fire. This resulted in a daily use of the 3 stone fire, sometimes interspersed by the sawdust pot when there was availability of wooden dust around the campus and when simple meals had to be prepared.

For what concern the sawdust pot, the quantity of sawdust contained in one single pot was measured equal to 4 kg. The weekly utilization rate of the sawdust pot was also asked in the questionnaire and therefore the consumption of wooden dust computed on a monthly basis. The table below shows the results of monthly consumption of sawdust among the 21 households where the sawdust pot is used:

	kg sawdust /household
Maximum monthly consumption	64
Minimum monthly consumption	2
Mean monthly consumption	33

Table 3.5 Firewood consumption per household

The firewood purchased by each household was completely intended for burning in a 3 stone fire for cooking or water heating. The quantity purchased was investigated and, three categories of firewood consumers could be distinguished. In the first categories, there were those people who used to buy the firewood on a weekly basis on the main road outside the campus. In this category, wood was sold in heaps of wet Eucalyptus Grandis logs split in small pieces, for a total volume of around 1 yd^3 (0.765 m^3) and an average weight of 25 kg. The unit price was 40 CFA/kg. In the second category, there are those people who used to buy firewood in larger quantities on a monthly or yearly basis by using pickups that transported a standard quantity of 50 logs of wet Eucalyptus Grandis of 49 kg each on average. Then, the total quantity of wood bought from a pickup was around 2.45 tons on average. The cost in this case varies according to the supplier and the availability in that period of the source; the unit price ranged from 3 to 10 CFA/kg, substantially lower than for the first category. The third category included those people who owned a forestland and have access to firewood for free. However, in this case the reference wood weights of the first and second categories were used to quantify the monthly consumption because for people was easier to answer in this way. The results of firewood purchased are summarized in Table 3.6:

	kg/household	**kg/pp**
Maximum monthly consumption	1000	306
Minimum monthly consumption	25	6
Mean monthly consumption	360	91

Table 3.6 Firewood monthly consumption per households and per capita

Even if the maximum consumption per month can reach 1 ton, a better indication is given by the consumption per capita that is 306 kg at most. The consumption of firewood was also influenced by the presence of a gas stove in the same house. The gas consumption is analysed in the next paragraph.

Primary and final Energy Consumption of firewood

In order to quantify the primary and final energy consumption for each final use of wood at the domestic level the net heating value of Eucalyptus Grandis with 40% of moisture content was calculated using equation *Eq 2.1*.

$$EHV = 12{,}43\ \frac{MJ}{kg}$$

The consumption of primary energy of wood purchased by each household was computed by applying *Eq 2.2*. This primary energy included both water heating and cooking. To evaluate the share of the two final uses in the consumption of wood, the water heated for bath was investigated. In fact, the average quantity of water heated weekly was sought through the questionnaire and the results were extended on a monthly basis. The assumption of water heated up to 60°C enabled to compute the consumption of final energy using *Eq 2.3*. The efficiency of the 3 stone fire allowed to quantify the consumption of primary energy for water heating (*Eq 2.4*). Then, the primary energy for cooking purpose was computed by difference of primary energy of wood purchased and primary energy for water heating (*Eq 2.5*). In the same way, the final energy for cooking was computed by applying the equation *Eq 2.4* in the opposite way. Finally, summing up primary and final energy consumption of sawdust for cooking use, the final results were obtained. The following tables 3.7 and 3.8 and pie charts 3.6 and 3.7 show the most relevant outcomes:

	FE_{wh} [GJ]	PE_{wh} [GJ]	FE_{cook} [GJ]	PE_{cook} [GJ]
Mean consumption per household	6.4×10^{-2}	0.43	0.71	4.44
Total monthly consumption	2.06	13.74	27.64	172.98
Monthly consumption pp	1.2×10^{-2}	7.7×10^{-2}	0.15	0.97

Table 3.7 Final and primary energy consumption for cooking and water heating

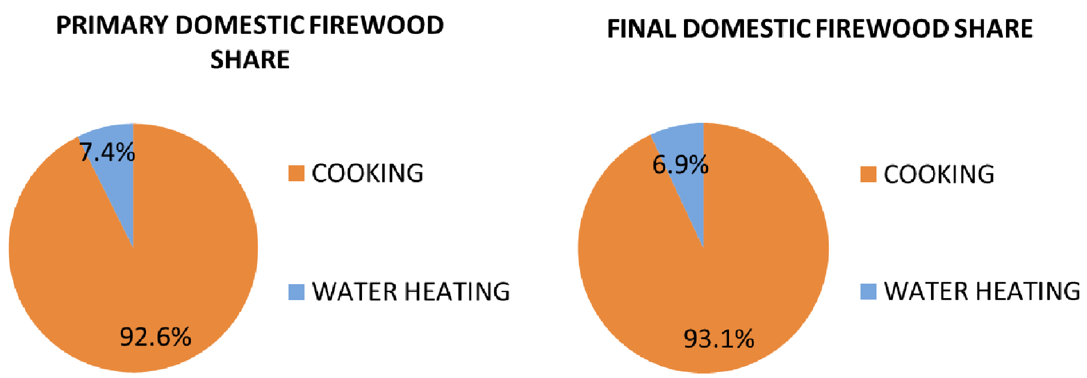


Chart 3.6 Domestic share of primary (left) and final (right) energy for cooking and water heating

	FE [GJ]	PE [GJ]
Total consumption 3SF	24.7	164.8
Total consumption SDP	2.9	8.2

Table 3.8 Final and primary energy consumption differentiated by cooking system

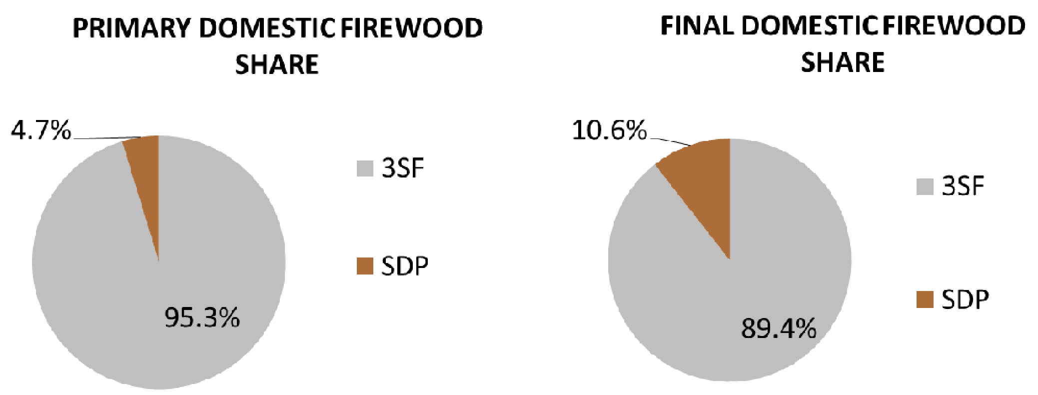


Chart 3.7 Share of primary (left) and final (right) energy consumption between 3SF and SDP

Gas use and supply

33 households, more than 73%, used the LPG pressurized and stocked in gas cylinders. The only use is for cooking although sometimes small quantities of water were boiled as for making tea. This case was included in the final use of cooking and not in the heating water comprehending only hot water for bath. Independently from the type of gas bottle, the standard mixture of mainly propane and butane of 12.5 kg was contained inside. The frequency of refill was asked and it ranged from one time in a month to even one occasion in a year. Then, the average monthly consumption of primary and final energy of each household was computed considering a LHV of 46.15 MJ/kg and a mean efficiency of gas stoves of 63% [46]. The results are summarized in Table 3.9.

	FE_{LPG} [GJ]	PE_{LPG} [GJ]
Mean consumption per household	0.17	0.28
Total monthly consumption	5.8	9.2
Monthly consumption pp	3.2×10^{-2}	5.1×10^{-2}

Table 3.9 Domestic final and primary energy consumption of LPG

The comparison of primary and final energy consumption for cooking from firewood and LPG source is represented in Chart 3.8.

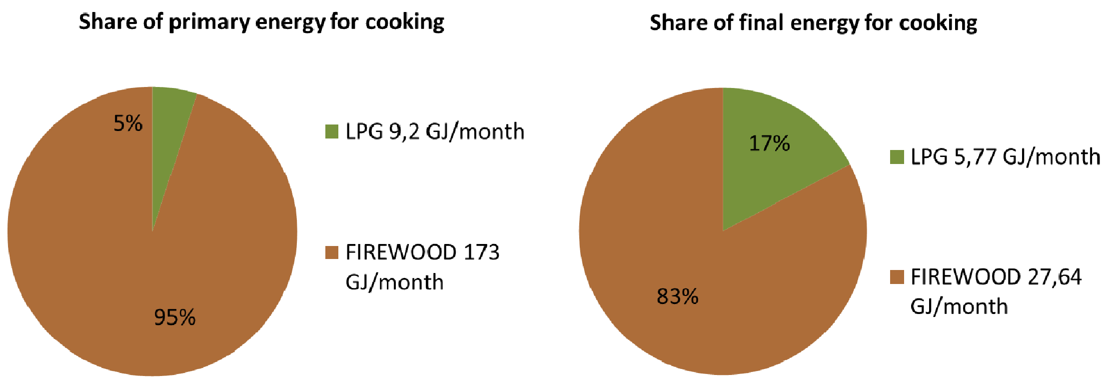
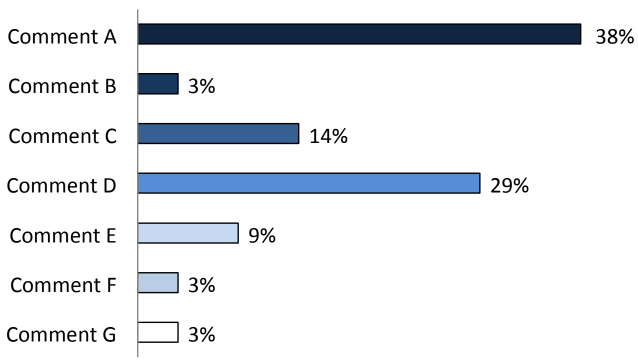


Chart 3.8 Share of fuel in primary (left) and final (right) energy for cooking

The local price per bottle of LPG ranged between 6500 and 8500 CFA. Considering the LHV of LPG of 46.15 MJ/kg, the price per unit of primary energy is on average 13 CFA/MJ, while for firewood ranges from 3.22 CFA/MJ (firewood purchased on the road) to 0.24 CFA/MJ (firewood purchased with a pickup). The price for LPG is at least one order of magnitude higher than for firewood, remembering that for some families the latter was even for free. This factor explained why firewood was generally preferred. The reason of the preference of LPG or firewood was clearly demonstrated as is shown in Chart 3.9.



A. Firewood is cheaper
B. Gas is cheaper
C. Firewood provides more heat, it is suitable for large families
D. Gas is a clean energy source. It is faster to be used
E. Firewood is more available than gas
F. Gas is dangerous, especially for the kids
G. Gas is less risky than firewood

Chart 3.9 Cooking fuel preferences for the households.

As assumed before, the main factor leading people to prefer firewood was the higher cost of LPG. However, a good percentage of people preferred LPG because is cleaner, producing less smoke and it is faster to be used. Then, 14% of people prefer firewood because it was more suitable when heavy meals or large quantities of food had to be cooked. Finally, even the major availability of firewood was not of negligible importance when a family had to choose between the two sources.

Other sources of energy

The main alternative to gas and firewood was represented by kerosene used in appropriate stoves for cooking purposes. Kerosene was also the ignition element to start the fire, especially when wood was wet and caught the fire unlikely. A further application of kerosene was provided by bush lamps during period of power shortages to provide light. A total of 17 households used kerosene: 9 for lighting in bush lamps, 4 to light the fire and 4 for cooking in kerosene stoves. Lighting the fire was included in the final use of cooking, even though this occurs in 3 stone fire system. When the consumption of final energy was calculated, the difference between using kerosene in stoves or 3 stone fire was taken into consideration. The total and mean primary energy consumed in a month and the share among the different final uses is indicated in Table 3.10.

	PE_{KER} [GJ]	PE_{KER} [GJ /house]
Total consumption of kerosene	1.6	94.3×10^{-3}
Consumption of kerosene for cooking	1.3	165.2×10^{-3}
Consumption of kerosene for lighting	0.3	31.2×10^{-3}

Table 3.10 Total and per household monthly primary energy consumption of kerosene

The consumption of final energy for cooking was computed by applying *Eq 2.4* to kerosene using systems. The mean efficiency considered for kerosene stoves is 51% [46] while for 3 stone fire system is 15% [45]. This leads to the following result:

	FE_{KER} [GJ]
Total consumption of final energy	0.39
Consumption of final energy in 3SF	0.12
Consumption of final energy in KS	0.27

Table 3.11 Kerosene consumption for cooking differentiated by cooking systems

For what concerns the charcoal, only qualitative results were obtained. A total of 12 households used charcoal (27%) and the final use was mainly roasting fish or corns, followed by space heating and final ironing. The pie chart 3.10 shows the number of houses for each final use of charcoal.

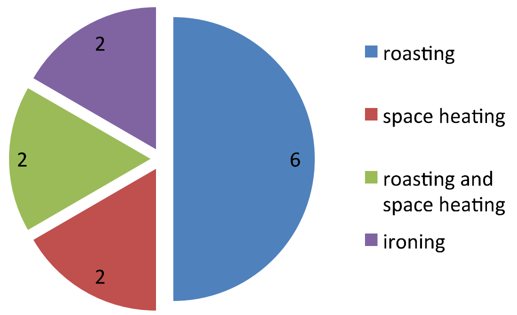


Chart 3.10 Number of houses using charcoal for different purposes

3.1.2 Public energy consumption

The second energy driver analysed is the public. According to Figure 3.1 the energy end uses are lighting, power appliances, cooking and baking. The first two were reported together while the thermal demand was analysed separately. It is important to remember that it is considered as "public" every space related to students' life within the study area which is not private.

Electricity use and supply

The supply of electricity for the study area was from the national grid utility, AES-SONEL. Electrical energy was used to provide lighting and to power appliances installed in dormitories, toilettes, classrooms, laboratories, administrative offices, staff room, dispensary, church, library, refectory, kitchen, bakery, canteen, workshop and along streets inside the campus. However, the public energy driver was treated as a whole aggregate. Upon surveys, all the lighting devices were found to be equal in term of rated power, according the differentiation reported in Table 3.12. This stratification was done in order to detail the description of the present devices.

	Bulbs	Tube	Mini-tube	UV Tube
Rated power [W]	26	36	18	18
Number of item	178	209	6	2
Consumption [kWh/week]	129.6	163.3	1.6	0.5

Table 3.12 Number and power rate of public lighting devices

The UV tube was intended to verify whether banknotes were original or not, in fact they were found in the financial clerk office and in the canteen, i.e. where money exchange occurs. If the rated power for lighting devices was equal to each other, the situation changed for what concerned power appliances, as they were of different type and model. Thus, to obtain a representation of the appliances present in any public place similar to that of lighting devices, an equivalent average rated power is reported for the items grouped according to their function and rate of use. In Appendix A the actual models found upon the conduction of surveys are classified with their peculiar specifications. The reason behind the choice of computing an average power instead of inserting the real one is twofold: first, the appliances have been grouped according to their operating hours; second, it is extremely helpful to recap a long list in only one value.

	Desktop PC / Laptop	Printer / Photocopier	Refrigeration	Other
Rated power [W]	57	153	49	8
Number of item	13	7	3	3
Consumption [kWh/week]	137.9	14	26.4	1.3

Table 3.13 Number and power rate of public power appliances

For what concerns the weekly consumption, the predominant item was represented by office devices such as desktop PCs and laptops. On the other hand, almost an extremely reduced consumption was represented by printer and photocopy machines. Despite the extremely high rated power, during the standby mode the electricity needed was low, implying a small value of the energy consumed. The same reasoning could be done for the refrigeration group. Being refrigeration a continuous process, fridges (two units in the kitchen and one in the library) were always plugged, although the power switches on only when the temperature level inside the fridge overcomes a threshold value. This entails a modest value in electricity consumption. Lastly, in the group *Other* various devices sporadically used were included with an almost negligible weekly consumption.

In terms of monthly energy consumption, the total public electric consumption amounted to 1.983 MWh/month. In the pie charts below the shares of the different devices can be visualized.

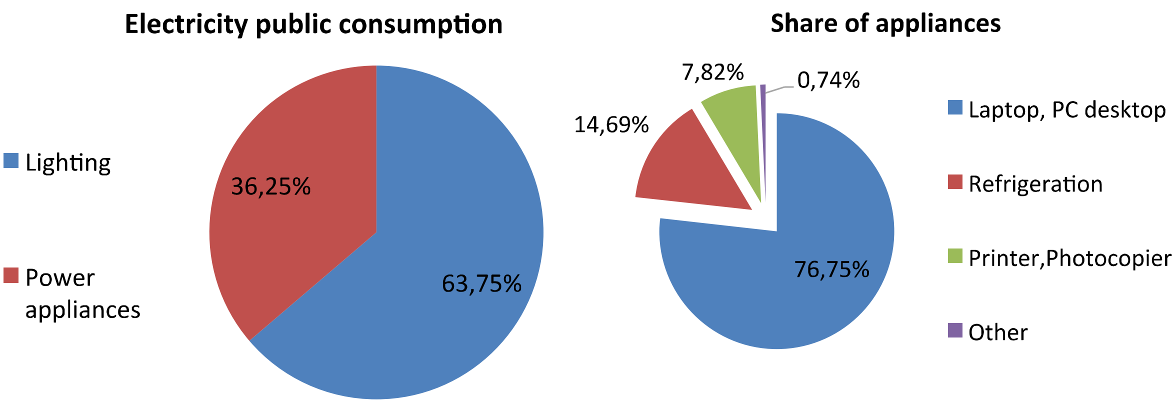


Chart 3.11 Share of public power consumption by final use (left) and power appliances (right)

Inversely to the domestic energy consumption, the share percentage of electricity consumed in the public driver for lighting is above 60%. This was due to the lack or the rare use of power appliances comparing to domestic driver. In general, the total was smaller than in the domestic driver.

Cooking and Baking

If the thermal energy assessment of the domestic driver featured a complex diversification of sources and several units of consumption following diverse patterns, at level of public driver the analysis was rather simple. The centres of consumption were identified in the kitchen and in the bakery. The former provided three meals every day for all the 1008 enrolled students, the latter baked bread for meals and for the canteen to be sold. The only used energy source is firewood for both facilities, abundantly available in the surrounding forest.

The weekly and total monthly consumption of firewood in the kitchen for cooking is reported in Table 3.14.

	Logs	Branches	Weekly Total	Monthly Total
Firewood consumption	282 kg	123 kg	2835 kg	11340 kg

Table 3.14 Kitchen firewood consumption

In order to highlight the energy consumed for cooking in the kitchen, the WBT was conducted on one of the seven improved stoves. The test was performed with the help of a local operator, as the protocol recommends [42]. The procedure is extensively explained in paragraph 2.1.2, while a complete list of the obtained values is reported in Appendix A. The test was performed two times with the same operator.

	WBT 1		WBT 2	
Phase	1	2	1	2
Efficiency	22.86%	17.21%	35.37%	20.32%

Table 3.15 WBT efficiencies

The efficiency of conversion primary source (firewood) to final supply was derived averaging the values of each phase, as done in previous works [44]. The obtained efficiency is 23.94%. This allows the calculation of the final energy supply or simply the energy required to cook meals for the students every month, considering the heating value reported previously, 12.43 MJ/kg.

	GJ / month
Primary energy supply	140.96
Final energy supply	33.74

Table 3.16 Primary and final energy consumption in the school kitchen

The firewood consumption in the bakery was also assessed over a week period. Bread was baked for all the students on a daily basis, except on Sundays. The oven had an internal volume of 3.6 m^3 (2.4 x 1.5 x 1) and was heated by firewood burning in a chamber below the oven. The daily production is 1506 pieces of bread when 2 flour bags of 50kg each were used (five days per week), while the output for 1 bag is of 1022 pieces (one day per week). The total flour used per week was 550 kg. Approximately, each 100 grams of flour requested 60 grams of water, thus a quantity of 880 kg of dough was baked every week. The registered time for the baking cycle of one tray was 40 minutes, with a total of 120 minutes every day. Nevertheless, since the oven has to be extremely warm, the fire was started approximately five hours in advance. In addition, the oven presented a capillary water pipe inside which allowed an auto-thermal regulation distributing the heat uniformly. The resulting average daily consumption of firewood was measured over a week time. As for the kitchen, according with the two operators working in the bakery, the strategy was to cut the firewood and place it in two bundles of 200kg of logs and branches every day. At the end of each day the unused quantity of wood was scaled and so the mass consumed quantified by difference. The weekly and total monthly consumption is reported in Table 3.17.

	Logs	Branches	Weekly Total	Monthly Total
Firewood consumption	188 kg	133 kg	1926 kg	7704 kg

Table 3.17 Bakery firewood consumption

As explained in the methodology, 1.37 MJ/kg is the net mean energy to bake bread. Since the quantity of dough to bake every week is approximately fixed, the consumption of final energy to bake bread can be computed. The energy efficiency index was finally computed as ratio of final energy and primary energy.

	GJ / month
Primary energy supply	95.76
Final energy supply	4.82
Energy efficiency index	~5%

Table 3.18 Primary and final energy consumption in the school bakery

The pie charts below show in a graphic way the share in the monthly consumption of primary and final energy from firewood within the public driver:

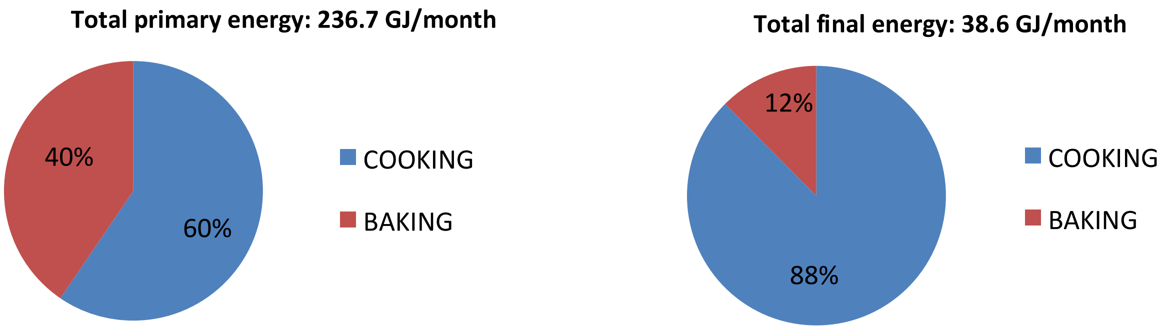


Chart 3.12 Share of primary and final energy consumption from firewood at public level

3.1.3 Load curve

The load curve was built after two weeks (one in September and one in October) of monitoring the central meter of the school as explained in the methodology by taking snapshots alternatively with two smartphones. The central meter showed the energy consumption of the whole school giving the kWh consumed in real time. As the graphs elaborated show below, the peaks of the load curves were well below 20 kW. This suggested that to build an accurate curve, information on the watt-hours consumed in real time would have been necessary. In order to overcome this issue, it was chosen to take snapshots every 10 seconds. In this way, the exact time of the day of each kilowatt-hour consumed was known. Interpolating linearly all the couples of points (time, kWh) was the last step to draw the load curves as shown in Figure 3.2. The two main peaks of the load curve are around 5 am and between 6 pm and 9 pm, since power consumption was connected to school activities and staff domestic driver activities. During the office hours the load was less than the expected one because in September the CCU was still closed and the offices not fully operating. For what concern the total daily energy consumption, the study are usually consumed around 145 KWh every day in September. In particular, on Saturday the consumption was slightly lower with almost 140 KWh consumed, while maximum on Friday with 153 KWh. However, even if the energy consumption on Saturday was the lowest, the highest power load was on Saturday with a maximum peak of almost 16 kW at 7 pm. This kind of analysis gave relevant insights when future systems were thought to replace the current electricity supply. Indeed, both the total electrical energy consumption and the power load had to be always assured during the day in order to provide reliable and safe supply of electricity.

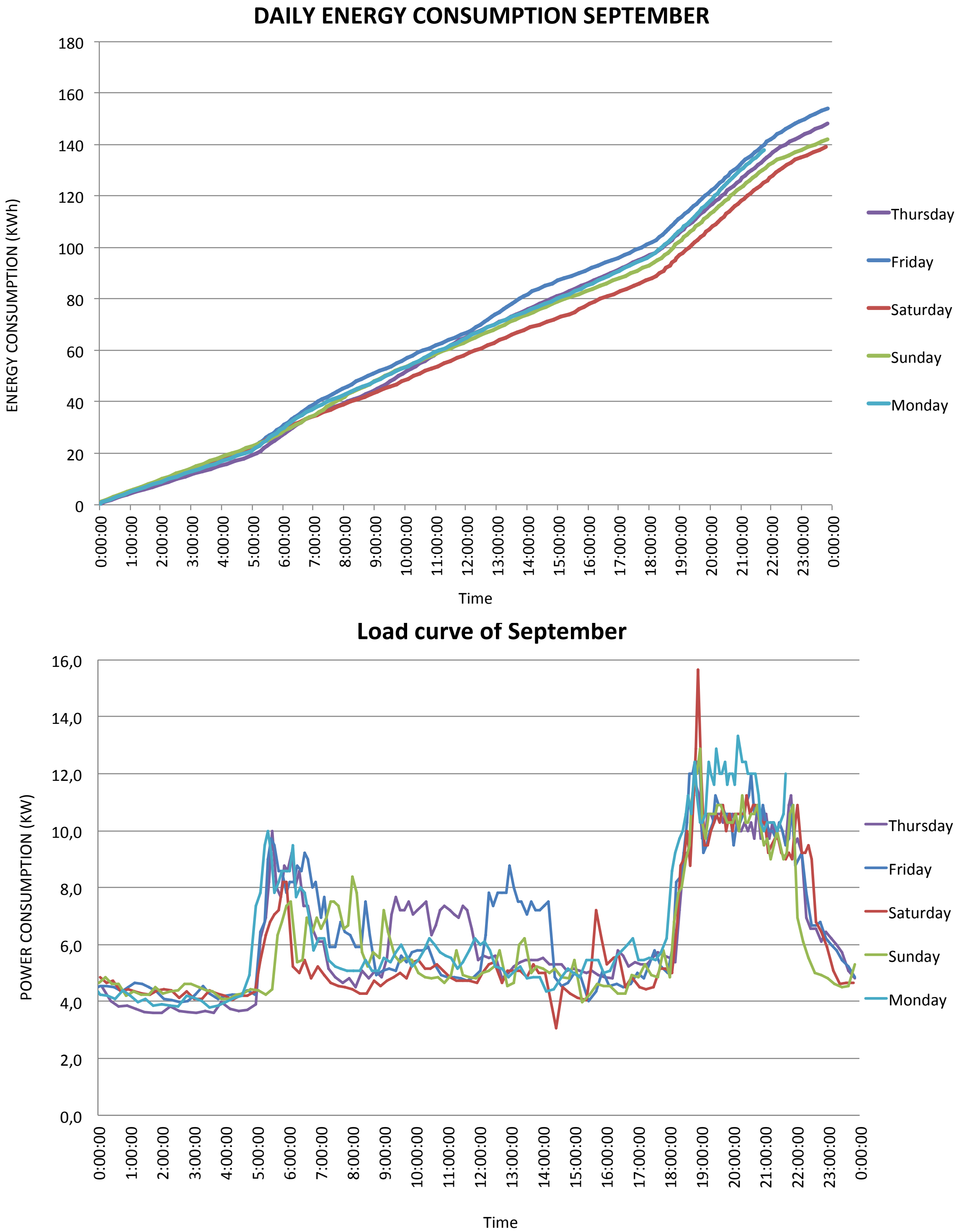
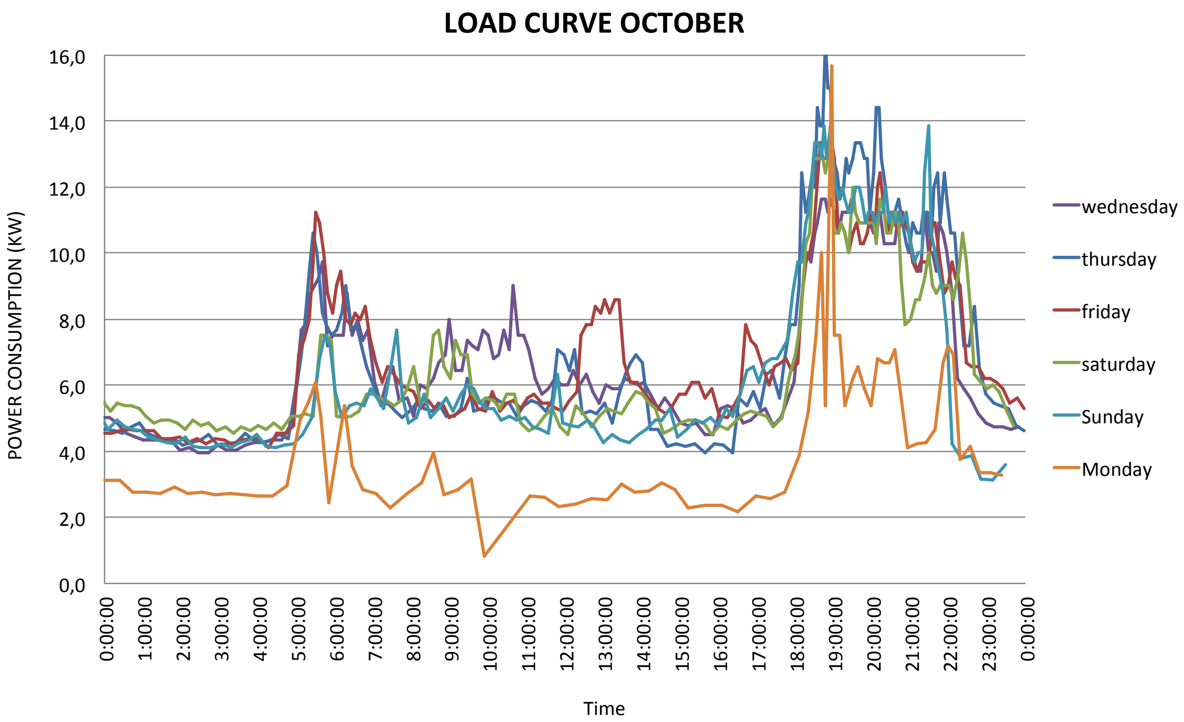


Figure 3.2 Plots of load profile and power consumption in September

The same procedure was repeated for the month of October in order to observe any differences of the power load and the energy consumption after the school had fully started as well as the CCU academic year. The plots related to the period going from the 22th to the 27th of October are shown in Figure 3.3. Comparing the load found in October with the one in September, slight differences were found in the trend; this means that minor changes in habits occurred between the two periods. What was instead interesting to notice was that both the power load and the energy consumption had marginally increased in October. The maximum power, being still in the evening time, overcame 16 kW on Thursday 23th of October, while the maximum energy consumption has again occurred on Friday (24th of October) reaching 161 kWh, with an average consumption of 152 kWh/day. Moreover, the ending part of the orange load curve (Sunday) and the grey curve (Monday) appeared to be well below the power loads of the other days. This could be explained since during the night of Sunday 26th a failure occurred to the power grid and a period of low voltage followed. During low voltage many appliances worked irregularly; this was reflected in the curve of Monday, being shifted down.



