

POLITECNICO DI MILANO

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

**MASTER OF SCIENCE IN ENERGY ENGINEERING
FOR AN ENVIRONMENTALLY SUSTAINABLE WORLD**



Improvement of the energy supply and energy efficiency of St. Theresa's Catholic Medical Center in Cameroon

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Academic Year 2014-2015

ABSTRACT

The concept of *sustainable energization* in rural energy planning, adopting the Advanced Local Energy Planning (ALEP) methodology, is applied within this thesis on a group of facilities located in Bafut, a rural area of Cameroon.

The goal of this research is to improve the energy supply and efficiency of the study area through four specific objectives: assess the current energy situation of the study area, assess the energy resources locally available, identify the strategies to improve the energy efficiency and the energy supply and propose a more sustainable energy system for the study area.

The total primary energy consumption amounts to 186.2 GJ/month, corresponding to 53.37 toe/year, losses are equal to 70% and final energy of 56.2 GJ/month (16.01 toe/year) is consumed to provide the main services. Three energy drivers are present in the control volume: domestic, public and artisan. The energy sources currently used are firewood, electricity from the national grid, LPG, diesel, and kerosene.

The RES locally available are: hydro, wind, solar and biogas. Hydropower annual potential from a nearby river was 140.7 GJ. Wind annual potential was equal to 0.005 GJ/m² of swept area, while solar potential was 0.02 GJ/m². The feedstocks assessed for biogas - human, animal, kitchen and agricultural waste - give an expected production equal to 44.85 GJ/month.

Energy solution planning was based on matching energy demand with local available RES. Electricity planning was developed by simulating a new supply system with the software HOMER® in *Off-grid* and *Grid-RES* options both including hydropower. Grid-RES optimal solution was favorable respect to Off-grid presenting a lower NPC and LCOE. Thermal planning was based on ad-hoc solutions: installation of biogas stoves, ICS and improved bakery oven. In the suggested scenarios TPES was equal to 133.1 GJ/month (38.15 toe/year), losses reduced to 38% and a new service is provided, water heating using biogas boilers and solar thermal collectors, therefore the final consumption increased to 87.2 GJ/month (24.99 toe/year).

Keywords: sustainable energization, rural energy planning, Renewable Energy Sources.

ACKNOWLEDGMENTS

First of all we would like to express our gratitude to Professor Emanuela Colombo for the inspiration and the ideas that she has given us as well as for the fantastic opportunity that she has granted us.

We would like to deeply thank Dr. Jerome Ndam Mungwe, for his continuous support on-field and once back in Italy, for his precious suggestions and advices and for the experiences he shared with us regarding Cameroon.

A very special thanks is dedicated to Doctor Venantius Mutsu Bumaha, the Chief Medical Officer of St Theresa's Catholic Medical Centre, for his enthusiasm and trust in our work.

We would also like to thank the Tertiary Sisters of St Francis for their hospitality and the warm environment that they have created for us, together with all and each one of the persons working and living in the study area.

Our gratitude goes to Dr. Wanzie Boniface and Dr. Ndong Ignatius Cheng of the Catholic University of Cameroon (CATUC) in Bamenda for the valuable cooperation and help during the field period. A special thanks goes to the students of CATUC for the support in the field work, especially to Levis and Willy for their dedication.

Ringraziamo profondamente la famiglia Faldini, impegnata da anni in missioni presso il centro ospedaliero a Bafut tramite l'Onlus Orthopaedics, che ci ha fornito il primo contatto con la realtà africana.

Uno speciale ringraziamento va alle nostre famiglie per il supporto continuo, per aver creduto in noi ed averci appoggiato in questa esperienza affascinante, senza le quali tutto questo non sarebbe stato possibile. Σας ευχαριστώ, φαμίλια, μέσα από την καρδιά μου. Εκτιμώ τη στήριξη και την αγάπη σας, τίποτα δε θεωρώ δεδομένο.

We are sure that we have not thanked properly every person that contributed to this work, so, thank you!

Gloria & Malama

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NOMENCLATURE

Symbol	Description	Unit
$\%TS$	Total solids content of waste	
$\%VS$	Volatile solids content of waste	
α	Wind shear exponent	
γ	Specific weight of water	[kN/m ³]
δ	Diurnal pattern of strength	
ΔE_{evap}	Energy consumed to evaporate water	[kJ]
Δh_{H_2O}	Enthalpy of vaporization of water	[kJ/kg]
Δt	Average traveling time of floating object	[s]
ΔT_{H_2O}	Difference between ambient and boiling temperature of water	[°C]
$\eta_{collector}$	Solar thermal collector efficiency	
$\eta_{conversion}$	Conversion efficiency	
η_{oven}	Baking oven efficiency	
η_{system}	Solar thermal system efficiency	
ρ_{water}	Density of water	[kg/m ³]
σ	Standard deviation	[m/s]
φ	Hour of peak wind speed	[hr]
A	Mean cross sectional area of the river	[m ²]
A_{corn}	Area dedicated to maize cultivation	[m ²]
c_p	Specific heat capacity	[kJ/kg/K]
$E_{i \rightarrow i+1}$	Energy consumption from hour i to hour $i+1$	[kWh]
E_{baking}	Energy needed for baking one kilogram of bread	[MJ]
EHV	Effective calorific value	[MJ/kg]
EL	Energy losses	[MJ]
f_s	Fraction of water heating demand satisfied by solar collector	
f_w	Functioning window	[s]
$FE_{hot-water}$	Water heating demand	[MJ/day]
G	Minimum average sun irradiation along the year	[Wh/m ² /day]
h_{gross}	Gross head	[m]
Ir_d	Daily solar insolation	[Wh/m ² /day]
LCOE	Levelized Cost of Energy	[\$/kWh]

LF	Load Factor	
LHV	Lower heating value	[MJ/kg]
m_{bread}	Mass of bread produced	[kg]
$m_{dung,k}$	Mass of dry dung produced per animal	[kg]
$m_{f,c,dry}$	Mass of dry firewood	[kg]
$m_{firewood}$	Mass of firewood consumed	[kg]
m_{H_2O}	Mass of water reaching boiling temperature	[kg]
$m_{H_2O,evap}$	Mass of water evaporated	[kg]
m_{waste}	Mass of organic waste	[kg]
m_{wood}	Mass of firewood consumed	[kg]
MC	Moisture content of firewood	
NPC	Net Present Cost	[\$]
$P_{absorbed}$	Power absorbed during one hour	[W]
P_{peak}	Peak Power	[W]
$P_{theoretical}$	Theoretical power	[kW]
PE	Primary Energy	[MJ]
q	Lag autocorrelation coefficient	
Q	Volumetric flow rate of river	[L/s]
r_q	Autocorrelation factor	
R	Solar radiation	[W/m ²]
SD	Slope distance between powerhouse and river intake	[m]
\overline{SW}	Average wind speed	[m/s]
SWH_{area}	Solar thermal collector capacity	[m ²]
T_{amb}	Ambient temperature	[°C]
T_b	Boiling temperature	[°C]
TFC	Total Final Energy Consumption	[GJ]
TPES	Total Primary Energy Supply	[GJ]
v	Average stream velocity	[m/s]
v_{ref}	Wind velocity at reference height z_{ref}	[m/s]
V_{biogas}	Biogas potential production	[Nm ³ /month]
$V_{hotWater}$	Amount of hot water required per person daily	[L]
VD	Vertical distance between powerhouse and intake	[m]
x	Length traveled by the floating object	[m]
Y_{biogas}	Biogas yield	[Nm ³ /kg_VS] [Nm ³ /t_maize]
$Y_{corn,dry}$	Maize stalks yield	[t/ha/year]
z_0	Roughness length	[m]
ZA	Zenith angle	[°]

LIST OF ABBREVIATIONS

3SF	Three-Stone Fire
AC	Alternating Current
ALEP	Advanced Local Energy Planning
CATUC	Catholic University of Cameroon
CFL	Compact Fluorescent Lamp
COP21	21st Conference of Parties
DC	Direct Current
EDI	Energy Development Index
EDM	Electromagnetic Distance Measuring
EHV	Effective Heating Value
FCFA	Central African CFA Franc
FE	Final Energy
GDP	Gross Domestic Product
HDI	Human Development Index
ICS	Improved Cook Stove
IEA	International Energy Agency
IPD	In-Patient Department
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost Of Energy
LF	Load Factor
LHV	Lower Heating Value
LPG	Liquid Petroleum Gas
MC	Moisture Content
MDGs	Millennium Development Goals

NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
O&M	Operation and Maintenance
OPD	Out-Patient Department
PCM	Project Cycle Management
PE	Primary Energy
PV	Photo-Voltaic
RES	Renewable Energy Sources
RET	Renewable Energy Technologies
SAJOCAH	St Joseph's Children and Adults Home
SDGs	Sustainable Development Goals
SE4All	Sustainable energy for all
SJCHS	St Joseph's Comprehensive High School
STCMC	St Theresa's Catholic Medical Centre
TFC	Total Final Consumption
TPES	Total Primary Energy Supply
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
WBT	Water Boling Test
WHO	World Health Organization
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

Goal 7 of the Sustainable Development Goals adopted in September 2015 by the United Nations consists in achieving universal access to energy by 2030. Energy is a key driver to sustainable development and a means to eradication of poverty. Energy access can be considered to have a double face: not only access to electricity but also access to modern, more efficient fuels and clean cooking facilities. Both aspects of energy access are captured by the concept of *energization*. The Energy Access group of the UNESCO Chair in Energy for Sustainable Development, Department of Energy, Politecnico di Milano, have analyzed the concept of *sustainable energization* and developed a new rural energy planning procedure within the Advanced Local Energy Planning (ALEP) methodology called “a comprehensive rural energy planning consisting of *Seven Steps planning procedure*”, which has been used as framework for the development of this thesis.

Cameroon, where the field work of this study was carried out, belongs to sub-Saharan Africa, the part of the world with the highest share of people without access to electricity. Human Development Index, (ranging between 0 and 1) is low in Cameroon and equal to 0.512, as well as Energy Development Index, (with values from 0 to 1) equal to 0.14. The mix of sources for electricity generation includes hydropower, oil, natural gas and waste, while for cooking 70% of the population of Cameroon depend wholly on firewood. In urban areas the grid electricity access equals to 50% while in the rural areas the access arrives only up to 15%.

The study area was the Mambu, a part of the village of Bafut in the Northwest Region of Cameroon, it consisted of the following facilities: a medical center, a high school, a physiotherapy and rehabilitation center, a convent and a postulancy. The area had a dynamic population estimated at about 600 persons. The control volume, due to its characteristics was considered as an entity independent at a socio-economic level; therefore, within the frame of this research has been treated as a *micro-village*. The study area was expanding in size and range of services provided, leading to an increase in the energy demand. Electricity was supplied by the national grid that suffers from voltage fluctuations and frequent power shortages: lack of drinkable water was one of the

consequences of the power shortages since the water was provided by electrical pumps. Diesel backup generators were present in the study area but diesel was expensive and its supply difficult in a rural area. Firewood was the main primary source used for cooking causing health problems due to its intensive use in poor efficiency cooking facilities.

The current study, developed as a pre-feasibility study investigated solutions to ensure access to affordable, reliable and modern energy services in the study area. The focus was set on renewable energy sources locally available. The general objective of this work was to improve the energy efficiency and the energy supply of the study area.

In order to achieve the general objective, four specific objectives were set:

- I. To assess the current energy situation of the study area.
- II. To assess the energy resources locally available with focus on hydro, wind, solar and biogas.
- III. To identify the strategies to improve the energy efficiency and the energy supply of the study area.
- IV. To propose a more sustainable energy system for the study area.

The general methodology adopted was field study with the application of several methods and tools as appropriate in cooperation with local students from the Catholic University of Cameroon (CATUC).

In order to assess the current energy situation of the study area, the reference energy system was adopted after identifying the energy sources, the energy drivers and the energy services demanded. Energy was supplied to the study area by the national electricity grid and by the following fuels: kerosene, liquefied petroleum gas (LPG), diesel and firewood. These fuels, within the context, were treated as “primary energy sources” in the analysis of the PES. Three main energy drivers were identified: domestic, public and artisan. The domestic driver consisted of the households and the guesthouses of the study area; the public driver consisted of the following functional units: SAJOCAH, SJCHS, STCMC, Convent, and Postulancy, while the artisan driver consisted of the productive activities of the canteens, the bakery and the workshops. The energy services demanded that were identified included: powering of appliances, cooking, lighting, baking, cooling and water heating. Data regarding the energy consumption in

the domestic energy driver were collected by means of questionnaires administered during peer-to-peer interviews. Similar questionnaires were provided in the public and artisan energy drivers, where additional checklists were used in order to estimate the consumption of electrical devices with non-regular usage pattern. Complementary information was extracted from bills and receipts provided by the administration. Firewood consumption data were acquired by questionnaires and direct measurements. After data elaboration the energy flows were obtained and presented in a Sankey diagram.

The primary energy supplied (PES) to the study area was 186.2 GJ/month, the TPES per capita was equal to 0.09 toe/year, lower respect to the country average 0.33 toe/year/capita, compatible with 0.11 toe/year/capita of the Cameroonian Protestant College in Bali.

The bulk of the TPES was from firewood, (75.3%), followed by the electricity from the grid, (14.4%). The rest of the PES was from LPG, diesel and kerosene with the following shares: 5.3%, 3.6% and 0.8%, respectively. All the energy sources supplied the three energy drivers except for kerosene that was used only in the domestic and the public drivers.

The major part of the PES was absorbed by the public and the artisan energy drivers, corresponding to 50.9% and 46.4% respectively. The limited number of households justifies the low amount of energy supplied to the domestic driver.

The total final energy consumption (TFC) within the control volume was 56.2 GJ/month. Due to low efficiency conversion technologies a very large amount of thermal energy was lost, amounted to 130.5 GJ/month, representing about 70% of the TPES.

Powering of appliances and cooking were the most energy consuming services within the study area, with shares of 44% and 37.5% of the TFC respectively. These services, as well as lighting (8.5%), were needed in all three energy drivers. Baking (6.2%) was attributed only to the artisan energy driver, while energy consumption for cooling (1.4%) and water heating (0.9%), was present only in the public energy driver.

The potential of locally available energy sources was assessed with focus on RES, namely hydro, wind, solar and biomass (biogas).

The hydropower potential was assessed by carrying out direct measurements in a river found in the study area. The gross head, was measured by using both Google Earth and a total station instrument. The values for the flow rate calculated from the direct measurements were considered as mean values for the corresponding months, and a regression technique was applied in order to obtain the annual flow pattern. A design flow rate was chosen equal to the minimum residual flow of the river 43 l/s, therefore the minimum theoretical power output was 14.6 kW, assuming an overall hydro system efficiency equal to 50% and a capacity factor of 55% the minimum annual energy was 140.7 GJ. The energy production increases with the adoption of cross-flow turbine able to follow the variable flow rate of the river.

Data regarding wind and solar potential were acquired with a dedicated weather station for the months of May, June, July, August and October and regression techniques were applied to obtain annual values.

The annual average wind speed was equal to 1.8 m/s, therefore the theoretic power per unit of swept area was 2.13 W/m² and with a capacity factor equal to 7% the annual energy production was 4.7 MJ/m².

Daily and monthly average insolation values ranged between 12.2 and 23.8 MJ/m², with an annual average equal to 17.3 MJ/m².

For the biogas potential assessment the following sources were identified: human, animal, kitchen and agricultural waste. The potential from the four different types of feedstock in one month within the whole study area amounted to 1494.9 Nm³, of which 235.1 Nm³ from human waste, 858.2 Nm³ from animal dung, 294.8 Nm³ from agricultural waste and 106.8 Nm³ from kitchen waste. The biogas potential was 44.85 GJ/month.

An evaluation of the electricity supply by the national grid in terms of reliability was realized with a dedicated section of the questionnaire and direct observation. 70% of the interviewees replied that power shortages occur every day, moreover none of the answers reported an outage frequency above once a week. Regarding the duration of the outages 40% of the interviewees claimed that in a week it can range from 3 to 24 hours. The results of direct registration showed that the occurrence of multiple blackouts within the

same day was not a rare, while duration varied a lot ranging, during the experimental period, from a few minutes up to 33 hours. Apart from the power shortages, also voltage fluctuations occurred often causing serious damages to the electric appliances. The supply of kerosene, LPG and diesel fuels to the study area was difficult, the buyer needed often to travel long distances to avoid the extra costs of delivery, at the same time the prices fluctuated continuously.

The internal electricity grid of the study area was evaluated in terms of complexity, automation and efficiency. The current wiring scheme was constructed without any specific design and without an emergency line, moreover the back-up generators were switched on and off manually in case of power shortage.

Various types of wood burning cook stoves were used in the study area, with age and operation and maintenance conditions affecting their performances. Different types of stoves were used: a modified Plancha, a multi-pot brick rocket stove, a two-pot and a three-pot improved cook stove (ICS) and numerous 3SF with efficiencies estimated through WBT equal to 20%, 17%, 20.8%, 15.2% and 13% respectively. Two twin ovens were used in the bakery of the study area, with efficiency estimated to be equal to 6.6%.

In the electrical planning a simpler common wiring scheme including an emergency line and able to accept RES supply was proposed to improve the internal grid. An increase of the automation of the grid was suggested by installing automatic main switches for the shift between normal and emergency lines; the efficiency can be furthermore increased by installing solar light detecting sensors for the security lamps and time-regulated switches for the operation of the lamps. Finally, demand side management was suggested in the Convent and Postulancy, where no priority loads were present, by rescheduling some activities to off-peak hours.

Energy solution planning was focused on matching needs and local energy resources. Two major options for electricity supply were investigated: Off grid and Grid-RES option. In the Off grid option the study area was isolated from the national grid and depended entirely on its local resources for electricity generation. In the Grid-RES option the system made use of its local resources for electricity generation as well as connectivity to the national grid to buy and sell electricity as appropriate. The

components of the suggested energy systems were chosen by analyzing the electrical daily load curve of the whole study area together with the potential of the local resources. The hydropower could satisfy the majority of the load throughout the year both in Off grid and Grid-RES options. For the Off grid option a PV system with batteries storage was considered, with sizes ranging from 5 to 10 kW, covering from 15% to 30% of the peak load; the use of two currently present diesel generators each one of 12 kW of size was considered to guarantee system stability. For the Grid-RES option the national grid was considered to provide electricity during peak demand and absorb the excess. The combinations of different sizes of the components were then modeled with the software HOMER® in order to investigate their technical and economic feasibility.

The optimal solution suggested by HOMER® for the Off grid option produced 639.2 GJ/yr from the hydropower system (94%), 25.6 GJ/yr from the PV system (4%), and 12.2 GJ/yr from back-up generators. The electricity demand of 290.1 GJ/yr was fully met. The excess of electricity produced by the energy system reached a high value of 378 GJ/yr due to continuous hydro power production compared to a high difference between peak and base loads to be satisfied. The solution presented a net present cost (NPC) equal to \$116185 and a levelized cost of energy (LCOE) equal to 0.148 \$/kWh. In the Grid-RES option the hydropower production was the same (639.2 GJ/yr) and the electricity purchased from the national grid were 37.8 GJ/yr. The excess of energy production was reinjected in the national grid. The NPC of the Grid-RES system was equal to \$90383, with a LCOE equal to 0.049 \$/kWh. Due to the high penetration of hydropower in both scenarios the reduction in CO₂ emissions was appreciable: equal to 5649.7 kg of CO₂ per year for the Off grid option and to 6664.1 kg of CO₂ per year for the Grid-RES option.

A sensitivity analysis was conducted to evaluate how different values of specific inputs, namely a variation of hydropower investment cost of $\pm 12.5\%$, a variation of PV investment cost of $\pm 10\%$, and variation of diesel price and electricity tariffs impact the optimal solutions. The analysis proved the stability and robustness of both solutions. In Off grid and Grid-RES options the variation of the capital cost of hydropower system reflected on a correspondent magnitude of variation of LCOE. For Off grid option the PV system investment cost and diesel price had low influence on LCOE due to their limited

energy production. For Grid-RES option the system was robust in changes to the electricity tariff.

Ad-hoc approach was used in thermal solution planning with focus to reduce the firewood consumption and to adopt cleaner and more efficient technologies for cooking and for baking. Solutions based on RES to provide energy for water heating were investigated.

The amount of energy production estimated from biogas was equal to 36.2 GJ/month in case of installation of a single digester to serve part of public and artisan driver (SAJOCAH, STCMC, Convent and Postulancy). Considering an efficiency equal to 42% for biogas stoves, 15.2 GJ/month were obtained from biogas which covered 73% of the energy needed for cooking (20.7 GJ/month). Therefore it was suggested the installation of biogas stoves to substitute the currently present firewood stoves in some selected kitchens in the public and artisan driver namely: SAJOCAH kitchen, Convent kitchen, Postulancy kitchen and the two canteens. From the estimated biogas production (36.2 GJ/month), 17.9 GJ/month was used to meet the cooking needs in the selected kitchens.