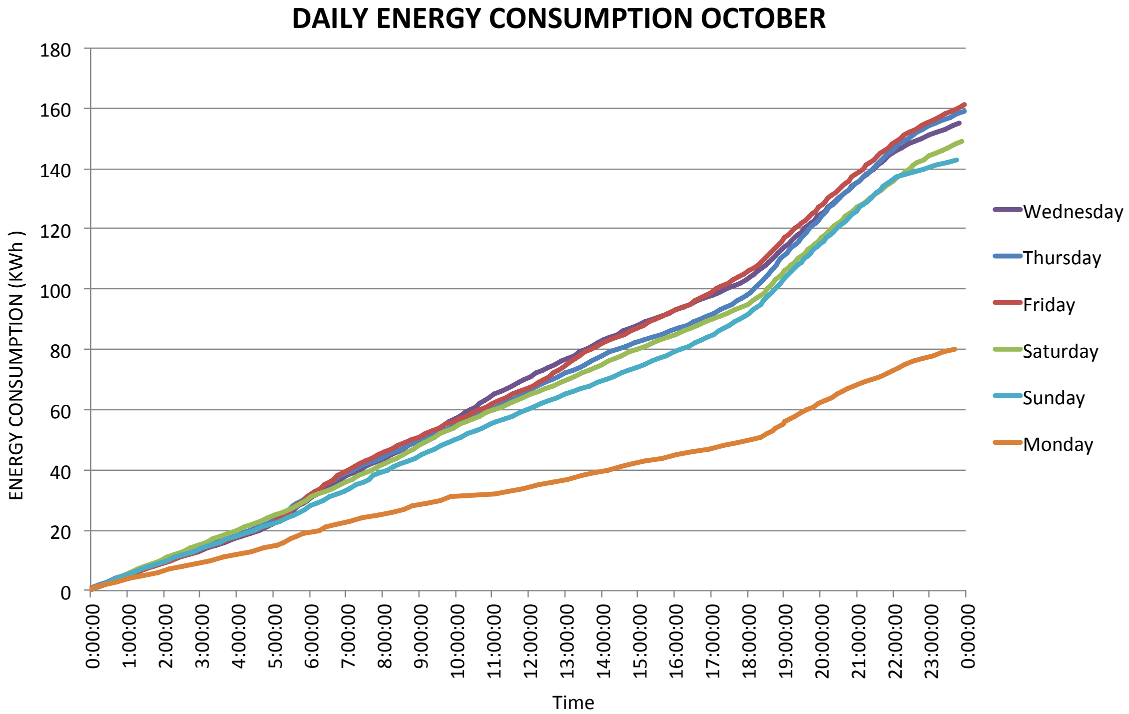


Figure 3.3 Plots of load profile and power consumption in October

Finally, it is interesting to compare the findings of this analysis with previous results. In particular, it was found that the power consumption of the study area is around 2.84 MWh/month for the domestic driver and 1.98 MWh/month for the domestic driver, giving a total of 4.82 MWh/month. If one multiplies the average daily consumption of the month of October times 30 days finds the close value of 4.56 MWh/month. The higher value found in previous analyses can be explained by the tendency of people to overestimate the use of some appliances at domestic level.

3.1.4 Power shortages and Diesel consumption

Being the power supply rather unreliable in developing countries, Cameroon is included in this context. The quality of the power supply was assessed in the form of hours of power failure, during the stay in study area. Events of low voltage, blackouts and intermittency of the power supply were considered as power failures since they prevented the functioning of any power appliance. The period of study was from September 1st until 12th of November, during which an average electricity supply shortage of 4 full days was counted, this amounts to about 13% of the total monthly load demand. The longest consecutive time without power occurred between the 1st and the 3rd of October, this timespan is in line with the 50 days per year reported elsewhere [17]

During periods of power cut from the national grid, the study area relied on a Yamaha, model EDL26000TE, diesel generator installed on site with manual switching, activated by a technician on fixed time windows:

- Morning, from 5 a.m. to 6:30 a.m.
- Evening from 6 p.m. to 10:30 p.m.

Using the data from the energy consumption of Friday 24th of October as reference (see section 3.1.3), the average electrical energy produced by the diesel generator during a full day of blackout was computed. In fact, within the functioning windows the electricity request is of 59.8 kWh for each of the four days of blackout, amounted to 239.4 kWh of electricity produced by the diesel on average every month. The necessary specifications of the generator [75], [86] and the diesel fuel [87] for this analysis are show in Table 3.19.

Specific consumption	Density	LHV
285 g/kWh	0.85 kg/l	42.78 MJ/kg

Table 3.19 Diesel fuel properties

The generator consumed 80.3 litres of diesel on average. With these specification of the generator, the energy consumption was estimated as show in Table 3.20

	GJ / month
Primary energy supply	2.92
Final energy supply	0.86

Table 3.20 Public primary and final energy consumption from diesel source

The estimated diesel consumption was compared to the actual diesel consumption derived from the collection of bills. In the archive of the school it was possible to find invoices concerning the diesel fuel purchases in the past, from year 2012 to August 2014 inclusive. The yearly average consumption is reported in table 3.21:

Year	Average kWh / month	Average l / month
2012	263	88.2
2013	265.2	88.9
2014	147.6	49.5

Table 3.21 Average monthly consumption of diesel in 2012, 2013 and 2014

The low value referring to 2014 is due to the lack of data for the remaining four months of the year, from September until December. The average electricity supplied by the back-up generator totals 225.3 kWh/month while the diesel consumption to 75.5 litres/month. If this average is compared to the estimated amount of 80.3 litres/month, it reflects a deviation of 6.27%, which might be negligible in the system circumstances.

For the purpose of the energy balance assessment, a last step is necessary in order to relate the diesel consumption to the energy driver. Considering a total consumption of electricity (public and domestic) of approximately 4.83 MWh/month, the supply of electric energy is aligned with the share of 59% for the domestic sector and 41% for the private sector. This hypothesis could be argued since the real share of electricity use during the diesel generator functioning windows should be selected. However, it should be also understood that these represent the only times of the day with availability of power, pushing the domestic driver users to compress their activities. Thus, the proportion would result unvaried practically, with the following results in terms of energy:

	Final energy supply [GJ]	Primary energy supply [GJ]
Domestic	**0.507**	**1.723**
Lighting (22%)	0.112	0.379
Power appliances (78%)	0.396	1.344
Public	**0.353**	**1.197**
Lighting (63.8%)	0.225	0.764
Power appliances (36.3%)	0.128	0.435

Table 3.22 Primary and final energy consumption from diesel by drivers and final uses

3.1.5 Energy flow diagram of CPC

In this section all the results found in the previous sections are put together in order to have an overall view of the energy balance of CPC Bali. The IEA approach to realize an energy flow diagram was applied. The features of the diagram are primary energy sources, energy drivers, final uses of energy and lastly the energy flows linking them. According to Figure 3.1 the primary sources of energy are firewood, LPG, diesel, electricity and kerosene. Charcoal is another primary source, but its consumption could not be quantified as explained in previous sections. These primary sources of energy are exploited in different proportion by the two energy drivers, domestic and public services. With the exception of LPG and kerosene that are only consumed at domestic level, both energy drivers need the other sources. Among the final uses of energy illustrated in Figure 3.1 only the energy for space heating has not been quantified for reasons stated in previous sections. At this level, the conversion from primary source to final energy occurs though specific technologies, characterized by referenced or measured efficiencies. In the diagram below, the consumption of final energy is represented as an arrow going into each final use, while energy losses due to conversion processes are symbolized as arrows deviating from the main direction. The values of primary and final consumption of energy found in previous sections have been used and summed up together to obtain the totals. The results are then average monthly consumption of energy. The overall flow diagram drawn with eSankey 3.0 software is illustrated in figure 3.4.

Among the primary sources, firewood is the predominant with 423.4 GJ consumed every month, followed by LPG (9.2 GJ), diesel (2.9 GJ) and kerosene (1.6 GJ). Electricity is expressed differently in the diagram since the typical unit of measure is the MWh. The scale of MWh and GJ are different in the diagram with the one of MWh deliberately bigger so that the related arrows can be visualized easily. The power consumption is 4.8 MWh per month, as the adopted timescale. Apart from kerosene and LPG that are consumed only at domestic level, the other sources are split amongst the two energy drivers. The public energy driver consumes more primary energy (237.9 GJ) but less electricity (1.98 MWh) than the domestic driver (199.2 GJ, 2.84 MWh). The consumption per capita of primary energy is 0.37 GJ/pp per month while power consumption is 4 kWh/pp per month. The final consumption of electricity is shared between lighting and power appliances uses. In the public driver the demand for lighting is higher, while in the domestic driver is higher for power appliances. The final uses of energy for cooking is bigger for the domestic driver. Finally the energy for water heating is only related to the domestic driver and the need is partially unmet, while it is completely unmet in the public sector.

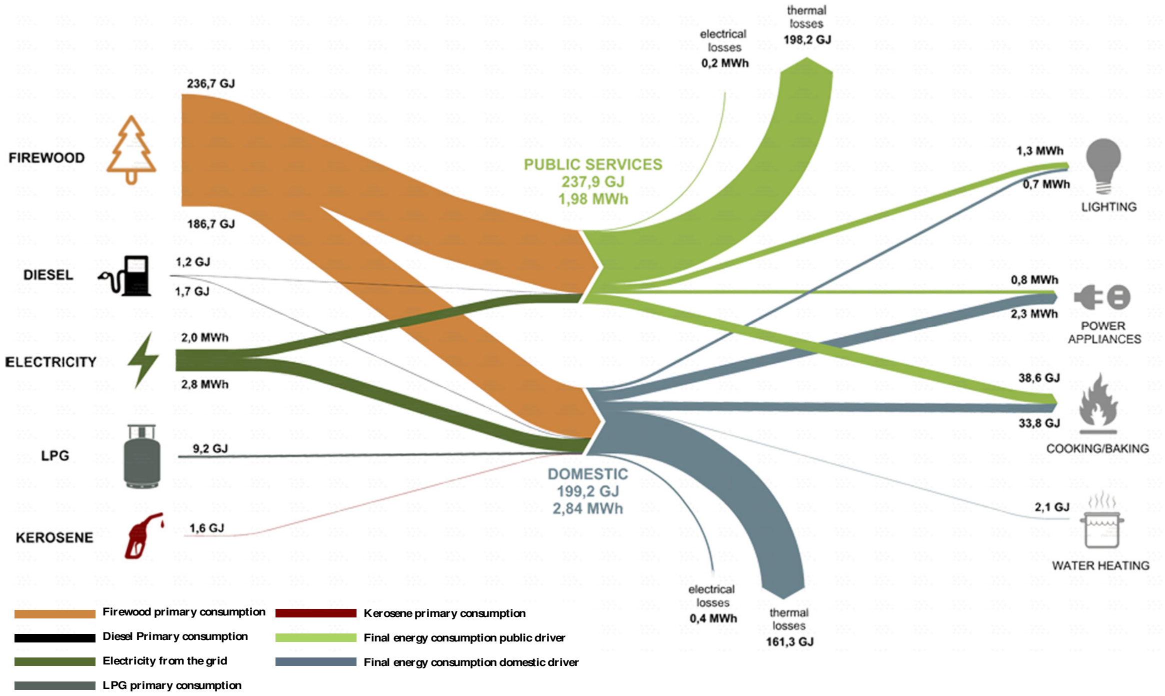


Figure 3.4 Energy flow diagram of CPC Bali

Prior the description of the RES assessment, it is worth delineating the principal weaknesses of the current situation. At the moment of investigation, the supply of electricity from the grid was characterized by high unreliability with frequent occurrence of shortages. This prevented the attendance of basic school activities limiting the education of students since laboratories and library were useless. In addition, activities in offices, kitchen and canteen were forced to stop, worsening the actual discomfort as they were necessary for the proper flow of life for both students and personnel. Lastly, simple domestic tasks resulted difficult to be performed. The electrical losses are those referred to the diesel generator that provides electricity during period of power shortages. Grid losses are not quantified in this analysis. Beside electric energy, which is treated as final energy supply, the energy flow diagram shows important elements of the consumption pattern and the adopted conversion technologies. As clearly visible, the amount of thermal losses is huge, comparing to the primary and final energy supply. This feature is common to both the energy drivers considered, domestic and public. Such weakness derived from the poor efficiencies of the thermal conversion devices found, referring to those fuelled with firewood. In particular, during the period on the field of study, WBTs on the kitchen improved cooking and a literature review on the 3SF established conversion efficiencies of 23.94% and 15%, respectively. Despite a moderately spread diffusion of sawdust pot and LPG stoves with higher efficiency among the population of CPC Bali, firewood remained the pillar primary energy source. Thus, the modest efficiencies led to the remarkably consistent thermal losses highlighted in the energy flow diagram. A further denoted issue of not minor importance was the supply of energy only from fossil fuels and firewood used unsustainably. Consumables pose boundaries to a green development and constrain it to the unpredictable variability of oil prices while continuously depending on it. At last, the current energy consumption of the studied system left some needs unmet. For instance, hot water was a necessity for all the people living inside the school campus, whilst only a slightly small fraction could use it, especially children, for bathing purposes. Upon questionnaires and daily life experiences, it was found that approximately every person, being a student or not, would have used hot water for shower, hygiene and laundry if only it was available and affordable.

The period on the field of study has given fundamental insights on the energy consumption, highlighting the urgent need of improvement of access to energy. Strongly enhancing the actual supply would converge the efforts into higher level of education with a regular execution of school activities and better learning from students. Moreover, a secure and reliable energy supply would boost the productive activities to maintain the school, increasing the living standards of the personnel with their families and satisfying needs previously unmet.

3.2 Renewable source assessment

In this section, the potential of the studied renewable energy sources is quantified through the application of the different methods and procedures in Chapter1.

3.2.1 Biogas

As explained in the methodology, the biomass potential is expressed in terms of equivalent biogas production. Three possible sources of biomass have been quantified:

corn, human and animal waste. In the following sub-paragraphs first domestic waste production is quantified, then the biogas potential from the three sources is presented. Finally the analysis of the current digester is conducted.

Domestic waste production

In this section of the questionnaire the domestic wastes of each households were quantified. A total of 43 households owned a farm. The main plantation cultivated are summarized in the Table 3.23. Corn, bean and tubers (potatoes, yams, etc.) were the most recurrent, followed by vegetables, banana, cereals and other fruits. 22 households consumed all the products harvested, 20 households consumed only a part of the harvest while selling the remaining for business mainly in the market; finally, only one household cultivates for just commercial purposes.

PLANTATION	HOUSEHOLDS
corn	41
banana/plantain	27
beans	40
cereals	9
tubers	39
pineapple	7
vegetables	27
other fruits	8

Table 3.23 Houses cultivating different plantations

The hectares of cultivated land are summarized below:

	Hectares
max land extension per household	8
min land extension per household	0.05
mean land extension per household	0.56
total cultivated land	24.1

Table 3.24 Cultivated land per household and overall

Since the aim of this part was to quantify the waste coming from the farm as potential source of biogas, the attention was primarily on corn. The total land of households that cultivate corn amounted to 23.2 ha (very close to the total land cultivated since only two households had no corn crops). From the interviews arose that corn was the main cultivation of the farm; beside that, from direct observations, corn plantations usually occupied a larger lot than the other cultivations. Indeed, it often happened that in the same portion of land different plantations grow concurrently or in different seasons. In light of the above statement, the assumption made is that corn grew for half of the cultivated land. The resulting tonnes of dry matter harvested with a yield between 9 and 30 tonnes per hectare cultivated is showed in Table 3.25:

yield of corn per hectares [tons/ha]	9 - 30
corn cultivated land [ha]	11.6
yield of corn [tons/yr]	104 – 347

Table 3.25 Specifics of corn yield

The animals owned by the households of CPC were pigs, cows, goats and fowls. A total of 33 households have animals, among those 20 have pigs, 9 have goats, 1 has cows and 30 have fowls. In Table 3.26 are shown the total heads for each species, mean tonnes of manure per year per head and total monthly availability of manure:

animal species	heads	dry solid [tons/yr], hd	dry solid [tons/month]
pigs	77	0.216	1.39
goats	30	0.222	0.56
cows	2	1.54	0.26
fowls	622	0.02	0.52

Table 3.26 Number of animals and manure monthly production

Biogas potential

The tonnes of dry matter of corn yearly harvested from lands cultivated by CPC's people were between 104 and 347 (see Table 3.25). If an average production of biogas per ton of corn of 530 Nm^3 is assumed, the potential biogas derived every year is between 55120 and 183910 Nm^3, which corresponds to an average production of 9960 Nm^3/month.

For what concern animal dung, Table 3.27 was taken as reference. The second column of the table has been already computed in the previous section (see Table 3.26), while the third was found in literature [49]. The total production of biogas from animals is around 1225 Nm^3, one order of magnitude less than the production from corn.

animal species	dry solid [tons/month]	Nm^3 biogas/dry solid ton [49]	Nm^3 biogas/month
pigs	1.39	649	900
goats	0.56	120	67
cows	0.26	281	72
fowls	0.52	359	186

Table 3.27 Potential of biogas from animal manure

Finally the production of biogas from human faeces and urines represented the third source to produce biogas. As stated in the chapter 1, the average daily production of faeces and urines, dry organic matter and biogas yield were found in the literature [52] and summarized in the table 3.28:

	g/day, hd	% oDM	Nm^3 biogas/kg oDM	Nm^3 biogas/day, hd
faeces	140	30	0.45	0.0189
urines	1500	3	0.34	0.0153

Table 3.28 Potential of biogas from human faeces and urines

These values were referred to adults, thus for people younger than 16 years old half of average production was taken as approximation, while infants were not included in the analysis. Within the staff, the total number of adult people was 98, while 46 were people between 6 and 16 years old. Students above 16 years old were 510, so to be considered as adult, while 498 were younger. Knowing that the overall number of adult people inside CPC was 608 and 544 were part of the young population, the potential biogas coming from human waste could be computed. The monthly availability of biogas from human waste was approximately 903 Nm^3.

	Nm^3 biogas/month
adult	624
young	279

Table 3.29 Overall potential of biogas from human waste

The calorific value of biogas ranges from 21 to 37.5 MJ/m^3. An average value of 29.3 MJ/m^3 is taken for the calculations. Table 3.30 and Chart 3.13 present the share of biogas resource potential of the study area from the identified sources.

	Nm^3/month	GJ/month
corn waste	9960	291.8
animal waste	1225	35.9
human waste	903	26.5
total	12088	354.2

Table 3.30 Potential of biogas from corn, animal and human waste

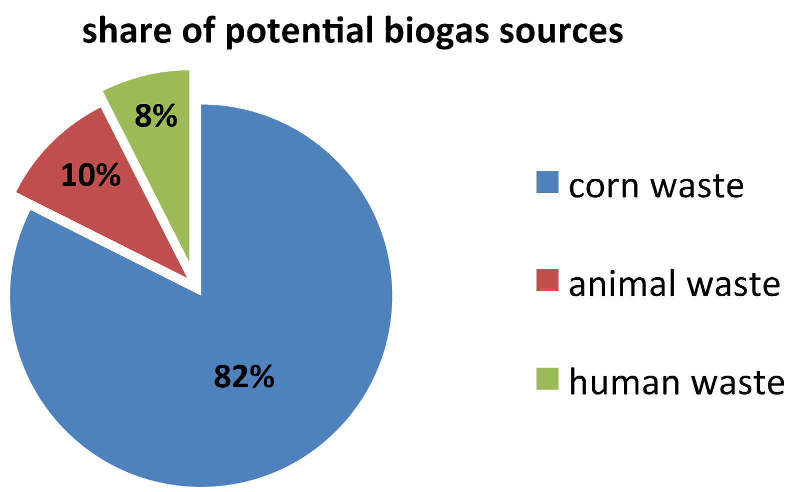


Chart 3.13 Share of biogas potential from corn, animal and human waste

Current biogas system

In previous analysis, all the students' wastes have been quantified and biogas potential estimated. However, male students actually fed an existing biogas system. An interesting analysis was to calculate the potential of the current biogas system and compare the result to the observations on the field. Male students were 543, whose 276 above 16 years old and 267 below, so the theoretical production of biogas computed was 14 Nm^3 per day. The current production of biogas was computer trough on field observations. The result of monitoring the biogas production from the installed biogas digester is as show in Figure 3.5.

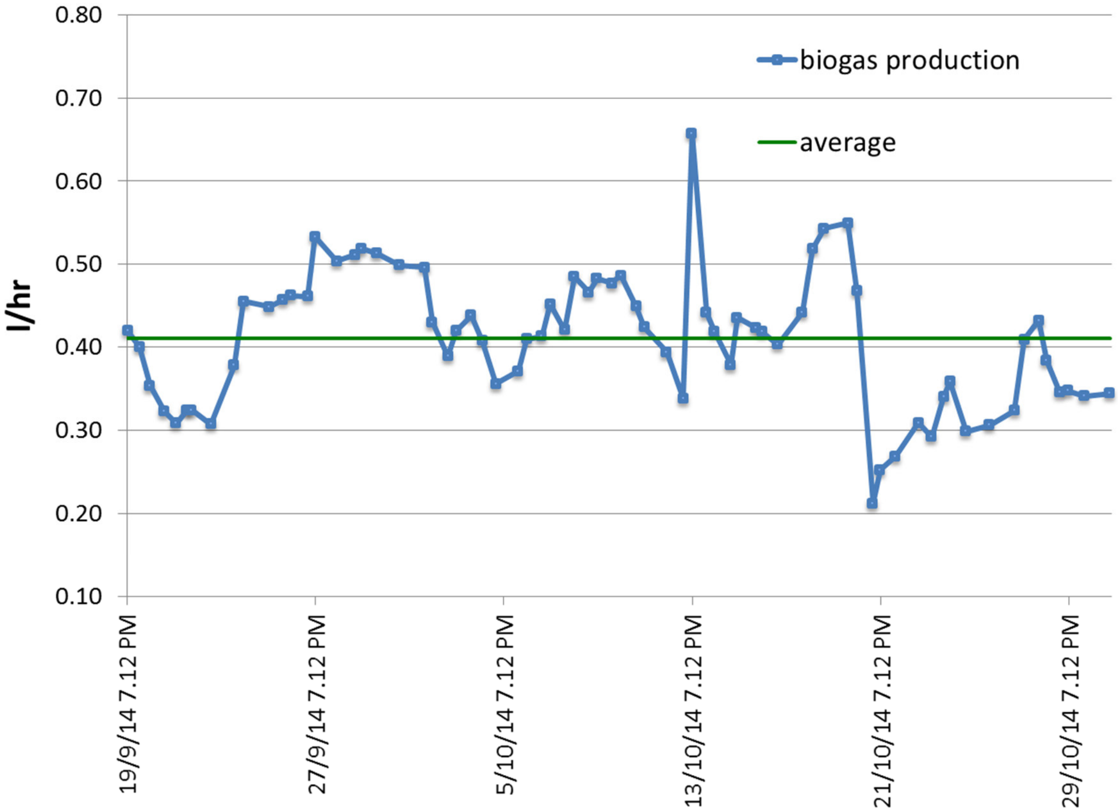


Figure 3.5 Trend of current biogas production

The initial reading was of 388.734 Nm^3 while the final one of 796.321 Nm^3, so around 408 Nm^3 had been produced giving an average daily production of 9.48 Nm^3/day. However, from the graph the trend of biogas production in the period of measurements could be appreciated. The highest production occurred on the 13th of October when it reached 0.66 Nm^3/h while the lowest was registered on the 21st of October and amounted to

0.21 Nm^3/h. Taking an average of production of biogas per hour, the average value of 0.41 Nm^3/hr was obtained (straight green line in the plot) corresponding to 9.84 Nm^3 produced per day.

The mean production found, although lower than the estimated 14 Nm^3 per day, was in line with the theoretical production and even higher on certain days. This gives an important insight when future systems shall be designed to exploit the source, since it is quite irregular and a minimum requested quantity of biogas might not be always granted.

3.2.2 Hydro

In the methodology, all the procedures to get the hydro potential have been explained in detail. Basically, hydro potential is based on two parameters, water flow and head, as *Eq 2.7* showed in the methodology.

$$P_{gross} = g * H * \rho_{water} * \dot{Q}$$

Water flow and head were assessed on field by means of the floating object test and a pocket altimeter respectively. However, Google Earth was used afterward in order to locate the positions and compute height differences. In this paragraph the outcomes of the analysis are presented.

River flow rate (Q)

Table 3.31 shows the results of two experimental measurement of the flow rate of the river within the vicinity of the study area.