For the kitchens of the medical center the option of substitution of 3SF with Chitetezo stoves was suggested. The Chitetezo is an ICS that can be built with local material and with an efficiency of 31%. By adopting ICS instead of 3SF, 2.4 GJ/month of primary energy from firewood was required. In SJCHS improvement to the currently used stove were suggested: relocation of the feeding openings on the outside wall, introduction of a chimney to decrease the level of smoke and doors to close the combustion chamber. These modifications could move the efficiency of the stove towards that of an Astra stove (40%) reducing the primary energy consumption to 20 GJ/month.

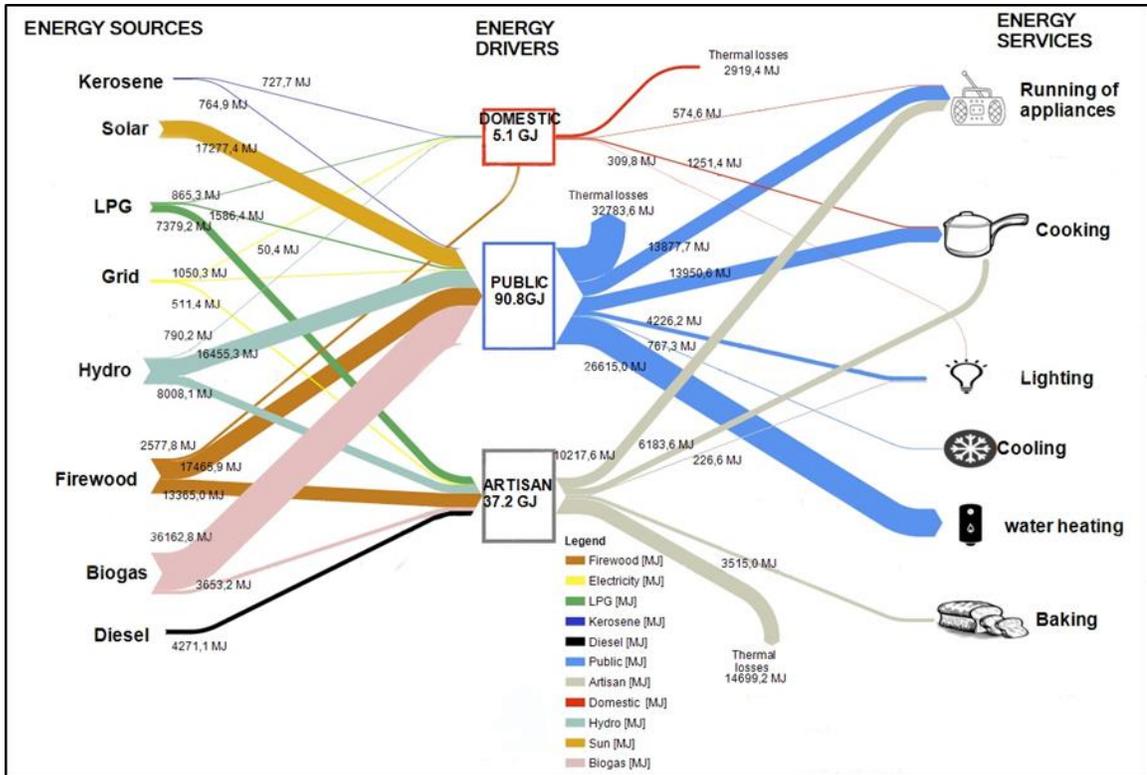
The energy required for baking can be substantially reduced by substitution of the current ovens with improved ones. The first option was the installation of a firewood-oven with firewood reduction efficiency of 75% with respect to traditional ovens. Therefore the primary energy supply required to satisfy completely the energy needed for baking amounted 13.4 GJ/month.

The second option was the substitution of the actual oven with the electric oven Blodgett mark V11, with a production rate of 44 kg/hour, and an efficiency of 73%. The monthly

electricity consumption for the oven (power 9.7 kW) was 3.1 GJ/month, The Grid-RES system with the oven was evaluated, assuming a load shifting of the electric oven from 3p.m. to 7p.m. NPC was \$92574 per year, increased of \$2191 (2.4%) and an LCOE equal to 0.50 \$/kWh, increased of 0.01\$/kWh (2%). Considering issues related to imported technologies, the installation of improved firewood oven was suggested among the two alternatives.

The solution suggested to satisfy the hot water demand for STCMC and SAJOCAH was the installation of biogas boilers. The total demand for hot water was 10.5 GJ/month; using biogas boilers with efficiency of 80%, 13.2 GJ/month of biogas would be required. This amount was met from the excess of 18.3 GJ/month after the use of biogas for cooking.

For the hot water demand of SJCHS students it was suggested the installation of biogas boilers and solar thermal collectors. The total final energy required for water heating corresponded to 15.7 GJ/month. The biogas production for SJCHS was estimated at 8.7 GJ/month, therefore the biogas boilers can cover 43.9% of the energy demand for hot water. The remaining 66.1% could come from solar thermal collectors of total area of 44.2 m², 15 collectors of 2.99 m² were required, manageable within socio-economic context of the rural area. The improvement of energy supply, the reduction of losses and penetration of RES in the study area provided a more sustainable energy system, are summarized in the energy flow diagram below.



For the suggested option, Grid-RES, the TPES was 133.1 GJ/month, corresponding to 38.15 toe/year, losses were equal to 38%, while TFC was 82.7 GJ/month corresponding to 24.99 toe/year, the increase in final consumption is attributed to an extra service provided, water heating. The set objectives of the study conducted to improve access to energy in rural areas of developing countries within the theme of SE4All were fully met through the field application of the proposed seven step rural planning methodology.

RIASSUNTO ESTESO

L'obiettivo numero 7 degli obiettivi di sviluppo sostenibile (SDG), adottati dalle Nazioni Unite nel settembre 2015 consiste nell'ottenere l'accesso universale all'energia entro il 2030. L'energia è un motore chiave per lo sviluppo sostenibile ed un mezzo per sradicare la povertà. L'accesso all'energia può avere due facce: non solo l'accesso all'elettricità, ma anche l'accesso a combustibili moderni ed efficienti e a tecnologie pulite per cucinare. Entrambi gli aspetti sono catturati nel concetto di energizzazione. Il gruppo per l' Accesso all'Energia della Cattedra UNESCO in Energia per uno Sviluppo Sostenibile, Dipartimento di Energia del Politecnico di Milano ha analizzato il concetto di energizzazione sostenibile e sviluppato una nuova procedura di pianificazione energetica rurale inclusa nella metodologia di Pianificazione Energetica Locale Avanzata (ALEP) chiamata "una procedura comprensiva di pianificazione energetica rurale composta da una Procedura di Pianificazione in Sette Punti", che è stata usata come base nello sviluppo di questo lavoro di tesi.

Il Camerun, dove si è svolto il lavoro sul campo, fa parte dell'Africa sub-sahariana, la parte del mondo con la più alta quota di popolazione senza accesso all'elettricità. In Camerun l'Indice di Sviluppo Umano (HDI compreso tra 0 e 1) è basso, uguale a 0.512, così come è basso l'Indice di Sviluppo Energetico (EDI compreso tra 0) uguale a 0.14. Il mix di risorse per la generazione di potenza include idroelettrico, petrolio, gas naturale e rifiuti, mentre per cucinare il 70% della popolazione del Camerun è ancora completamente dipendente dal legname. Nelle aree urbane l'accesso alla rete elettrica raggiunge il 50% mentre in quelle rurali solamente il 15%.

L'area di studio si trova a Mambu, una parte del villaggio di Bafut nella provincia di Nord Ovest del Camerun ed è composta dalle seguenti strutture: un centro medico, una scuola superiore, un centro fisioterapico e di riabilitazione, un convento ed un noviziato. L'area ha una popolazione dinamica stimata di 600 persone. Il volume di controllo, date le sue caratteristiche è stato considerato come un'entità indipendente a livello socio-economico, quindi in questa ricerca è stato trattato come un micro - villaggio. L'area di studio si sta espandendo in taglia e servizi erogati con conseguente incremento del

fabbisogno energetico. L'elettricità è fornita tramite la rete elettrica nazionale che soffre di fluttuazioni di tensione e numerose interruzioni di fornitura. Dato che l'acqua è fornita all'area di studio tramite pompe elettriche, una conseguenza delle interruzioni di potenza è la mancanza d'acqua potabile. Nell'area sono presenti generatori diesel ma il costo del carburante è proibitivo e la fornitura difficoltosa in un'area rurale. La legna da ardere è la fonte principale di energia per cucinare causando problemi di salute dovuti al suo intenso uso usando tecnologie di conversione a bassa efficienza.

Lo studio corrente, sviluppato come studio di pre-fattibilità analizza le soluzioni per assicurare accesso a servizi energetici affidabili moderni ed al giusto costo nell'area in esame. L'obiettivo principale di questo lavoro è il miglioramento dell'efficienza energetica e della fornitura di energia nell'area di studio.

Per ottenerlo sono stati definiti quattro obiettivi specifici:

- I. Valutare la situazione energetica attuale dell'area di studio.
- II. Valutare le risorse energetiche disponibili localmente concentrandosi su idroelettrico, eolico, solare e biogas.
- III. Identificare le strategie per migliorare l'efficienza energetica e la fornitura di energia nell'area di studio.
- IV. Proporre un sistema energetico più sostenibile per l'area di studio.

La metodologia generale adottata è lo studio sul campo applicando diversi metodi e strumenti appropriati in cooperazione con gli studenti locali della Catholic University of Cameroon (CATUC).

Per valutare la situazione energetica attuale è stato adottato un sistema energetico di riferimento per l'area di studio identificando le risorse energetiche, i settori energetici e i servizi energetici richiesti. L'energia è fornita tramite la rete elettrica nazionale e i seguenti combustibili: cherosene, gas petrolio liquido (GPL), diesel e legname. Questi combustibili sono stati trattati come primari nell'analisi della fornitura di energia primaria (PES) dell'area in esame. Sono stati identificati tre settori energetici principali: domestico, pubblico e artigianale. Il settore domestico è costituito da abitazioni e foresterie dell'area di studio; quello pubblico è costituito dalle seguenti unità funzionali: SAJOCAH, SJCHS, STCMC, Convento, e Noviziato; mentre quello artigianale include le

attività produttive delle mense, panetteria e piccole officine, botteghe. I servizi energetici richiesti che sono stati identificati includono: dispositivi di potenza, attività di cucina, illuminazione, panificazione, raffrescamento e riscaldamento dell'acqua. Dati riguardanti i consumi energetici nel settore domestico sono stati ottenuti tramite questionari sottoposti attraverso interviste dirette. Simili questionari sono stati usati nel settore pubblico e artigianale dove checklist aggiuntive sono state adottate per stimare il consumo di dispositivi elettrici con utilizzo non regolare. Informazioni complementari sono state estratte da bollette e ricevute ottenute in amministrazione. Il consumo di legname è stato misurato sia direttamente che tramite questionario. Dopo l'elaborazione i flussi energetici sono stati riportati in uno schema di Sankey. La fornitura di energia primaria (PES) dell'area di studio era 186.2 GJ/mese, il TPES pro capite era di 0.09 tep/anno, basso rispetto alla media paese uguale a 0.33 tep/anno/capite e compatibile con lo 0.11 tep/anno/capite del Cameroonian Protestant College in Bali. La quota maggiore da legname, (75.3%), seguita dall'elettricità dalla rete, (14.4%). La restante parte da GPL, diesel e cherosene con quote rispettive del 5.3%, 3.6% e 0.8%. Tutte le risorse erano usate in ogni settore energetico ad eccezione del cherosene usato solo nel settore pubblico e domestico.

Le quote maggiori di PES erano assorbite dal settore pubblico e artigianale rispettivamente il 50.9% e 46.4%. Il numero limitato di abitazioni giustifica il basso fabbisogno energetico del settore domestico.

Il consumo totale finale di energia (TFC) nel volume di controllo ammonta a 56.2 GJ/mese. Una grande quantità di energia, 130.5 GJ/mese, circa il 70% della TPES è persa a causa delle tecnologie di conversione a scarsa efficienza adottate.

Dispositivi di potenza e attività di cucina erano i servizi a maggiore consumo nell'area di studio con quote rispettive del 44% e 37.5% del TFC. Questi servizi così come l'illuminazione, 8.5% del TFC, sono richiesti in tutti i settori, mentre la panificazione (6.2%) è attribuita al solo settore artigianale e il raffrescamento (1.4%) e riscaldamento d'acqua (0.8%) sono richiesti solo nel settore pubblico.

Il potenziale delle risorse energetiche disponibili localmente è stato valutato concentrandosi sulle risorse rinnovabili (RES): idroelettrico, eolico, solare e biomassa (biogas).

Il potenziale idroelettrico è stato stimato tramite misure dirette presso un fiume adiacente all'area di studio. La prevalenza lorda è stata misurata usando sia Google Earth che una stazione totale. Il valore di portata d'acqua ottenuto dalle misurazioni è stato considerato come media dei mesi corrispondenti ed una tecnica di regressione è stata adottata per ottenere il modello annuale. Una portata di progetto, corrispondente alla minima portata residua del corso d'acqua, 43 l/s è stata scelta, quindi la potenza teorica ottenibile corrisponde a 14.6 kW, assumendo un'efficienza totale del 50% del sistema idroelettrico e un fattore di capacità annuo del 55% la produzione minima di energia corrisponde a 140.7 GJ. Questa cresce adottando una turbina capace di seguire la variabilità stagionale della portata del fiume, come una turbina a flusso incrociato.

Dati per ottenere il potenziale eolico e solare sono stati acquisiti con una stazione meteo dedicate per i mesi di maggio, giugno, luglio, agosto e ottobre e tecniche di regressione sono state applicate per ottenere una stima annua.

La velocità annua media del vento era di 1.8 m/s, quindi una potenza teorica per unità d'area spazzata dalla turbine uguale a 2.13 W/m², considerando un fattore di capacità tipico del 7% la produzione energetica annuale corrisponde a 4.7 MJ /m².

Valori giornalieri e mensili di insolazione variano tra 12.2 e 23.8 MJ/m², con una media annuale uguale a 17.3 MJ/m².

Le seguenti risorse sono state identificate per la valutazione del potenziale energetico del biogas: deiezioni, letame, scarti agricoli e di cucina. Il potenziale mensile di produzione per l'area di studio ammonta a 1494.9 Nm³, di cui 235.1 Nm³ da deiezioni, 858.2 Nm³ da letame, 294.8 Nm³ da scarti agricoli and 106.8 Nm³ da scarti di cucina. Per un potenziale di 44.85 GJ/mese.

Una valutazione della affidabilità della rete elettrica è stata realizzata tramite una parte di questionario appositamente dedicate e osservazione diretta. Il 70% degli intervistati ha riportato una frequenza giornaliera di interruzione del servizio, inoltre nessuno ha segnalato una frequenza superiore alla settimana. Per la durata delle interruzioni, il 40%

degli intervistati indica una durata settimanale compresa tra le 3 e le 24 ore. Da osservazione diretta si nota la presenza frequente di interruzioni multiple nella stessa giornata e una grossa variazione di durata nel periodo di osservazione, da pochi minuti fino a 33 ore. Inoltre sono presenti anche frequenti fluttuazioni di tensione che causano seri danni ai dispositivi elettrici. L'approvvigionamento di cherosene, diesel e GPL all'area di studio è difficoltoso, il compratore necessita spesso di percorrere lunghe distanze per evitare gli extra costi di consegna, inoltre i prezzi variano continuamente.

La rete elettrica interna è stata valutata qualitativamente in termini di complessità, automazione e efficienza. Lo schema elettrico corrente è stato costruito senza specifica progettazione e senza una linea di emergenza, inoltre i generatori di back-up sono azionati manualmente in caso di interruzione di fornitura dalla rete nazionale.

Vari tipi di stufe a legna sono usati nell'area di studio, con differente stato di manutenzione ed età che ne influenzano le prestazioni. Molti tipi di stufe sono usati: Plancha modificata, Rocket di mattoni, una stufa migliorata a due fuochi ed una a tre fuochi e 3SF le cui efficienze stimate tramite WBT corrispondono rispettivamente al 20%, 17%, 20.8%, 15.2% e 13%. Due forni a legna identici sono presenti nella panetteria, con efficienza del 6.6%.

Per la pianificazione elettrica è stato proposto uno schema elettrico interno migliorato, comune e semplificato con una linea di emergenza, capace di accogliere produzione da rinnovabili. Un incremento del livello di automazione è stato proposto tramite installazione di interruttori principali automatici per passare da linea normale a linea di emergenza. L'efficienza può essere migliorata ulteriormente installando sensori crepuscolari per le luci di sicurezza e temporizzatori per operare le luci. Inoltre una gestione diversa lato consumo è stata proposta per il Convento e Noviziato dove non ci sono carichi prioritari, tramite spostamento di alcune attività in orari fuori dai picchi di carico.

La pianificazione energetica è stata focalizzata sull'accoppiamento tra bisogni e risorse energetiche locali. Due opzioni per la fornitura elettrica sono state analizzate: Off grid e Grid-RES. Nell'opzione Off grid l'area di studio è isolata dalla rete nazionale e dipende interamente sulle risorse locali per la generazione elettrica. Nell'opzione Grid-RES il

sistema utilizza sia le risorse locali per generare elettricità che la rete nazionale per vendere e comprare elettricità quando consono.

I componenti dei sistemi energetici suggeriti sono stati scelti analizzando il carico elettrico giornaliero dell'area di studio e il potenziale delle risorse locali. L' idroelettrico può soddisfare la maggior parte del carico durante l'anno, quindi è stato incluso in entrambe le alternative: Off grid e Grid-RES. Per l'opzione Off grid un sistema fotovoltaico con stoccaggio a batterie è stato considerato con taglie tra i 5 e 10 kW, per coprire dal 15% al 30% del carico di picco. L'uso di due generatori diesel già presenti, ognuno di taglia 12 kW è stato considerato per garantire stabilità del sistema. Per l'opzione Grid-RES la rete nazionale è considerata per fornire elettricità durante i picchi di carico e per assorbire gli eccessi di produzione. Le combinazioni di diverse taglie di componenti sono state modellate tramite il programma HOMER® per determinare la loro fattibilità tecnica ed economica.

La soluzione ottima suggerita da HOMER® per l'opzione Off grid produce 639.2 GJ/anno dall'idroelettrico (94%), 25.6 GJ/anno dal fotovoltaico (4%) e 12.2 GJ/anno dai generatori. Il fabbisogno elettrico di 290.1 GJ/anno è completamente soddisfatto. L'eccesso di produzione, raggiunge l'elevato valore di 378 GJ/anno dovuto alla produzione continua dall'idroelettrico comparata alle grosse differenze tra picchi di carico e carico di base da soddisfare. La soluzione presenta un costo netto attualizzato (NPC) di \$116185 e un LCOE di 0.148 \$/kWh. Nell'opzione Grid-RES la produzione dell'idroelettrico è la stessa (639.2 GJ/anno) e l'elettricità comprata dalla rete nazionale corrisponde a 37.8 GJ/anno, l'eccesso di produzione è re immesso nella rete. L' NPC del sistema Grid-RES è uguale a \$90383, con un LCOE di 0.049 \$/kWh.

Grazie all'alta penetrazione di idroelettrico di entrambe le opzioni, le riduzioni di emissioni di CO₂ sono considerevoli ed uguali a 5649.7 kg di CO₂ l'anno per l' Off grid e 6664.1 kg di CO₂ l'anno per il Grid-RES. Un' analisi di sensitività è stata condotta per valutare l'impatto di diversi input, nello specifico la variazione del costo dell' idroelettrico del $\pm 12.5\%$, la variazione del costo del fotovoltaico del $\pm 10\%$, la variazione del prezzo del gasolio e delle tariffe elettriche, sulle soluzioni ottime delle due opzioni. L'analisi prova la stabilità e robustezza di entrambe le soluzioni. In opzione sia Off grid

che Grid-RES la variazione dell'investimento per l'idroelettrico corrisponde alla stessa percentuale di variazione del LCOE; mentre per il sistema Off grid il costo del fotovoltaico e il prezzo del diesel influenzano poco l' LCOE data la loro limitata produzione elettrica. Il sistema Grid-RES è robusto a variazioni delle tariffe elettriche.

La pianificazione termica è stata applicata per ridurre il consumo di legname e per adottare tecnologie più pulite ed efficienti per cucinare e panificare, anche soluzioni per fornire acqua calda basate su fonti rinnovabili son state valutate.

La quantità stimata di energia prodotta da biogas corrisponde 36.2 GJ al mese in caso di installazione di un singolo digestore per servire parte del settore pubblico e artigianale (SAJOCAH, STCMC, Convento e Noviziato). Considerando un efficienza del 42% per i fornelli a biogas, 15.2 GJ/mese possono essere ottenuti da biogas, capaci di coprire il 73% di domanda energetica per cucinare (20.7 GJ/mese). Perciò è suggerita l'installazione di fornelli a biogas per sostituire le stufe a legna correnti in alcune cucine selezionate nel settore pubblico e artigianale: cucina di SAJOCAH, del Convento e del Noviziato nonché delle due mense. Dalla produzione di biogas stimata (36.2 GJ/mese), 17.9 GJ/mese è stato usato nelle cucine selezionate per soddisfare il fabbisogno di energia per cucinare.

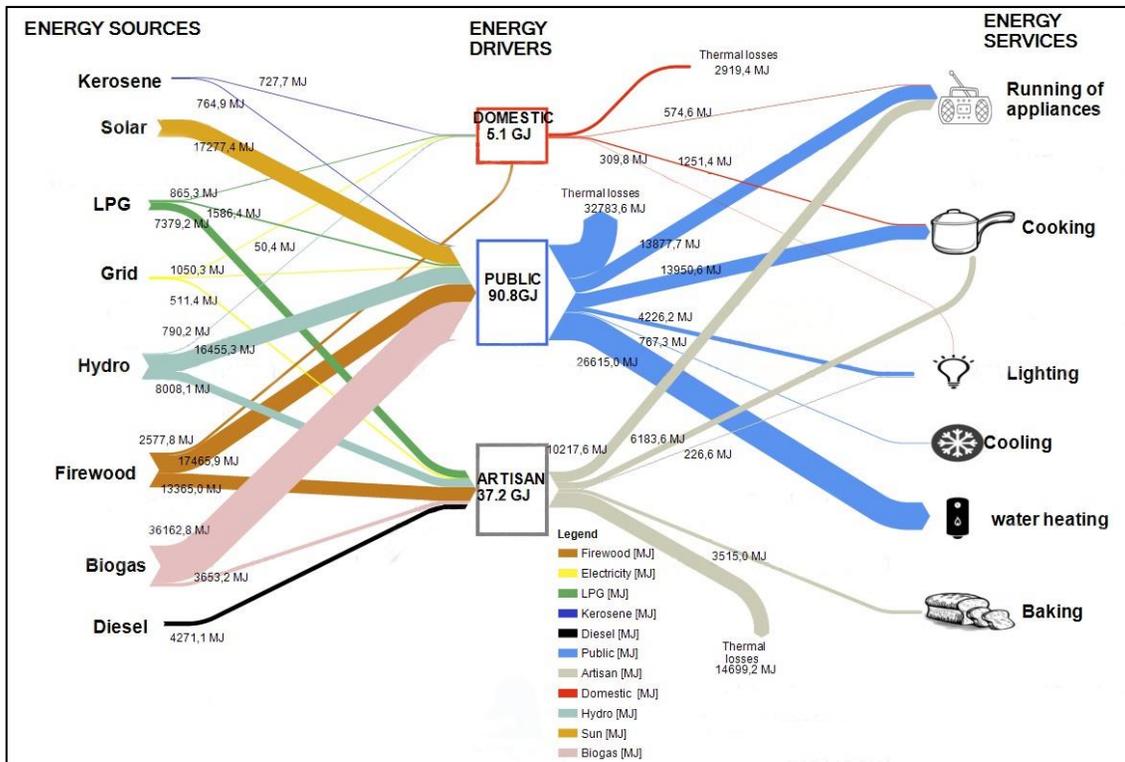
Per le cucine del centro medico è suggerita la sostituzione delle 3SF con stufe Chitetezo, stufe migliorate costruite con materia prima locale, che raggiungono efficienze del 31%. Adottando queste ICS invece delle 3SF presenti sono richiesti 2.4 GJ/mese di energia primaria da legname. In SJCHS sono suggeriti miglioramenti della stufa corrente: rilocalizzazione delle aperture per caricare il legname sulla parete sterna e introduzione di un camino per ridurre i livelli di fumo e sportelli per chiudere le aperture nella camera di combustione. Queste modifiche potrebbero portare l'efficienza verso quella di una stufa migliorata modello Astra (40%) e ridurre il consumo di energia primaria a 20 GJ al mese. L'energia richiesta per panificare può essere molto ridotta tramite la sostituzione del forno corrente. La prima opzione è l'installazione di un forno a legna con un efficienza di riduzione del combustibile del 75% rispetto a forni tradizionali, perciò la fornitura di energia primaria necessaria per soddisfare completamente il consumo per panificare ammonta a 13.4 GJ/mese. La seconda opzione è la sostituzione con un forno elettrico

Blodgett mark V11, con capacità produttiva di 44 kg/ora, ed efficienza del 73%. Il consumo elettrico per il forno ammonta a 3.1 GJ/mese, con necessità di riorganizzare i tempi di produzione tra le 15 e le 19. L'aggiunta del carico elettrico è stata valutata per il sistema Grid-RES suggerito. Il NPC corrispondeva a 92574\$ l'anno con un incremento di 2191\$ (2.4%) e l' LCOE corrispondeva a 0.50 \$/kWh, incremento di 0.01\$/kWh (2%). Considerando problemi derivanti dall'importazione di tecnologie, l'installazione del forno a legna migliorato è consigliata tra le due alternative.

La soluzione suggerita per soddisfare il bisogno di acqua calda in STCMC e SAJOCAN è l'installazione di caldaie a biogas con efficienza del 80%. Il bisogno energetico totale ammonta a 10.5 GJ/mese, usando biogas sono necessari 13.2 GJ/mese. Questa quantità è disponibile dall'eccesso di biogas di 18.3 GJ/mese rimanente dopo l'uso per cucinare.

Per il bisogno di acqua calda degli studenti di SJCHS è suggerita l'installazione di caldaie a biogas e collettori solari. Il bisogno di energia per riscaldamento dell'acqua ammonta a 15.7 GJ/mese. La produzione di biogas per SJCHS è stata stimata come 8.7 GJ/mese, quindi le caldaie a biogas sono in grado di coprire il 43.9% del fabbisogno di acqua calda. Il restante 66.1% viene prodotto da collettori solari termici con un area (SWH) di 44.2 m².

Il miglioramento della fornitura energetica, la riduzione delle perdite e la penetrazione di risorse rinnovabili ha fornito un sistema energetico più sostenibile per l'area di studio, riassunto nello schema di flusso energetico sottostante.



Per il sistema Grid-RES suggerito il TPES corrispondeva a 133.1 GJ/mese, uguale a 38.15 tep/anno, con perdite del 38%, mentre il TFC era uguale a 82.7 GJ/mese corrispondente a 24.99 tep/anno, il cui incremento si deve alla soddisfazione del bisogno di acqua calda. Gli obiettivi della ricerca per migliorare l'accesso all'energia in aree rurali di paesi in via di sviluppo nel contesto dell'energizzazione sostenibile sono stati completamente raggiunti grazie all'applicazione sul campo della metodologia in 7 passi proposta per la pianificazione energetica rurale.

1. INTRODUCTION

1.1 Background

In September 2000 all United Nations member states and many international organizations agreed on and adopted a 15-year development agenda including eight anti-poverty targets, known as Millennium Development Goals (MDGs). Despite the progress made, poverty has not been ended for all [1]. It was noted the importance of energy for the attainment of the MDGs.

In September 2015 a new agenda was adopted, the 2030 Agenda, consisting of 17 new targets, the Sustainable Development Goals (SDGs). The SDGs are broader and more ambitious than MDGs [2] and require that all three dimensions -economic, social, and environmental- of sustainable development are taken into account. Remarkable amongst the SDGs which is Goal 7 focused on achievement of universal access to energy by 2030 i.e. *”Ensure access to affordable, reliable, sustainable and modern energy for all.”* [4]

The goal of energy access for all by 2030 recommends access to be provided in order to enhance services such as lighting, cooking, heating and running of appliances for populations in developing countries. Energy is a key driver to sustainable development [5] and a means to eradication of poverty. But poverty is a multidimensional problem. Access to modern energy can reduce poverty by promoting gender equality, empowering women, fostering education and improving women’s and children’s health. Besides, access to sustainable energy means a more equitable distribution of resources, which can be achieved by utilizing the renewable energy sources available at a local level ensuring harmony with nature. The phrase of UN Secretary-General Ban Ki-Moon summarizes it all: “Energy is the golden thread that connects economic growth, increased social equity and an environment that allows the world to thrive.”

Energy access may be considered to have a double face: access to electricity and access to modern and more efficient fuels and clean cooking facilities for cooking. So far on the way to the achievement of the MDGs the focus was on *electrification* of, mainly, the rural areas in the developing countries and grid extension being the traditional approach

for increasing electricity access in rural areas. The issue of access to energy is better captured by the theme of *energization*, a concept that includes: matching of energy needs and energy resources, improving of the energy supply, promoting cleaner and more efficient fuels, covering household needs, providing public services, promoting economic development, emphasizing cultural and social aspects and local empowerment as well as promoting renewable energy systems [5].

1.2 Problem statement

Despite an increase in global access to energy during the last years the issue of energy access remains prominent in the developing world. According to IEA [6] about 1.2 billion people - 17% of the global population - are still without access to electricity and more than 2.7 billion people - 38% of the global population - rely on the traditional use of biomass for cooking. More than 95% of the people without electricity are in sub-Saharan Africa and developing Asia, and live mainly in rural areas. [7]

Republic of Cameroon is located on the Atlantic coast of Central Africa and belongs to sub-Saharan Africa, where the share of people without access to electricity is the highest

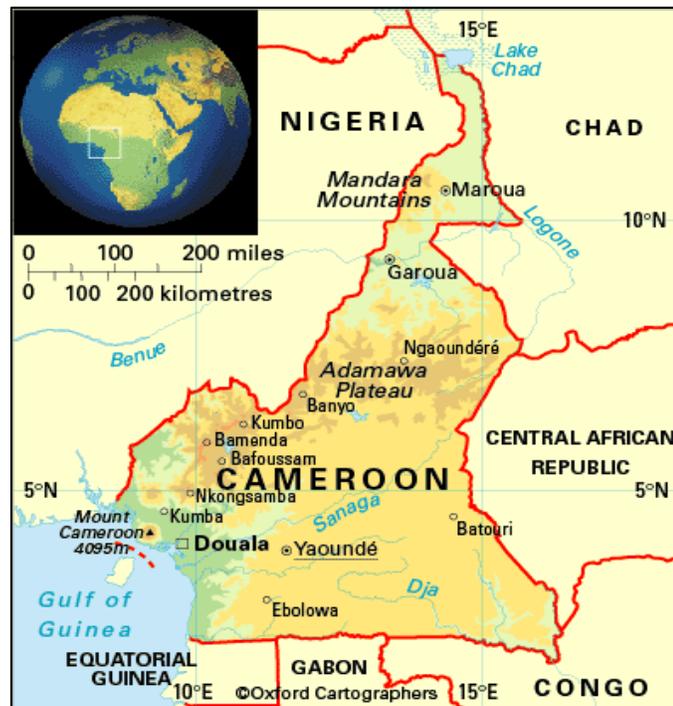


Figure 1. 1: Geographical location of Cameroon, country of the project. Source: Oxford Cartographers

in the world, almost half of the total worldwide and increasing due to rapid economic development and population growth [8]. In addition, more than three quarters of the population rely on inefficient and dangerous forms of cooking based on use of solid biomass. [9]

Cameroon has a low Human Development Index (a composite indicator used to rank countries based on life expectancy, education and income per capita), equal to 0.512 in 2014, and an Energy Development Index (expressing the energy development of the country) low as well and equal to 0.14 in 2012.

The mix of sources for electricity generation in Cameroon for the year 2013 is shown in Chart 1.1.

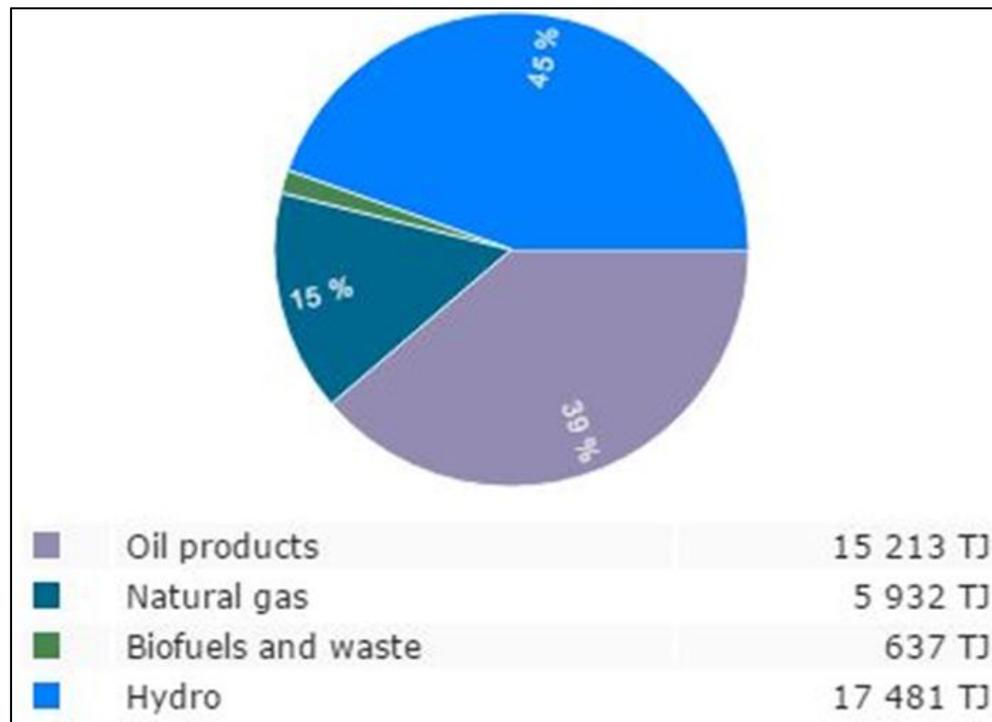


Chart 1. 1: Share of sources for electricity production in Cameroon. Source: IEA

The total energy used for electricity generation amounts to 39263 TJ; the largest share of source was from hydropower, followed by a large use of petroleum products.

The energy balance for the country for the same year is reported in Appendix A.1, where are shown the energy sources, the flows towards the different sectors and their share of energy consumption [10].

According to World Bank [11], 53.7% of the population had access to electricity in 2012. The grid electricity access was 15% in rural areas compared to 50% in urban [12]. For cooking, 70% of the population of Cameroon depend wholly on firewood [13].

According to IEA [9], the energy resources of sub-Saharan Africa are more than sufficient to meet the needs of its population, but they are largely underexploited.

The first page on the Cameroonian newspaper *L' Effort* of June 2015, presented in Appendix A.2, brings the attention to the energy issue of the country, consisting of the lack of both reliable electricity and a shift towards cleaner and alternative renewable energy sources.

The Cameroonian government's long term development policy aimed to get the country out of underdevelopment through the implementation of a long-term energy plan (PDSE 2030) by investing in the energy sector, which attracts investments especially because of Cameroon's hydroelectric potential in Central Africa [14].

The objective of the Rural Electrification Agency of Cameroon was to achieve rural electrification rate above 20% by 2020 [15] by electrifying 660 localities through grid extension but also isolated diesel and mini-hydro grids [16].

Affordable and reliable energy supply is crucial to provide adequate and modern services in developing countries. In Cameroon energy demand is rising, while energy supply is stagnant; moreover, the access to modern and reliable energy services in rural areas is limited.

The study area is represented by a small part of the village of Bafut, called Mambu, in the northwest region of Cameroon. It is located in a rural area at a distance of about 15 km from the city of Bamenda, the capital of the region. The control volume includes a group of non-profit institutions run by the Tertiary Sisters of St Francis providing public services in the healthcare and educational sector serving the rural population of Bafut of about 50,000 inhabitants.

In the study area were present the following Institutions:

- *St Theresa's Catholic Medical Center (STCMC)*, a hospital specialized in orthopedic treatments. In the hospital were present an out-patient department, including an antenatal clinic and a laboratory as well as an in-patient department, including maternity care, radiology and a theatre, where surgical operations are performed. Moreover, inside the medical center was present a canteen serving meals to patients and staff, a household and two guest houses.
- *St Joseph's Children and Adult Home (SAJOCAH)*, a physiotherapy center where patients, especially children, suffering from orthopedic malformations were treated. This institution includes a physiotherapy treatment area, a dormitory, a dedicated kitchen and an administration office. Educational services were provided as well to visually impaired students in a school that was open from September until the end of May. In SAJOCAH artisanal activities were carried out in the orthopedic, metal, cane and shoe workshops, the bakery and the canteen. Few households and a guest house were also present.
- *St Joseph's Comprehensive High School (SJCHS)*, in session from September to June, where educational services were provided to around 300 students with an expected increase up to 500 students. Households were available in the school for the teachers.
- Convent, where the Sisters, administrating and working in the study area, were living.
- Postulancy, where young girls, trained to become Sisters stayed for a period of two years.

The energy situation of the study area of this thesis work makes the delivery of healthcare and educational services challenging and costly. The study area was expanding in size and range of services offered. This leads to an increase of the energy demand to provide these services at an affordable cost. All the study area was connected to the national grid for the supply of electricity; however, the grid suffers from frequent blackouts and voltage fluctuations. In case of power shortages the study area suffers also from the lack of drinkable water since the water was supplied by electrical water pumps. In the study area were present diesel backup generators, but running the diesel gensets was costly, and

the supply of fuel was difficult in a rural area. The access to modern fuels to satisfy the thermal demand in the study area was limited, and the main primary source used for cooking was firewood, burnt in poor efficiency cooking facilities.

1.3 Rationale

Affordable and reliable energy supply was crucial for the study area to continue to provide healthcare and educational public services. The frequent and long power shortages from the grid affected the provision of healthcare services: clinical test cannot be executed in the laboratory; X-ray scans cannot be carried out, deliveries in the maternity department are performed without the proper equipment and the surgical operations need to be rescheduled, if not urgent or performed without the proper equipment.

In the school the students need to study and prepare their exams using candlelight. Besides, no clean water was available in case of long power shortages.

The level of smoke induced in the kitchens by the currently used stoves will remain high if no action was taken and it will continue to cause respiratory and eye problems to the women that were working every day in this unhealthy environment.

Implementation of the results of this thesis work could lead to an increase in the quality of the services provided to the community which would otherwise continue to suffer from the current problematic energy situation.

The results of this thesis work, if implemented, will affect an immediate population of about 600 people that live, work or study in the control volume. Furthermore, it will improve the quality of services provided to the rural population of Bafut, about 50,000 inhabitants, with a positive impact on the whole community.

1.4 Objective

The work presented in this thesis was developed and organized following the guidelines of Project Cycle Management (PCM). According to [17], PCM includes a sequence of steps to implement a project, from the conception of the idea until its completion; the present work includes the Identification step of the PCM. The general objective of this

study was to improve the energy supply of the study area based on the use of indigenous energy resources.

In order to achieve the general objective, four specific objectives were formulated, namely:

- I. To assess the current energy situation of the study area.
- II. To assess the energy resources locally available with focus on hydro, wind, solar and biogas.
- III. To identify the strategies to improve the energy efficiency and the energy supply of the study area.
- IV. To propose a more sustainable energy system for the area.

The general methodology adopted was field study with the application of several methods and tools as appropriate. The detailed methodology, methods and tools are described in Chapter 3.

1.5 Thesis structure

The thesis is divided into six chapters. The first chapter, the present one, contains background information, the problem statement and its importance in the rationale, moreover the general and specific objectives of the thesis are presented. Chapter 2 includes a review of literature which has been used as guideline and basis for developing the thesis work. The general methodology and the specific methods and tools adopted to meet the thesis' specific objectives are explained in detail in Chapter 3. In Chapter 4 are reported the results of the assessment of energy consumption, the potential of local energy sources with focus on RES as well as the areas for possible energy efficiency improvements. In Chapter 5 are presented the strategies and the future scenarios to improve the energy efficiency and energy supply to the study area through energy solution planning. In the last chapter, discussion, final remarks and suggestions for future research and development are presented.

2. LITERATURE REVIEW

A review of the literature that has been used as framework for the development of this thesis is proposed in this chapter. The thesis was based on the concept of *sustainable energization* required on the field of local energy planning. A definition of this concept has been developed by Nissing et al. [18]. The Energy Access group of the UNESCO Chair in Energy for Sustainable Development, Department of Energy, Politecnico di Milano, have analyzed the concept of *sustainable energization* and developed a new rural energy planning procedure within the Advanced Local Energy Planning (ALEP) methodology called “a comprehensive rural energy planning consisting of seven steps planning procedure”, which has been used as framework for the development of this thesis.