FLOATING OBJECT TEST	Experiment 1	Experiment 2
Average cross section [m^2]	0.81	0.74
Correction coefficient	0.45	0.45
Repetition	10	10
Average velocity [m/s]	0.82	0.75
Average flow rate [m^3/s]	0.30	0.25

Table 3.31 Specifics of the floating object test

The average cross section of the river (first row), was measured with the help of a meter stick. Three cross sections were established along the picked length and calculations are included in Appendix A. The selected correction factor, accounting for the stream bed, was of 0.45 due to the condition of flat and shallow flow (about 5m). A reduction of 50 l/s could be noted between the first test sustained in October and the second in November. Indeed, approaching the drying season marked by a reduction of precipitations, higher temperatures and, as consequence, a reduction of the river flow rate, having its minimum in March. As explained in the chapter 2, a regression technic was used to estimate the water flow along the whole year. It consisted on regressing the short flow records against the known flows of the river Mewou using the overlap period and then predicting a relationship between the two-flow series outside the overlapping period. By applying *Eq 2.10* within the overlap period of the month of October and November, the river flow was estimated for the rest of the year. Below the correlation between the two rivers is presented, then Table 3.32 shows the measurements of the Mewou river and the Bali river are showed each month.

$$\dot{Q} = a + b * \dot{Q}_a$$

$$a = 0.0134$$

$$b = 80.035$$

	Mewou river [l/s]	Bali river [l/s]
Jan	3727	130.0
Feb	2373	111.8
Mar	2151	108.9
Apr	5372	152.0
May	5513	153.9
Jun	9037	201.1
Jul	11630	235.9
Aug	12786	251.4
Sep	13831	265.4
Oct	16326	299.0
Nov	12598	249.0
Dec	7543	181.1

Table 3.32 Mewou and Bali river stream flows along the year

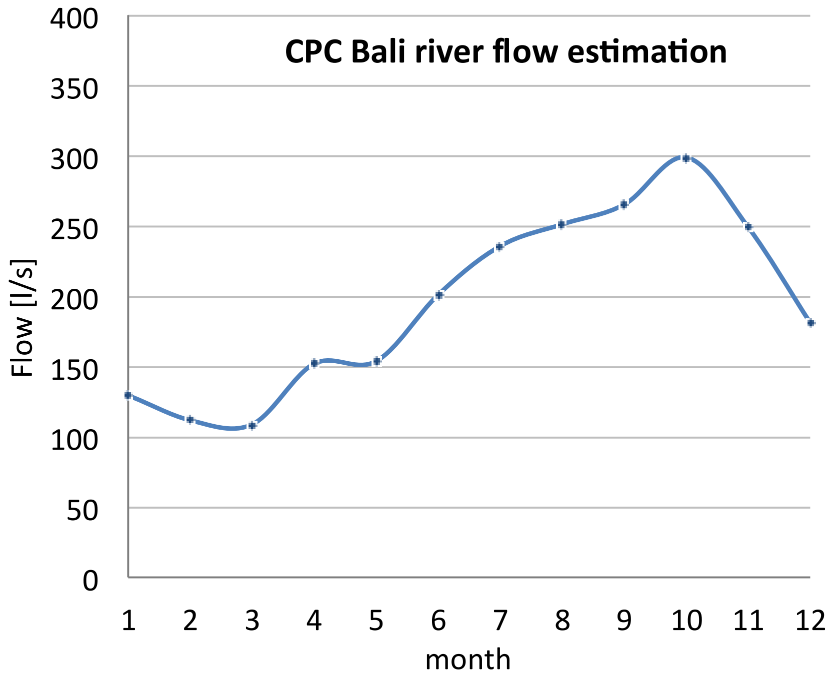


Figure 3.6 Plot of Bali river flow along the year

In Figure 3.6 the trend of the river is computed by means of a linear regression with the Mewou river. The minimum flow rate 108.9 l/s occurs in March. This value is somehow close to the one estimated on the field. In fact, at this regard, two interviews to the technician of the school and the caretaker of the filtering system were conducted in order to investigate and quantify the reduction of the flow rate. According to them, the river flow reaches the minimum level in the second part of the dry season, so from February to April. During an on-site visit with them it was possible to quantify the reduction of cross section of the river at the filtering system, from 1.65 m^2 in November to the lowest section of 0.9 m^2 when dry season occurs. This corresponds to percentage reduction of the cross section of around 45% and an equivalent reduction of the flow rate, if the velocity of the stream is assumed to remain constant all over the year. So the minimum flow rate foreseen on the field is approximately 137 l/s (55% of the river flow measured in November Q_{nov}).

50% of the flow rate was taken a residual flow rate. Therefore, when a hydro turbine is intended to be installed, the maximum design flow rate should lie below half of the minimum flow, so 54.4 l/s. In the graph below, the blue area is the minimum residual flow to maintain for safeguard aquatic life, the green area represents the exploitable flow rate and the baseline indicates the maximum flow rate design of a hydro turbine:

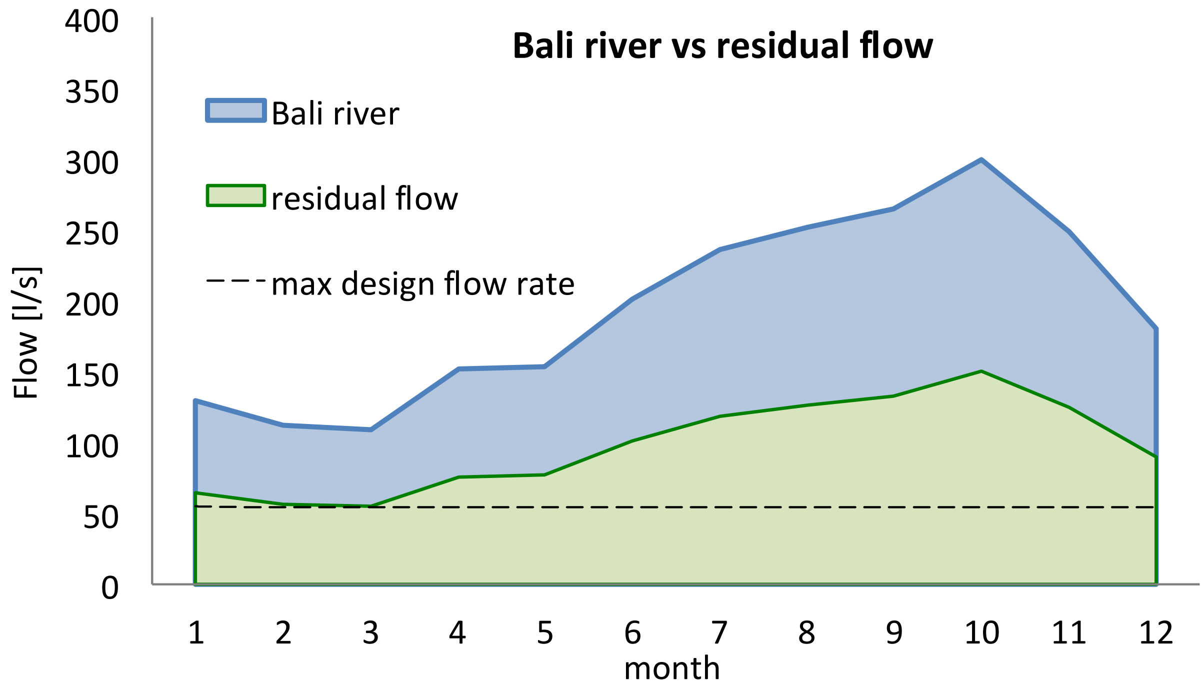


Figure 3.7 Stream flow, residual flow rate and maximum turbine design flow rate admissible

Hydraulic head (H)

The hydraulic head was assessed on the field by means of a pocket altimeter. The height difference was measured during three visits; the day of the visit the altimeter was calibrated, since the local weather conditions could have affected the atmospheric pressure. The height difference between a reference position in the campus (biogas system) and four different places along the river were measured. The spots considered were:

- biogas system (reference position, h=0 m)
- filtering system
- river catchment
- power room
- water discharge

The possible river catchment was downward the already installed potable water catchment. It embedded a high potential since an old disused dam was already in place as the water was diverged for cattle drinking. Table 3.33 shows the mean height differences measured between each spot and reference position:

Spot	Height [m]
filtering system	53
river catchment	37
power room	-15
water discharge	-17

Table 3.33 Height difference between reference position and different spots

Since the accuracy of the altimeter could be unreliable due to small number of measurements, Google Earth was used as well. Indeed, all the locations above listed were identified in Google Earth. Beside the information of height difference, penstock length and power line could be estimated thanks to the 'land distance' tool of Google Earth. Figure 2.8 in chapter 2 shows the proposed micro hydropower scheme layout.

Google Earth provides the relevant data of latitude, longitude and latitude of each spot in the map. They are summarized in Table 3.34.

Spot	Latitude	Longitude	Altitude [m]	Height [m]
biogas system	5°53'35.84"N	10° 2'18.08"E	1364	0
filtering system	5°52'58.29"N	10° 3'33.10"E	1426	62
river catchment	5°53'2.71"N	10° 3'21.87"E	1402	38
power room	5°53'14.92"N	10° 2'50.79"E	1347	-17
water discharge	5°53'25.45"N	10° 2'48.10"E	1342	-22
meter room	5°53'33.52"N	10° 2'11.41"E	1370	6

Table 3.34 Latitude, longitude, altitude and height difference of different spot

No big difference was recognized comparing to the measurements taken with the altimeter and those taken from Google Earth. The hydraulic head (difference between river catchment and power room) was estimated at 55 m. Finally, when a path was drawn in the map, Google Earth provided the length and the altitude profile along path. The penstock length was set equal to 1 km, while the resulting power line was 1.36 km. Beside that, it was possible to see the altitude path of the whole river and the one of the penstock (see Appendix B).

Lastly, the hydro potential was computed in energy terms. According to *Eq 2.8* and *Eq 2.9*, assuming a turbine efficiency of 75% and head losses equal to 40%, so a total efficiency of 45%, and the maximum design flow rate calculated previously, the net potential of the hydro source is:

$$P_{net} = \eta * g * H * \dot{Q} = 13.21\ kW$$

Assuming a full operation 70% of the year (6132 hr) hours per year, the yearly electricity production is 81 MWh (6.8 MWh monthly).

Month	Residual flow rate [l/s]	Turbine flow rate [l/s]	% of design flow rate
Jan	65.0	65.0	72%
Feb	55.9	55.9	62%
Mar	54.4	54.4	60%
Apr	76.0	76.0	84%
May	77.0	77.0	85%
Jun	100.6	99.79	110%
Jul	117.9	99.79	110%
Aug	125.7	99.79	110%
Sep	132.7	99.79	110%
Oct	149.5	99.79	110%
Nov	124.5	99.79	110%
Dec	90.6	90.6	100%

Table 3.35 Residual flow rate, turbine flow rate and % of flow ratio by month

The value of hydro potential is only a first approximation. In fact, beside an efficiency of 75%, no other assumptions on the turbine to apply have been made. Micro hydro turbines can hold the maximum efficiency under partial load conditions. Generally, cross flow turbines have efficiencies over 75% when they work between 60% and 110% of the design flow rate. This entails that the hydro source could be exploited furtherly. For example, if a design flow rate of 90.7 l/s is chosen, the turbine can work between 54.4 l/s and 99.8 l/s and so can follow better the available flow along the year. In Table 3.35, residual flow, turbine flow rate and % of design rate are computed each month.

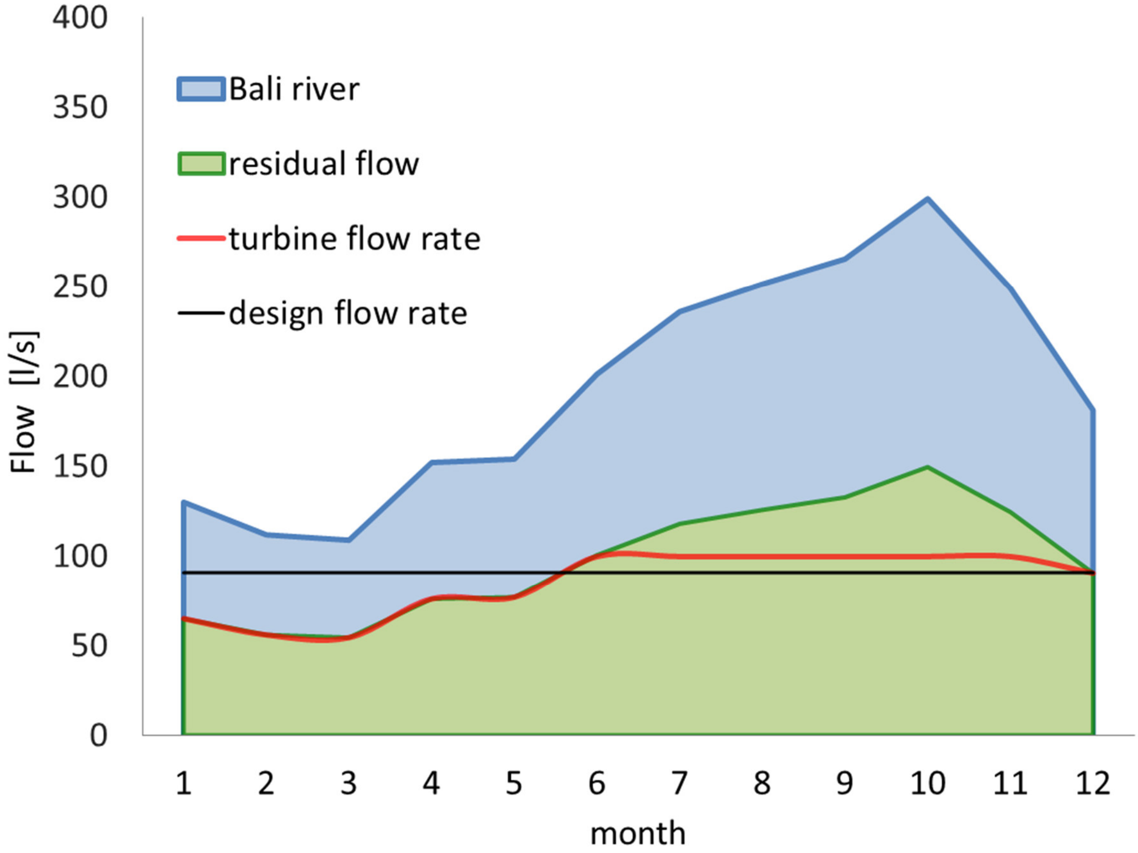


Figure 3.8 Turbine flow rate in partial flow conditions

In the example proposed the power and energy output are consistently increased as Table 3.36 shows:

	Average power [kW]	Average monthly energy [MWh/month]
Turbine partial flow	20.6	10.53
Turbine fixed flow	13.2	6.8

Table 3.36 Average power and monthly energy production in partial or fixed flow condition

3.2.3 Wind

The potential of the wind blowing in the study area was assessed by means of direct measurements taken by an anemometer. The characteristics of the wind regime are reported in Table 3.37:

Average wind speed	3.297 m/s
Standard deviation	1.865 m/s
Autocorrelation factor	0.918
Hour of peak wind speed	14
Diurnal pattern strength	0.329
Surface roughness Z_0	0.010 m

Table 3.37 Main parameters of wind source

The average wind speed was low, evidence of a not windy region. If it has to be considered the modest height of the anemometer installation, it should be also clear that micro wind turbines have hub heights in the range of 15 - 40 meters. Thus, the value of wind average will remain around the measured one by the anemometer. The autocorrelation factor was in the normal interval of 0.80 - 0.95 determining a quite good to strong dependence of wind measurements according to the previous time step. The hour of peak wind speed reflected the usual occurrence during the central hours of the day, when the sun irradiation is the maximum causing stronger winds; whilst, the diurnal pattern strength was rather high, considering the typical range of 0.0-0.4. Lastly, the surface roughness of the surrounding area was selected equal to 0.010 m [1], entailing a rough pasture land. This parameter is vital for the vertical wind shear profile according to the logarithmic law which describes the wind speed behaviour depending on the height.

The Weibull distribution, characterizing the wind source, is expressed by two parameters: the shape factor (k) and the scale factor (c). The application of three possible methods (2 empirical and 1 analytical) led to the results reported in Table 3.38.

	Analytical method [1]	1st Empirical method [61]	2nd Empirical method [62]
Shape factor – k	1.8324	1.8598	1.8566
Scale factor – c	3.7103	3.7126	3.7149

Table 3.38 Shape factor k and scale factor c with three different methods

For the shape factor, it was in the reasonable range of 1.5 – 2.5 with the empirical methods overestimating the real value compared with the analytical method, computed with the help of an Excel spreadsheet. The scale factor has extremely small variations. The frequency distribution of the real wind speed measurements for a time step equal to one minute, during the period June-November 2014 and January 2015, is reported in Figure 3.9 with the Weibull frequency distribution, considering shape factor of 1.850 and scale factor of 3.713, as average values of the three different methods. Since their difference is negligible, also the deviation of the curve is practically absent. As visible from figure 3.9, the occurrence of wind speed measurements was concentrated for values up to 11 m/s, with almost a 0% of probability to have wind speed of greater than this value. The estimated Weibull curve approximated exhaustively the real dataset.

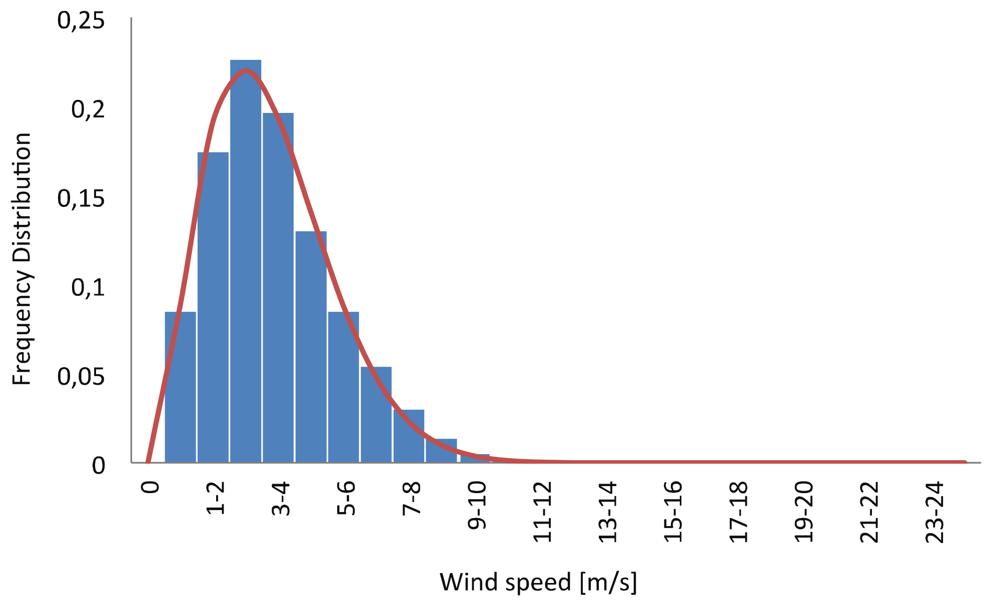


Figure 3.9 wind speed frequency distribution in the study area

Additional available information (see Appendix A) on the wind speed was the diurnal distribution, i.e. the average wind speed for every hour in a day weighted over the whole observation timeframe. It resulted a much consistent average wind speed of 5.13 m/s during the central hours, with peak between 12 p.m. and 1 p.m., while in the early morning it was less than the half of the peak. Besides that, it was possible to obtain the prevalent direction along which the wind blows. The spider graph indicated that the wind blew almost exclusively along the south direction (180°). Also, the average wind speed direction was given, assessing that the largest average (4.43 m/s) was along the direction south-south-east (202.5°).

The last step to properly define the wind regime at CPC Bali, after having determined its characteristics from the measurements, was to scale the available dataset to the whole year. Table 3.39 reports the values and the calculation steps. In the second column there are values from the NASA database [63], while the measured values are in the third column. As it appears, the first values are much lower than the second. Therefore, the interpolations suggested by [64] and [65] have been necessary.

Month	NASA [m/s]	Measured [m/s]	Linear Interpolation [m/s]	Exponential interpolation [m/s]
January	2.1	3.59	3.59	3.59
February	2.2	-	3.84	3.83
March	2.1	-	3.67	3.67
April	1.9	-	3.35	3.35
May	1.8	3.10	3.10	3.10
June	2.0	3.22	3.22	3.22
July	1.9	3.62	3.62	3.62
August	2.0	3.77	3.77	3.77
September	1.8	3.17	3.17	3.17
October	1.6	2.85	2.85	2.85
November	1.7	3.01	3.01	3.01
December	1.8	-	3.19	3.19

Table 3.39 Linear and exponential interpolation of wind speed

The linear interpolation is the following:

$$V_{estimated} = 1.6119 * V_{NASA} + 0.289 \qquad \textit{Eq. 3.1}$$

The exponential interpolation is the following:

$$V_{estimated} = 1.8601 * V_{NASA}^{0.916} \quad \textit{Eq. 3.2}$$

From the chart and from the equation is clear that the curves are extremely similar, almost overlapping completely; for this reason the estimated scaled average wind values are unsurprisingly coincident. Lastly, the yearly trend of the wind speed is reported in Figure 3.10. The wind regime during one year presents two periods of peak wind speed, January-March and July-August, corresponding to the central months of dry and rainy season, respectively. On the other hand, during the transition months an average lower wind speed is registered, with October having the lowest value equal to 2.85 m/s.

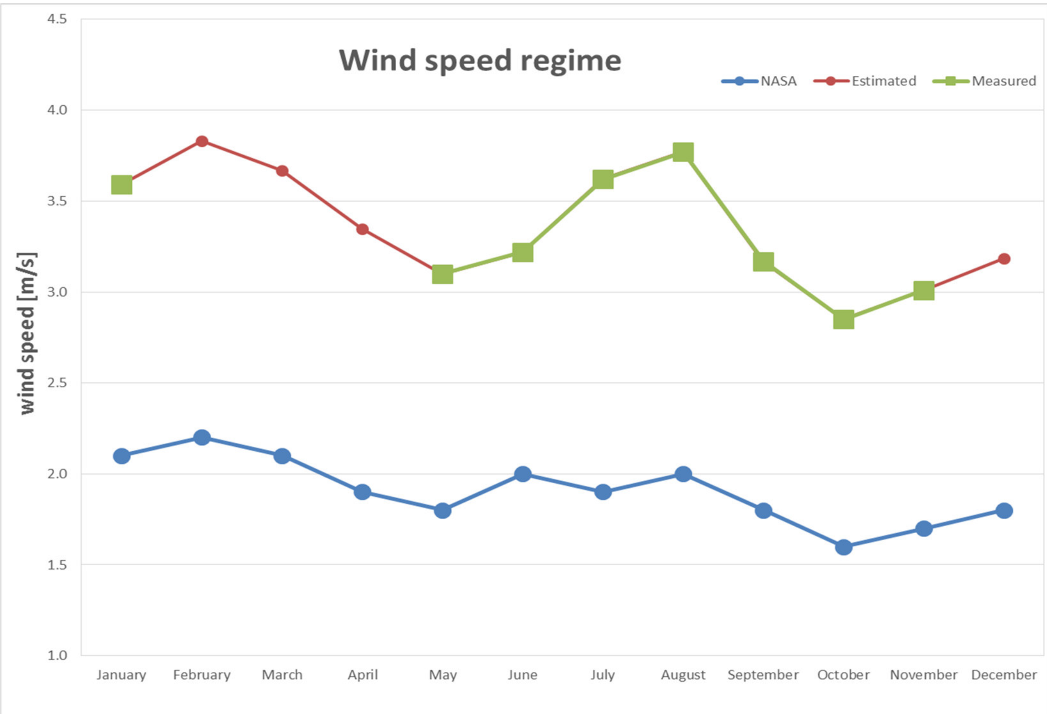


Figure 3.10 NASA, measured and estimated average wind speed

To estimate the wind potential in terms of energy production, the power per unit swept area was found equal to 11.25 W/m^2, considering the Betz maximum of 0.593 and a mean value of 3.36 m/s for the average annual wind speed [1]. Thus, considering a capacity factor of 7% [88], it meant an annual energy production of 6.899 kWh/m^2, or 0.575 kWh/m^2 in a month.

3.2.4 Solar

The sun radiation of the study area was approximated with that of Bamenda, 16km from the study site. The values reported in Table 3.40 were taken from the NASA database [63]. In the second column there is the daily average sun radiation for every month, with a computed yearly average of 5.24 kWh/m^2/day. The third column reports the values of sun radiation for the entire month duration: it is calculated by multiplying the daily average for the number of days in the relative month. The aim is to obtain the yearly sun radiation, which is 1908.84 kWh/m^2; also, from the daily average over the year it could have been possible to compute it, with a result of 1911.69 kWh/m^2, a very similar value. The importance of the yearly average sun radiation was the comparison with solar map provided by SolarGIS® (Figure B.7) according to which the city of Bamenda is placed in a region with sun radiation in the range of 1900-2000 kWh/m^2 in a year. Therefore, it can be considered a reliable estimation matching with the NASA information.

Month	Daily I_{mean} [kWh/m^2]	Monthly I_{mean} [kWh/m^2]
January	6.39	198.09
February	6.56	183.68
March	5.93	183.83
April	5.28	158.40
May	5.00	155.00
June	4.57	137.10
July	4.22	130.82
August	4.17	129.27
September	4.38	131.40
October	4.63	143.53
November	5.60	168.00
December	6.12	189.72

Table 3.40 Mean daily and monthly solar irradiation

4 Energy solution planning

In chapter 3, the energy balance has provided insights about the current energy consumption pattern of CPC, although not all the energy needs are currently met. The energy resource assessment has helped to identify which are the potentials of locally available RES, in particular hydro potential, biogas, wind and solar energy. In the optics of energizing rural areas of developing countries, satisfying unmet needs in a sustainable manner together with favouring the access to modern and cleaner fuels through a need-resource matching strategy, CPC represents a fertile ground where global green solutions can be tested and then implemented fully. In this chapter, solutions to achieve the main objective of the thesis, energy self-sufficiency of CPC Bali, are presented. The suggested solutions concern the electrical and thermal self-sufficiency of CPC, with the former having two possible scenarios, 100% off-grid and grid-RES hybrid, while the latter only one scenario. The electrical energy solution planning is presented as the results of HOMER® simulations. Optimization and sensitivity analyses on the most relevant inputs identify key issues instrumental for the energy self-sufficiency objective. The thermal solution planning, cooking and water heating needs are unfolded and suggestions are made to overcome them.

At the end of the chapter, two summarizing energy flow diagrams, as the one built in section 3.1.5, illustrate possible evolutions of CPC energy layout after proper RETs implementation.

4.1 Electricity

In this paragraph, the results of the renewable electrical system simulated with the HOMER® software are presented. The structure of the paragraph follows closely the approach proposed in the methodology that consists of a three level analysis comprising simulation, optimization and lastly a sensitivity analysis.

In the first part, the simulated system is structured. It has to include all the possible technologies available based on renewable sources, the grid and the load demand. Since resource potentials and load demand have been assessed on the field, the majority of the inputs come from the results of data analysis; alternatively, references have been used to support the setting of the system in all its features, in particular for the cost-related inputs. In order to shrink the analysis and focus directly on the final findings, the process of selection of the proper technologies has been omitted, thus input data herein presented are already those concerning the optimized solution.

In the second part, the simulation and optimization phases are conducted simultaneously. Basically two base cases are individuated: the configuration without grid and the hybrid configuration where also the grid is modelled. Eventually, two optimized systems are found representing the best techno-economic solutions.

Finally, in the third part, sensitivity analyses are conducted in order to verify the previously optimized system configurations under the variation of some parameters, considered as the most uncertain or likely to vary. The sensitive variables are the capital cost of hydropower system, PV panel and wind turbine, the unit price of electricity when the grid is included in the simulation and the unit price of diesel. At the end of this part, the competitiveness of all the renewable technology solutions are tested as well as the influence of grid price and diesel price on the proposed optimized solutions.

4.1.1 System modelling

The overall electrical system of CPC was modelled with HOMER® including what the software calls equipment. The following equipment were modelled:

- load curve
- power grid
- water turbine
- hybrid (diesel/biogas) generator
- PV panel
- wind turbine (SEI-BNY 1.5)
- battery strings (6FM200D)
- AC and DC buses
- Converter

HOMER® schematizes the whole system in the following way:

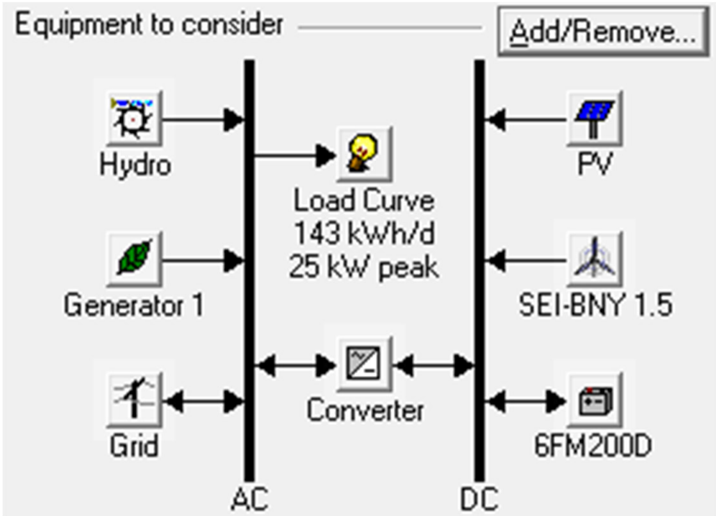


Figure 4.1 Structure of CPC energy system through HOMER®

In the scheme above, hydro turbine, hybrid generator and grid are connected to the AC bus which supplies power to the campus whose load is schematized at the centre. The converter is a fundamental component since connects AC and DC buses by converting AC into DC and vice versa. On the DC side, there are all the technologies working in direct current: PV, wind and batteries. All the input parameters by each piece of equipment and related sources are reported below.