The current energy balance and needs of the study area was developed in accordance to the approach presented by Johnson et al [19]. Energy supply and consumption assessment was conducted by Johnson et al [19] in a remote village in Mali by identifying all the energy consuming activities in the area and organizing them into the following categories: domestic, artisan, public service and transport. Each use category constitutes an energy driver typical of a rural area of a sub-Saharan African country. Energy consumption attributed to each energy driver was assessed for all the energy services demanded that were identified in the study area of this thesis following the approaches of both Johnson and Bekele [20]. Within their feasibility study on electrical solution planning in a district of Ethiopia, Bekele et al developed an analysis of the locally available renewable energy sources, (RES), in order to estimate their potential, by applying proper methods and tools. In order to design a sustainable energy system based on RES a number of papers were used as guidelines. A comprehensive study on rural energy planning developed by Bandiera and Accarona [21] in the Cameroon Protestant College in Bali, Cameroon, was adopted as reference structure for the development of this step since both thermal and electrical planning were addressed. In Bekele et al an evaluation of the most suitable solution to supply electricity for the community of the district was investigated by using the software HOMER®, appropriate for the simulation

and comparison of hybrid solutions with high RES penetration. The study analyzes the feasibility of applying hybrid RES-based systems as suitable alternatives for rural electrification. A feasibility study of hybrid systems for remote villages in Cameroon developed by Nfah [22] confirms the suitability of applying this software for providing energy solutions with RES based power generation. In this thesis HOMER® was used in order to investigate the appropriateness and profitability of the suggested electricity solutions.

Regarding the thermal solution planning, ad-hoc solutions were adopted in order to reduce the firewood consumption and shift towards modern fuels as suggested by Accarona and Bandiera in their Master thesis [21]. Appropriate technological alternatives, based on solar thermal collectors, boilers and improved cook-stoves are suggested in the Master thesis of Riva [23]. In order to evaluate the feasibility of ad-hoc thermal solutions the Master thesis of Ndam Mungwe [24], regarding the improvement of the energy supply in rural households taking as case study the Efah village in Cameroon, was used as guideline. In this work renewable energy technologies (RET), including biogas digesters, solar cookers and improved cook-stoves are analyzed.

References to scientific papers and other specific publications can be found throughout the whole thesis' body to support the adoption of methods and tools, the design choices and to define the country framework in order to achieve the specific objectives of this thesis.

3. METHODOLOGY

The research was conducted through desk and field work. Preparatory desk work included preliminary literature review, collection of information about the study area, drafting of the reference energy system, preparation of a presentation for the local partner Catholic University of Cameroon (CATUC) in Bamenda, drafting of questionnaires and checklists, identification of possible energy drivers, and selection and testing of needed instruments.

The preparatory work started approximately two months before the on-field work in Cameroon.

The field work included tests, direct observations, direct measurements, surveys and interviews based on questionnaires to obtain primary data. The field work lasted for two and a half months in cooperation with students from CATUC.

In a subsequent phase of desk work, primary data were elaborated. The on-field study and the data elaboration methods and tools are presented in detail in the next paragraphs.

The field study and consequent desk work was based on “a comprehensive rural energy planning consisting of seven steps planning procedure” and its steps are presented below:

- Integration of goals of sustainable energization into decision making process
- Current energy balance assessment
- Identification and prioritization of energy service demand according to energy drivers
- Local energy resource assessment
- Design of integrated renewable energy system
- Setup of energy service supply network structure including the required level of depth regarding energy service demand
- Control and adaptation of energy supply network

The first step is assumed to be already achieved taking into consideration the alignment with the Sustainable Development Goal 7 of the 2030 Agenda introduced in Chapter 1. The focus of this thesis work was set on the steps from 2 to 5 of the proposed methodology.

3.1 Assessment of current energy situation

Educational and healthcare services are provided in the study area while a few productive activities and a limited number of households were present as well. The same administration manages all the units of the complex which can, therefore, be considered as an entity independent at a socio-economic level. Consequently, due to these characteristics the whole study area is regarded within the frame of this research as a micro-village [21].

Within each unit of the micro-village, namely STCMC, SAJOCAH, SJCHS, Convent and Postulancy, the energy consuming activities being conducted were, at first, identified. Then, in order to proceed with the energy accounting of the study area, the activities were categorized into rural energy drivers according to the approach suggested by Johnson et al [19]. Thus a reference energy system was established as shown in Figure 3.1.

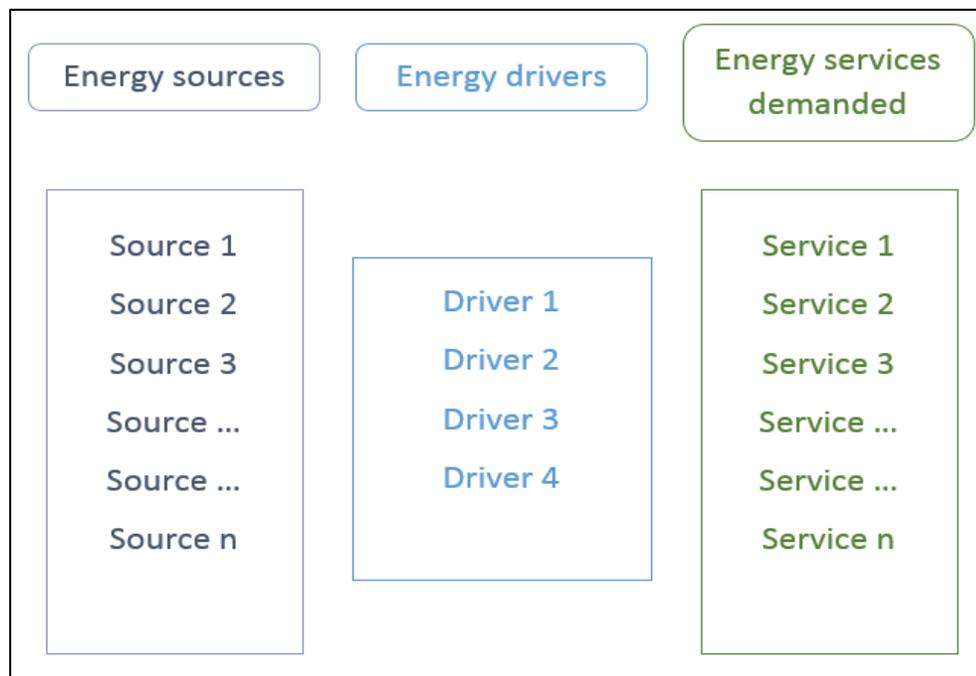


Figure 3. 1: General scheme of an energy system. Source: Authors

For each energy driver the primary sources of energy were identified and the total primary energy supplied was estimated. Energy services demanded at each energy driver were then identified and for each of them were analyzed the census data on the

conversion technologies adopted to transform the total primary energy supplied into the total final energy consumed.

3.1.1 Identification of relevant energy drivers

According to Johnson et al [19] the energy consumption of a rural community can be organized in the following energy drivers: *artisan* or *productive activities*, *domestic*, *public services* and *transport*.

Three categories were recognized on the field by direct observation:

- Domestic, including households and guest houses.
- Public services, divided in: health care, education and religious institutions.
- Artisan, including all the income generating activities, like canteens and workshops.

Transport flows towards and from the study were not taken into account and no energy was consumed for transportation.

3.1.2 Assessment of current energy consumption

Direct measurements regarding energy supply were performed to assess the current energy consumption for each energy driver.

Data collection on-field

Domestic

For the Domestic energy driver, ten households inhabited by workers of the study area, most of them without family, were identified through direct observation.

The data regarding energy consumption for this energy driver were collected by means of a questionnaire..

The questionnaire was administered in the form of peer-to-peer interviews during the field period: this strategy allowed mutual understanding and gave the possibility to clarify the questions and ensure cooperation of the interviewee.

The questionnaire, fully reported in Appendix B, consisted of six parts meant to assess energy sources, uses and supply.

The first part, *Interviewee and family description*, aimed to gather few personal information regarding profession and family status of the interviewee.

The second part, *Electricity supply*, was intended to investigate the means and security of electricity supply.

In the third one, *Electricity consumption*, questions related to the single electric devices (type, peak power, and hours of use) were asked to collect data such as equipment characteristics, operation and usage patterns, as suggested by A.C. Menezes et al. [25].

The fourth section, *Firewood consumption*, was dedicated to the supply, consumption, energy services and conversion technologies regarding firewood.

The fifth part, *Other primary fuels*, was addressing supply, consumption and uses of LPG, kerosene and charcoal.

The sixth part, *Biogas potential*, was meant to assess the amount of biogas that can be potentially produced by animal dung and agricultural waste.

The model was based on other sample questionnaires used for energy assessment in rural areas [22].

Public and artisan

For Public and Artisan energy drivers, energy consumption was preliminary estimated by gathering data through a survey questionnaire. This questionnaire was administered to the responsible of each department or workshop through a peer-to-peer interview.

Regarding the use of electricity, some appliances with a not well defined pattern of use, as emerging from the surveys, were selected to proceed to a more detailed analysis of their electrical consumption: a weekly checklist in table form was developed (See Appendix C.1) where the effective hours of use of the single device was marked. Every day for a period of four weeks the responsible for each department was asked to complete the checklist with the actual intervals of use of each selected device.

Preliminary data on consumption of firewood and other primary fuels (LPG, kerosene, diesel) in public and artisan energy drivers were gathered through the questionnaire.

Since firewood appeared already in the early stages of the investigation to have a high impact on the study area, a consumption assessment with a detailed measurement campaign and analysis of the collected data was performed.

In the kitchens of the public energy driver and in the canteens and the bakery belonging to the artisan driver the energy consumption related to firewood was assessed directly. For each subunit the daily consumption of firewood was registered every day for a period of two weeks in terms of type and mass of firewood.

Elaboration of the data

For all the relevant energy drivers - domestic, public and artisan - the data from the questionnaires were gathered and transferred to Excel spreadsheets to proceed with elaboration.

The main approach to address the characterization of electrical demand was bottom-up: The approach focuses on the single electric appliance for which information about device type, peak power, usage diversity and typical hours of operation were collected as explained in the previous section. The total primary energy consumption of electricity was obtained by data aggregation: the daily consumption of every single appliance was estimated and by summing up the consumption of all appliances used in one energy driver, the consumption of the relevant energy driver was estimated. In order to simplify the elaboration of a large amount of data, single electric appliances were categorized in usage classes based on the intensity and regularity of use. This approach was meant to determine load curves and total energy consumption for a given period of time.

Once collected, the data were elaborated using the software Excel in order to build the desired load curves.

Some assumptions have been made in the curves' characterization:

- For the electric appliances where the peak power was not directly available, nor obtainable from the specification's plate, some typical values found in literature were used. (Appendix C.2)

- For the power ratings expressed in form of apparent power, where no power factor was specified, it has been assumed a factor $\cos\phi$ equal to 0.9 in order to compute the real power.

For each appliance in the energy drivers the main method to assess the consumption was based on load factors (LF) found in literature (Appendix C.2). The LF were used to estimate the absorbed power according to Equation 3.1 and Equation 3.2 [26] since electric appliances do not absorb the rated peak power but a fraction of it.

$$LF = \frac{P_{absorbed}}{P_{peak}} \quad (\text{Eq. 3.1})$$

$$P_{i \rightarrow i+1} [kW] = \frac{1}{n_{hour}} \sum_{m=1}^{number\ of\ appliances} LF_m * P_{peak,m} * fw_m \quad (\text{Eq. 3.2})$$

Where the index i represents the hour of the day, the index m represents the appliance, n_{hour} is always equal to 1 and fw stands for functioning window, i.e. the amount of time the appliance is ON, therefore consuming energy.

A preliminary step to obtain the sample daily profile consisted in estimating the average functioning window of each appliance present in the study area according to their pattern of use.

The load curves were obtained for each energy driver distinguishing between distinctive days of the week. By this detailed approach to computation, it became then easy to build aggregated load curves for each energy driver, for each unit and for the whole study area. In order to verify the estimation of the daily electrical consumption two real-time energy consumption assessments were completed for the two major units: SAJOCAH and STCMC. Even though the units account for more than one energy driver this data was used just as a means of verification. A smartphone was placed (as shown in Figure 3.2) to take snap pictures of the electricity counter at a defined interval of time (10 minutes) using a time-lapse application, as suggested in [21].



Figure 3. 2: Load profile estimation using a smartphone. Source: Authors

Through the recorded pictures it was possible to obtain, as differential, the consumption of energy (E) of the whole unit for every hour (i) of the day as:

$$E_{i \rightarrow i+1} [kWh] = E_{i+1} - E_i \quad (\text{Eq. 3.3})$$

The data regarding the mass of firewood consumed in a day were gathered through questionnaires and direct measurements and elaborated to obtain the monthly consumption. By applying Equation 3.4 the total primary energy supplied by firewood in a month was estimated.

$$PE [MJ] = m_{firewood} * EHV \quad (\text{Eq. 3.4})$$

where EHV represents the effective calorific value accounting for the moisture content of the wood and was obtained by Equation 3.5:

$$EHV \left[\frac{MJ}{kg} \right] = LHV * (1 - MC) - MC * \Delta h_{H_2O} \quad (\text{Eq. 3.5})$$

in which LHV represents the lower calorific value of firewood on dry basis. The LHV of firewood was found in literature according to the specific type of wood [27]. MC , representing the firewood moisture content in wet basis. The MC was estimated directly on field through a dedicated test explained in detail in paragraph 3.2.2. Δh_{H_2O} represents the change in enthalpy of the water between evaporation state at boiling temperature (T_b) and initial state within the wood at ambient temperature (T_{amb}); it was calculated according to Equation 3.6:

$$\Delta h_{H_2O} = h_{H_2O,gas,T_b} - h_{H_2O,T_{wood}} \cong \Delta h_{H_2O,evap} + c_p(T_b - T_{amb}) \quad (\text{Eq. 3.6})$$

$\Delta h_{H_2O,evap}$ was assumed equal to 2260 kJ/kg and c_p was assumed constant and equal to 4.186 kJ/kg/K.

The energy consumption for all the other primary fuels has been calculated as:

$$E[MJ] = m_i * LHV_i \quad (\text{Eq. 3.7})$$

The values of LHV were adopted from literature equal to 43.1 MJ/kg for kerosene, 45.8 MJ/kg for LPG [28] and 42.78 MJ/kg for diesel.

Since the consumption of diesel and kerosene was expressed in units of volume, the values of the corresponding LHVs were converted using standard densities.

The energy flows within the study area were visualized using Sankey diagrams expressing for each energy driver the estimated energy supplied by the sources and the energy consumed in order to satisfy the energy services demanded.

3.2 Local energy resource assessment

Bafut is located in the geographic zone of highlands, typical of the northwest region of Cameroon where two seasons were present: the *wet*, lasting from March to October, and the *dry*, the rest of the year. Weather and season variability affects the availability of local RES.

The assessment of the energy resources locally available was divided by energy source starting and focusing on renewables: hydro, solar, wind energy and biomass.

An evaluation of the national centralized electrical grid in terms of power shortages' frequency and duration and voltage fluctuations was performed; moreover, the availability of kerosene, diesel and LPG was assessed.

3.2.1 Hydropower potential

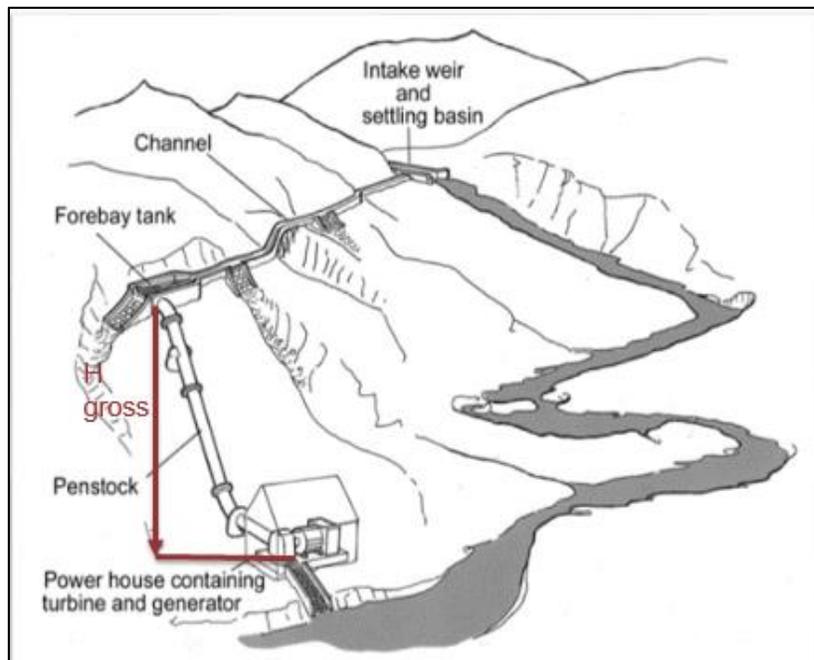


Figure 3. 3: Scheme of a run-of-the-river micro-hydro system. Source: Practical Action

The typical range of micro-hydro systems lies between 5 and 100 kW based on run-of-the-river schemes, [29].

In order to assess the power potentially available at a river site two parameters are required, the volumetric flow rate of water (Q) and the gross head (h_{gross}). The theoretical power was estimated using Equation 3.8:

$$P_{theoretical}[kW] = Q \cdot \gamma \cdot h_{gross} \quad (\text{Eq. 3.8})$$

where γ is the specific weight of water.

In every component of a micro-hydro system, where energy conversion takes place, occur losses, expressed as efficiency of the energy conversion process. Penstock, turbine, generator and transmission efficiencies introduce a factor reducing the theoretical power.

Regarding the hydropower potential assessment of this thesis, only one stream (*River A*) was initially planned to be taken into account based on the information available before departure from Italy. Once on field, through a survey, a second river (*River B*) was identified in the surroundings of the study area and was taken into consideration as well.

Direct measurements of flow rate and gross head were performed on both rivers as described in detail in the following paragraphs.

Flow rate

The average volumetric flow rate of the water is the quantity of water flowing past one point in a given time. Flow rate measurements were realized using the *floating object* test (or *float* method) as described in [30]. Five measurements of flow rate were performed from May to July at spacing of two weeks from each other in order to appreciate the increase of water level due to the ongoing rainy season.

The materials used for the *floating object* method were a measuring tape, a stopwatch, objects of small size that can float and if lost will not pollute the environment (tomatoes and passion fruits), a meter stick and two extra bamboo sticks. A suitable part of the river, as straight as possible for a specific length of approximately 6 meters and uniform in width and depth was selected. The site was delimited with the two bamboo sticks as

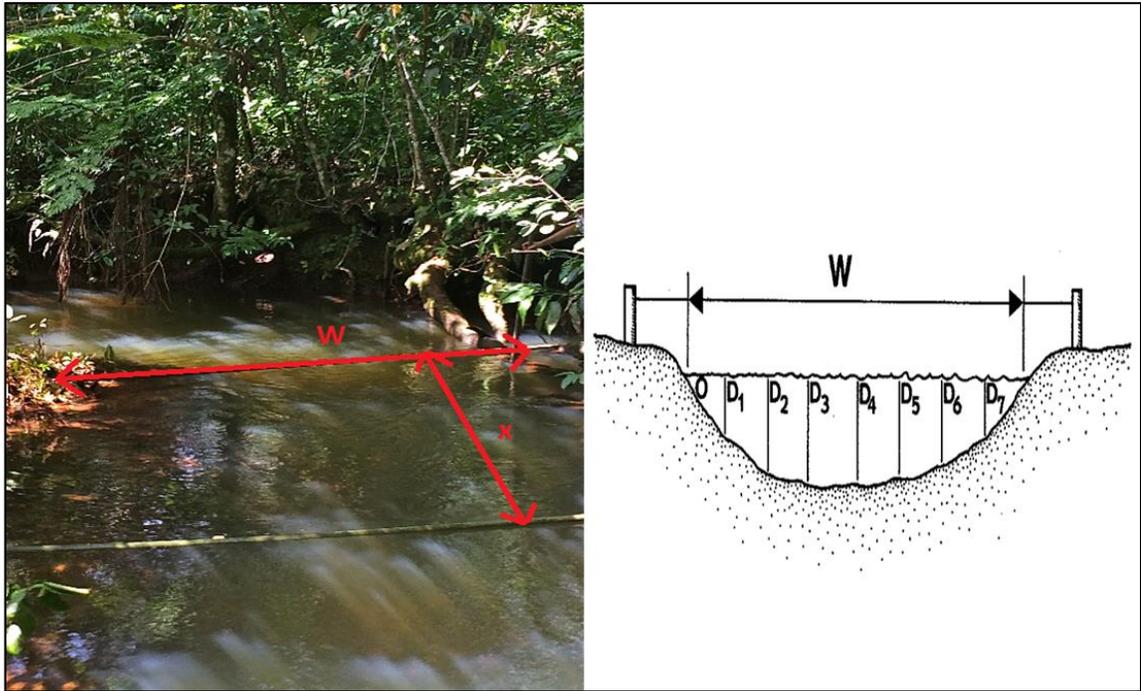


Figure 3. 4: Length (x), width (W) of the stream divided into intervals with depths (D_i). Source: [30] shown in Figure 3.4 and the length (x) was measured.

The floating object was thrown just before the upstream stick and the time needed to arrive from the "starting" (upstream) stick to the "ending" (downstream) stick was registered. This step was repeated ten times to estimate the average travel time (Δt) [30]. The average velocity was obtained as ratio between the constant length, x , and the average time, according to Equation 3.9:

$$v \left[\frac{m}{s} \right] = \frac{x}{\Delta t} \quad (\text{Eq. 3.9})$$

The river was then divided along the width (W) at specific intervals of around 40 cm and the depths (D_i) at each point (see Figure 3.4) were measured with the help of the meter stick.

The value of cross sectional area below the "starting" (upstream) and "ending" (downstream) stick was obtained applying the trapezoidal rule then, the mean cross sectional area A was approximated as the average of these two cross sectional areas.

The average volumetric flow rate Q , was the computed using Equation 3.10 [30]:

$$Q \left[\frac{l}{s} \right] = A \cdot v \cdot c \quad (\text{Eq. 3.10})$$

where A [m^2] is the mean cross sectional area of the stream, v [m/s] is the average stream velocity and c a correction factor, which accounts for the type of stream bed [31].

Due to the observed morphology the streambeds of both rivers were characterized as rocky, therefore a value equal to 0.6 was chosen for the correction factor in both cases.

In order to estimate the hydropower potential, daily measurements for at least one year are required. Since only five measurements in a period of ten weeks were carried out, a regression technique as describe in [34] was applied in order to estimate the annual flow pattern.

The reference river was River Mewou, flowing into the west region of Cameroon. The catchment of the reference river, River Mewou, is geographically close to the ungauged one, thus the climatic and hydrogeological conditions were assumed the same. Although the rivers were not similar in size, the introduced approximation was acceptable for the purpose of this research [34]. The values for the flow rate measured were considered as mean values for the months of May, June and July, while average monthly values available for River Mewou, from February 2012 till January 2013 were used [35]. Finally, based on the minimum levels of the residual flow, the design flow rate of the hydro turbine was selected [36].

Gross head

The total head available is the height difference between the water level at the intake and the possible powerhouse location [32].

A preliminary topology check was performed in both rivers by identifying the positions closest to the study area for the possible construction of the powerhouse and by registering the difference in elevation at possible positions for the intake and the

powerhouse. GPS was also used for determining the coordinates necessary for further elaboration on the map.

More accurate head measurements were carried out using a total station instrument which is made up of a combination of an electromagnetic distance measuring instrument (EDM) for measurements of slope distances and an electronic theodolite for measurements of horizontal and zenith angles [33].



Figure 3. 5: Mounting and targeting of the total station on site. Source: Authors

As soon as the station was mounted on a tripod, as shown in Figure 3.5, and levelled with the help of operating levelling screws, the target was sighted and the horizontal and zenith angles (ZA), between the possible positions for the powerhouse and the intake were measured. The vertical distance (VD), corresponding to h_{gross} , was calculated as follows:

$$VD[m] = SD \cdot \cos(ZA) \quad (\text{Eq. 3.11})$$

In order to obtain the theoretical potential Equation 3.8 was then applied. A capacity factor of 55% [87] the minimum annual energy was computed. The energy production increases with the adoption of cross-flow turbine able to follow the variable flow rate of the river.

3.2.2 Wind and solar potential

Data about the wind speed, wind direction and solar global radiation were collected using a wind and solar weather station. The weather station was installed during the first week of the field work and was left on field for further data acquisition.

Installation of the instruments and data collection

The collection of data of wind speed, wind direction and solar global radiation has been carried out directly on site with real-time measurements using a tailored weather station perfectly in agreements with the guidelines of the World Meteorological Organization [37],[38].

The weather station was carefully selected and tested in Italy before the departure.

It consists of:

- Pyranometer for measurement of global solar radiation over a horizontal surface based on silicon photodiode [W/m^2]
- Cup anemometer for measurement of wind speed
- Wind direction sensor for measurement of wind direction
- Data-logger with both analogic and digital input channels to store data on an built in SD card
- 2 L-shape arms of 1 m for correct positioning of the sensors on the pole
- 3 cables for the connection of the sensors to the data-logger of 12 m each
- Mast, 12.2 m long, acquired in Cameroon due to the impossibility of transportation from Italy

The most suitable site was chosen respecting the technical criteria for wind sensors [39] and pyranometers [40].



Figure 3. 6 Installation of the measuring instruments. Source: Authors

The first data acquisition was performed after two days as a test showing appropriate data collection, while subsequent data were collected once a month until the departure and then, further data were collected and sent to Italy by trained local staff.

Data elaboration

The data directly acquired on site included: Solar radiation (R [W/m^2]) with average, maximum and minimum values, Wind speed (S_w [m/s]) with average, minimum, maximum and standard deviation, and Wind Direction, all computed every 10 minutes.

The acquired values were transferred from the text files to an Excel spreadsheet and were aggregated per month.

Manual elaboration was performed on global radiation [W/m^2] and wind speed collected data to obtain a monthly average value for insolation [$\text{Wh}/\text{m}^2/\text{day}$] and wind speed. The values for solar insolation (Ir_d) and wind speed (S_{w_d}) were obtained using Equation 3.13 and Equation 3.14, respectively.

$$I_r_d \left[\frac{Wh}{m^2 day} \right] = \frac{1}{N_{S_{day}}} \sum_{k=1}^{N_{S_{day}}} (R_k * \frac{24h}{day}) \quad (\text{Eq. 3.13})$$

$$S_{W_d} \left[\frac{m}{s} \right] = \frac{1}{N_{S_{day}}} \sum_{k=1}^{N_{S_{day}}} S_{W_k} \quad (\text{Eq. 3.14})$$

where $N_{S_{day}}$ is the number of samples acquired in one day. These values were further elaborated by making an average of the daily values of each month.

Wind speed frequency for one year, i.e. the number of occurrences for each wind speed, was obtained by estimating its probability density function as Weibull distribution according to [41]. Knowing for the dataset average wind speed ($\overline{S_w}$) and standard deviation (σ), expressed by Equations 3.15 and 3.16, the scale and shape parameters for the Weibull distribution were estimated comparing *Weibull probability plotting*, as suggested by [42], *Justus method* and *Lysen method*, according to [43].

$$\overline{S_w} \left[\frac{m}{s} \right] = \frac{1}{N_{measurement}} \sum_{j=1}^{N_{measurement}} S_{W_j} \quad (\text{Eq. 3.15})$$

$$\sigma \left[\frac{m}{s} \right] = \sqrt{\sum_{j=1}^{N_{measurement}} (S_{W_j} - \overline{S_w})^2} \quad (\text{Eq. 3.16})$$

The characteristics of the wind speed in the study area were fully described by estimating also the autocorrelation factor, the hour of peak speed and the diurnal pattern of strength.

The autocorrelation factor (r_q), expressing how strongly the wind speed in one hour depends on the wind speeds in the previous hour, was obtained, under the assumption that the observation are equi-spaced in time, as:

$$r_q = \frac{\sum_{j=1}^{N_{hours}-q} (S_{W_j} - \overline{S_w}) * (S_{W_{j+q}} - \overline{S_w})}{\sum_{j=1}^{N_{hours}} (S_{W_j} - \overline{S_w})^2} \quad (\text{Eq. 3.17})$$

where S_{W_j} , with $j=1,2,3\dots N_{hours}$, is the wind speed and the coefficient q represents the lag of autocorrelation and equals to 1 [44].

The hour of peak speed for each day was determined graphically by plotting the wind speed at every hour and selecting the most recurrent value for the data set.

The diurnal pattern of strength (δ), that reflects how much the wind speed tends to be dependent on the time of day, was computed as:

$$\delta = \left(\frac{S_{w_j}}{S_w} - 1 \right) / \cos \left(\frac{\pi}{12} * (j - \varphi) \right) \quad (\text{Eq. 3.18})$$

where φ stands for the hour of peak speed computed in the previous step.

The measurements taken from the weather station started right after the installation on the 22nd of May 2015 allowing to collect data till October 2015 for a total of almost six months. However, this sample of data was not enough to determine the effective wind regime in the study area since data for one year are required to consider seasonal fluctuation.

In the case of this research a longer measurement period was not feasible, therefore a comparison with a reliable database, adopting scaling and regression techniques, was required both for solar and wind data. The reference dataset was chosen to be the one of NASA considered well-known, reliable and having data available for a long observation period for free [45]. (See Appendix C.3).

The reference dataset was taken for the city of Bamenda (5.9333° N, 10.1667° E), capital of the northwest region of Cameroon, at approximately 17 km away from the field of study, thus an acceptable distance, according to Manwell [43], to be taken as reference.

Wind data

In order to compare the field data with the ones of NASA, acquired at 50 meters from the ground, the values need to be scaled to the same height, and since wind speed presents a gradient, i.e. the magnitude of wind speed increases with height, depending on the distance from the ground and the ground conditions.

In wind energy studies, two mathematical laws have generally been used to model the vertical profile of wind speed over regions of homogenous and flat terrain, namely the *log* and the *power* laws. Both approaches are subject to uncertainty caused by the variable and complex nature of turbulent flows [43].

The first approach, the *log law*, has its origins in boundary layer flow in fluid mechanics and in atmospheric research. It is based on a combination of theoretical and empirical research and is expressed by Equation 3.19

$$v \left[\frac{m}{s} \right] = v_{ref} * \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \quad (\text{Eq. 3.19})$$

where v is the velocity to be calculated at height z , v_{ref} is the known velocity at height z_{ref} and z_0 is the roughness length whose values are reported in Appendix C.4. The second approach is the *power law*:

$$v \left[\frac{m}{s} \right] = v_{ref} * \left(\frac{z}{z_{ref}} \right)^\alpha \quad (\text{Eq. 3.20})$$

where α represents the shear exponent. Since α varies with parameters as elevation, time of day, season, temperature, terrain, and atmospheric stability it is important to perform shear calculations where valid upper and lower wind speed measurements are available for a given time interval. Although the power law is a useful engineering approximation of the average wind speed profile, actual profiles will deviate from this relationship. Therefore, in this research the log approach has been chosen with a roughness class equal to 2, also because it well adapts to actual variation in the first 100 meters from the ground. The wind speed data finally used were the measured ones for the months of the experimental period and the estimated values, obtained by regression with NASA data after scaling with log law, for the remaining months.

The annual average wind speed was used to determine the available power per unit of swept area according to Betz's law [42] (Equation 3.21), the energy production per unit area was estimated with a capacity factor equal to 7% [88].

$$P \left[\frac{W}{m^2} \right] = \frac{1}{2} c_{Betz} * \rho * v^3 \quad (\text{Eq. 3.21})$$

Solar data

In order to estimate the expected annual values for the solar insolation based on the comparison between the collected with the NASA data, three regression approaches were adopted, namely Rogers approach (linear correlation), Derrick's approach and the exponential correlation.

The daily solar insolation (Ir_d) in the following equations has the suffix "Bafut" in case it is directly measured on field and "NASA" in case of reference value.

The linear correlation of Rogers approach [46] is expressed in Equation 3.22.

$$Ir_{dBafut} = m * Ir_{dNASA} + q \quad (\text{Eq. 3.22})$$

Derrick's approach [47] can be expressed by the following correlation:

$$Ir_{dBafut} = a * Ir_{dNASA}^b \quad (\text{Eq. 3.23})$$

The coefficients m and q , a and b , s and r are computed from the months of the experimental period.

Adopting the regression techniques was possible to obtain the yearly sun radiation.

3.2.3 Biogas potential

Measurements and analysis were performed for the following identified biodegradable sources:

- Human waste
- Animal dung
- Kitchen waste
- Agricultural waste

For each of the former classes of feedstocks an ad-hoc strategy was applied in order to obtain the available daily quantities and, by using literature values for biogas yield, to obtain finally the potential for energy production from biodegradable materials.

The analysis of the available biodegradable material was performed based on the results of the questionnaires for the domestic energy driver and by applying direct measurements for the public energy driver.

Regarding the artisan energy driver, there were no sources for agricultural waste and animal dung; while for human and kitchen waste categories it was not possible to distinguish its waste production from the public one, since the facilities for the disposal were common.

Due to the units' geographical dispersion the data for each energy driver were also categorized by unit to facilitate the design of ad-hoc solutions.

Human waste

Human waste can be converted into energy in form of biogas by anaerobic conversion, meanwhile also the content of bacteria is substantially reduced facilitating the final waste disposal [48].

In the domestic energy driver the biogas potential by human waste was assessed based on the number of family members, while in the public energy driver the availability of human waste for biogas production was assessed by direct measurements:

In Postulancy, Convent, Theatre and Laboratory, where the number of users was quite constant and all of them speak and read English, some checklists were distributed to record the use of the toilets every day for a week and therefore estimate the human waste quantity. In the checklist proposed (Appendix C.5) also a brief explanation of the goal of the data collection was included to ensure the cooperation in filling in the checklists in this delicate topic.



Figure 3. 7: “Bucket method” to assess the available human waste for biogas potential. Source: Authors.

In SAJOCAH, IPD and OPD, in order to collect the same type of data from patients, outside of each toilet was placed a system including two buckets, a bag containing a large number of small gravels and a poster with instructions as shown in Figure 3.7. Every time that a person was using the restroom was asked to move a gravel from the bag to the correct bucket: blue one for faeces and transparent for urine. The number of gravels in each bucket was directly counted every night around 8 p.m. This simple method was explained to the patients and relatives during the morning meeting, both in English and French. After a test day, the data were collected for one week. This direct method of data collection allowed us to obtain an average value of human waste production based not only on the number of hospitalized patients but also taking into account the variable presence of the patients’ relatives and patients coming only for visits in the OPD.

In SJCHS a direct measurement was not applicable since the facility was not open to students for the period of the field work due to summer holidays, therefore the human waste production was estimated based on the average population.

The biogas potential from human waste was determine according to:

$$V_{biogas} \left[\frac{Nm^3}{month} \right] = m_{waste} * \%TS * \%VS * Y_{biogas} \quad (\text{Eq. 3.24})$$

Relying on literature for the total solid content, volatile solid content and expected biogas yield from faeces, equal to 0.45 Nm³/kg_{VS}, and from urine, equal to 0.34 Nm³/kg_{VS} [49].

Animal dung

The biogas potential of animal dung feedstock was assessed based on the average number of animals present in the study area, all belonging to the public energy driver.

Biogas potential yield was estimated using values from literature [50].

The resource potential was estimated using the following equation:

$$V_{biogas} \left[\frac{Nm^3}{month} \right] = \sum_{k=1}^{N_{animal\ species}} N_k * m_{dung,k} * Y_{biogas_k} \quad (\text{Eq. 3.25})$$

where $m_{dung,k}$ represents the mass of dry dung produced per head, Y_{biogas_k} the biogas yield related to the single species and N_k the number of heads of each species.

Kitchen waste

Kitchen waste assessment was conducted in public and artisan energy drivers as a whole, since the waste were collected all together by the local personnel so it was not possible to make a separation by energy driver.

Only in some constituent units (Convent, Postulancy and SAJOCAH) organic waste was already separated from residual waste since it was recycled as feed for the animals.

In the other units, as preliminary action, a simple separation of the waste in two categories was put in place and demonstrated to the users.

Kitchen waste data was collected every day for a period of two weeks in each unit through refined separation, weighing and categorization of the different waste masses into animal feed, manure and combustion, based on their final disposal.

The biogas production was estimated according to Equation 3.25

$$V_{biogas} \left[\frac{Nm^3}{month} \right] = m_{waste} * \%TS * \%VS * Y_{biogas} \quad (\text{Eq. 3.24})$$

where m_{waste} represents the mass of organic waste in a month, $\%TS$, the total solid content of the waste, $\%VS$ the volatile solid content and Y_{biogas} the biogas yield.

The total solid content, volatile solid content and biogas yield are common for all the organic wastes coming from kitchen and assumed equal to 20%, 60% and 0.35 m³/kg_VS, respectively, according to [51].

Agricultural waste

Local farms within the study area include: bananas, plantains, tubers, corn, nuts and green vegetables. Only the biogas production potential of corn was taken into account and analyzed in this study as the more relevant for energy purposes because of the larger area dedicated to corn plantation and since most of the residues produced by the other cultivation were ending to be part of the kitchen waste.

The biogas potentially coming from corn was assessed considering as proxy data the plantation area obtained from direct measurements on site as expressed by the following equation:

$$V_{biogas} \left[\frac{Nm^3}{y} \right] = A_{corn} * Y_{corn,dry} * Y_{biogas} \quad (\text{Eq. 3.26})$$

The average quantity of harvest product per unit of square meter was estimated considering annual maize stalks yield $Y_{corn,dry}$ in 2013 for Cameroon [52].

The biogas potential production Y_{biogas} average value equal to 530 m³ /tonne was adopted in this study. [53]

3.2.4 Conventional, non-RES

Since the study area was connected to the national electricity grid while at the same time conventional primary fuels were used, an evaluation of both the grid and these fuels was performed.

Based on the definition of access to modern energy services [55] a qualitative evaluation of the electricity supply was performed in terms of affordability and reliability.

The part *Electricity supply* of the questionnaire, present in Appendix B, was meant to assess the reliability of the national grid. From the answers it was possible to evaluate the frequency and duration of power shortages and the presence of voltage fluctuations, detected on the field by observing the behavior of some electrical and electronic

equipment, like flickering of CFL lamps, malfunctioning of TV sets and burnt out of equipment. In order to obtain a deeper understanding of these outages, “blackout registration”-checklists were distributed in each energy driver of the study area (See Appendix C.5). The time of the beginning and the end of each blackout were registered for seven weeks. This allowed to create a graph in order to get a clear idea about the time of the day when blackouts usually occur as well as to obtain an average duration within one week.

In order to assess the affordability of the electricity supply from the grid, data from the electricity bills of the last five years were collected and analyzed, and electricity tariffs (Appendix C.6) were compared with tariffs of other countries.

Within the part “*Other primary fuel*” of the questionnaire in Appendix B the cost and the supply of diesel, LPG and kerosene were assessed to determine the fuels’ affordability.

3.3 Identification of energy losses

3.3.1 Electrical

In order to identify electrical losses in the current energy system an evaluation of the internal electrical grid was performed by direct qualitative observations. The focus was on:

- 1) *Improvement of the efficiency of the internal electricity grid.* The inefficiencies were evaluated from a qualitative standpoint. The following aspects were taken into account: aging and state of maintenance of the wiring system, level of automation, counter-measurements adopted in case of power shortages from the main grid, safety and existence of non-authorized connections from outside the control volume, introducing non-technical losses.

Since the current connections were not reported on a proper wiring setup scheme, this was drawn with the help of technicians in the study area.

These activities were performed in cooperation with students from CATUC.

- 2) *Identify demand side management strategy.* Detailed analysis of the obtained electrical load curves was performed in order to assess the possibility of load shifting. The availability of users to apply some demand side management strategies was informally investigated by focus group discussions.

3.3.2 Thermal

In the following paragraphs the strategy adopted during the field work to assess the conversion efficiency of stoves and oven is presented.

The energy losses (EL) are computed accordingly to Eq. 3.27

$$EL[MJ] = PE * (1 - \eta_{conversion}) \quad (\text{Eq. 3.27})$$

In case of LPG and kerosene stoves the thermal conversion efficiencies were taken from literature. An average equal to 63% was assumed for LPG and 51% for kerosene stoves [57].

In the study area a wide range of cooking facilities based on firewood were used:

In domestic energy driver three-stone fire stoves (3SF) were used.

In the public energy driver both 3SF and improved firewood stoves (ICS) were present, in particular 3SF were identified in the kitchens in STCMC and SAJOCAH, while in the kitchens of Convent, Postulancy, SAJOCAH and SJCHS the stoves present included a separate combustion chamber and a chimney, characteristics of ICS.

Regarding the artisan energy driver, in both the canteens (SAJOCAH, STCMC) and in the bakery 3SF were used.

Improved cook stoves (ICS) were defined, according to [7], as closed stoves with chimney or open stoves with hood based on traditional biomass or RES, while according to [58] ICS should meet some minimum standards: energy source sufficient to cook enough meals per day, 40% fuel reduction compared to 3SF, and guarantee a clean environment for cooking and living.



Figure 3. 9: 3SF present in the study area while performing efficiency test. Source: Authors



Figure 3. 8: Baking oven while functioning. Source: Authors

The stoves with separate combustion chamber and chimney present in the study areas could not be clearly identified as ICS because of their local design and poor maintenance. For each type of firewood stove, including 3SF, a specific WBT test to evaluate their efficiency was performed on field. The firewood moisture content was estimated adopting a dedicated experimental test.

Moisture content evaluation test: oven drying

An estimation of the firewood moisture was necessary in order to perform WBT

Moisture content evaluation test was repeated three times on samples coming from the same piece of wood, once in a conventional oven and twice in a microwave.