The yearly load profile was designed thanks to the estimation model developed by Losa and Mandelli [70] based on the result of the field data collected. The model needed as input: consumer classes (e.g. household, school, stand shop, clinics, etc.), number of consumers and info about appliances (power, number of units, working windows, working time and random variation). The data collected in field though questionnaire and surveys were revised and processed to be inserted as inputs. The result was an hourly load curve characterized by a daily random variability. The 8760 values vector was then loaded on the software. Moreover, to account for variations in the electrical consumption patterns over an entire year, four different periods were established to model the load change, according to the school:

- September: reduced load (university closed)
- October – May: full load
- June: reduced load (school closed)
- July – August: low load (vacation)

As can be seen in the icon of Figure 4.1 the average simulated load along the year is 143 kWh/day, slightly lower than 145 kWh measured in September and rather inferior to 152 kWh measured in October (see section 3.1.3). This is due to the reduced load of the vacation period decreasing the entire yearly average electricity demand. In the icon is also figured the maximum peak of 25 kW that results to be remarkably higher than 16 kW found in October. Indeed, due to the random variability of the model, days when the evening peak is very high are also included. This should be regarded as a plus for the simulation process because more contingencies can occur and an overestimation of the peak guarantees a certain tolerance to the analysis.

The modelling of water turbine in HOMER® gives only the chance to include or exclude it from the system configuration without considering different dimensions and rated powers. Instead, it is possible to do it for PV panels and other RETs. To by-pass such an issue, an adapted sensitivity analysis was performed to study the optimal size of water turbine expressed in terms of investment costs and design flow rate. Hydro turbine cost related data are reported in Table 4.1.

Capital cost [$/kW rated]	Replacement cost [$/kW rated]	O&M [% of capital/yr]	Lifetime [yr]	Design flow rate [l/s]
4000	4000	3% - 4%	25	9.06 – 77.02

Table 4.1 Hydro turbine cost related data

The turbine considered was a cross-flow hydro turbine. The implicitly considered sizes range from 4.4 kW rated to 37.8 kW rated power without any efficiency accounted. Other necessary input parameters were the electro-mechanic efficiency fixed at 75% and pipe head losses of 40%. The choice to have fixed pipe head losses implies a variable pipe diameter that is automatically calculated by the software. This modelling strategy was adopted to focus the simulation on the system configuration optimization and to simplify it by considering a “worst case scenario” by setting penstock length of 1 km leading to 40% of head losses. Such value may seem high but it results from a compromise between penstock length, electric cables investment and power required. Eventually, the simulated output net power ranged between 2 kW and 17 kW (overall system efficiency of 45%). Hydro source was modelled by using as input the available head of 50 m and the average flow rate per month as computed in section 3.2.2. The residual flow was fixed at 54 l/s, 50% of the flow rate during the month of lowest stream flow (March).

Solar panels are practically standardized in type, therefore there was no choice upon the model in HOMER®, but only costs were to be inserted. The sizes considered were 0, 3, 6, 9, 12, 15, 16, 17 and 18 kW. The coordinates are 5°53’ North, 10°3’ East with GMT of West Africa.

Capital cost [$/kW]	Replacement cost [$/kW]	O&M [$/kW/yr]	Lifetime [yr]
3000	3000	30	20

Table 4.2 PV solar panel related cost

The derating factor was 90%, the ground reflectance 20% and the slope of installation 5.88 degrees, as set by default in HOMER®. Considering also the effect of temperature on the production, the parameters to insert were efficiency at standard condition of 17%, power temperature coefficient equal to -0.5 %/°C and nominal operating cell temperature of 47 °C.

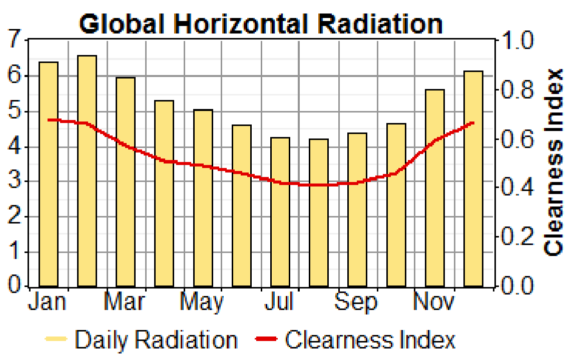


Figure 4.2 Mean daily radiation and clearness index at CPC

Solar source was modelled including clearness index and average daily radiation (kWh/m^2/day) of each month. Data was exactly the same previously found in section 3.2.4. The other parameters inserted by the user were time zone and satellite coordinates. The scaled annual average radiation resulted to be 5.23 kWh/m^2/day. Above, clearness index and daily radiation are reported graphically in Figure 4.2.

The selected wind turbine from the new updated database [17] was the SEI-BNY 1.5/4 of 1.5 kW rated power, with hub height of 36 meters. The considered number of turbines was from 0 to 10 items.

Capital cost [$/turbine]	Replacement cost [$/turbine]	O&M [$/kW/yr]	Lifetime [yr]
6600	6600	75	20

Table 4.3 Wind turbine cost related data

For what concerned the wind source, the average wind speed computed in section 3.2.3 was used as input. Besides, altitude above sea level (1400 m), anemometer height (11 m), Weibull coefficient (k = 1.85), hour of peak wind speed (14), diurnal patter strength (0.329) and autocorrelation factor (0.918) were also inserted by the user. The scaled annual average wind speed resulted to be 3.37 m/s.

The possibility of using biogas as fuel was translated in terms of costs only with an investment of 250$ [74] on the existing generator of 24kW, which had a remaining lifetime of 10’000 hours, considering it was bought by the school in 2011 and it had been used. The minimum partial load was set at 30% as set by default in HOMER®.

Capital cost [$]	Replacement cost [$]	O&M [$/kW/yr]	Lifetime [hr]
250	12660	0	10000

Table 4.4 Hybrid generator cost related data

The availability of biomass was quantified by HOMER in terms of tonnes per day; then the biogas was calculated once the gasification ratio ($kg_{biogas}/kg_{biomass}$) had been fixed. However, in the case of CPC Bali the biogas was already produced by a digester as explained, so the average daily availability of biogas was the biomass input requested by the software, while the gasification ratio was fixed equal to 1 $kg_{biogas}/kg_{biomass}$. The average daily production was 0.011 t/day.

The selected type of converter restricted the maximum allowable power that can flow between AC and DC buses. The costs depended on the size considered, as expressed by the Table 4.5.

Size [kW]	Voltage [V]	Capital cost [$]	Replacement cost [$]	O&M [$/kW/yr]	Lifetime [yr]
5	24	930	930	100	15
10	48	3000	3000	200	15

Table 4.5 Converter size, voltage, lifetime and cost related data

In case of inverter (from DC to AC) the efficiency was 90%, while in case of rectifier (from DC to AC) the efficiency was 85%, with a 100% of capacity relative to inverter for both sizes.

The selected model9 of battery was the Vision 6FM200D already in the catalogue of HOMER®, with 12V, 200Ah of capacity and an initial state of charge set to 100%.

Capital cost [$/battery]	Replacement cost [$/battery]	O&M [$/battery/yr]	Lifetime [kWh]
175	175	2	917

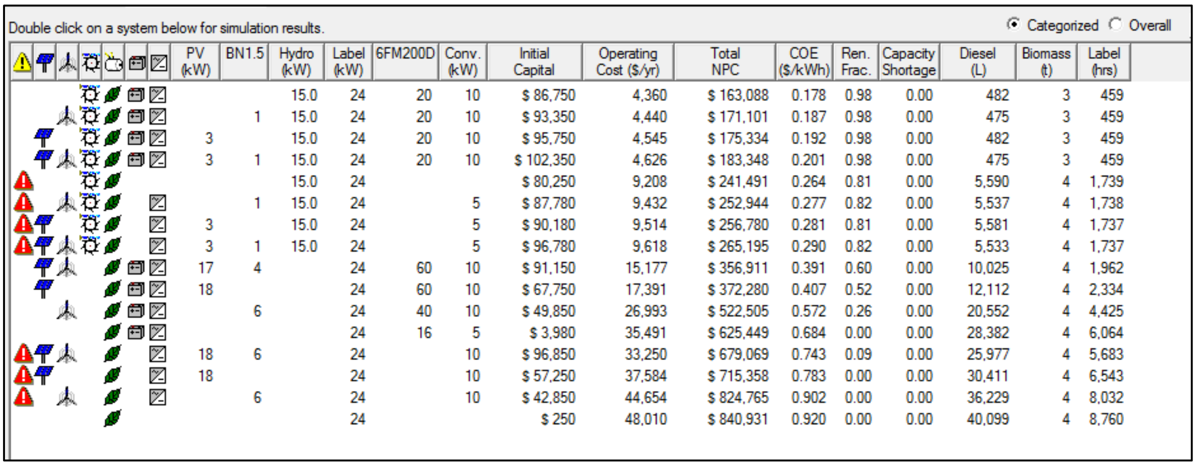
Table 4.6 Battery lifetime and cost related data

Strictly correlated to the choice of converter was the number of batteries for each string. In fact, series connection of batteries establishes the voltage of the string while parallel connection the total capacity. It meant that for the 24V converter 2 Vision batteries per string were considered, while in case of 48V the number rose to 4 units per string. The total number of strings considered in the search space of HOMER® ranged from 0 to 15.

Additional necessary data concerned the annual real interest rate of Cameroon, which was 2.95% [13], the price of diesel set at 0.93$/litre and the price of electricity purchased from the grid, found at 0.173$/kWh. The lifetime of the simulation of the system was 25 years, the average lifetime of the most durable equipment, the water turbine.

4.1.2 Off-grid system

In this section the best configuration of the off-grid system is presented. In system without grid, hydropower resulted to be the most techno-economic feasible solution. Indeed, in order of NPC, it is the cheapest technology actually available, as shown in Figure 4.3.


Double click on a system below for simulation results. Categorized Overall

PV (kW)	BN1.5	Hydro (kW)	Label (kW)	6FM200D	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Biomass (t)	Label (hrs)
		15.0	24	20	10	$ 86,750	4,360	$ 163,088	0.178	0.98	0.00	482	3	459
	1	15.0	24	20	10	$ 93,350	4,440	$ 171,101	0.187	0.98	0.00	475	3	459
3		15.0	24	20	10	$ 95,750	4,545	$ 175,334	0.192	0.98	0.00	482	3	459
3	1	15.0	24	20	10	$ 102,350	4,626	$ 183,348	0.201	0.98	0.00	475	3	459
		15.0	24			$ 80,250	9,208	$ 241,491	0.264	0.81	0.00	5,590	4	1,739
	1	15.0	24		5	$ 87,780	9,432	$ 252,944	0.277	0.82	0.00	5,537	4	1,738
3		15.0	24		5	$ 90,180	9,514	$ 256,780	0.281	0.81	0.00	5,581	4	1,737
3	1	15.0	24		5	$ 96,780	9,618	$ 265,195	0.290	0.82	0.00	5,533	4	1,737
17	4		24	60	10	$ 91,150	15,177	$ 356,911	0.391	0.60	0.00	10,025	4	1,962
18			24	60	10	$ 67,750	17,391	$ 372,280	0.407	0.52	0.00	12,112	4	2,334
	6		24	40	10	$ 49,850	26,993	$ 522,505	0.572	0.26	0.00	20,552	4	4,425
			24	16	5	$ 3,980	35,491	$ 625,449	0.684	0.00	0.00	28,382	4	6,064
18	6		24		10	$ 96,850	33,250	$ 679,069	0.743	0.09	0.00	25,977	4	5,683
18			24		10	$ 57,250	37,584	$ 715,358	0.783	0.00	0.00	30,411	4	6,543
	6		24		10	$ 42,850	44,654	$ 824,765	0.902	0.00	0.00	36,229	4	8,032
			24			$ 250	48,010	$ 840,931	0.920	0.00	0.00	40,099	4	8,760

Figure 4.3 Categorized results of HOMER® simulation for off-grid configuration

In Table 4.7 the most relevant technical features of this configuration of the system are summarized:

	Hydro	Diesel Generator (Label)	Vision 6FM200D	Converter
Installed power [kW] (n° for batteries)	15	24	20	10
Yearly electricity production [MWh/yr]	78.84	4.53	6.97	-

Table 4.7 Power and energy features of the without grid optimized system

The hydro turbine minimizing the NPC was the one with 15 kW of nominal power with a volumetric flow rate of 40.77 l/s, so below the residual flow rate. The hybrid diesel generator operating at an average power of 24 kW was also necessary to supply electricity and cover the load during the peak times. It consumed 482 litres of diesel and 3 tons of biogas per year. In Table 4.7, the power production per year per component are also shown. The total electrical production amounted to 83.4 MWh/yr, thus satisfying the entire electrical demand of 52.2 MWh/yr. In this configuration 20 batteries are needed to store electricity when there was excess, rather than release it during period of peaks. A converter of 10 kW was selected to connect AC and DC lines. However, an excess of electricity of 27.6 MWh/yr still remained. This huge excess of electricity is a result that the software does not see as a constraint of the analysis. In other words, in order to meet the load and the energetic demand with the goal function represented by the net present cost of the whole system, the excess of electricity is not minimized by the software. The capacity of batteries to store electricity is limited, so the excess of electricity rises; this is clearly shown by Figure 4.4 in which the capacity of batteries to store electricity during charging cycles (green area) is overcome by the excess (dark pink area), especially during the vacation period (July, August and September).

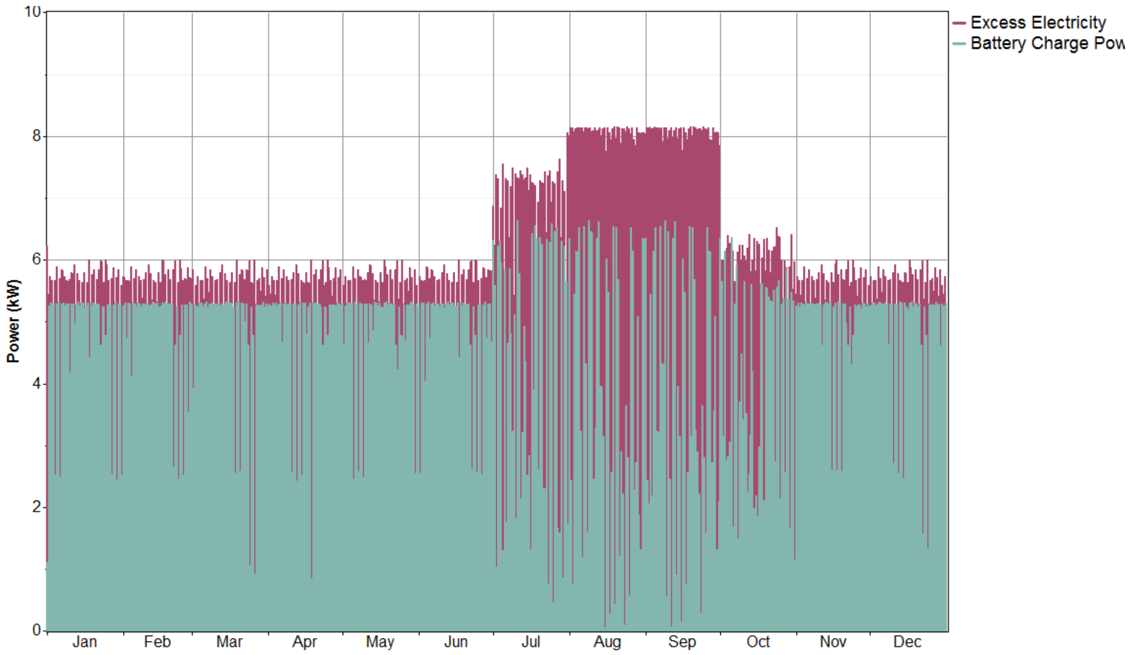


Figure 4.4 Trend of the excess of electricity (pink) and batteries charge (green)

A practical example of what occurs on a daily basis is given by the load curve (see Figure 4.5): during the night hours the supply provided by the hydro turbine (blue line) is far above the demand (green line). Having no constraints upon the excess of electricity, the software does not see the reduction of supply as an option to limit the excess. The best solution to limit the excess of electricity, when there is no connection to the grid, is to reduce the output power from the turbine by making it work in partial flow conditions.

Cross flow turbines can work at 60% of the rated flow without losing in efficiency. If during the night hours and during the day between the two peaks the turbine could work in partial flow conditions, the power supply may be reduced to 5.4 kW at most and the excess would be drastically cut.

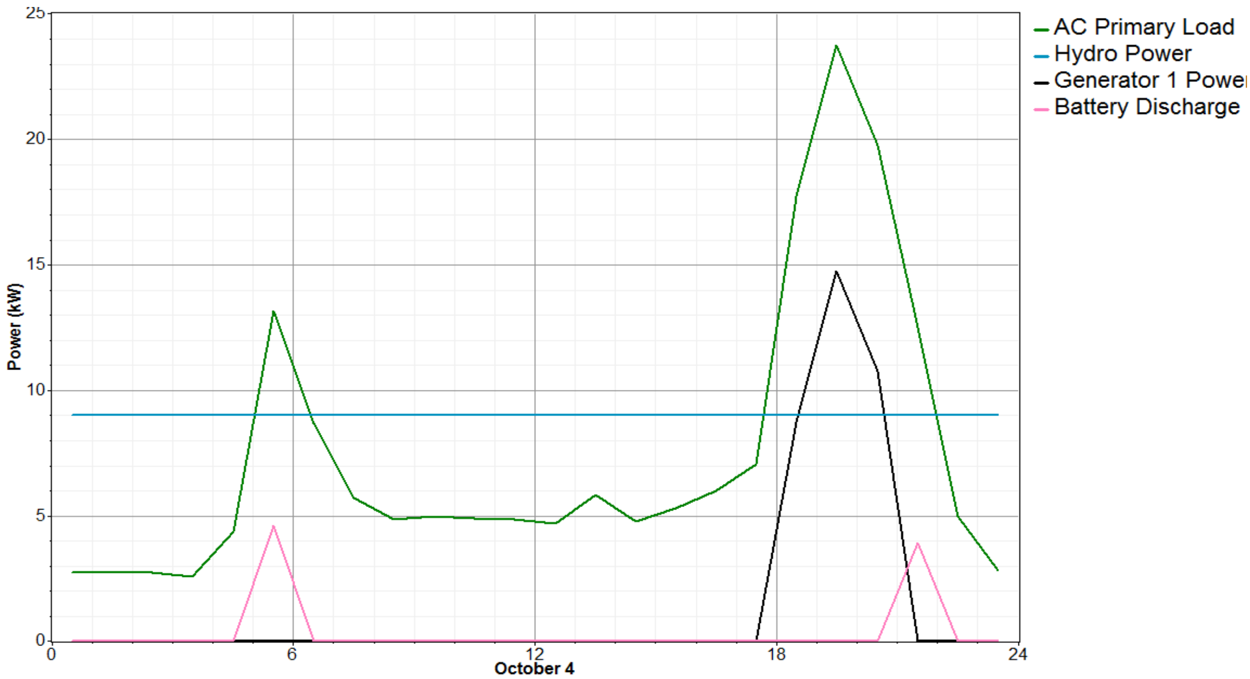


Figure 4.5 4th October load curve and supply by different technologies (off-grid system)

Other options are represented by possible aside exploitations as the supply of further loads in specific time windows of the day, the sale of electricity to the grid or dissipation through electrical resistances at worst. Above all, it might be possible to extend the distribution grid and supply electricity to the population living around the school. However, these solutions are left for further studies since they are beyond the scope of the present thesis.

In Figure 4.5, the typical trend of load and power supply is showed for the 4^{th} of October; in 0 two more graphs illustrate the load and power supply curves in other days (1^{st} of February and 3^{rd} of July) when electricity is supplied in a different way. In Figure 4.5 it can be seen how the load peak in the morning is supplied partly by batteries that give a contribution to the hydropower supply, while the peak in the afternoon is supplied almost equally by the generator and the hydro turbine. In other periods of the year the peak load would be met differently. In the curve referred to the 1st of February (see Figure C.1), the evening peak is satisfied almost equally by hydro, batteries and generator; whereas on the 3rd of July (Figure C.2), when the load is assumed to be lower, batteries could supply the residual power during the evening peak. In Figure 4.6 the monthly average supply is showed:

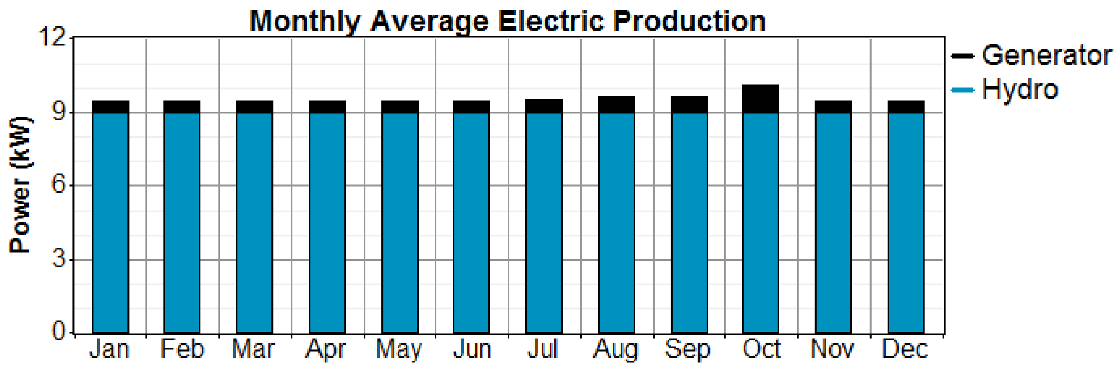


Figure 4.6 Monthly average power production by technology

Beside the technical features, the economical outcomes of the system mainly powered by the hydro turbine are in table 4.8 and Figure 4.7:

Capital cost [$]	NPC [$]	Ann. Cap. Cost [$/yr]	Ann. Repl. Cost [$/yr]	O&M Cost [$/yr]	Fuel Cost [$/yr]	Operating cost [$/yr]	LCOE [$/kWh]
86750	163088	4954	1372	2540	448	4360	0.178

Table 4.8 Economic features of the optimized off-grid system

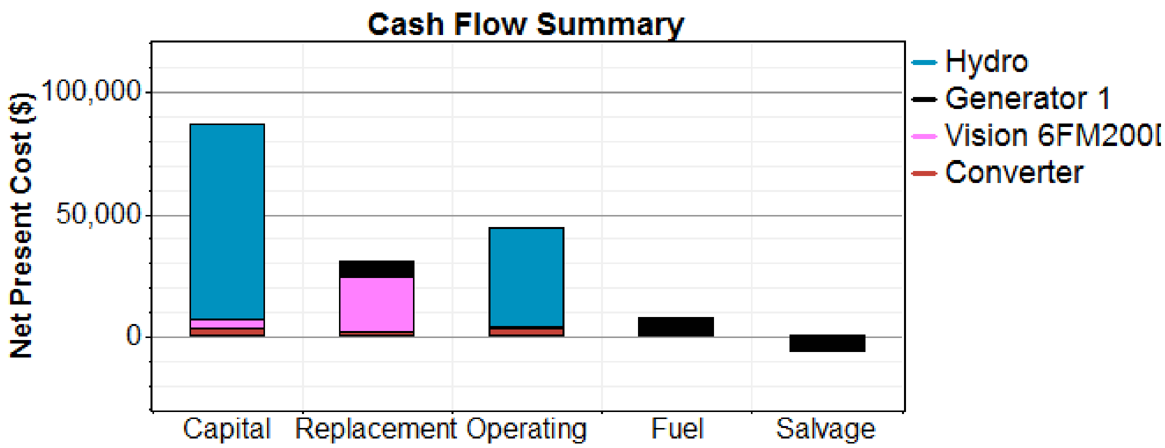


Figure 4.7 NPC by cost type and technology for the optimized off-grid system

The NPC over 25 years of lifetime of the system amounts to 163088 $ that is distributed among capital costs, replacement costs, operating costs and fuel costs. The levelized cost of energy is 0.178 $/kWh that is very competitive with the current national cost of 0.17 $/kWh. In Figure 4.7 the share of cost type among the different component is also illustrated, with the hydro constituting the highest part of capital and operating cost, while batteries cause the majority of replacement cost and diesel is the only fuel paid. Finally the nominal cash flow over 25 years is reported in Figure 4.8 and Figure 4.9, one per type of cost and the other one per component, respectively.

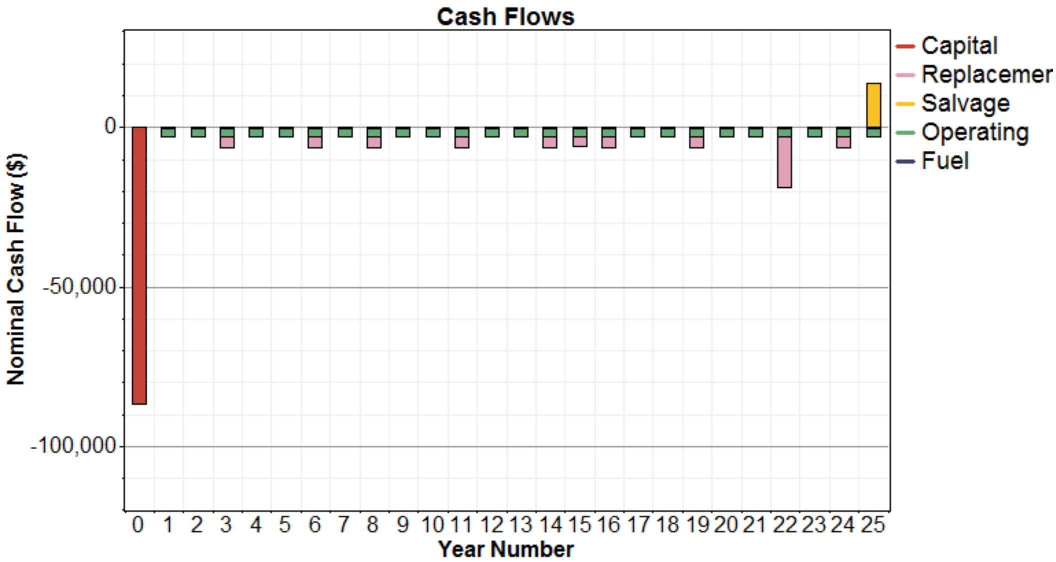


Figure 4.8 Nominal cash flow by cost type for the off-grid system

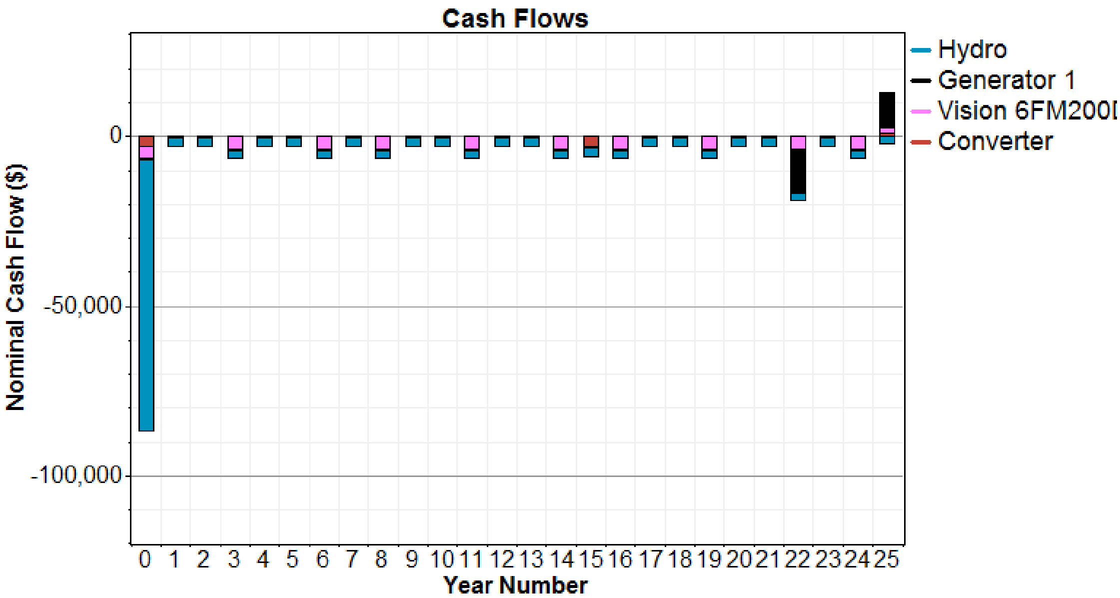
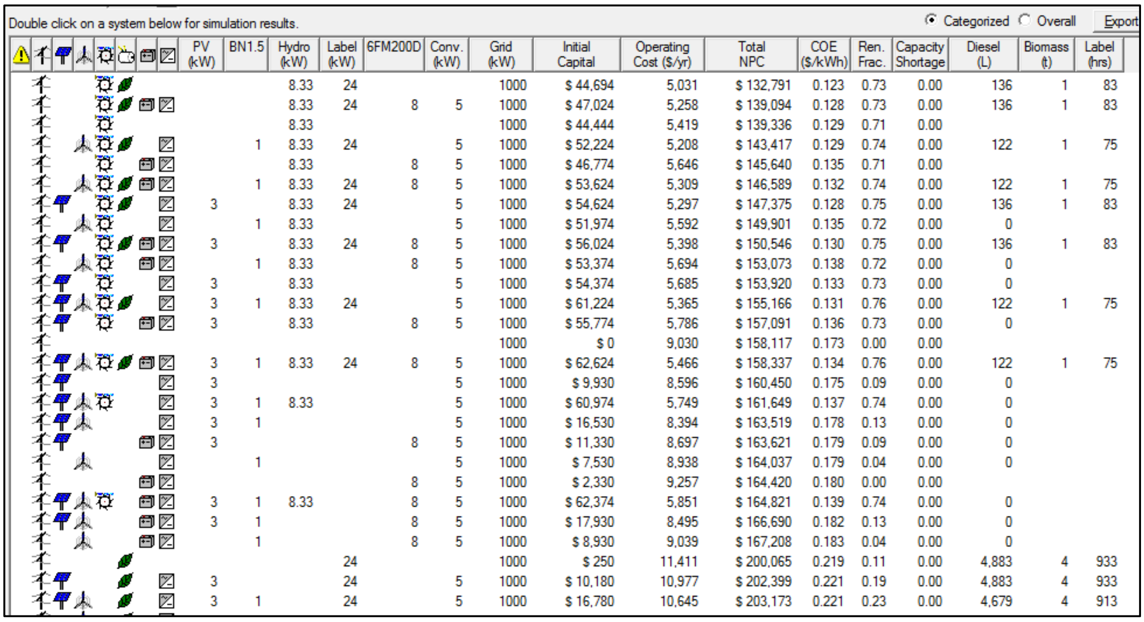


Figure 4.9 Nominal cash flow by technology for the off-grid system

4.1.3 Grid-RES hybrid system

The system with the grid was modelled as well. In this case the best configuration found still comprised hydropower meeting the power demand together with the grid supply. The hybrid grid-hydro configuration proved again the high competitiveness of hydropower against PV panels and wind turbine, as shown in Figure 4.10.