Samples preparation: The sections of wood used as samples during the test were cut from the wood piece in full cross sections of 20 mm thickness and at a distance of 0.5 m from the ends of the wood sticks, since the moisture content at the extremes of the wood stick is influenced by the external conditions and therefore it does not represent the average MC of the wood piece. A hand saw was used for this operation, instead of an electric one, in order to limit as much as possible the moisture content decrease due to overheating of the piece, caused by friction. Samples with a mass of minimum 50 g were considered, so that, by using a scale with resolution of 0.01g, the maximum error induced in the weighing by the scale was less than 0.2%. Pieces were then wrapped in aluminum foils to reserve the humidity content as much constant as possible. [59]



Figure 3. 10: Preparation of firewood samples for the moisture content evaluation test. Source: Authors

Conventional oven-drying: test pieces were weighed on a laboratory scale with a resolution of 0.01g. The samples were then placed in an electric oven with forced

ventilation at a constant temperature of 100 °C, well separated on the tray to ensure good air circulation around them. After 8 hours the samples were removed, weighed and put back in the oven; this step was then repeated every two hours until the samples reached constant mass, i.e. the change in mass was lower than 0.1g, after about 20 hours [59].

Microwave oven-drying: The following procedure was followed during the test:

- the sample was weighed on the laboratory scale to determine its initial mass
- the test piece was subjected to an initial period of heating in the microwave on defrost setting of 5 minutes
- the piece was removed, weighed again and cooled down unwrapped in air for 3 minutes.

The heating, weighing and cooling steps were repeated until a constant mass of the sample was reached.

Although the test with a traditional electric oven was the more accurate respect to using a microwave it is also very time consuming; therefore, the microwave oven-drying test was performed as well giving results in about 30 minutes.

From both drying techniques and for each test piece the mass of moisture and the moisture content in wet and dry basis were obtained according to the following equations [59]:

$$m_{H_2O} = m_{in,wood} - m_{fin,wood} \quad (\text{Eq. 3.31})$$

$$MC_{wet} = \frac{m_{H_2O}}{m_{in,wood}} \quad (\text{Eq. 3.32})$$

Finally, an average value of the MC_{wet} obtained by the two methods was adopted for the WBT.

Water boiling test

Water Boiling Tests were conducted according to the protocol [27] and following as much as possible the procedure. Since some measuring instruments required were not available on site, few modifications were applied to the standards. Instead of a digital thermometer, accurate to 0.5 °C, with thermocouple probe suitable for immersion in

liquids, a chemical thermometer, able to reach temperature above 100 °C was used during the test to measure the water temperature.

Considering low accuracy in case of very wet wood and unavailability of moisture meter, a series of tests was performed on site for each type of wood and storage condition to estimate the moisture content. (See following paragraph).

The WBT was conducted for a 3SF and for all the other types of wood stoves present in the study area. For stoves including a door, to close the combustion chamber, the test was repeated twice simulating the real cooking conditions: door open and door closed.

The WBT test was conducted including all three consecutive phases shown in the figure below:

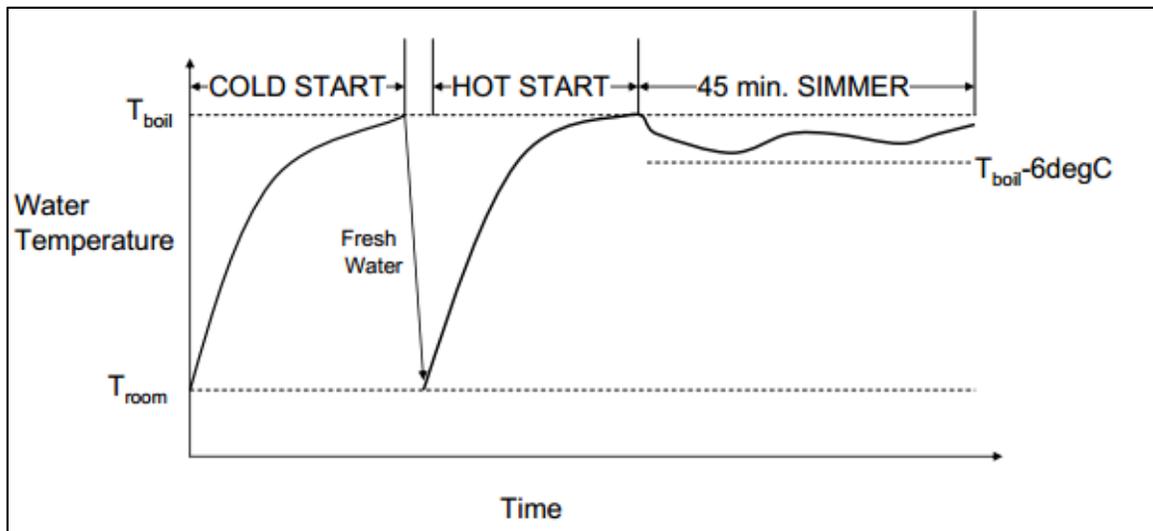


Figure 3. 11: Phases of water boiling test on a *water temperature VS time* plot. Source [27]

- 1) *Cold-start high-power phase*, starting with stove at room temperature firewood was used to boil a known quantity (10 liters) of water in a standard pot.
- 2) *Hot-start high-power phase*, the water was replaced with water in ambient - temperature on the still hot stove and it was brought to local boiling temperature, equal to 94 °C, adding fuel to the fire.
- 3) *Simmer phase*, without changing the water, a temperature between 3 and 6 °C below the boiling one was kept for 45 minutes.

The primary energy consumption and thermal losses of energy conversion were obtained by applying respectively Equation 3.4 and Equation 3.27, while the effective calorific value by applying Equation 3.5 as presented in paragraph 3.1.2

The thermal conversion efficiency was obtained as:

$$\eta_{conversion} = \frac{m_{H_2O} \cdot c_p \cdot \Delta T_{H_2O} + \Delta E_{evap}}{m_{f,c,dry} \cdot LHV} \quad (\text{Eq. 3.28})$$

where m_{H_2O} is the actual mass of water that has reached the boiling point, obtained as the difference between the final mass of the pot full of water and the empty pot;

$m_{f,c,dry}$ is the mass of dry firewood that was calculated according to:

$$m_{f,c,dry} [kg] = m_{firewood} * (1 - MC_{wet}) \quad (\text{Eq. 3.29})$$

and ΔE_{evap} corresponding to the energy used to evaporate water was computed as:

$$\Delta E_{evap} [kJ] = m_{H_2O, evap} * \Delta h_{H_2O, evap} \quad (\text{Eq. 3.30})$$

where $m_{H_2O, evap}$ represents the water evaporated in the process, i.e. the difference between initial and final mass of the pot with water.

Bakery ovens

Regarding the bakery ovens their description and information on their use were obtained by direct observation and through an interview with the baker. The average amount of flour used to produce bread in the oven and the firewood consumption of the oven in a week were used to estimate the efficiency of the oven (η_{oven}) according to the following equation [60]:

$$\eta_{oven} = \frac{E_{output}}{E_{input}} = \frac{m_{bread} \cdot E_{baking}}{m_{wood} \cdot EHV} \quad (\text{Eq. 3.33})$$

where m_{bread} represents the mass of bread produced in one week; m_{wood} is the firewood mass consumed in one week; EHV, the effective heating value of firewood, computed according to Equation 3.5; the energy needed for baking one kilogram of bread (E_{baking}) with a conventional baking processes in a traditional firewood oven was estimated as 2 MJ, according to [60].

3.4 Energy solution planning

Energy solution planning was focused on matching needs and local energy resources. Energy needs were approximated as current consumption plus marginal increase taking into account future development and unmet needs. Specifically, some electric appliances already present in the study area that were not currently used were considered as unmet needs. Two new workshops were planned therefore, their electric appliances were considered in estimating the required electric energy demand. The approach was to examine the electrical and the thermal solutions separately.

3.4.1 Electric solution planning

Two major options were investigated: Off grid and Grid-RES option. In the Off-grid option the study area is isolated from the national grid and depends entirely on its local resources for electricity generation. In the Grid-RES option the system makes use of its local resources for electricity generation as well as connected to the national grid to buy and sell electricity as appropriate. Different combinations of technologies were investigated for the most economically feasible in terms of life-cycle cost. In the Off-grid option several combinations of hydro, wind solar, diesel generators and storage through batteries were investigated. In the Grid-RES option were analyzed combinations of RES technologies and national grid replaced the batteries.

The different combinations were evaluated using the software HOMER[®] and the discrimination of the options was based on net present cost (NPC). The software HOMER[®] requires as inputs description of technology options for generation and storage, component costs, and resource availability. The modeling process involves three consequent levels:

- I. simulation
- II. optimization
- III. sensitivity analysis

Simulation: HOMER[®] was used in order to simulate the operation of a system by solving energy balances for each hour in one year, comparing the electric demand with the

energy that the system can supply and calculating the flows of energy to and from each component of the system.

The simulation was adopted to determine whether a configuration was economically feasible and to estimate the cost of installing and operating the system over the life time of the project [61].

Optimization. The best possible system configuration, defined by the optimal value of each decision variable (size of the PV array, number of wind turbines, presence of a hydro system, size of each generator, number of batteries, size of the AC/DC converter), that minimize the net present cost (NPC) satisfying was determined in the optimization process.

An explanation of the technologies and resources inputs required for simulation and optimization is presented here below.

Hydropower turbine

Crossflow turbine was selected based on available head and flow rate with a wide range of operating flow rate without steep decreases in efficiency (about 82%) thanks to its design. Costs regarding turbine was determined based on local market research.

PV solar panel

Considering the load possible PV system sizes were preliminary selected in a range between 5 and 10 kW. Costs were estimated based on the average of European market in case on crystalline silicon PV cells [63]. A margin of increase was considered to include installation and local market supply chain expenses. A derating factor (a scaling factor accounting for power losses due to different reasons) was taken from a case study in Nigeria.[89]

Wind

From catalogue available of micro wind turbine, the turbine Honeywell 6500 [72], [73] suitable for low wind speed and with low cut-in velocity, was selected for simulations.

Diesel generators

Specifications of the six diesel generators were acquired by direct observation on the field. Since they were already present in the study area, the investment cost was considered null and only maintenance and replacement costs were estimated based on the

aging, obtained through interviews with the technicians. Fuel cost equal to 0,87 \$/l and maximum allowed consumption equal to 1000 litres/year were used based on surveys and invoices.

Converter and Batteries

The maximum size of the converter and the batteries was decided among the available types in the software catalogue. The Surrette 4KS25P was selected, adopting a study in Ethiopia as reference [20].

Sensitivity Analysis.

Sensitivity analysis was used to verify the robustness of the system to changes in selected input variables. For the diesel fuel price, capital costs of hydro and PV power systems and electricity tariffs of the national grid, ranges of values were set to reveal how sensitive the outputs were to changes in the inputs.

The diesel fuel price has been evaluated in the range between 0.73 \$/l and 1.05 \$/l with steps correspondent to about 20% according to the bills for the study area.

The electricity tariffs were selected between 0.149 \$/kWh and 0.176 \$/kWh according to increasing tariffs applied by ENEO.

For the capital cost of the hydro and PV system, an increase and decrease of the cost corresponding to 10% was analysed.

The sensitivity analysis was adopted in order to evaluate the consequences of uncertainties and to determine if combinations of technologies are optimal under different conditions [62].

3.4.2 Thermal solution planning

Thermal solution planning was applied with the goal of reducing the consumption of firewood for cooking, in the public energy driver, and for baking and cooking, in the artisan energy driver.

Besides, suitable energy solutions based on RES to provide energy for water heating were investigated in the public energy driver - where most of the demand occurred.

Based on the results of the energy consumption assessment, solutions for the domestic energy driver were not investigated in this study because of the low share in consumption.

Cooking: public and artisan energy driver

In order to satisfy the cooking demand in the public and artisan energy driver, the possibility of using biogas stoves was investigated. The availability of biogas was obtained from the assessment of the available feedstock developed in paragraph 3.2.3.

From the estimated production of energy from biogas and considering the possible design and location of the digesters, the share of energy demand that was possible to be covered using biogas stoves was calculated.

Regarding the improvement of wood burning cooking facilities, two main strategies were analyzed to enhance the stoves' quality, based on the actual conditions and efficiency parameters obtained in paragraph 3.3.2. These strategies were:

- Replacement of the present stoves with ICS.
- Modifications of the actual stoves to meet some ICS characteristics, like separate closed combustion chamber and chimney.

Baking: artisan energy driver

Based on the actual ovens' characteristics two options were proposed:

- An alternative firewood oven with separate combustion chamber between existing models that was able to reduce the fuel consumption and guarantee a more constant temperature in the baking chamber so as to reduce the observed bread waste that reaching up to 20% of the daily production. The choice of the design has been based on the current bread production and space available in the bakery referring to models present in literature.
- A suitable electric oven with size based on the desired bread production that ensures electronic control of the temperature; this option compatibility was considered based on the electrical system obtained with HOMER®.

Water heating: public energy driver

Need for water heating according to the WHO minimum standards was currently unfulfilled in the public energy driver.

Based on the number of students and patients in the public energy driver without access to hot water, the energy demand for water heating ($FE_{hot-water}$) was computed according to the following Equation [64]:

$$FE_{hot-water} [MJ/day] = N_{persons} * V_{hotWater} * \rho_{water} * c_p * \Delta T_{water} \quad (\text{Eq. 3.33})$$

where the volume of hot water ($V_{hotWater}$) required per person daily was assumed equal to 20 liters according to WHO [65] considering only the use for bathing. The water temperature difference (ΔT_{water}) was assumed equal to 20 °C from ambient temperature to approximately 45 °C.

The energy required to provide hot water, two options were considered: solar thermal collectors and biogas boilers.

The hot water daily demand was used to size the suitable collector considering the losses in distribution pipes.

The area required for the installation of a solar thermal collector, assuming rooftop installation with a flat plate collector was estimated by applying Equation 3.34.

$$SWH_{area} [m^2] = \frac{f_s}{\eta_{collector} * \eta_{system}} * \frac{FE_{hot-water}}{G} \quad (\text{Eq. 3.34})$$

Where f_s is the fraction of the water heating demand ($FE_{hot-water}$) satisfied by the solar collector, $\eta_{collector}$ is the efficiency of the flat plate collector and η_{system} the efficiency of the whole system, according to [66], and G is the minimum average sun irradiation along the year.

The second option, the installation of biogas boilers was evaluated based on biogas availability. Biogas boilers are adapted gas boilers with efficiency equal to 80%. [86]

4. RESULTS

In this chapter are presented the results of the energy consumption and local resource assessment. Firstly, the analysis were focused on aspects of current electricity and fuel consumption in domestic, public and artisan energy drivers to achieve the first specific objective of this research. The results are summarized in an energy flow diagram including all energy drivers. Secondly, results of the main characteristics of RES potential are reported to evaluate the sources available in the study area.

4.1 Current energy balance

4.1.1 Relevant energy drivers

The study area was represented by a group of units directed by the same administration where domestic, public and artisan energy drivers were identified. The domestic driver consisted of ten households and two guest houses. The public driver was composed two religious institutions (Convent and Postulancy), a high school (SJCHS) and two healthcare units: physiotherapy and rehabilitation center (SAJOCAH) and a medical center (STCMC).

Within SAJOCAH and STCMC are present some productive activities that generate income in the study area, therefore a third energy driver, artisan driver, was identified.

The following units were included in the artisan driver:

- STCMC and SAJOCAH canteens since the meals cooked are sold to customers
- SAJOCAH bakery where bread and typical sweets are produced and sold
- SAJOCAH workshops (cane, metal, shoe, orthopedic)

The reference energy system investigated in the study area is presented in Figure 4.1, in which were reported energy sources, energy drivers and energy services demanded corresponding to the community energy needs: lighting, power of appliances, cooking baking, cooling and water heating.

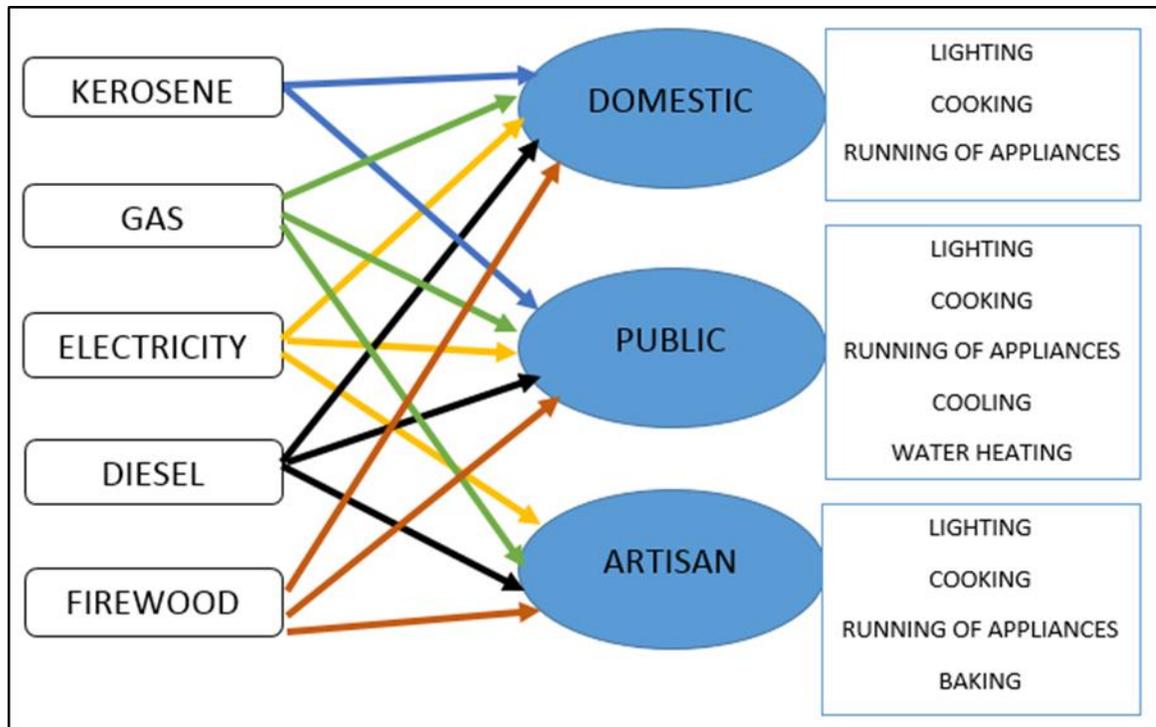


Figure 4. 1: Reference energy system of the study area. Source: Authors.

4.1.2 Current energy balance

The energy sources identified in the study area were electricity from the national centralized grid and fuels, such as kerosene, LPG, diesel and firewood. All these sources were treated as "Primary Energy Sources".

Energy supply from kerosene amounts to 1.5 GJ/month, from LPG amounts to 9.8 GJ/month, from diesel amounts to 6.8 GJ/month and from firewood amounts to 140.3 GJ/month. The electricity consumption from the national grid was equal to 26.9 GJ/month.

The total primary energy supply (TPES) amounted to 186.2 GJ in a month, 2.8% in the domestic energy driver, 50.9 % in the public driver and 46.4% in the artisan driver. The total final energy consumption (TFC) amounts to 56.2 GJ/month to satisfy the energy need within the study area namely lighting, running of appliances, cooling, cooking, baking and water heating. The difference between TPES and TFC expresses the electrical and thermal energy losses, 4.3 GJ/month and 125.8 GJ/month respectively corresponding

to about 70%. Results from the energy consumption assessment of each energy driver are presented in the following paragraphs.

Domestic

Ten households and two guest houses made up the domestic energy driver.

The guest houses hosted either training students or medical volunteers of foreign missions. Students from nursing school came for internships of 4 to 6 weeks every three months, while foreign volunteers, surgeons and physiotherapists stayed in the guest houses three times a year for a period of maximum two weeks.

Diesel was used to run back-up generators, common for public, artisan and domestic users, in case of power shortages, satisfying part of the demand for lighting and running of appliances. Kerosene, LPG and firewood were used to fulfill the cooking demand within the households.

In the Chart 4.1 are presented the shares in energy consumption by source.