Double click on a system below for simulation results. Categorized Overall Export

PV (kW)	BN1.5	Hydro (kW)	Label (kW)	6FM200D	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Biomass (t)	Label (hrs)
		8.33	24			1000	$ 44,694	5,031	$ 132,791	0.123	0.73	0.00	136	1	83
		8.33	24	8	5	1000	$ 47,024	5,258	$ 139,094	0.128	0.73	0.00	136	1	83
		8.33				1000	$ 44,444	5,419	$ 139,336	0.129	0.71	0.00			
	1	8.33	24		5	1000	$ 52,224	5,208	$ 143,417	0.129	0.74	0.00	122	1	75
		8.33		8	5	1000	$ 46,774	5,646	$ 145,640	0.135	0.71	0.00			
	1	8.33	24	8	5	1000	$ 53,624	5,309	$ 146,589	0.132	0.74	0.00	122	1	75
3		8.33	24		5	1000	$ 54,624	5,297	$ 147,375	0.128	0.75	0.00	136	1	83
	1	8.33			5	1000	$ 51,974	5,592	$ 149,901	0.135	0.72	0.00	0		
3		8.33	24	8	5	1000	$ 56,024	5,398	$ 150,546	0.130	0.75	0.00	136	1	83
	1	8.33		8	5	1000	$ 53,374	5,694	$ 153,073	0.138	0.72	0.00	0		
3		8.33			5	1000	$ 54,374	5,685	$ 153,920	0.133	0.73	0.00	0		
3	1	8.33	24		5	1000	$ 61,224	5,365	$ 155,166	0.131	0.76	0.00	122	1	75
3		8.33		8	5	1000	$ 55,774	5,786	$ 157,091	0.136	0.73	0.00	0		
						1000	$ 0	9,030	$ 158,117	0.173	0.00	0.00			
3	1	8.33	24	8	5	1000	$ 62,624	5,466	$ 158,337	0.134	0.76	0.00	122	1	75
3					5	1000	$ 9,930	8,596	$ 160,450	0.175	0.09	0.00	0		
3	1	8.33			5	1000	$ 60,974	5,749	$ 161,649	0.137	0.74	0.00	0		
3	1				5	1000	$ 16,530	8,394	$ 163,519	0.178	0.13	0.00	0		
3				8	5	1000	$ 11,330	8,697	$ 163,621	0.179	0.09	0.00	0		
	1				5	1000	$ 7,530	8,938	$ 164,037	0.179	0.04	0.00	0		
				8	5	1000	$ 2,330	9,257	$ 164,420	0.180	0.00	0.00			
3	1	8.33		8	5	1000	$ 62,374	5,851	$ 164,821	0.139	0.74	0.00	0		
3	1			8	5	1000	$ 17,930	8,495	$ 166,690	0.182	0.13	0.00	0		
	1			8	5	1000	$ 8,930	9,039	$ 167,208	0.183	0.04	0.00	0		
			24			1000	$ 250	11,411	$ 200,065	0.219	0.11	0.00	4,883	4	933
3			24		5	1000	$ 10,180	10,977	$ 202,399	0.221	0.19	0.00	4,883	4	933
3	1		24		5	1000	$ 16,780	10,645	$ 203,173	0.221	0.23	0.00	4,679	4	913

Figure 4.10 Categorized results of HOMER® simulation for the grid-RES hybrid system

In Table 4.9 and Table 4.10 the power share and yearly electrical production are shown:

	Grid	Hydro	Diesel Generator (Label)
Installed power [kW]	1000	8.33	24

Table 4.9 Power features of the for grid-RES hybrid system

Hydro production [MWh/yr]	Genset Production [MWh/yr]	Grid Purchase [MWh/yr]	Grid Sales [MWh/yr]	Grid Net Purchase [MWh/yr]	Total production [MWh/yr]
43.8	1.37	16.66	9.63	7.03	61.83

Table 4.10 Electric feature of the optimized with grid system

The hydro turbine installed in this case is of 8.33 kW of nominal power with a volumetric flow rate of 22.64 L/s. The cross-flow water turbine produces the main part of electricity (71%), while the rest is provided by the grid (27%) and only a small part by the hybrid generator (2%) consuming 136 litres of diesel and 1 ton of biogas every year. The total electrical production amounts to 61.83 MWh/yr, thus covering the entire electrical demand of 52.2 MWh/yr. The excess of electricity is considered null by HOMER® as it assumes the possibility to sell electricity when the grid is modelled, or at least the absorption of excess by the grid. The total grid sales amounts to 9.63 MWh/yr; this quantity could supply further loads in specific time windows of the day.

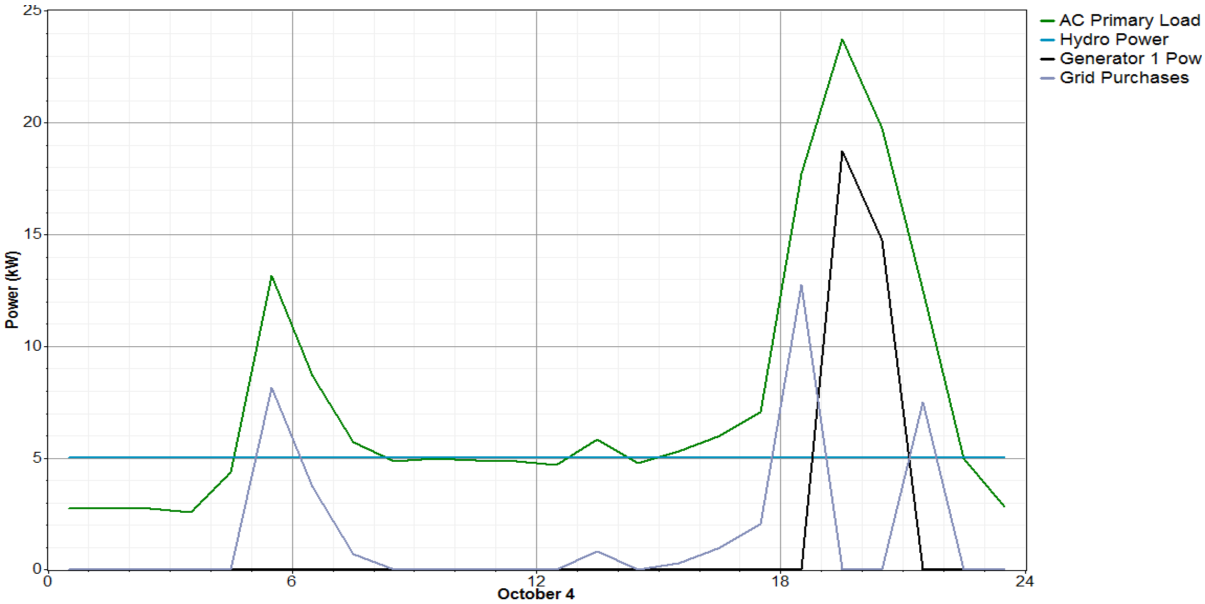


Figure 4.11 4th October load and supply by different technologies (grid-RES hybrid system)

Again the typical trend of load and power supply is showed for the 4th of October in Figure 4.11. In Appendix C (Figure C.3 and Figure C.4) two more graphs illustrate the load and power supply curves in other two days (1st of February and 3rd of July).

In the month of October the load is assumed to be higher; during the peak times the load is met by hydro and grid supply (morning peak) or hydro, grid and generator (evening peak). When the load has a different profile as during February or July, the supply during peak times is generally provided by grid and hydro. The excess of electricity and consequent sale back to the grid occur during the night hours, when the load is very low. As for the previous case the monthly average supply is represented in Figure 4.12:

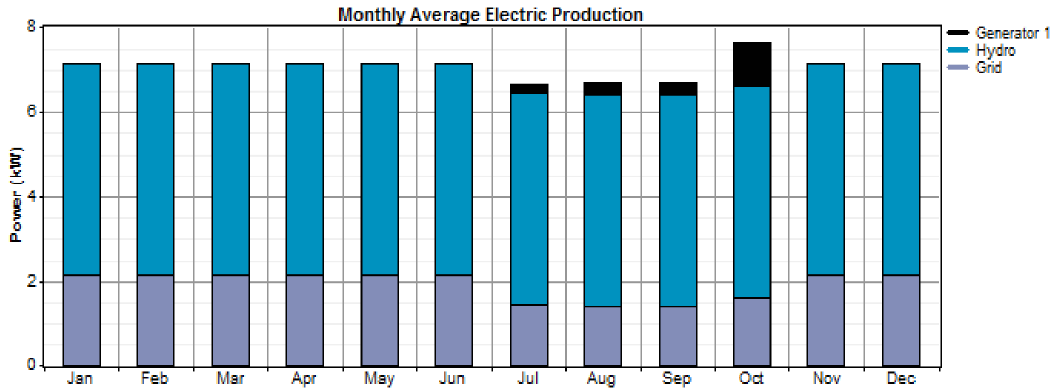


Figure 4.12 Monthly average power production by technology

The economic outcomes of the hybrid grid-hydro-generator system are shown in Table 4.11.

Capital cost [$]	NPC [$]	Ann. Cap. Cost [$/yr]	Ann. Repl. Cost [$/yr]	O&M Cost [$/yr]	Fuel Cost [$/yr]	Operating cost [$/yr]	LCOE [$/kWh]
44694	132791	2552	-277	5182	126	5031	0.123

Table 4.11 Economic features of the grid-RES hybrid system

The total NPC of this configuration amounts to 132791 $. It is lower than the system without grid since the capital and replacement costs are considerably reduced. Contrariwise, the operating costs occupy a bigger share of the NPC, mainly due to the electricity purchases from the grid (see the purple band in Figure 4.13). The levelized cost of energy is sensibly reduced to 0.123 $/kWh. This indicates how this configuration may be very convenient not only in the optics of being independent from the grid, even though only partially, but also under the economical point of view. The nominal cash flow over 25 years is reported with two graphs, one per type of cost and the other one per component.

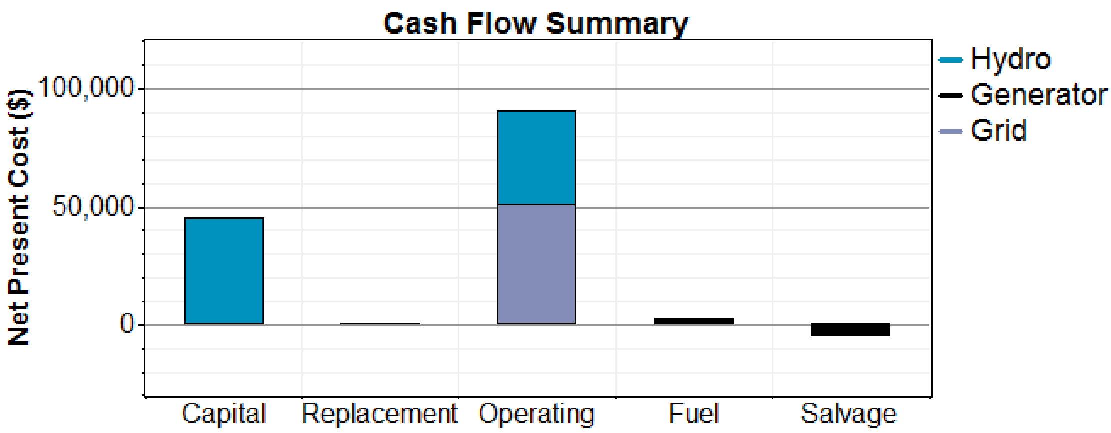


Figure 4.13 NPC by cost type and technology for the grid-RES hybrid system

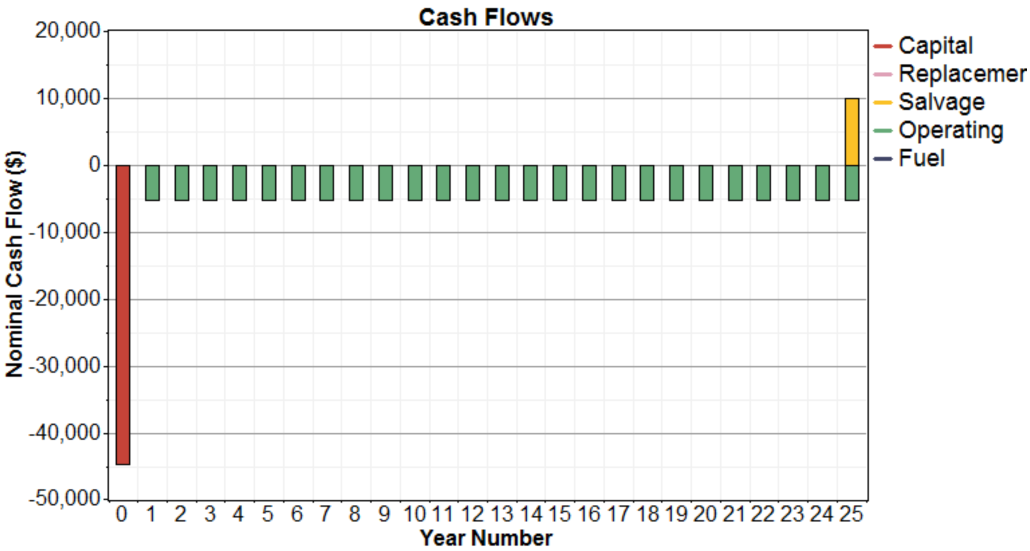


Figure 4.14 Nominal cash flow by cost type for the grid-RES hybrid system

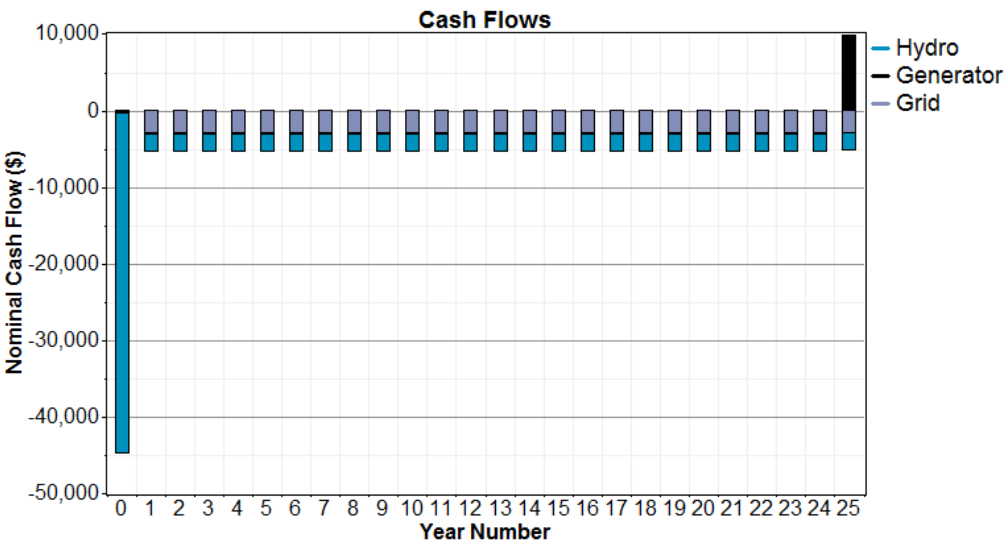


Figure 4.15 Nominal cash flow by technology for the grid-RES hybrid system

Environment Impact of the Choices

Beside technical and economical consideration, a further output of the simulation by HOMER® is the GHG Emission pattern of the two systems. In both cases emissions are low. In Table 4.12 the emissions of both cases are compared:

	CO_2 [kg/yr]	CO [kg/yr]	UHC [kg/yr]	PM [kg/yr]	SO_2 [kg/yr]	NO_x [kg/yr]
Off-grid case	1249	16	2	1	3	140
Hybrid case	4794	4	0	0	20	45

Table 4.12 GHG Emissions between off-grid and hybrid systems

4.1.4 Sensitivity analyses

In the next sections, the results of sensitivity analyses are presented. The aim of sensitivity analyses was to verify the resilience of the optimized configuration upon variation of diesel and grid unit purchase price. In addition, for this work it was instrumental in order to investigate the competitiveness of other RETs comparing to hydropower, particularly solar PV and wind turbine that were not selected in the systems presented previously. However, the first sensitivity analysis was performed on the hydro capital cost. Being hydropower the most desirable and promising solution for the future system as resulted from the previous simulations, a deeper study on how the cost of installation of hydropower influenced the NPC was the first step to take.

Sensitivity on hydro capital cost

The hydro capital cost per rated kW installed was for both cases 4000 $/kW. As explained before, this value came from on field survey. In the cost of hydropower installation economies of scale were not considered, since the dimension of the turbines simulated varies only slightly. In the literature, multiple examples of micro hydropower systems were found where the capital cost was less than 4000 $/kW and sometimes even less then 1000 $/kW when the construction had come about specific local circumstances [89]. In the optics of cost savings, the sensitivity analysis performed simulated a cost reduction of hydro capital cost of 25%, 50% and 75% for both the optimized solutions found previously. All the operational costs were the same, since power installed and energy produced by each equipment were left untouched. The capital cost of hydro influenced the NPC and LCOE that were sensibly reduced. Tables 4.13 and 4.14 outline the findings of the analysis:

	Capital cost [$/kW$_{rated}$]	NPC ($) off-grid	NPC ($) hybrid	ΔNPC [$]
Base case	4000	163088	132791	30297
sensitivity analysis 1	3000	143088	121680	21408
sensitivity analysis 2	2000	123088	110569	12519
sensitivity analysis 3	1000	103088	99458	3630

Table 4.13 NPC variations for sensitivity cases on hydro capital cost

	Capital cost [$/kW$_{rated}$]	LCOE ($/kWh) off-grid	LCOE ($/kWh) hybrid	ΔLCOE [$/kWh]
Base case	4000	0.178	0.123	0.055
sensitivity analysis 1	3000	0.157	0.112	0.045
sensitivity analysis 2	2000	0.135	0.102	0.033
sensitivity analysis 3	1000	0.113	0.092	0.021

Table 4.14 LCOE variations for sensitivity cases on hydro capital

Clearly the more the capital cost decreases the more the NPC and LCOE are reduced as well. The most interesting result is reported in the last column, where the NPC and LCOE difference between the optimized case without grid and the optimized case with grid is calculated. The difference becomes smaller when the hydro capital cost declines. This means that in case the actual cost of hydro was lower than the hypothesized, the solution seeing CPC electrically independent from the national grid would be viable and convenient under different perspectives.

Sensitivity on PV and wind capital cost

In the optimized configurations found in the previous analysis, wind and solar technology were never present. The main reason of their exclusion is the limited, if not absent, competitiveness due to the high capital cost of technology. Besides that, the theoretical potential of these sources is more difficult to exploit in order to satisfy the electrical demand of the campus. For instance, the sun hours occur in a period of the day when the energy demand is moderate, while the peaks of the load curve are outside the sunlight window. This involves the utilization of an enormous amount of batteries to store electricity, with severe implications on further conversions and losses aside of a higher capital cost. This is proved in the following calculations, where systems including wind turbine and solar PV are presented.

The aim of the sensitivity analyses in this case was to check at which capital cost PV and wind turbine became competitive RETs to hydropower. The minimum cost reduction simulated was of 90%, thus 10% of the initial capital cost for both wind and solar technologies.

When the off-grid case with the maximum cost reduction assumed (90%) was simulated, the best techno-economical solution still remained hydropower. The first configurations that include PV and wind turbine were both hybrid, with a minimum percentage of power installed from the alternative technology and the majority of power installed being still from hydro. Batteries, generator and converter were still necessary pieces of equipment. In this case a slight increase in the NPC was found (second and fourth row of Table 4.15). On the other hand, the configurations without hydropower installed and the maximum output from solar and wind sources were characterized by a much higher NPC (third and fifth row of Table 4.15). The results of the sensitive analysis on wind and solar capital cost in the case with no grid modelled and a capital reduction of 90% are summarized in Table 4.15. In 0 two more tables give further information on the same configurations, as installed power and energy output per equipment (Table C.1 and Table C.2).

Technology with reduced cost	NPC [$]	LCOE [$/kWh]
PV_hybrid	165643	0.181
PV_max	311599	0.341
Wind_hybrid	163994	0.179
Wind_max	394021	0.431

Table 4.15 NPC and LCOE if capital cost of PV and wind turbine are reduced by 90%

The NPC of the hybrid solution wind-hydro is the closest to the optimized configuration. However, as can be seen from the tables in 0, only 1 wind turbine is installed and the main output energy is still from hydro 92%, against less than 3% from wind. For what concerns the best solution without hydropower, the configuration with the maximum output from solar is better than the wind, but the NPC is extremely high in this case (311599 $). Indeed, an installation of 18 kW of PV panels requires the use of 90 batteries to store electricity for the reasons stated above, thus the capital cost dramatically increases, preventing any economic feasibility of this configuration type. The electrical output from PV is almost 30 MWh/yr, a poor number if one considers the almost 80 MWh/yr when 15 kW of hydropower are installed. Eventually, it is observed that solar and wind technologies are still far to be competitive with hydropower in a solution fully independent from the grid.

From the sensitivity analyses on PV and wind, in the case with grid simulated, RETs would be competitive with hydropower. Thanks to the support of the grid, batteries and diesel generator would be unnecessary. The results of the sensitive analysis are summarized in Table 4.16. In 0 two more tables give further information on the same configurations, as installed power and energy output per equipment (Table C.3 and Table C 4). NPC of wind and solar configurations with grid are very close to the optimized hydro configuration. The levelized cost of energy is sensibly increased. The feasibility of these configurations relies on the possibility of a drastic reduction of capital cost, eventuality rather unlikely to happen in the short-term unless grand incentives are provided from outside in favour of these specific technologies.

Technology with reduced cost	NPC [$]	LCOE [$/kWh]
PV	134314	0.142
Wind	133108	0.140
Hydro	132791	0.123

Table 4.16 NPC and LCOE if capital cost of PV and wind turbine are reduced by 90%

Sensitivity on diesel and power unit prices

The last sensitive analyses tested the influence of diesel and power unit prices on the optimized solutions found. The unit price of diesel in Cameroon was 0.93 $/L at the time of the study; in the last years it had a fluctuating trend, following the oil quotations on the international market. The sensitivity analysis simulated an increase and a decrease of the unit price of 20%. On the other hand, the unit price of power purchased from the grid had had only an increasing trend in the last years, settling currently at 0.173 $/kWh. The sensitive analysis simulated an increase in the unit price of power of 5%, 10% and 20%.

The price of diesel had a poor influence on the configuration without grid. The optimized system was not modified in terms of installed capacity of hydro and number of batteries. The production of electricity was shared between diesel generator and hydro turbine as the in the optimized case. The price of diesel had a higher influence when the grid was included in the system. In this case, the hydropower installed was still 8.33 kW as in the optimized case; what had changed was the average production of electricity from the generator and the purchase of electricity from the grid. With an increase of 20% the production from the generator was reduced by about 70%, while the purchase from the grid augmented by the same quantity. Conversely, when the price of diesel decreased of 20% the purchase from the grid was reduced by about 5MWh every year; the same quantity was additionally produced by the generator. In Table 4.17 the variation of NPC and LCOE are showed for both cases:

Change in diesel price	NPC [$] off-grid	NPC [$] hybrid	LCOE [$/kWh] off-grid	LCOE [$/kWh] hybrid
-	163088	132791	0.178	0.123
+20%	164656	133474	0.180	0.123
-20%	161519	129694	0.177	0.120

Table 4.17 NPC and LCOE variations along sensitive analysis on diesel price

The unit price of power from the grid had an influence on the configuration of the system. Especially when the price was supposed 20% higher than the current level, the optimal installed capacity of hydropower moved up to 10 kW. In this case the electrical production from the hydro source rose by almost 9 MWh every year, while the grid purchase was halved. When the price of power was simulated 5% or 10% higher, the installed capacity of hydropower remained 8.33 kW. In this case the grid purchase was still reduced versus a higher electrical production from the diesel generator. These features are summarized in the Table 4.18.

Increase in power price	Hydro inst. power [kW]	Hydro production [MWh/yr]	Label production [MWh/yr]	Grid purchase [MWh/yr]	Grid sales [MWh/yr]
-	8.33	43.8	1.37	16.66	9.63
5%	8.33	43.8	2.8	15.23	9.63
10%	8.33	43.8	5.59	12.44	9.63
20%	10	52.56	6.77	8.71	15.84

Table 4.18 Installed power and energy production variations under grid price increases

For what concerned the economic perspectives of the sensitive analysis, the NPC increased when the price of power was higher. The biggest rise occurred when the price rose by 20% due to the higher capital cost of hydropower installation. The levelized cost of energy augmented smoothly when the price of energy stepped up of 5% and 10%, while decreased to 0.12 $/kWh when price of energy was 20% higher because more electricity was produced by hydro the source. The Table 4.19 illustrated the economic results of the sensitive analysis on unit price of power.

Increase in power price	NPC [$]	LCOE [$/kWh]
-	132791	0.123
5%	134639	0.124
10%	135111	0.125
20%	143161	0.120

Table 4.19 NPC and LCOE variations under grid price increase

4.2 Thermal

In this section the results of the thermal solution planning of study are presented. Particularly, the needs of thermal energy are:

- public cooking
- public baking
- public water heating
- domestic cooking
- domestic water heating

As explained in the Chapter 2 some of the above needs are not fully met in the current situation. In order to satisfy the requirements of thermal energy, ad-hoc solutions were investigated. Those solutions had to be based on locally available RES, potentially enough to assure the whole thermal load. Furthermore, the aim was to reduce the monthly consumption of firewood and thermal losses and to improve the current system in terms of reliability and quality of energy or fuel. Below, the solutions are presented for each thermal need.