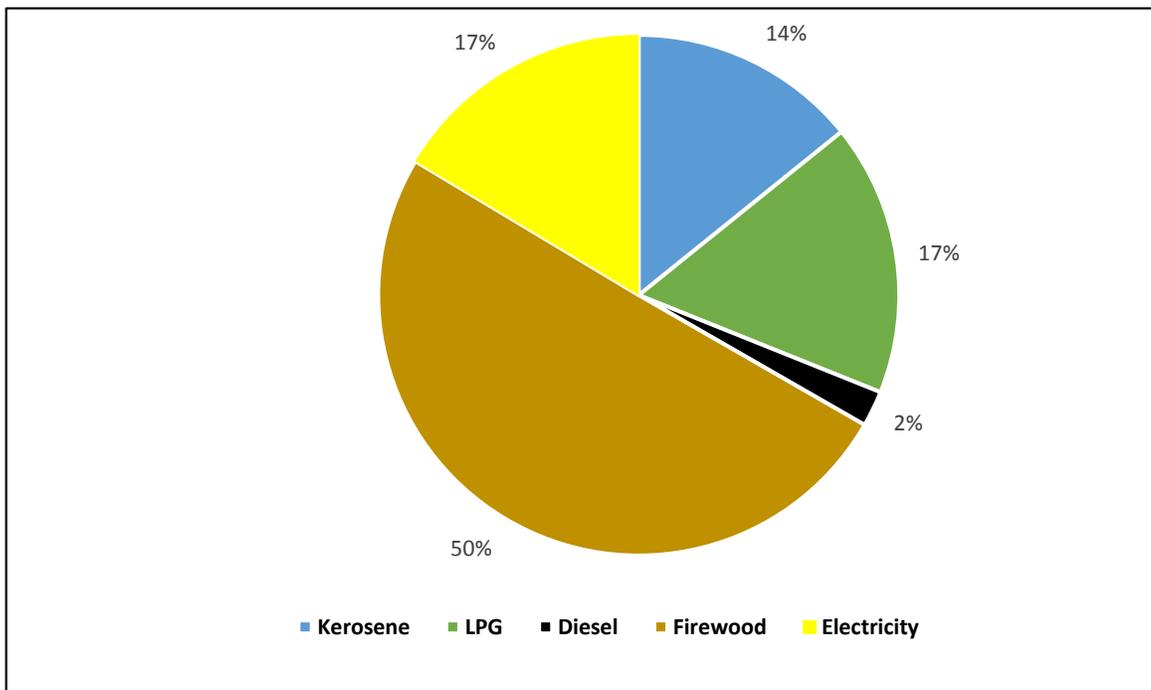


Chart 4. 1: Energy mix present in the domestic energy driver.

Half of the primary energy consumption from firewood equal to 2.58 GJ/month followed by LPG and electricity from the grid with the same share of 17% corresponding to 0.87 GJ/month and 0.84 GJ/month respectively. Kerosene accounts for 14% of the share corresponding to 0.72 GJ/ month, and finally diesel consumption has a share of 2% equal

to 0.11 GJ/month obtained comparing the consumption of diesel used to produce electricity to the electricity consumption share in the domestic driver. The high share of firewood consumption can be attributed to the low cost of firewood, around 8 FCFA/MJ if bought in very small quantity on the side of the road or 4-5 FCFA/MJ if delivered at home in a small truck, compared to the cost of LPG and kerosene. LPG bought locally has a cost on average of 8500 FCFA for a 12.5 kg bottle corresponding to a cost per unit energy of 15 FCFA/MJ, assuming a LHV equal to 45.8 MJ/kg [28], while for kerosene the cost was slightly lower on average equal to 14 FCFA/MJ. The firewood stoves available in the households were only three stone fire (3SF) that have a poor efficiency, therefore more wood was required to obtain the same energy output.

The energy services identified in the domestic energy driver and their relative share of final consumption are presented in Chart 4.2.

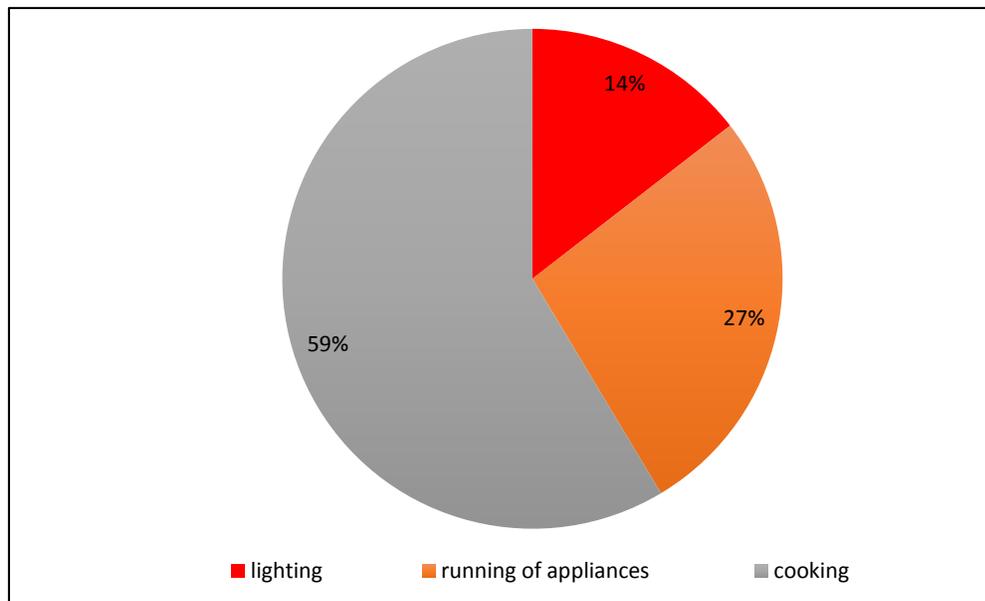


Chart 4. 2: Share of final energy consumption in the domestic driver.

The major share of final energy consumption goes for cooking, equal to 59% and corresponding to 1.3 GJ/month. For running of appliances goes 27% of the final energy supplied, corresponding to 0.6 GJ/month, and 14%, equal to 0.3 GJ/month, goes for lighting. Demand for cooking was satisfied by using kerosene, LPG and firewood while energy for lighting and running of appliances was supplied through electricity. Total energy consumption in form of electricity, estimated by appliance census as explained in

paragraph 3.1.2, was equal to 0.84 GJ/month, of which 65% was used for running of electric appliances and 35% for lighting.

Most common electrical appliances present in the domestic energy driver were: TV with decoder (6 sets), radios (5 pieces) and irons (4 pieces). The lighting demand was equally covered by CFL and fluorescent tubes while incandescent bulbs were not present at all in the study area.

Public

In the public energy driver the fuels used were: kerosene, LPG, diesel and firewood. Another source of energy was the electricity from the national grid, moreover a small size PV system was used to light few lamps in the Convent and was used during power shortages. The contribution of each category is shown in Chart 4.3.

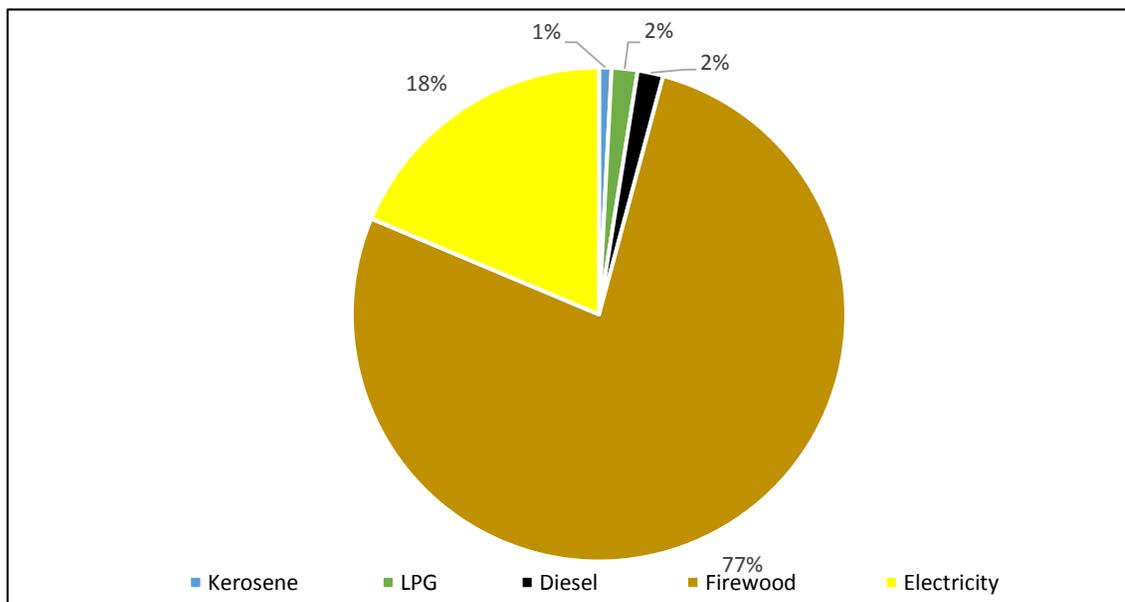


Chart 4. 3: Energy mix present in the public energy driver.

The 77% of the primary energy consumption in the public energy driver is attributed to firewood, corresponding to 72.4 GJ/month. Because of its dominant share firewood supply and consumption are analyzed in details in the following paragraphs.

In the public energy driver three different types of firewood were used to satisfy the cooking demand: Eucalyptus Grandis (red gum) in the kitchens of the Convent and Postulancy; Mangifera Indica (Mango) in SJCHS kitchen and mixed hardwood, coming

from the surrounding forests, in SAJOCAH kitchen. Firewood for the public energy driver was purchased in large quantities (20 tonne trucks) and stored in deposits for at least three to four months. Compared to the domestic energy driver since it is bought in large quantities the cost is lower, on average between 3 and 4 FCFA/MJ. For this reason, for the large availability and for cultural habit is preferred to other fuels. In Table 4.1 are presented the results of the direct measurements performed in the public energy driver for one week in the kitchens of all the units. In every kitchen a different firewood type was used for cooking with a different moisture content that was directly measured on field for Convent, Postulancy and SAJOCAH, as explained in paragraph 3.3 of the Methodology. While for SJCHS a value of 30% was assumed based on other moisture content evaluation test performed on the same type of firewood and the same storage conditions. The total amount of energy was estimated according to Equation 3.5.

Table 4. 1: Firewood consumption measured in the public driver.

	Firewood type	Total amount of firewood measured [kg/month]	Total amount of primary energy [GJ/month]
Convent	Eucalyptus Grandis	884	10.8
Postulancy	Eucalyptus Grandis	572	8.5
SJCHS	Mangifera Indica	2552	35.5
SAJOCAH	Hardwood	818	11.8
Total			66.6

The highest primary energy consumption by firewood was attributed to SJCHS during the schooling period, since in the kitchen meals were prepared every day for more than 300 students, while for the rest of the year the consumption can be assumed null.

Energy services demanded in the public energy driver were identified namely: lighting, running of appliances, cooking, water heating and cooling. Cooling demand required in the Medical Center, in particular in the surgery rooms of the Theatre, where the temperature has to be kept low during operations. While water heating was partly satisfied in STCMC, Convent and Postulancy. In Chart 4.4 is shown the final energy

consumption in the public energy driver by energy service amounting to 33.8 GJ in total per month.

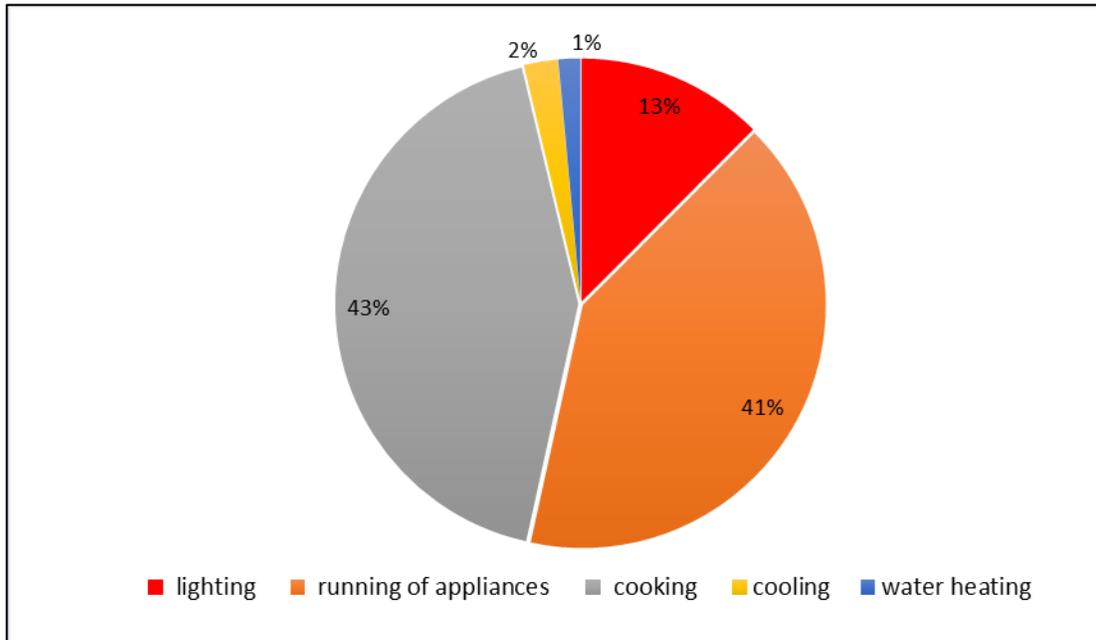


Chart 4. 4: Share of final energy consumption in the public driver

The energy required for cooking represents 43% (14.5 GJ/month) of the total final energy. The extensive use of firewood for cooking in stoves with poor conversion efficiencies induces high thermal losses (59.8 GJ/month) that represent the difference between the primary and the final energy consumption for cooking. The energy that goes to running of appliances was 41% (13.9 GJ/month), to lighting was 13% (4.2 GJ/month), to cooling 2% (0.8 GJ/month) and to water heating 1% (0.5 GJ/month). Demand for running of appliances, lighting, water heating and cooling was mainly covered by electricity with low losses corresponding to 1.0 GJ/month.

The sub-units belonging to the public energy driver (STCMC, SAJOCAH, SJCHS, Convent and Postulancy) were connected to the national electricity grid. In STCMC surgical operations were scheduled on two specific days during the week: Tuesday and Thursday. For that reason, the electricity consumption profile in the above mentioned days was high compared to the other working days of the week, Monday to Saturday. In SAJOCAH and SJCHS services were not provided on Sunday, therefore we have two daily electricity consumption profiles, estimated with appliance census, while in the

Religious Institutions a unique profile day for electricity consumption has been estimated as an average between all the days of the week.

In Figure 4.2 are shown the load curves obtained by appliance census in each unit of the public energy driver, namely STCMC, SAJOCAH, SJCHS, the Convent and the Postulancy, during an operation day.

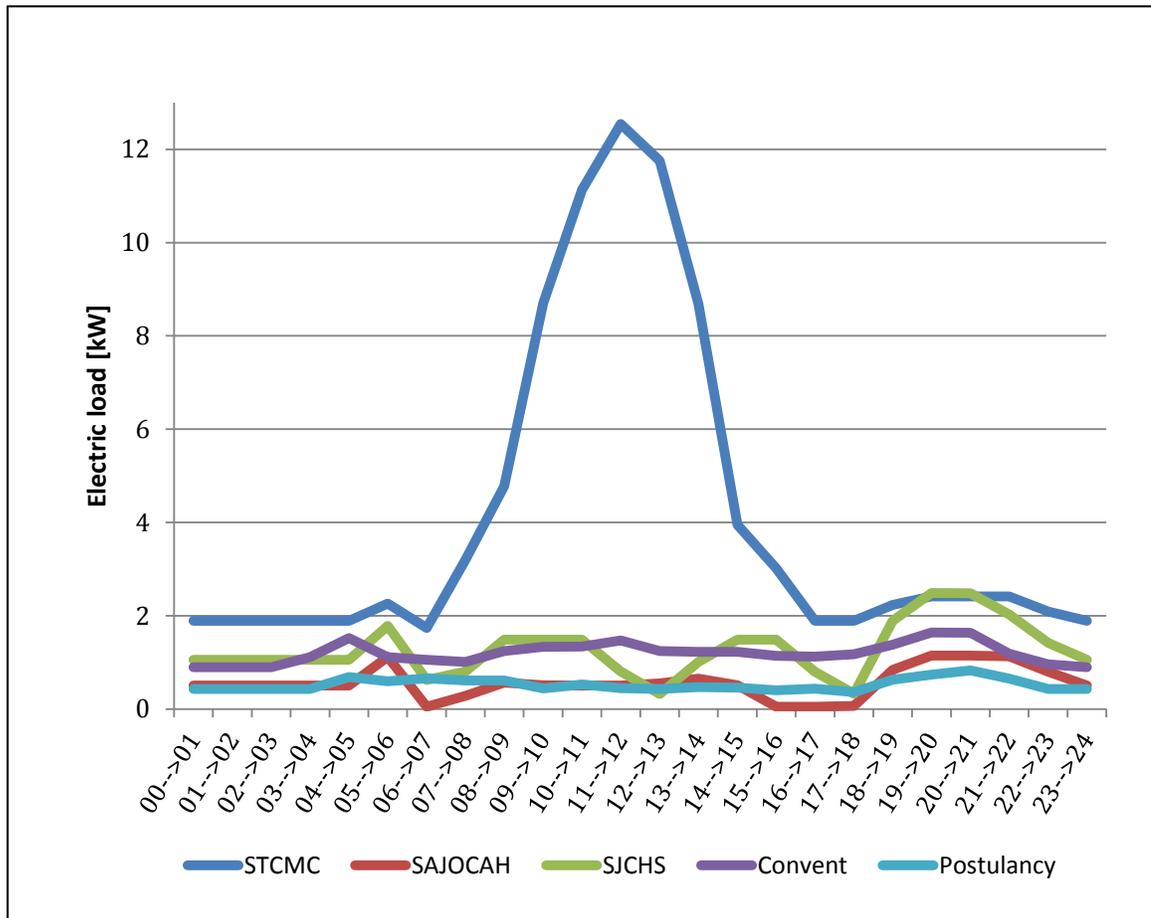


Figure 4. 2: Electrical load curves of the public driver.

As shown in Figure 4.2 the major part of the electric loads in the public sector is represented by STCMC that has also the highest peaks between 9a.m. and 3p.m..

Three electrical load curves have been estimated as the sum of all the units within the public energy driver for *operation day* (i.e. Tuesday and Thursday), *non operation day* and *holiday* and are shown in Figure 4.3.

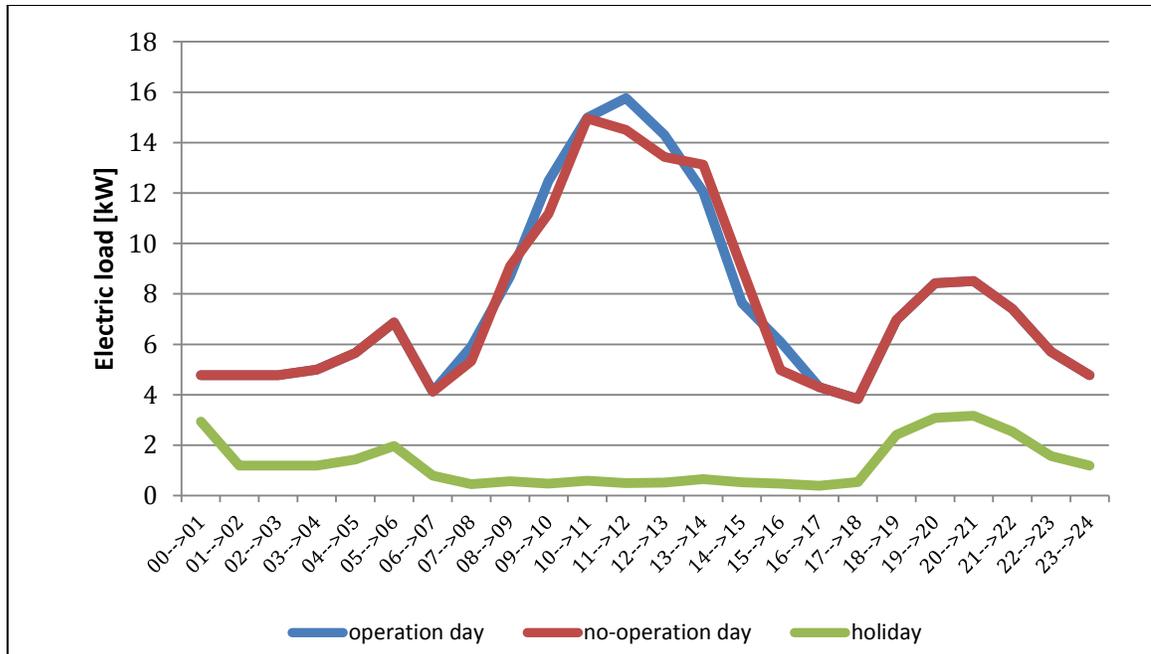


Figure 4. 3: Electrical load curves at different profile days in the public energy driver.

In both operation and no-operation days a high peak is present from 9 a.m. to 3 p.m. when medical and educational services were provided using high energy consumption appliances, while two peaks are present on holiday, one in the early morning and one in the evening. The electricity consumption in the public energy driver accounts for 17.5 GJ/month, of which more than half (54%) was attributed to STCMC, as shown in the chart below, where the electrical energy share per service demanded in each unit of the public driver is reported.