4.2.1 Public cooking

Cooking is current done using an improved stove whose efficiency is 23.94% (see section 3.1.2). With this stove the primary energy consumption is 140.96 GJ/month. For more efficient use of primary energy the selected possible replacement of the actual cooking stove in the kitchen is the ASTRA stove, fuelled with wood. As explained in section 2.3.2, the choice was based on the similarity in size and the context of application, i.e. schools, although its diffusion is mainly in India. The ASTRA stove has an efficiency of 40%. The required primary energy supply when the ASTRA stove is used was calculated leaving unchanged the current final energy consumption. In addition a comparison with the value found in the energy balance is done in order to highlight the savings that the school could benefit.

	Current stove Efficiency 23.94%	ASTRA stove Efficiency 40%
Final Energy Consumption [GJ/month]	33.74	33.74
Primary Energy Supply [GJ/month]	140.96	84.35

Table 4.20 Final and primary energy consumption using current stoves or ASTRA

The difference is appreciable and amounts to 56.61 GJ, with a reduction in PES of approximately 40% as the efficiency has increased by 67%.

4.2.2 Public baking

Baking bread is a current thermal need of CPC requiring around 7.7 tons of firewood every month (see Table 3.17) for a final energy consumption of 4.82 GJ/month (see Table 3.18). The quantity of flour to bake is 550 kg every week. The solution investigated consisted of replacing the current firewood oven with an electric oven.

Test voltage [V]	208
Electric cooking energy rate [kW]	5.5
Cook time [min]	55.53
Electric energy consumption [Wh]	5085.3
Food product	potatoes
Ambient temperature [°C]	24
Oven temperature [°C]	176
Production capacity [kg/hr]	35.9

Table 4.21 Main results of standard test on E32D5 oven

After a web research was found the convection electric oven E32D5 manufactured by Moffat, as explained in section 2.3.2. The specifics of this oven were tested under standard conditions in the FSTC (Food Service Technology Centre) laboratory facilities of San Ramon, California [81] and the ones of interest are reported in Table 4.21. The results of the test in Table 4.21, were to be re-adapted for the case of this thesis. First, the electric cooking energy rate, when the voltage is 220-240V, increases to 6.3 kW, as provided by the manufacturer [81]. Secondly, the production capacity, tested with potatoes, was to be converted to bread capacity production. The oven can bake food for a total of 5 flat pans of

0.45m x 0.66m. This pan resulted a bit smaller than the one used at CPC Bali (0,5m x 0,75m) and that used to contain 30 loafs; thus 20 loafs (5 x 4 rows) were considered per pan with for the electric oven. Assuming a mean cooking time of bread of 40 minutes at 176 °C, as the cooking time with the current wood oven, then the production rate for bread could be estimated at 150 loafs/hr. Now, since 5 days per week the bakery produced 1500 loafs from 100 kg of flour, then total working time of the electric oven was set at 10 hours. For the day of the week when the capacity was 1000 loafs, a working time of 7 hours was taken. The data of the E32D5 oven re-adapted to the bakery of CPC are schematized in Table 4.22:

Test voltage [V]	220-240
Electric cooking energy rate [kW]	6.3
Cook time [hr]	10 (40 min per 5 pans) (7)
Electric energy consumption [kWh]	63 (44.1)
Food product	1500 loafs of bread (1000)
Ambient temperature [°C]	24
Oven temperature [°C]	176
Production capacity [loafs/hr]	250

Table 4.22 Re-adapted data of E32D5 electric oven for CPC's bakery

The extra electricity consumption to be supplied is 63 kWh per day, 359.1 kWh per week and 1.5 MWh per month. The daily load would also increase and it represents a feature to pay great attention to. After the study of the load curve (Load curve section 3.1.3), it was seen that in the time of the day between 8 and 18 o'clock, which is between morning and evening peaks, the load was quite restrained with an average of 6 kW and sometimes peaks of 8 kW. The operation time of 10 hours from 8 to 18 was chosen to simulate the electric oven with HOMER®, thus the power load of the school in this time window would be increased by a factor of 6.3 kW.

Important observations on the power system of CPC Bali have to be made. Under an energetic point of view, the annual power consumption would grow by around 13.5 MWh. But the main concern is on the increase of the load due to the introduction of the oven into the system. In order to estimate the system response to the introduction of this extra load, HOMER® was used. Again two systems were simulated, off-grid and grid-RES hybrid system, and the optimized configurations reported.

In Table 4.23 power capacity and energy consumption of the off-grid optimized configuration including the bakery oven are summarized. Figure 4.16 illustrates the monthly average electric production divided by technology.

	Hydro	Diesel Generator (Label)	Batteries	Converter
Installed power [kW] (n° for batteries)	18.33	24	20	10
Yearly electricity production [MWh/yr]	96.36	1.23	-	-

Table 4.23 Power and electrical features of the off-grid system including the electric oven

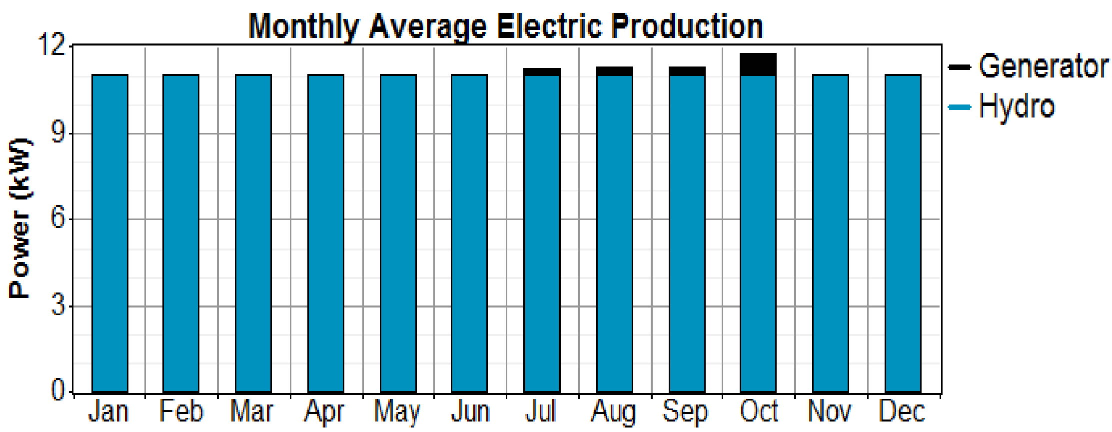


Figure 4.16 Monthly electric production of the off-grid system including the electric oven

The main difference of this system with respect to the optimal configuration found in section 4.1.2 where the oven was not modelled, is the capacity of hydropower, being 18.33 kW against 15 kW previously found. Diesel generator and 20 batteries complete the system. The AC primary load served has risen to 66.1 MWh/yr from 52.2 MWh/yr without including the oven and it is met by hydro (99%) and generator (1%). A big excess of electricity still remains 27.64 MWh/yr, mainly due to the problem to store electricity or reduce power supply during the vacation period when the school is closed as previously analysed. HOMER® cannot simulate a drastic reduction of the turbine output during the months of July, August and September, when the load is very low. In order to enforce this consideration, plot of supply and load profile is shown in Figure 4.17 and Figure 4.18:

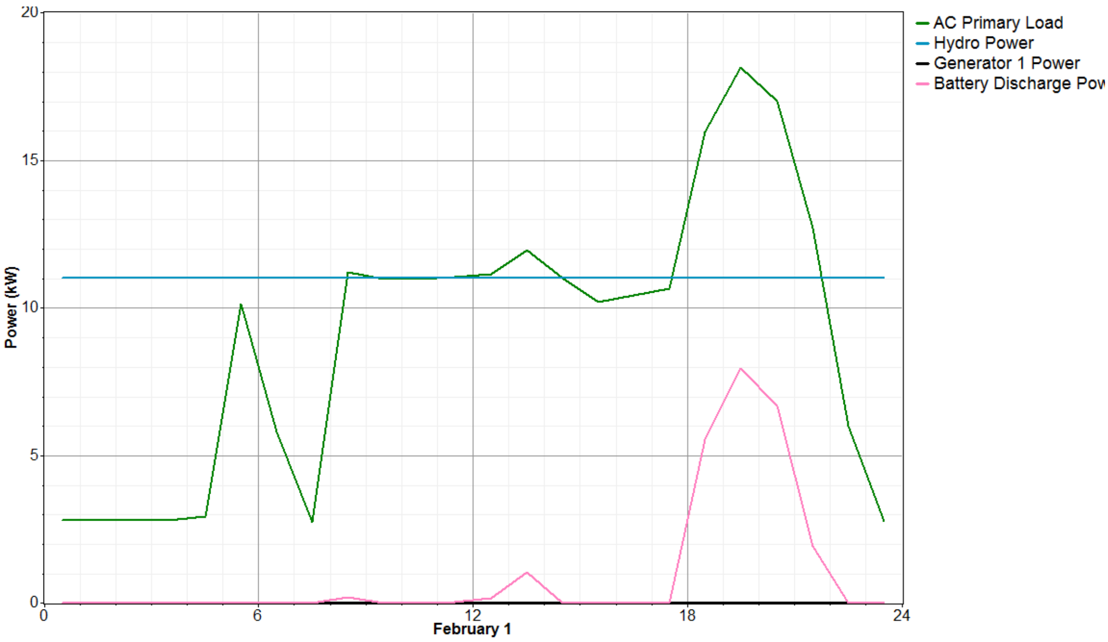


Figure 4.17 Load and supply curve on February 1st in the off-grid system with the electric oven

In Figure 4.17 and Figure 4.18 are shown the load and supply curves on the 1st of February and the 15th of July that represent two different school periods: the first with the school fully functioning, the second during vacation. It can be noticed the combination of hydro (blue), for the great part, diesel generator (black) and batteries (pink) to meet the load (green) during a typical school day (1st of February). The same cannot be said in July, when a big discrepancy between the hydro production and the load along large part of the day during July, is observed. The NPC of this configuration results to be higher than the case without oven, 171862 $ against 163088 $. This increase is mainly due to capital cost of the higher hydro capacity. The levelized cost of energy reaches 0.149 $/kWh.

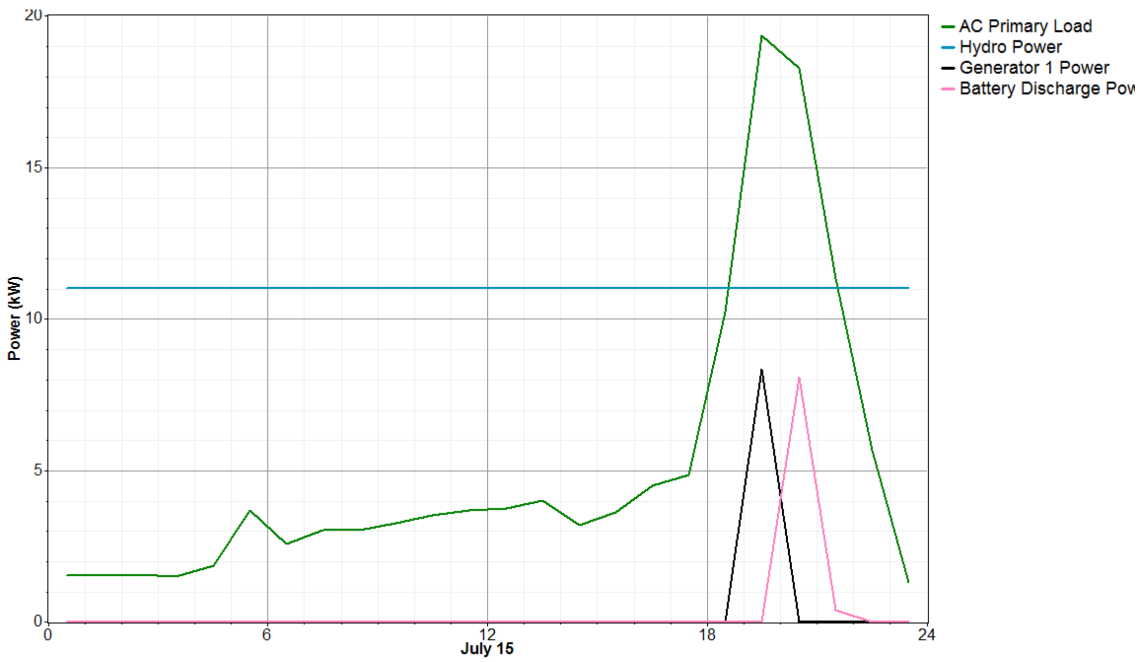


Figure 4.18 Load and supply curve on July 15th in the off-grid system with the electric oven

In the grid-RES hybrid optimized system that includes the electric oven, the NPC, being 154579 $ is higher than the one found for the hybrid system calculated in section 4.1.3 and being 132791 $. The levelized cost of energy is very low, 0.085 $/kWh, due to the great part of electricity supplied by hydropower. Indeed, in this configuration the main power output is still from hydro that has a nominal capacity of 18.3 kW, the double of the case without oven. Table 4.24 is a summary of the yearly power production from hydro turbine and the purchase/sell from the grid. Figure 4.19 shows the monthly average electric production from hydro and grid.

	Hydro production	Grid Purchase	Grid Sales	Grid Net Purchase	Total Electrical production
MWh/year	96.36	7.34	34.65	-27.31	103.7

Table 4.24 Electrical consumption of the grid-RES hybrid system with the electric oven

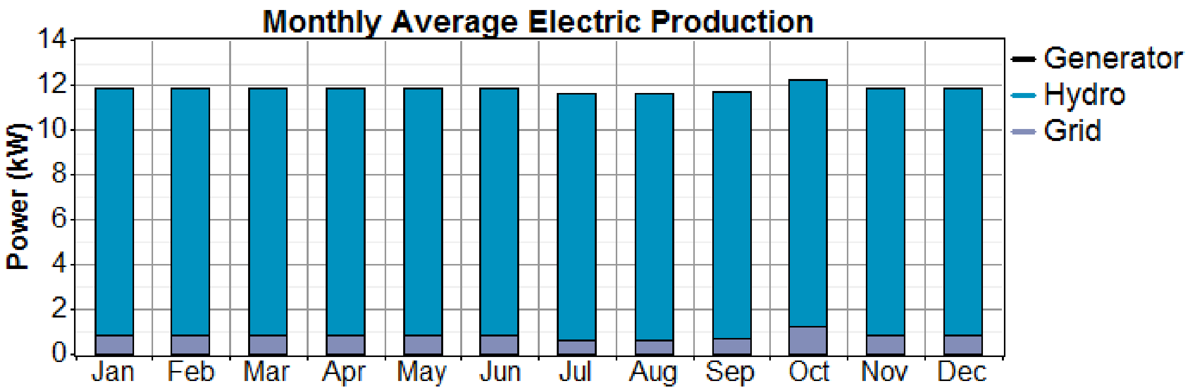


Figure 4.19 Monthly electric production of the hybrid system with the electric oven

Eventually, as for the off-grid system, the load and power supply curves are provided in Figure 4.20 and Figure 4.21 for two days when power demand changes greatly. The same considerations made in the off-grid system can be repeated herein, even though the excess of electricity is not counted by the software because it can be absorbed by the grid.

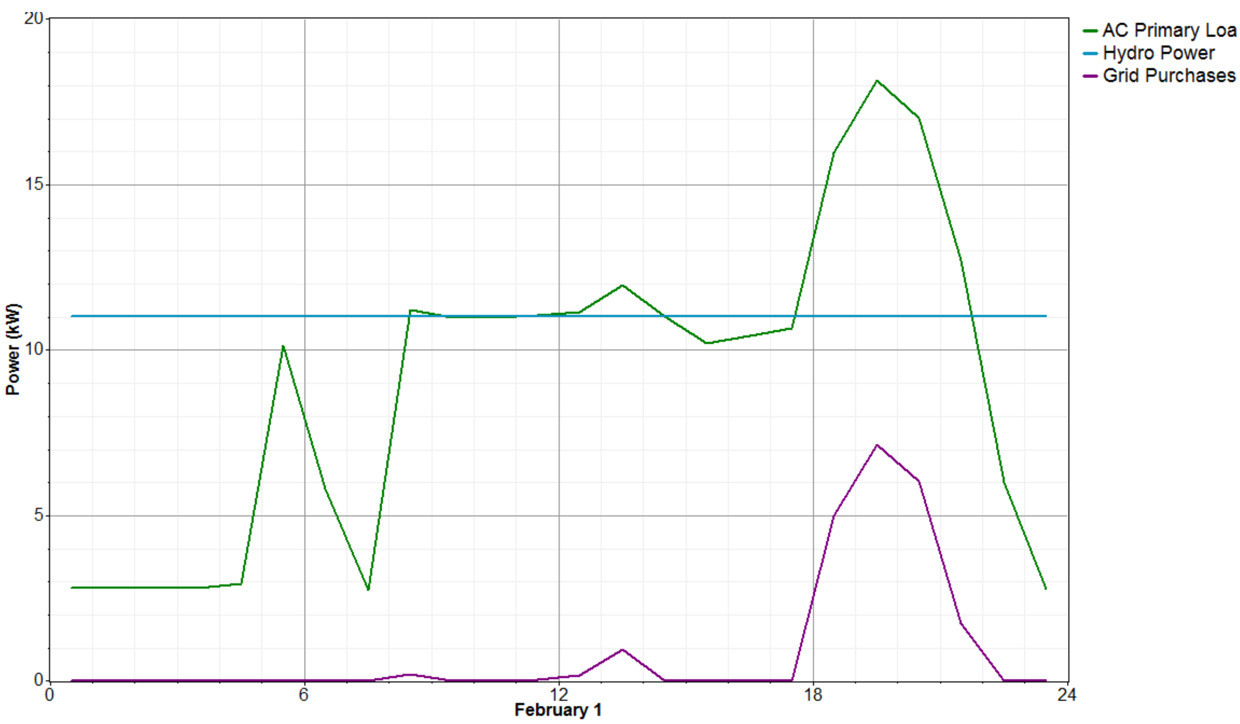


Figure 4.20 Load and supply curve on February 1st in the hybrid system with the electric oven

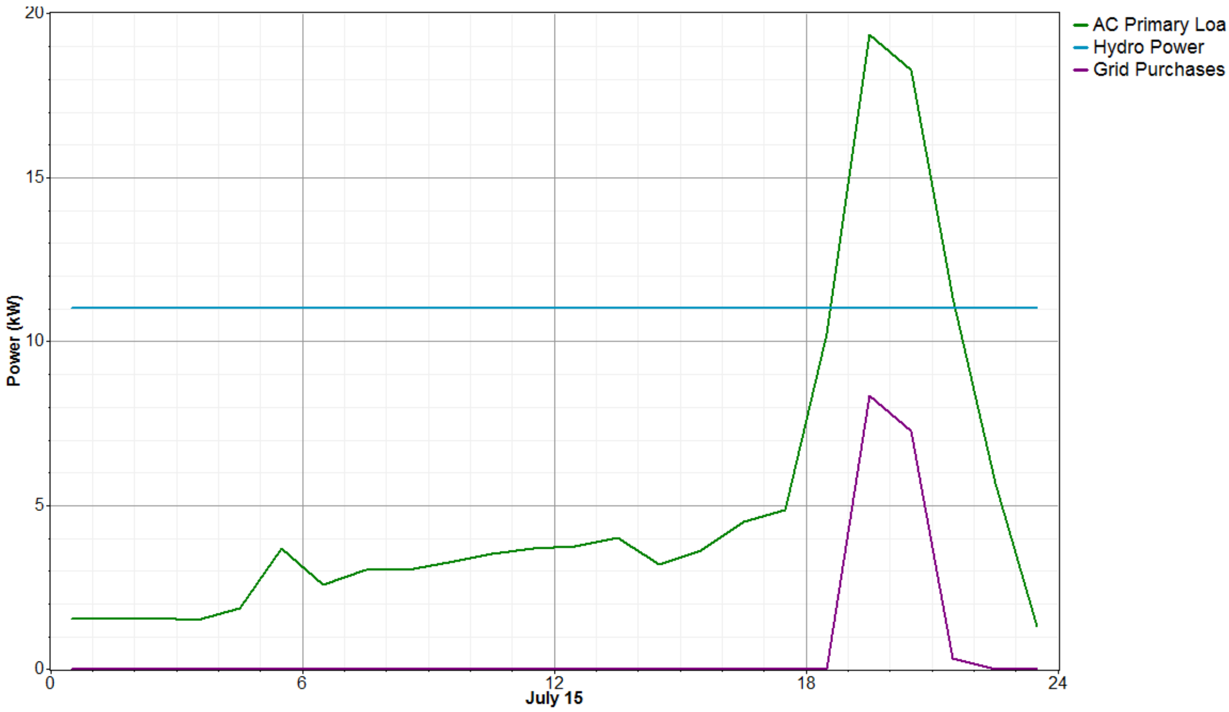


Figure 4.21 Load and supply curve July 15th in the hybrid system with the electric oven

4.2.3 Public water heating

The need of hot water for students was investigated by following two ways: biogas boilers and solar collectors. In the following sections the two ways are analysed.

Biogas boilers

The supply of hot water for students from biogas boilers was investigated. In the campus there were already installed three anaerobic digesters connected to the student toilets, but only one was functioning. The current production of biogas, computed in section 3.2.1, was 9.84 Nm^3/day, so a mean monthly production of 295.2 Nm^3. In order to get the minimum required quantity of biogas to meet the need of hot water, the final energy need was computed by applying *Eq 2.23*:

$$FE_{hot\ water\ public} = 2.11\ GJ/day$$

Taking the mean thermal efficiency of 80% of biogas boilers, as referenced in chapter 2, the need of primary energy could be derived by applying *Eq 2.4* to the biogas boiler system:

$$PE_{hot\ water\ public} = 2.64\ GJ/day$$

Then, considering the mean calorific value of biogas 29.3 MJ/m^3, the minimum required volume of biogas needed could be derived:

$$V_{min,biogas} = \frac{PE_{hot\ water\ public}}{LHV_{biogas}} \approx 90\ \frac{Nm^3}{day}$$

The monthly volume of biogas could then be easily derived and it is of 2700 Nm^3/month. The current production of biogas represented only 11% of the volume needed. However, production from all the students could be calculated. The potential of biogas from student faeces and urines was described in section 3.2.1 and was assumed to be 0.0342 Nm^3/day/pp (see the fifth column of Table 3.28). Students above 16 years old were 510, so to be considered adults, while 498 were younger. Under the assumption of half production from young people, and full production from adults, the overall potential of biogas resulted to be:

$$V_{stud.potential,biogas} = 0.0342\frac{Nm^3}{day, pp} \times\ (0.5\ \times\ 498 + 510) \times\ 30\ day = 778.73\ Nm^3$$

The potential production of biogas from students represented around 29% of the quantity needed. Although it's still far from the required, the feasibility of biogas boilers for hot water is based on the presence of three biogas systems in place that would minimizes the interventions to install the system.

The gap to meet the need of hot water is 71% of the required quantity. The gap could be covered in different ways. The production of extra biogas may be a solution. Additional 1917 Nm^3 of biogas has to be produced every month in order to meet the need of hot water. In section 3.2.1 it was estimated the potential of biogas from corn and it resulted to be 9960 Nm^3 per month. Therefore, corn is an available and abundant local resource to supply organic matter to be digested and converted into biogas. However, the use of corn would imply technical problems as collection and transportation of corn waste from farms to the school by the staff and a tricky re-adaption of the current digesters. Another solution is represented the extra production of biogas from cows dung. Still in section 3.2.1, it was estimated the production of biogas from the 2 cows actually being inside the campus (see Table 3.27 fourth column) and it was 72 Nm^3/month. If 1917 Nm^3 of extra biogas were to be produced, the school should own around 54 cows and the manure from the cows would feed extra dry matter into the digester.

Solar collectors

Solar collectors represent another solution to satisfy the need of hot water for students. If *Eq 2.24* is applied, the surface per capita of flat plate collector necessary to satisfy the need of water heating is given. In the equation there are two values of efficiency: the efficiency of a flat plate collector, chosen equal to 60%, and the SWHS efficiency set at 85% [85]. The solar fraction describes the quantity of solar energy to heat water over the total energy to heat water, so it is assumed to be 1. Finally the average annual irradiation is 573 MJ/m^2/month. Applying the equation, the total area of solar collectors needed is:

$$SWH_{capacity} = \frac{1 \times 30 \times 2.11 \times 1000}{0.6 \times 0.85 \times 573} = 216.6\ m^2$$

A very big extension of solar collectors would be needed to satisfy the need of hot water for students.

4.2.4 Domestic cooking

For the cooking in the domestic sector, the suggested system on which the scenario is based is the Envirofit G3300, an improved cooking stove of small size suitable for an average family and comparable to the 3SF. Its efficiency is 30% [83], entailing a doubling of the 3SF efficiency as reported in the literature and adopted previously. It is worth noting that also LPG and kerosene for cooking will be considered in the final energy consumption for cooking since the objective is the replacement with firewood, widely available in CPC Bali. The total amount of final energy consumption and primary supply is reported in Table 4.25.

	Firewood	LPG	Kerosene	TOTAL
Final Energy Consumption [GJ/month]	27.64	5.77	0.39	33.8
Primary Energy Supply [GJ/month]	173	9.2	1.3	183.5

Table 4.25 Primary and final energy consumption by energy sources for domestic cooking

The new possible situation can evolve towards a total relative reduction of 38.6% in the PES and the complete disappearance of fossil fuels in the supply mix of CPC Bali.

	Current stoves	Envirofit G3300
Final Energy Consumption [GJ/month]	33.8	33.8
Primary Energy Supply [GJ/month]	183.5	112.67

Table 4.26 Primary and final energy consumption by different stoves for domestic cooking

4.2.5 Domestic water heating

The unmet need of heating water in the houses requires a different perspective to take. If for cooking the final energy consumption has been considered satisfying, this is not the case of water heating. Thus, the quantity of energy embedded in the hot water has to be computed as the final energy. By applying the *Eq 2.22* it is found a daily need of 3.14 MJ/capita. It might be necessary to stress the fact that a quantity of 30 litres of water is enough for bathing and other activities, resulting in a conservative choice reflecting a strong improvement of the actual living standards.

The calculation of the SWH capacity in terms of m^2/capita needs to be addressed with a monthly variation since the solar radiation was found for every month, as described in Table 4.27. Before showing the results, it is important the choice of efficiencies according to *Eq 2.24*. The efficiency of a flat plate collector was chosen equal to 60%, determining again a rather safe analysis since it could be higher; on the other hand, the SWHS efficiency was set at 85% [85]. Lastly, the solar fraction describes the quantity of solar energy to heat water over the total energy to heat water; for CPC Bali it was chosen to set it at its maximum, 1 since water is heated without any other source than the sun.

Sun Irradiation [MJ/ m^2 / month]	Energy demand [MJ/month/capita]	SWH capacity [m^2/capita]
713.124	97.32	0.27
661.248	87.91	0.26
661.788	97.32	0.29
570.24	94.19	0.32
558	97.32	0.34
493.56	94.19	0.37
470.952	97.32	0.41
465.372	97.32	0.41
473.04	94.19	0.39
516.708	97.32	0.37
604.8	94.19	0.31
682.992	97.32	0.28

Table 4.27 Sun irradiation, energy demand and capacity of solar collectors per capita.

The energy demand varies due to the different number of days for each month. The found SWH capacity to be installed in CPC Bali is 0.41m^2 of flat plate collector for every person, as the greatest extension has to be selected according to the period with the smallest sun irradiation, occurring in July and August. Considering an average family of 4 people, this value implies that a system with 1.64 m^2 flat plate collector and a 200 litres water tank should be installed on every house. This size represents a technically feasible solution widely diffused in several countries.

4.3 Prospective energy balance

As already done for the current energy balance, in this conclusive paragraph two prospective energy balances are presented. The aim is to visualize the change in primary energy supply while reducing the losses. In this paragraph, two new energy flow diagrams are presented in order to figure how the energy layout of CPC may change in case the off-grid system or grid-RES hybrid system are implemented.

The thermal solutions proposed in the previous paragraph are included in terms of consumption, needs and source of primary energy. Compared to the first diagram (Figure 3.4) three new primary sources appear: hydro, solar and biogas. While solar and biogas are expressed in terms of GJ, hydropower figures in terms of MWh because this gives a better idea of the new flow of electricity coming into the system and replacing the grid. The potential of hydro can be easily obtained from the production of electricity if efficiencies along the chain are considered (60% of penstock and 75% of electro-mechanical conversion).

In Figure 3.4 the electrical production amounted to 4.8 MWh per month. With the introduction of hydropower and electric baking oven, the monthly electrical production has risen to 8 MWh. Besides, the extra load of 1.5 MWh due to the oven, the rest of electricity is an excess (around 1.7 MWh/month). The excess of electricity is represented as an energy loss, going away from the two drivers, while grid losses are not included. This excess can be managed according to the solutions proposed in section 4.1.2. Diesel is needed only for back-up function in the off-grid system (Figure 4.22), in fact its consumption is extremely low. In the grid-RES hybrid system, the function of back-up is provided by the grid (green flow in Figure 4.23) while diesel is not needed.

From the thermal point of view, the biggest change is represented by the reduction of primary energy from firewood in both configurations. Indeed, thanks to the introduction of new sources, such as solar and biogas, and improved cooking technologies into the system, the share of primary sources is more balanced and thermal losses are visibly reduced. Eventually, on the right side, final consumption of energy has not changed, except for water heating, that is an additional final use for the public driver and larger for the domestic driver respect to the current situation, and for baking that now involves electrical energy.

Below, first the energy flow diagram of the current situation is re-included in order to get easily the differences with the future energy flow diagrams that have been discussed in the paragraph. Eventually, the two new energy balances, off-grid and grid-RES hybrid system, are presented.

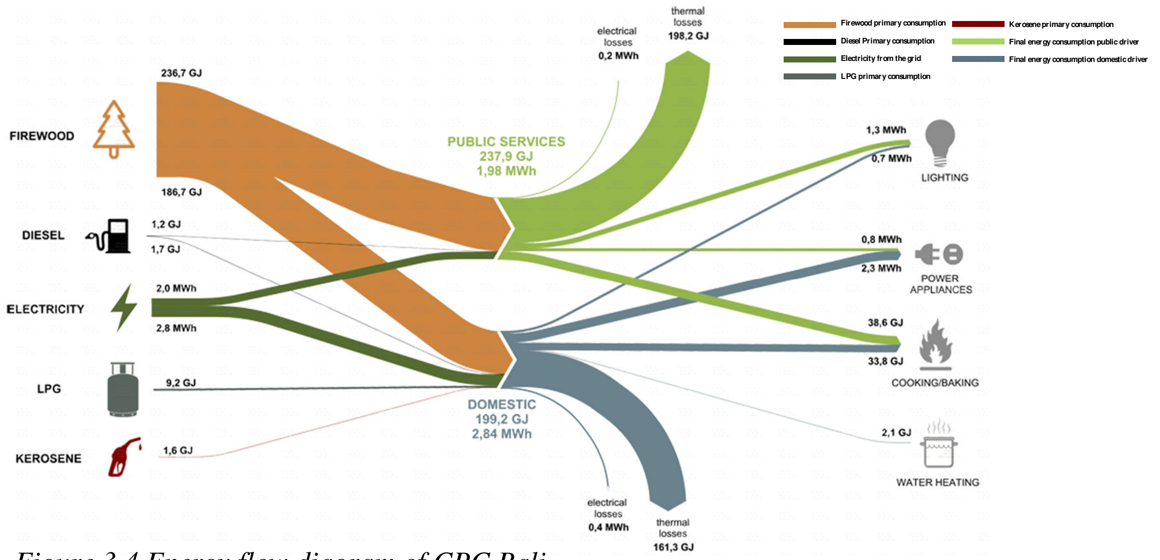


Figure 3.4 Energy flow diagram of CPC Bali

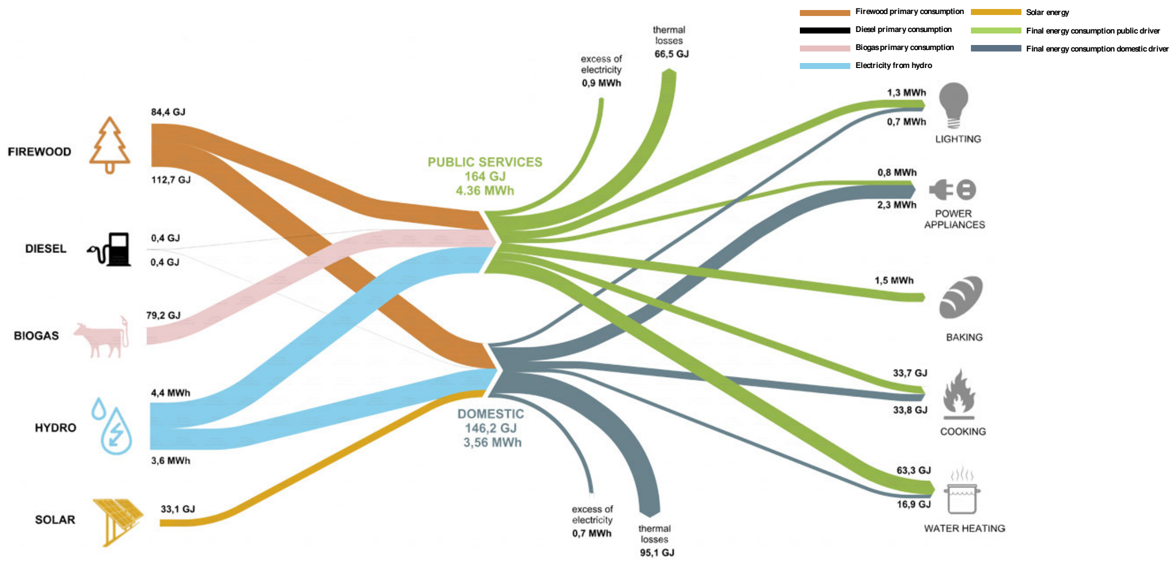


Figure 4.22 Future energy flow for off-grid system including thermal solutions

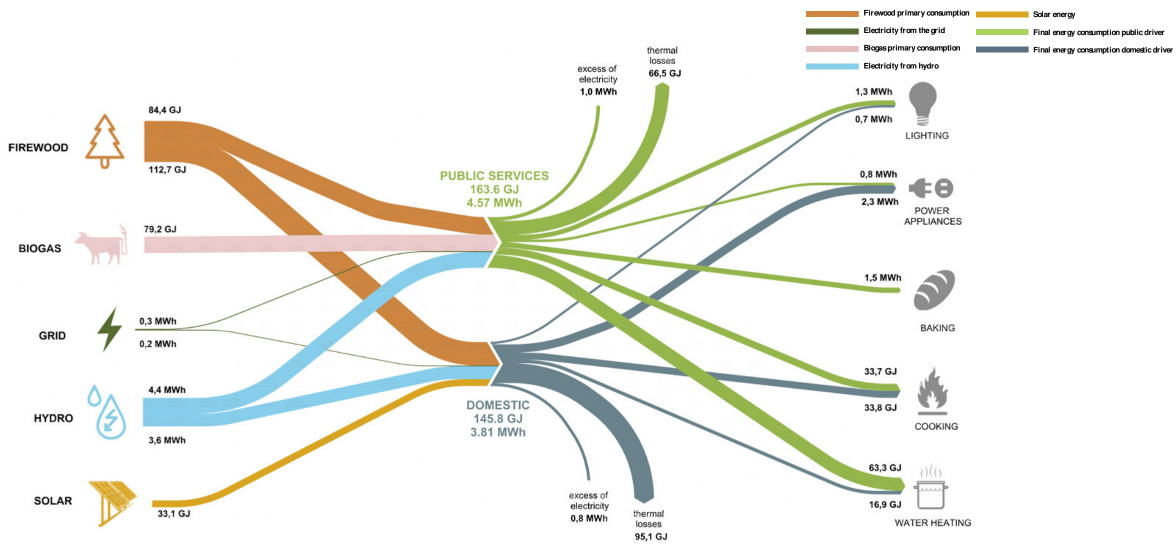


Figure 4.23 Future energy flow for grid-RES hybrid system including thermal solutions

5 Conclusions

Access to energy is the fundamental instrument to set the basement upon which development can be built. Achieving the objective of reliable, affordable and modern energy established by the seventh SDG imposes the research of a solution to this issue still persisting greatly in developing countries, with a major concern on Sub-Saharan Africa. Energisation is the concept to be adopted in order to overcome the limitations of standardized electrification. In particular it should be embedded with a long-term perspective, aiming at *Sustainable Energisation* in the most comprehensive manner. The necessary tool to apply is the combination of need with local resources, which would result in the maximization of efficiency whilst minimizing costs, as well as the likelihood of acceptance by the social context.

In this work, the necessity of supplying CPC Bali, in Cameroon, with reliable energy has been the central aspect. The main focus and the general objective has been not only to improve the ongoing situation, but also to drive the analysis towards the energetic self-sufficiency of the school campus. For this purpose, three specific objectives have been selected: energy balance assessment, energy RES assessment, energy solution planning through resource-need matching approach.

For the energy balance assessment, the resources individuated are electricity, firewood, diesel, LPG and kerosene for the domestic and public energy drivers, the only present drivers after a careful preliminary study of the area. The average consumption of electricity amounts to 4.82 kWh, divided between public (41%) and domestic energy driver (59%). The service is remarkably unreliable, with frequent shortages and voltage fluctuations due to power failures of the grid. The monthly consumption rate of firewood is 423.4 GJ, with a predominance of the public sector (236.7 GJ/month) against the domestic driver (186.7 GJ/month). A much lower consumption per month was found for LPG (9.2 GJ), diesel (2.9 GJ) and kerosene (1.6 GJ). Eventually, the uses could be highlighted, common to both sectors, as lighting, power appliances and cooking; water heating concerned only the domestic driver since students were unable to use hot water. In the public driver the electricity demand for lighting is higher, while in the domestic driver is higher for power appliances. The final uses of energy for cooking is bigger for the domestic driver. The energy consumption assessment outcome shows a basic human need satisfaction with a rather cycling electricity load curve. In addition, an enormous amount of thermal losses have been found, due to the extremely low efficiency of cooking stoves as well as their poor maintenance status.

The assessment of the RES potential has regarded biogas, hydro, wind and solar. As a whole, the availability is much greater than what is exploited at the moment and the current consumption levels. Only one of the three biogas systems built in the school is currently working, with an average production of 9.48 Nm^3/day. However, they could produce a remarkable additional quantity of digested gas considering also the waste from farming and animals, up to approximately 403 Nm^3/day. The hydro potential of the stream nearby would be sufficient to provide the school enough electricity, with a monthly production availability of 9.6 MWh. Solar energy is also an option to consider (1911.69 kWh/m^2 per year), although proper measurements were impossible because of the occurrence of rainy season during the period of stay on the field. On the contrary, anemometer detections of the wind have revealed a low potential of this resource, with an average wind speed of 3.297 m/s.

Subsequently, using the data collected in loco, a proper energy solution planning was performed by considering electric and thermal load separately. Simulations of RETs based system could be performed for what concerned electrification. The new system should bear also the load of an electric oven. In particular, the E32D5 model manufactured by Moffat with 6.3 kW of nominal power was the selected device to replace the current baking system. This oven enables to cook the same quantity of bread saving 95.76 GJ of primary energy from firewood every month, corresponding to almost 8 tonnes of fresh wood. The software used was HOMER®, suitable for this kind of analysis. The results, considering all the technologies related to the RES previously investigated, have disclosed the absolute predominance of the cross-flow water turbine as best solution, i.e. the most economically viable system configuration respecting all the constraints. In the off-grid system scenario, the best configuration is 18.33 kW of nominal power from hydro while diesel generator and batteries providing the rest of power supply. The NPC of this configuration is 171862 \$, with LCOE equal to 0.149 \$/kWh, lower than the current national cost of 0.17 \$/kWh. For the hybrid RES-based system, the optimized system consists of 18.33 kW water turbine and power purchases from the grid. The relative NPC is 154579 $ with a LCOE of 0.123$/kWh, lower than the off-grid case. In addition, the purchases from the grid amount only to 7% of the yearly electricity consumed, covering the load peaks. The reason of hydro-based systems may lie on the maturity of such technology leading to reduced costs and its relative durable lifetime. In addition, within this pre-feasibility study, it has been verified that the exploitation of the water stream should leave the surrounding environment and the school water supply unaffected. Furthermore, sensitivity analyses have been conducted on the most uncertain input data or those more likely to change in time, such as diesel or grid electricity purchase price, expressing the robustness of the optimized configuration. In order to check the competitiveness of PV solar panels and wind turbines, a sensitivity analysis was also performed on their capital costs with a cost reduction of 90%, actually showing a negative outcome as the hydro-base system has resulted the best choice again.

The thermal solution planning has involved only a technical perspective, neglecting the economic analysis. The currently satisfying level of cooking and the unmet need of water heating were considered both for public and domestic energy services. The proposed solutions imply the substitution of the cooking technologies with more efficient sets using firewood as fuel: the ASTRA stove for public driver and the Envirofit G3300-type stove for domestic driver, with a primary energy consumption reduction of 56.61 GJ/month and 70.83 GJ/month, respectively. On the other hand, heating water consists in providing 20 litres of water at 45 °C for hygienic purposes for the 1008 students of CPC, as minimum threshold. The technology proposed is the biogas boiler and the total quantity of biogas needed every month is 2700 Nm^3/month, or exploiting the currently available amount requiring 153 m^2 of surface occupied by solar collectors to satisfy the remaining demand. At domestic level, the need would be meet with 0.41m^2 of flat plate collector per capita.

The overall energy flow diagrams show a drastic reduction in terms of primary energy supply quantity, a dramatic fall in thermal losses during the conversion processes while satisfying new energy needs (i.e. water heating), using the locally available RETs by means of proven technologies and enhancing the living standard of students and college personnel. Based on simulations carried out with HOMER®, the hybrid solution could be seen as a first step towards a purely autonomous power system. In this optics, the two configurations found are even more supported by sensitivity analyses demonstrating that the hydro-based systems (with or without grid connection) are slightly influenced by diesel price and are even less grid-dependent when the unit power price increases. Thus, the proposed solutions entail an overall picture of energy self-sufficiency of CPC Bali.

Upon completing this pre-feasibility study, it could be affirmed that the energy self-sufficiency of CPC Bali could be attended. This implies that a truly sustainable development could be reached under the economic, social and environmental points of view in case a long-term perspective is adopted. The definition of *Sustainable Energisation* might find its complete fulfilment in this context. Due to the natural resources locally available and the disposition of the social tissue welcoming the presence of RETs, the improvement of the current energy supply and use levels is possible and desirable, with a setting towards the future.

The innovative application of the energy balance approach used in this thesis might constitute a first preliminary step towards the implementation of more scientifically rigorous methodologies for the energy assessment in similar case studies. Furthermore, with reference to the conducted research, a proper feasibility study on the most promising solution for the electrical system configuration should be attended. Additional topics to scrutinize are a comprehensive thermal demand satisfaction and a deep economic analysis. Lastly, due to the social fertile ground, activities of knowledge and know-how transfer first, capacity building in second instance might represent the final step intended to give local people the necessary tools for an all-encompassing self-sufficiency.

Appendix A

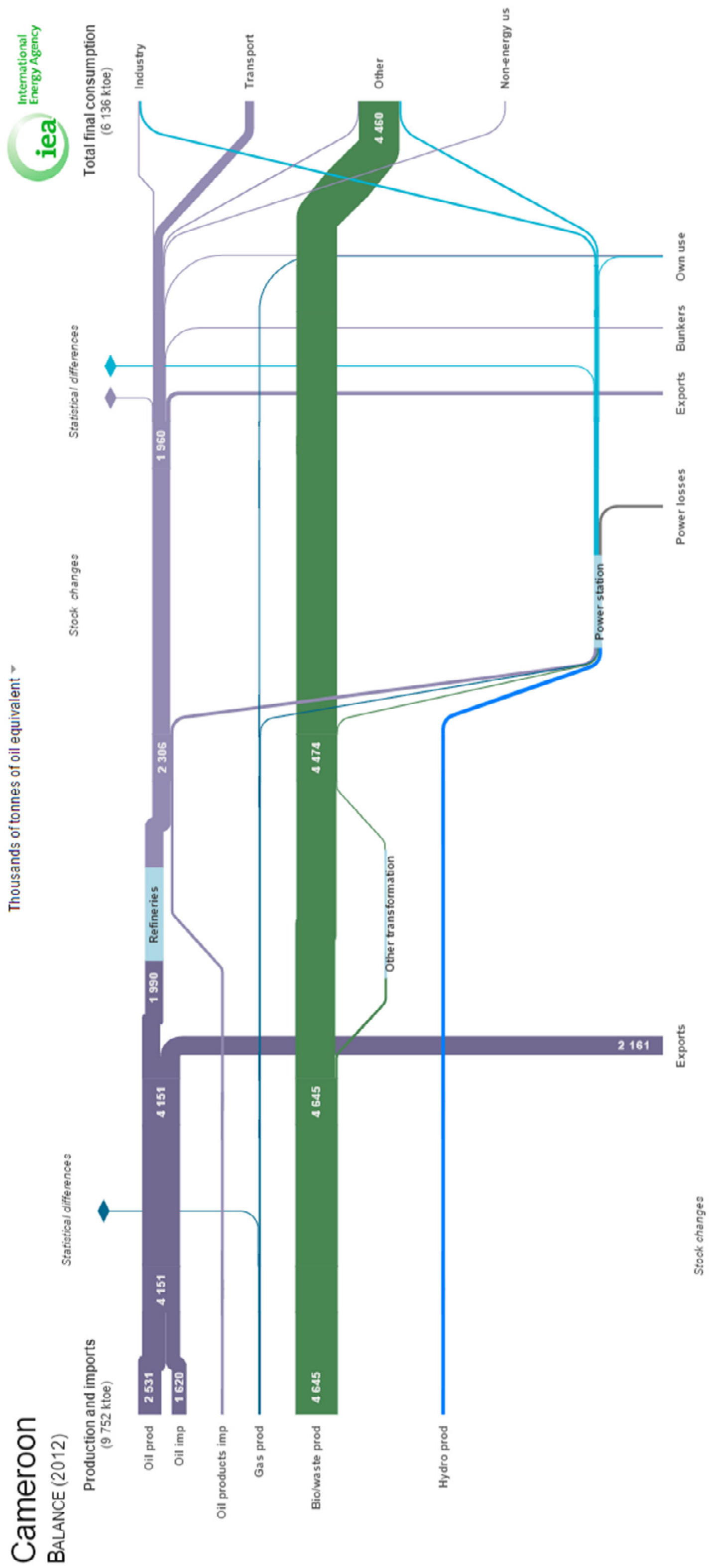


Figure A.1 Cameroon Energy flow diagram 2012 [90]

Questionnaire for households at CPC Bali about energy consumption and supply

Instructions

- Tick the right answer ☐ with a X
- Fill in the space ……….. when is needed
- Please specify if your answer is not listed
- Complete the empty cells where the answer is in form of a table

1. General information

House number: ……… Date: …../..… /….…

Sex: ☐ M ☐ F Age: ….

1.1. Position in the family:
- ☐ Head of the family
- ☐ Family member
- ☐ Other (please specify: ………….)

1.2. Number and sex of household members: Female …... Male ……

1.3. Age of household members:

	Infant (< 6)	6 - 16	16 - 30	30 - 65	above 65
female					
male					
total					

1.4. Which are the roles of the family members in CPC Bali?

- ☐ CPC Administration (principal, vice-principal, pastor, finance clerk)
- ☐ Teaching staff
- ☐ Non teaching staff
- ☐ Student
- ☐ Other (please specify:……….)

2. Electricity use and supply

2.1. Is your house connected to the national electric grid (AES-SONEL)? ☐ Yes ☐ No

2.2. Which are the devices using electricity in the house?

Items	Number	Average daily use
TV		
radio		
phone charger		
indoor lights (lamp, bulb)		
outdoor lights (lamp, bulb)		
fridge		
laptop		
electric iron		
others (please specify…..)		

2.3. Do you have a meter installed in your household? ☐ Yes ☐ No

2.4. Does anybody check the electricity consumption in the household? ☐ Yes ☐ No

2.5. Which is the average consumption per month? ……... kWh

2.6. Which is the average bill for electricity for this household? ……. FCFA

2.7. Could you estimate how many shortages occur per month?

	n° of shortages per month
below 10 minute	
10minutes – 1 hour	
above 1 hour	

2.8. Have you ever had any devices damaged or broken due to voltage fluctuations of the grid?

……………………..………………………..………………………..………………………..………………
………..……………………..……………………..…………………….…………

2.9. Do you have any comments about the electricity supply?

……………………..………………………..………………………..………………………..………………
………..……………………..……………………..…………………….…………

3. Firewood use and supply

Which are the main purposes of using firewood?

- ☐ Cooking
- ☐ Space heating
- ☐ Water heating (hot bath, tea, laundry, etc.)
- ☐ Others (specify:……..)
- ☐ Firewood is not used

3.1. Firewood for cooking (<u>if firewood is not used for cooking purpose skip to section 3.2</u>)

3.1.1. Which are the cooking systems used?

- ☐ 3 stones fire
- ☐ saw dust stove
- ☐ improved stove
- ☐ other (please specify …………)

3.1.2. Where is the kitchen placed in your household?

- ☐ inside the house
- ☐ outside the house
- ☐ common kitchen with other households

3.1.3. On a daily basis, how many meals do you cook using firewood? ……

3.2. Firewood for space heating (<u>if firewood is not used for space heating skip to section 3.3</u>)

3.2.1. How often is firewood used for space heating:

- ☐ daily
- ☐ weekly
- ☐ monthly
- ☐ only during the rainy season
- ☐ yearly

3.3. Firewood for water heating (<u>if firewood is not used for water heating skip to section 3.4</u>)

3.3.1. How many days per week do you heat water by burning firewood?

- ☐ 1-3
- ☐ 3-5
- ☐ 5-7
- ☐ 7

3.3.2.On average, can you estimate how much water do you boil every time? …..

3.4. Firewood supply (if you don't use firewood in your household skip to section 4)

3.4.1. Where do you take the firewood from?

- ☐ inside the campus for free
- ☐ inside the campus by purchasing it
- ☐ outside the campus for free (e.g. your farm)
- ☐ outside the campus by purchasing it
- ☐ other (please specify ………..)

3.4.2. How is the firewood transported to your household?

- ☐ by hands
- ☐ by motorbike
- ☐ by car
- ☐ by pick-up
- ☐ by truck
- ☐ other (please specify ………..)

3.4.3. How often do you provide firewood to your household? Once every ……….

3.4.4. How much do you purchase? (use the mean of transportation above as unit of measure) …….

3.4.5. How much do you pay for it? ……………………… FCFA

3.4.6. In your opinion, do you think the use of wood as fuel increases the ongoing deforestation (in Cameroon)?

- ☐ Definitely yes
- ☐ Yes, but only in the future if no other sources will replace firewood
- ☐ I don't think so
- ☐ I've no idea

4. Gas use and supply

4.1. Do you use gas in your household? ☐ Yes ☐ No (if No skip to section 5)

4.2. Which is the main purpose of using gas?

- ☐ Cooking
- ☐ Water heating
- ☐ Others (please specify ……..)

4.3. Which type of gas bottle do you have?

- ☐ SCTM (orange)
- ☐ CAM GAS
- ☐ TOTAL GAS
- ☐ GLOCALGAZ
- ☐ OILYBYA

4.4. Which is the size of your gas bottle?

- ☐ Extra-large (35 kg)
- ☐ Medium (12.5 kg)
- ☐ Small (6 k)

4.5. How often do you refill it on average? Every ……………..

4.6. How much do you pay? ……………….. FCFA

4.7. On a weekly basis, how many meals do you cook using firewood or gas?

.......… meals cooked with gas …….. meals cooked with firewood

4.8. Is there any other reason, aside the type of meal, of using firewood instead of gas?

- ☐ Yes, ……………..…………………………………………………………………
- ☐ No

5. Other sources of energy

5.1. Do you use any other source of energy?

	Yes/No	Main purpose	How much	Which is the cost
Charcoal				
Kerosene				
Candles				
Others (specify ………………)				

6. Domestic waste production

6.1. Do you have a farm? ☐ Yes ☐ No

6.2. Which kinds of crops do you have?

	Yes/No	Which is approximately the extension?
Corn		
Banana/plantain		
Beans		
Cereals		
Tuber (potatoes, yam, carrots, etc.)		
Pineapple		
Vegetables		
Other fruit trees (mango, papaya, etc.)		

6.3. Do you consume the products of your farm?

- ☐ Yes, we consume all of the products
- ☐ Only part is consumed, the rest is sold away
- ☐ All is sold

6.4. Which animals do you have (if any)?

	N°	How do you feed them? (choose among: animal feed, grass/bush, organic waste, mixture of animal feed and cereals)
pigs		
goats		
cows		
rabbits		
agrifowl		
countryfowl		

Thanks for your time and thanks for the great collaboration!!!

Figure A.2 Local sawdust pot

Category	Type	Model	Rated Power [W]	Stand-by power [W]	Number of appliances
Laptop, Desktop PC	Laptop	Lenovo	100	-	5
		Toshiba	65	-	3
		Dell	90	-	1
	Monitor	Lenovo	18	-	3
		HP	18	-	9
		Dell	50	-	8
		Belinea	60	-	5
	PC	HP	90	-	12
		Dell	80	-	10
		HP Compaq	200	-	4
Printer, Photocopy machine	Printer	HP	50	3.1	5
		Epson	30	3	2
	Photocopier	Canon	670	5	1
		Canon Image	1373	4	2
		HP	550	7	5
		HP Laserjet	510	10	1
		Riso EZ	300	3	1
Refrigeration	Refrigerator	LG	40	-	1
	Deep Freezer	Ocean	53	-	2
Other	Radio	NA	5	-	2
	Blade sharpener	NA	50	-	1

Table A.1 Power appliance for public user

Water Boiling Test Specifications

Improved cooking stove in the kitchen

	WBT 1		WBT 2	
Phase	1	2	1	2
Feedstock [kg]	45	42.5	34	28.5
Moisture content [%]	29	29	29	29
Dry Wood consumed [kg]	24.9	20.7	21.3	18.2
Charcoal produced [kg]	9.5	5.4	9.6	4.7
Efficiency [%]	22.86	17.21	35.37	20.32
Burning rate [kg fuel/min]	0.09	0.15	0.05	0.32
Specific fuel consumption [kg fuel / kg water]	0.108	0.145	0.062	0.131
Firepower [kW]	28.49	45.09	14.33	43.46

Table A.2 Specifications of the two WBTs applied to the kitchen stoves

Temperature profiles

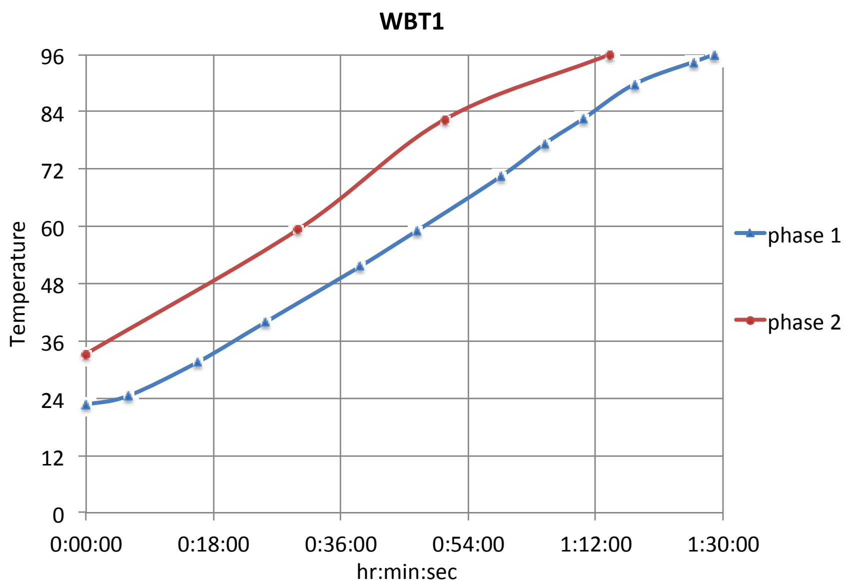


Figure A.3 Temperature profile of the first WBT. In blue cold-start phase 1, in red of the hot-start phase 2.

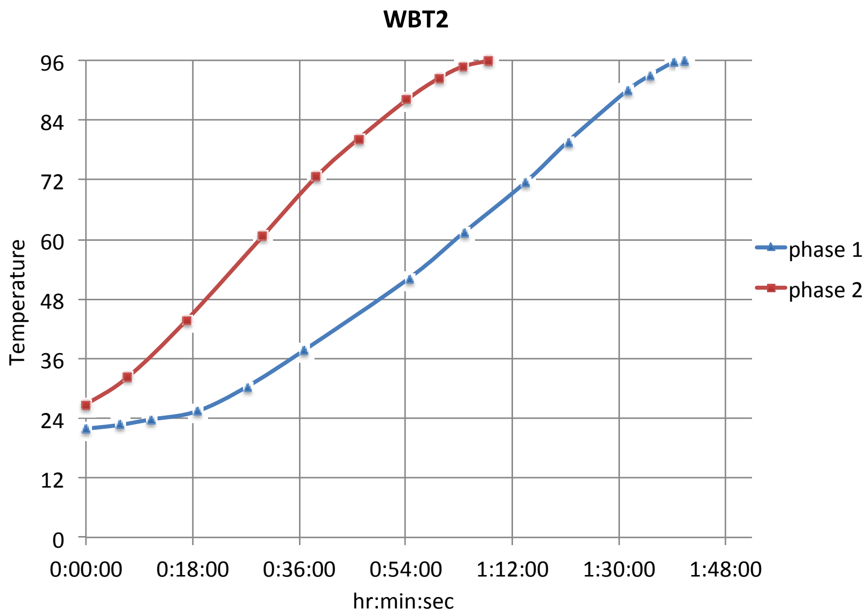


Figure A.4 Temperature profile of the second test. In blue is the profile of cold-start phase 1, in red of the hot-start phase 2.

Saw-dust pot

Feedstock [kg]	4.9
Moisture content [%]	29
Dry Wood consumed [kg]	1.1
Efficiency [%]	35.73
Burning rate [kg fuel/min]	0.01
Specific fuel consumption [kg fuel / kg water]	0.097
Firepower [kW]	2.53

Table A.3 Specifications of the WBT applied to the sawdust pot

Appendix B

cross section1			cross section2			cross section3		
depth1	20	cm	depth1	30	cm	depth1	21	cm
depth2	25	cm	depth2	30	cm	depth2	47	cm
depth3	40	cm	depth3	27	cm	depth3	55	cm
depth4	38	cm	depth4	30	cm	depth4	53	cm
depth5	26	cm	depth5	27	cm	depth5	60	cm
depth6	24	cm	depth6	27	cm	depth6	35	cm

Table B.1 Depth measurements in three sections along the river (first test)

RIVER GEOMETRY

length	10	m
width	2.8	m
cross section1	0.68	m^2
cross section2	0.69	m^2
cross section3	1.06	m^2
average cross section	0.81	m^2

Table B.2 River geometry (first test)

cross section1			cross section2			cross section3		
depth1	20	cm	depth1	10	cm	depth1	15	cm
depth2	22	cm	depth2	18	cm	depth2	21	cm
depth3	22	cm	depth3	22	cm	depth3	30	cm
depth4	28	cm	depth4	26	cm	depth4	45	cm
depth5	27.5	cm	depth5	30	cm	depth5	55	cm
depth6	27	cm	depth6	18	cm	depth6	55	cm
depth7	16	cm	depth7	18	cm	depth7	50	cm

Table B.3 Depth measurements in three sections along the river (second test)

RIVER GEOMETRY

length	10	m
width	2.8	m
cross section1	0.66	m^2
cross section2	0.55	m^2
cross section3	1.01	m^2
average cross section	0.74	m^2

Table B.4 River geometry (second test)

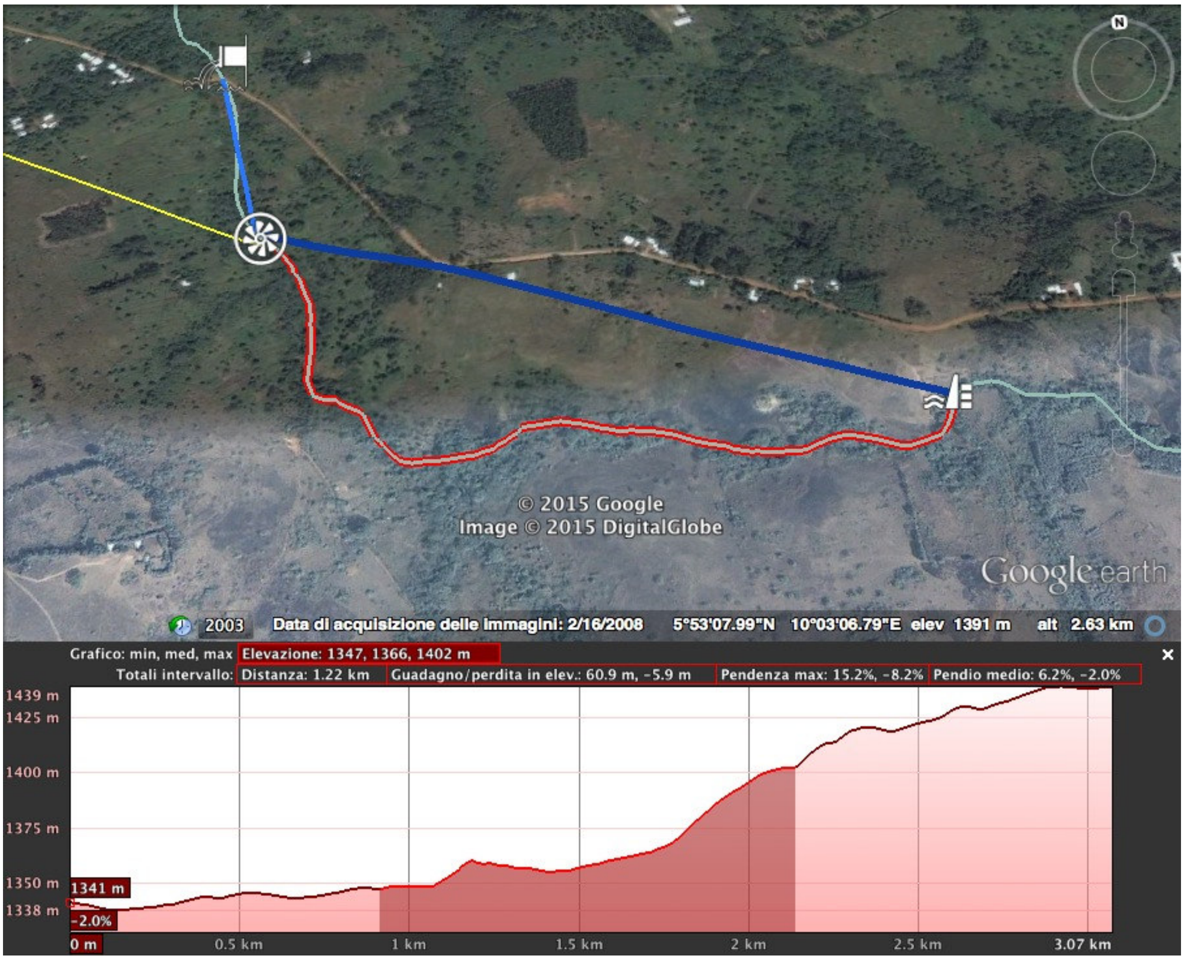


Figure B.1 Height profile of river

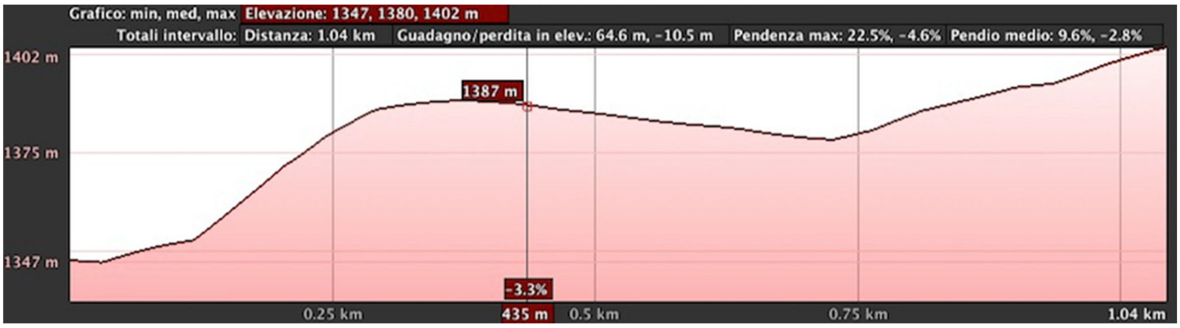


Figure B. 2 Height profile of penstock

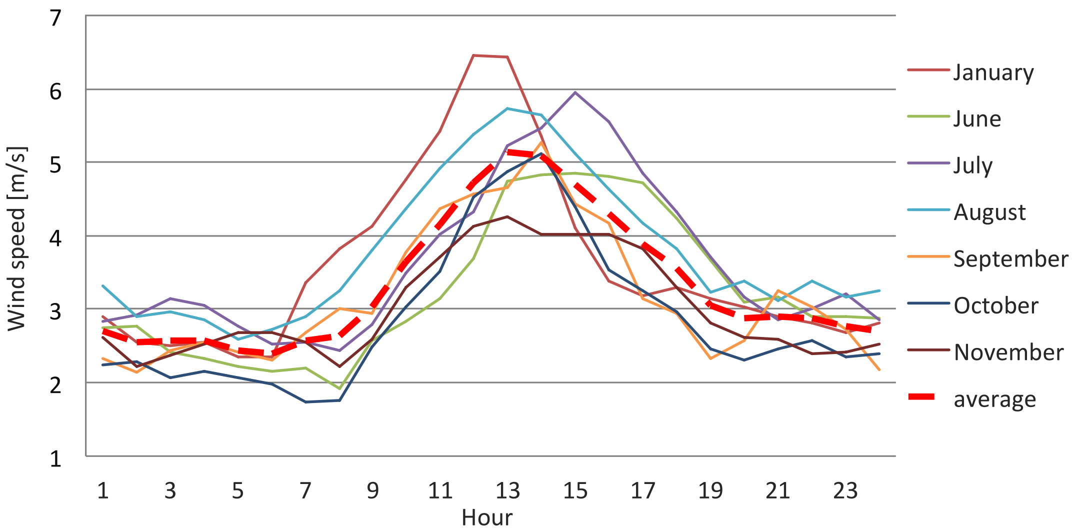


Figure B.3 Plots of monthly diurnal distributions and average distribution

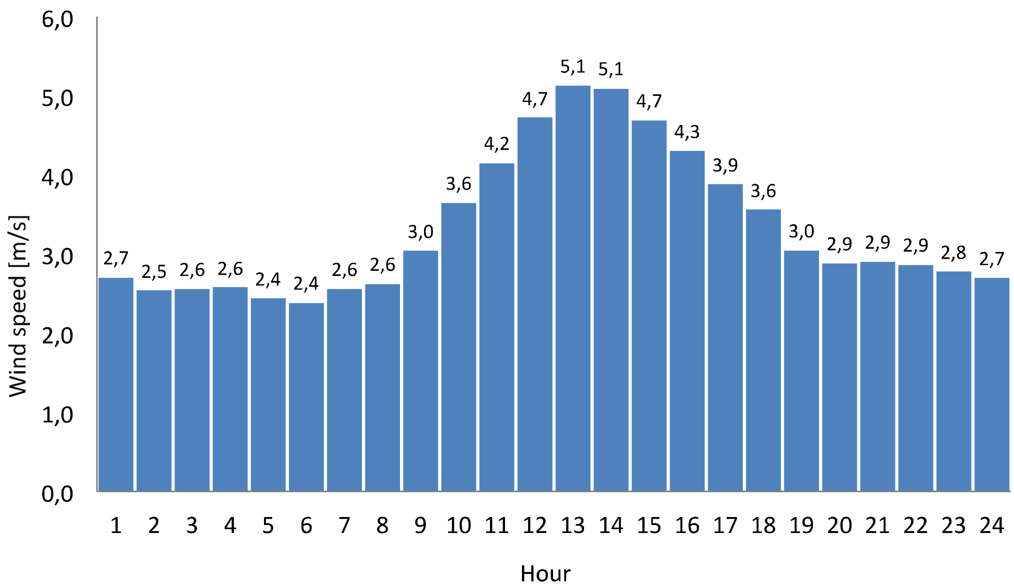


Figure B. 4 Plot of average diurnal distribution

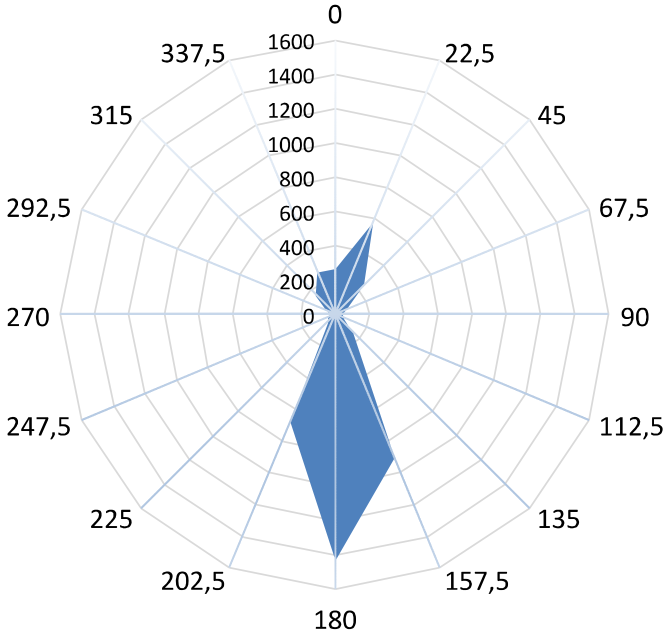


Figure B. 5 Spider plot of prevalent wind direction

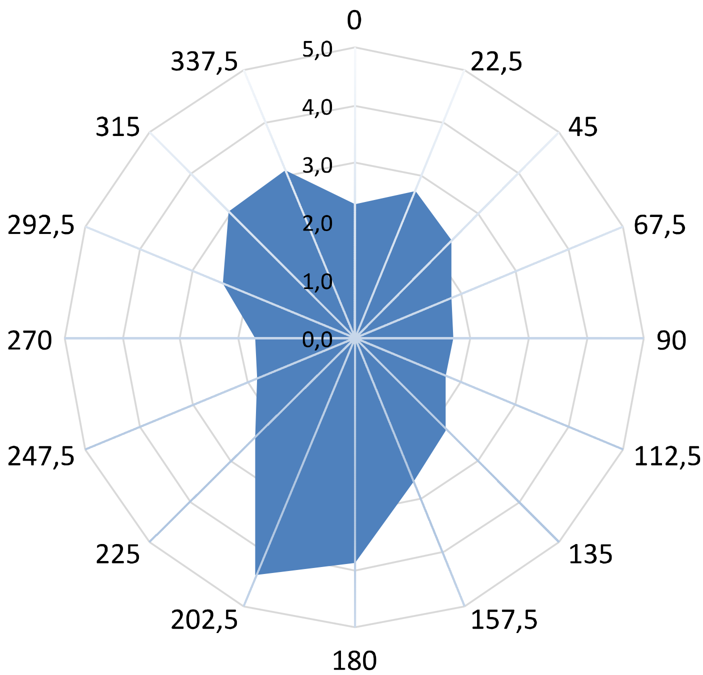


Figure B.6 Average wind speed direction

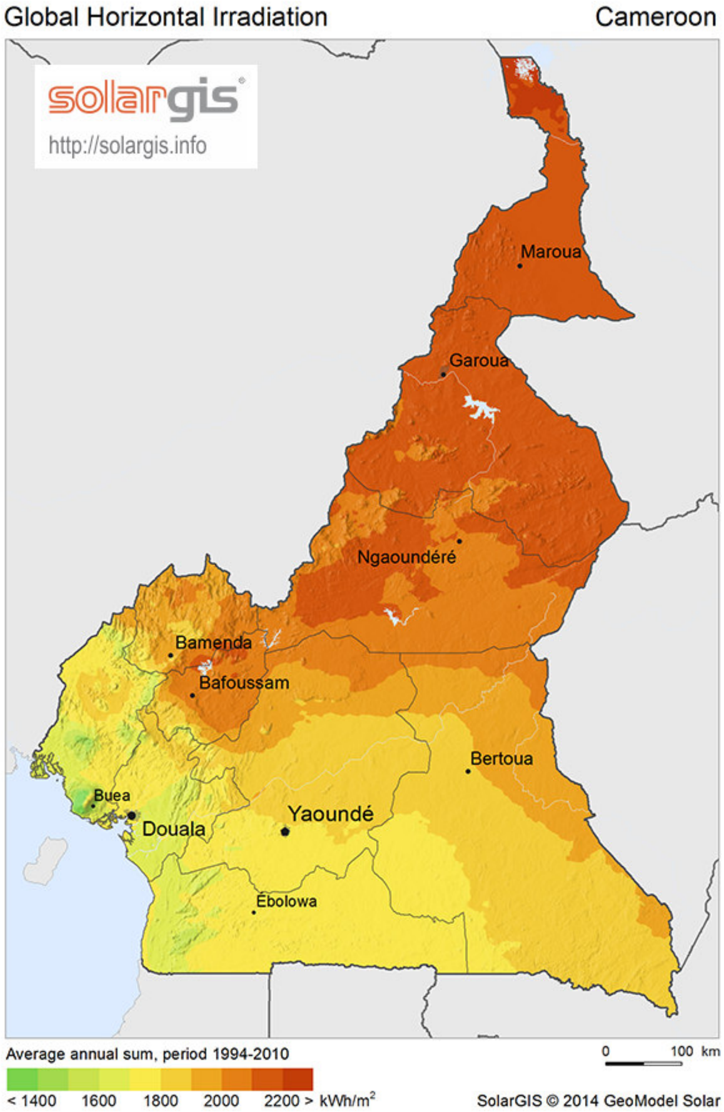


Figure B.7 Solar map by SolarGIS®

Appendix C

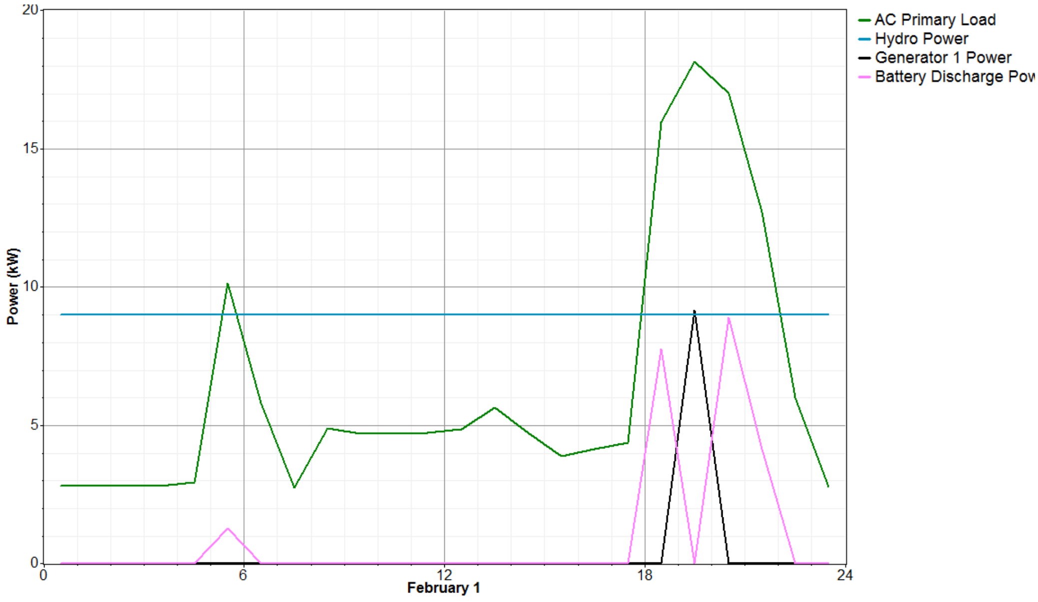


Figure C.1 1st of February load curve and supply by different technologies (off-grid system)

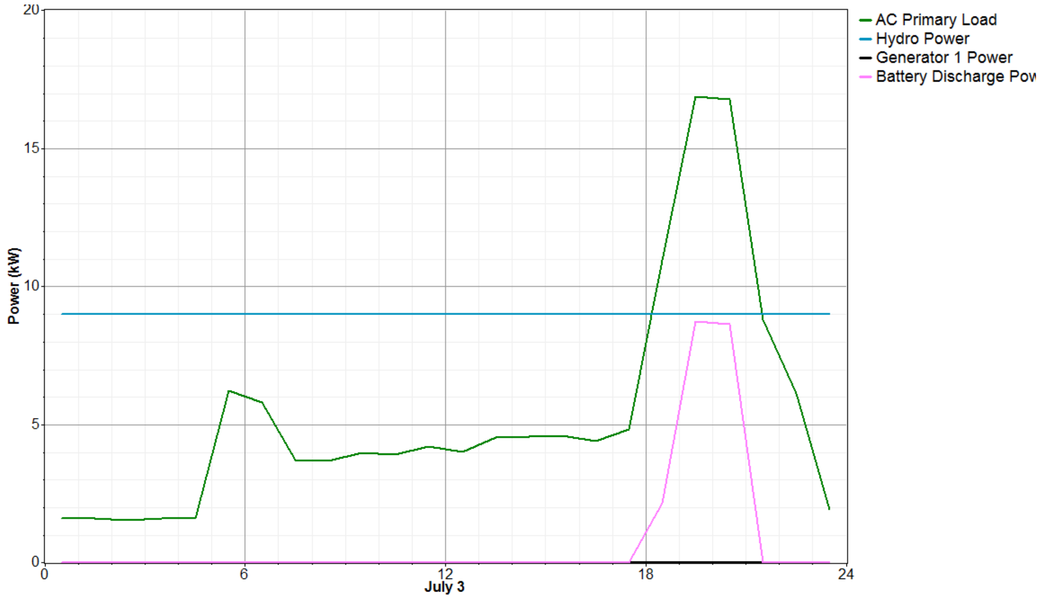


Figure C.2 3rd of July load curve and supply by different technologies (off-grid system)

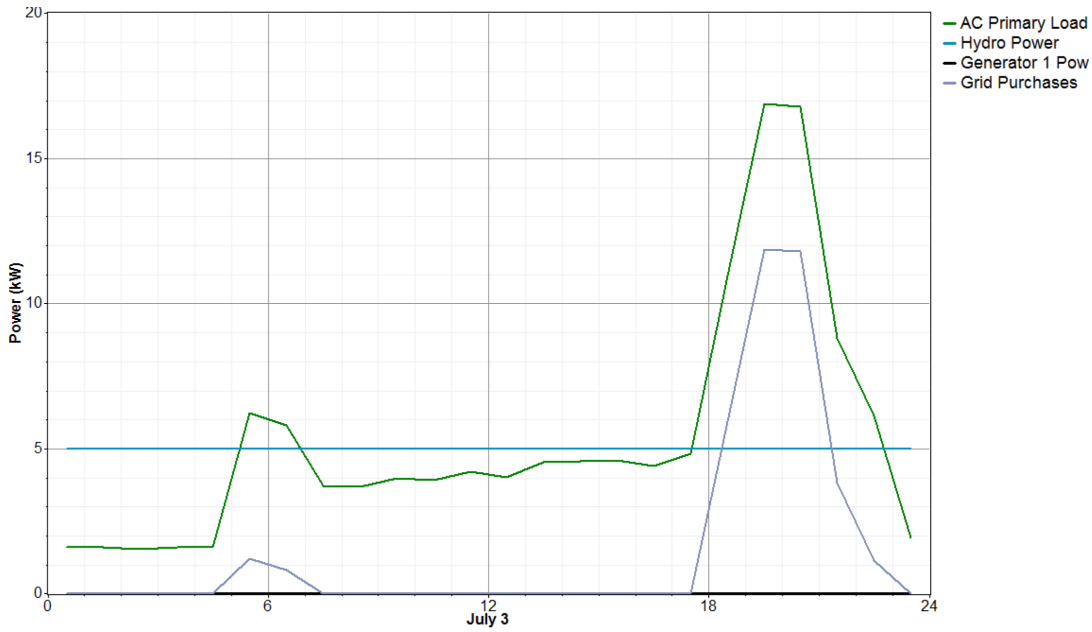


Figure C.3 3rd of July load curve and supply by different technologies (hybrid system)

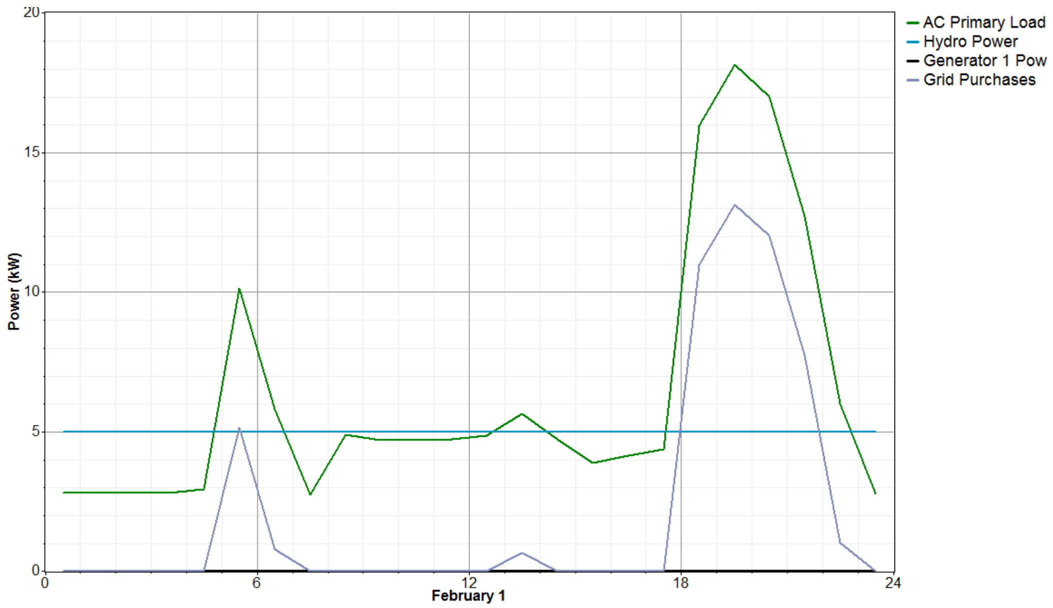


Figure C.4 1st of February load curve and supply by different technologies (hybrid system)

Technology with reduced cost	PV kW	BN1.5 n°	Hydro kW	Label kW	Batteries n°	Converter kW	NPC $	LCOE $/kWh
PV	3	0	15	24	20	10	165643	0.181
PV	18	0	0	24	92	10	311599	0.341
BN1.5 (wind)	0	1	15	24	20	10	163994	0.179
BN1.5 (wind)	0	10	0	24	40	10	394021	0.431

Table C.1 Power features if capital cost of PV and wind turbine are reduced by 90% (off-grid system)

Technology with reduced cost	PV MWh/yr	Wind MWh /yr	Hydro MWh /yr	Label MWh /yr	Total MWh /yr	Excess MWh /yr
PV	4.96	0	78.84	4.53	88.33	32.66
PV	29.75	0	0	29.44	59.19	1.08
BN1.5 (wind)	0	2.36	78.84	4.43	85.63	30.10
BN1.5 (wind)	0	23.58	0	35.13	58.71	1.43

Table C.2 Electrical production if capital cost of PV and wind turbine are reduced by 90% (off-grid system)

Technology with reduced cost	PV kW	BN1.5 n°	Converter kW	NPC $	LCOE $/kWh
PV	12	0	10	134314	0.142
BN1.5 (wind)	0	10	10	133108	0.140

Table C.3 Power features if cost of PV and wind turbine are reduced by 90% (grid-RES hybrid system)

Technology with reduced cost	PV MWh/yr	Wind MWh /yr	Grid Purchase kWh/yr	Grid Sales kWh/yr	Total MWh /yr	Excess MWh /yr
PV	19.83	0	39.80	1.87	59.63	3.98
BN1.5 (wind)	0	23.58	35.96	2.18	59.55	3.12

Table C 4 Electrical production if capital cost of PV and wind turbine are reduced by 90% (grid-RES hybrid system)

Service level	**Access measure**	**Needs met**	**Level of health concern**
No access (quantity collected often below 5 l/c/d)	More than 1000m or 30 minutes total collection time	Consumption – cannot be assured Hygiene – not possible, unless practised at source	Very high
Basic access (average quantity unlikely to exceed 20 l/c/d)	Between 100 and 1000m or 5 to 30 minutes total collection time	Consumption – should be assured Hygiene – handwashing and basic food: hygiene possible Laundry/bathing difficult to assure unless carried out at source	High
Intermediate access (average quantity about 50 l/c/d)	Water delivered through one tap onplot (or within 100m or 5 minutes total collection time)	Consumption – assured Hygiene – all basic personal and food: hygiene assured Laundry and bathing should also be assured	Low
Optimal access (average quantity 100 l/c/d and above)	Water supplied through multiple taps continuously	Consumption – all needs met Hygiene – all needs should be met	Very low

Table C.5 Table of water minimum requirements [76].

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