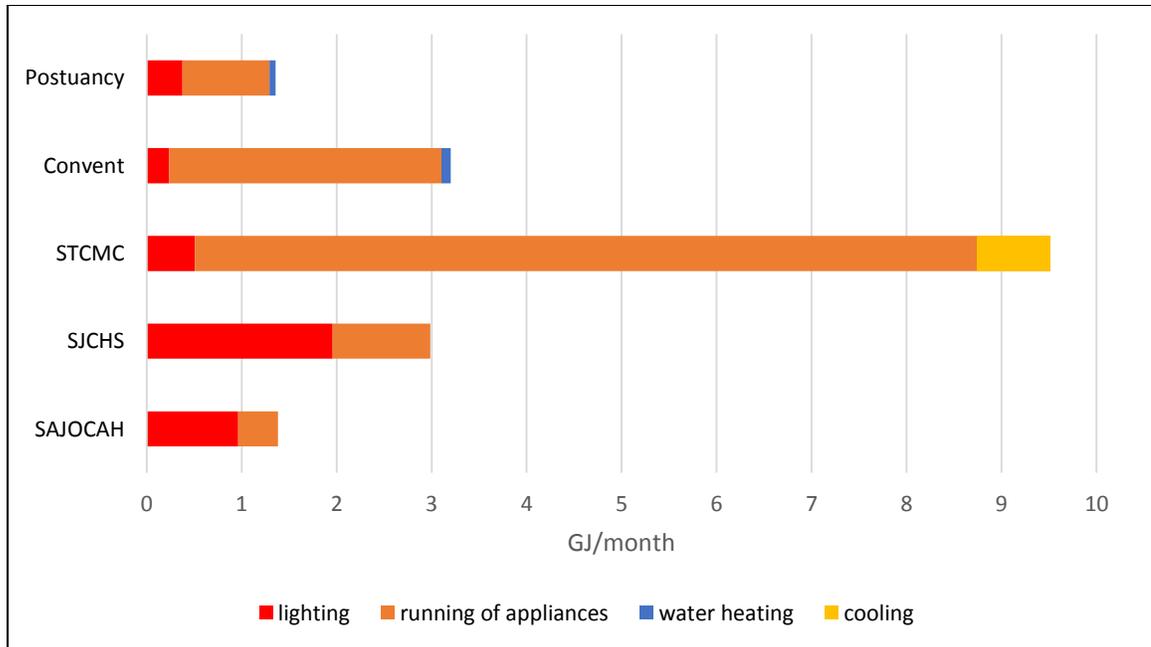


Chart 4. 5: Electricity consumed in the public driver.

In Postulancy, Convent and STCMC electricity share for running of appliances was predominant respect to lighting while in SJCHS and SAJOCAH electricity share for lighting was greater than electricity for running of appliances.

Water heating demand, satisfied using electrical boilers, was present only in the Religious Institutions and cooling demand, satisfied by electrical air-conditioners, only in STCMC. The high-consumption appliances used in Medical Centre to perform the surgical operations account for 8.2 GJ/month, equal to 87% of the unit’s electricity consumption.

Artisan

In STCMC and in SAJOCAH were present income generating activities that were isolated from the public sector and were considered as composing the artisan energy driver [19]. In STCMC the artisanal activities were carried out in the hospital canteen while in SAJOCAH the activities were in the bakery, a canteen and four workshops (metal, orthopedic, shoe and cane). Two additional carpenter and sewing workshops were about to be opened: the electric appliances were already present and the functioning windows were estimated through interview and included in the load curve.

Chart 4.6 shows the share of energy sources in artisan energy driver; electricity is estimated by appliance census, LPG and diesel obtained from questionnaires and firewood from direct measurements.

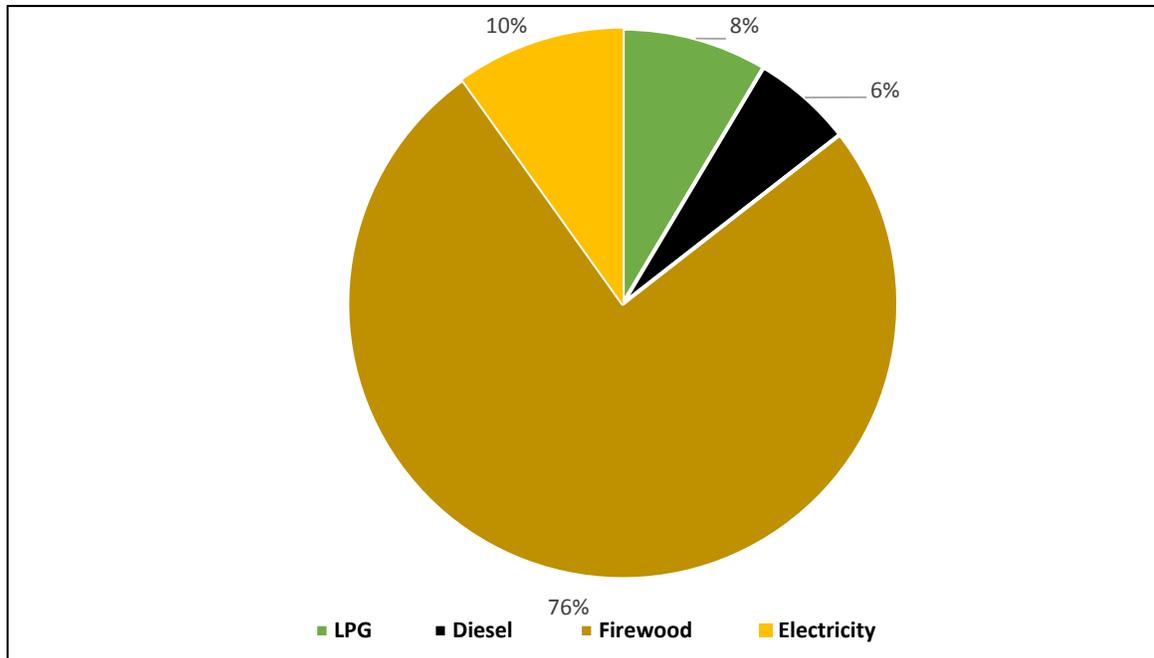


Chart 4. 6: Energy mix present in the artisan energy driver.

The share of firewood is dominant (76%, equal to 65.3 GJ/month) also in this energy driver as in the domestic and public. Electricity from the grid accounts for 10% of the total primary energy consumption, corresponding to 8.5 GJ/month. LPG is used for cooking in both the canteens and in the bakery, its consumption accounts for 8%, equal to 7.4 GJ/month. Diesel consumption represents 6%, equal to 5.1 GJ/month; this fuel is used not only to run back-up generators but also directly in the bakery to provide mechanical power. In the productive energy driver there is no consumption of kerosene.

In the artisan energy driver two different types of firewood are used for cooking and baking: *Mangifera Indica* (Mango) in STCMC canteen and mixed hardwood in SAJOCAH canteen and bakery. Each firewood type has a different moisture content that was directly measured on field as explained in paragraph 3.3 of the Methodology. The total amount of primary energy was estimated according to Equation 3.5. Firewood consumption was measured directly for one week also in the artisan energy driver, results from the analysis are reported in the following table.

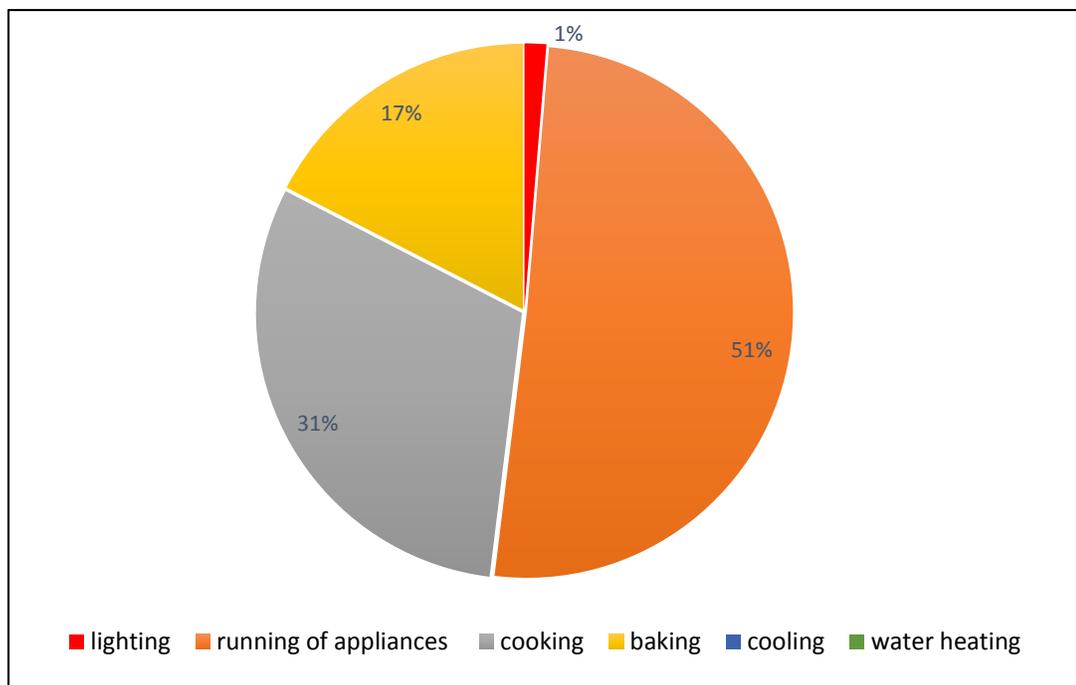
Table 4. 2: Firewood consumption measured in the artisan driver.

	Firewood type	Total amount of firewood measured [kg/month]	Total amount of primary energy [GJ/month]
STCMC cooking	Mangifera Indica	284	4.0
SAJOCAH cooking	Hardwood	542	7.9
SAJOCAH baking	Hardwood	4690	53.5
Total			65.4

The main consumption of firewood was for baking, representing 82% of the total consumption of firewood in the productive activities. Firewood is used for cooking in SAJOCAH not only in the canteen but also twice a week in the bakery to produce local brand sweets.

The total final energy consumed in the artisan driver is equal to 20.2 GJ/month; the energy services demanded that were identified in the artisan energy driver are: running of appliances, lighting, cooking and baking.

In Chart 4.7 is shown the share of final energy demanded by each service.

**Chart 4. 7 Share of final energy consumption in the artisan driver.**

The final energy for running of appliances accounts for approximately half of the total, corresponding to 10.2 GJ/month, due to the heavy duty appliances used in the workshops of SAJOCAH. Cooking energy demand, satisfied by use of primary fuels (firewood and LPG), showed a share of 31% corresponding to a consumption of 6.2 GJ/month.

The final energy for baking accounts for 17% equal to 3.5 GJ/month.

We can notice a very low share for lighting, only 1% (0.3 GJ/month), reasonable because all the productive activities are conducted during the day, from 8 a.m. to 3 p.m. where there is presence of natural light. Two of the demands, lighting and running of appliances, are satisfied using mainly electricity withdrawn from the national grid. In the two canteens are present a refrigerator and a deep freezer running on electricity. Heavy duty appliances are used in the shoe, orthopedic and metal workshops. Filing machines are the most common devices, while are present also three welding machines and a high energy consuming electric oven. In the bakery is present a three-phase electric mixer.

For the artisan activities the daily sample profiles of electrical energy consumption, estimated by appliance census, are plotted in Figure 4.4. Since no productive activities are carried out on Sunday, in this case two profile days are distinguished: weekday and Saturday when the working hours in SAJOCAH are reduced.

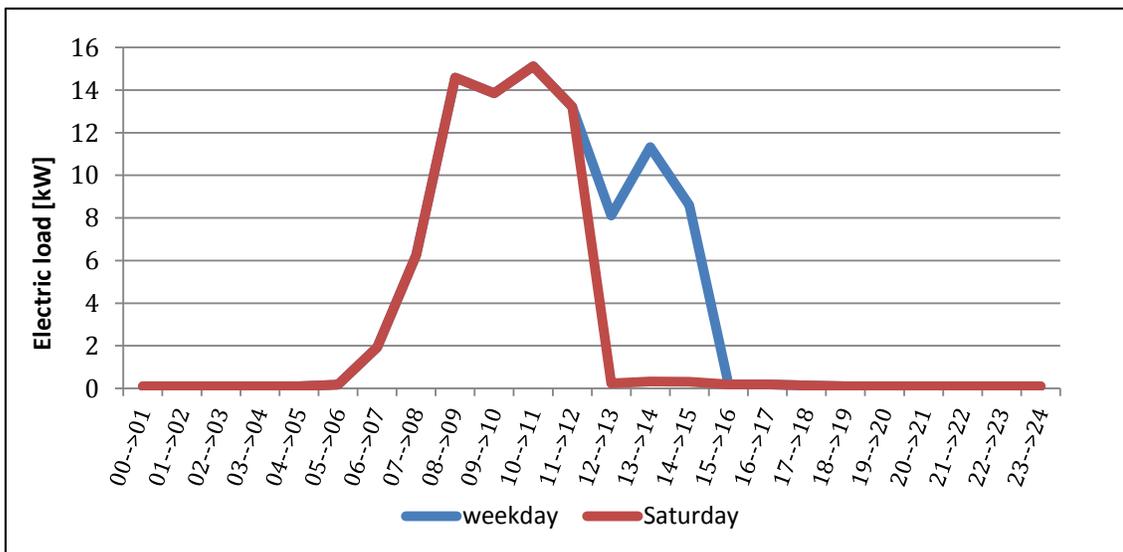


Figure 4. 4: Electrical load curves in different profile days in the artisan driver.

The time window of peak consumption represents exactly the working hours of canteens and workshops: from 5.30 a.m. when the activities in the bakery begin, till 3 p.m. on

weekday or midday on Saturdays when all the artisan activities stop. The two highest peaks reached in the morning have an approximate value of 15 kW, while the total electricity consumption is equal to 94.9 kWh for a weekday and to 67.7 kWh for Saturday.

Energy flow diagram of the study area

In the reference energy system five energy sources, three main energy drivers and six energy services demanded were identified. Results regarding the current energy consumption were aggregated in the overall energy balance of the study area for a sample month and reported in the Sankey diagram present in Figure 4.5. In accordance with IEA criteria for energy balance representation, the Sankey diagram, created using the software e!Sankey®, includes the energy flows of the study area represented in the figure with arrows and expressed in MJ.

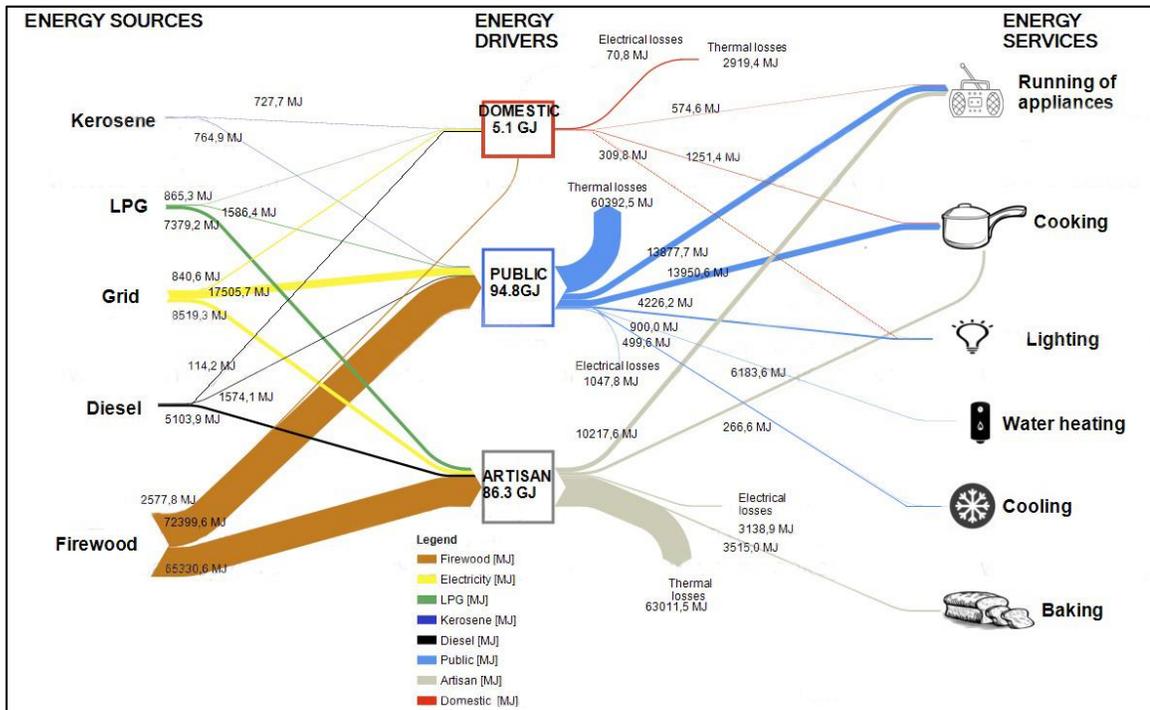


Figure 4.5: Energy flows in the study area. Source: Authors.

Among the energy sources investigated in the study area, there are five energy sources: kerosene, LPG, diesel, electricity withdrawn from the national grid and firewood.

Energy from firewood was the highest primary energy consumption in the study area accounting for a total of 140.3 GJ. Firewood was used in all the energy drivers, with the major consumption attributed to the public driver (72.4 GJ) followed by the artisan driver (65.3 GJ) and a substantially lower consumption in the domestic driver (2.6 GJ).

Electricity from the grid was the second highest energy consumption, 26.8 GJ in total, attributed to domestic, public and artisan energy drivers with the following consumptions: 0.8 GJ, 17.5 GJ and 8.5 GJ, respectively. LPG and diesel were used in all the energy drivers, while kerosene was used only in the domestic and public drivers.

The total primary energy supplied to the study area in one month is equal to 186.2 GJ per month corresponding to 53.37 toe/year. Public energy driver absorbs the highest amount of the primary energy corresponding to 94.8 GJ (27.17 toe/year). The energy consumption of the artisan energy driver is equal to 86.3 GJ (24.73 toe/year), while the domestic primary energy consumption was equal to 5.1 GJ (1.46 toe/year), one order of magnitude lower respect to the other two, as expected due to the limited number of households included in the control volume.

The energy services demanded in the study area were: running of appliances, cooking, lighting, baking, cooling and water heating. Running of appliances, requiring 24.7 GJ/month of energy as well as cooking, requiring 21.1 GJ/month and lighting, requiring 4.8 GJ/month, was needed in all the energy drivers. Baking, attributed to the artisan energy driver, has a total consumption of 3.5 GJ/month, while cooling and water heating related to the public energy driver have a final energy demand equal to 0.8 GJ/month and 0.5 GJ/month respectively. The TFC of the study area was equal to 56.2 GJ/month corresponding to 16.01 toe/year.

Electrical and thermal energy losses occurred in all the energy drivers. The losses attributed to the national electricity grid were not estimated quantitatively on field therefore in this research were not included. The total amount of electrical energy losses, corresponds to the losses from the diesel generators and was equal to 4.3 GJ. The conversion of fuel into thermal energy introduces thermal losses, accounting for 125.8 GJ and representing 68% of the total energy input. The large amount for thermal losses was due to use of conversion technologies with low efficiencies.

Considering a population of approximately 600 persons the TPES per capita was equal to 0.09 toe/year, much lower respect to the average of the country 0.33 toe/year/capita [93], compatible with public institution located in a rural area of NW Cameroon (Cameroonian Protestant College in Bali, 0.11 toe/year/capita) [21].

The overall energy balance shows a predominant use of firewood introducing high thermal energy losses compared to the other primary fuels. Electricity supply, with frequent and long power shortages, was used in all the energy drivers to provide the most important services for healthcare and education. Therefore the focus of the energy planning was to provide reliable electricity and efficient solutions to supply thermal energy.

4.2 Local energy resources potential

In this section the results from the local energy resources assessment are presented. The focus was in RES i.e. hydro, solar, biomass (biogas), wind. Also the frequency of grid outages is presented.

4.2.1 Hydropower

Hydropower potential, as expressed in Equation 3.8, was evaluated based on measurements to estimate flow rate and gross head that were performed in the two rivers flowing nearby the study area.

Considering the low available flow rate for River A the theoretic power output was considered not sufficient in order to proceed any further with the investigation and the focus was shifted on River B.

In River B was applied the *floating object method* and the estimated results are reported in Table 4.3.

Table 4. 3: Cross sectional area, velocity and flow rate in River B.

Date	Mean cross section area [m ²]	Velocity [m/s]	Flow rate [l/s]
23 rd May 2015	3.42	0.07	164.1
10 th June 2015	2.71	0.21	407.3
17 th June 2015	0.69	0.64	221.6
6 th July 2015	1.57	0.86	678.8

The values for flow rate obtained are generally increasing with the ongoing of the rainy season. A peculiar value for the flow rate was found for the 17th of June, lower respect to the one registered the week before. The change in value can be explained by the lack of precipitations during the week before the measurements, shown also by the decrease of flow rate estimated with conatiner method in River A.

A map of the river with the possible location for power house and intake is reported in Figure 4.6.



Figure 4. 6: River B with possible locations for intake and powerhouse.

The available gross head equal to 39 meters was estimated as the average of the value obtained by using Google Earth (42 m) and the value obtained with the total station (36 m). In Table 4.4 are reported the monthly values for the total flow rate of the river estimated by applying the linear regression technique according to [34] with river Mewou as reference.

Table 4. 4: Estimated river flow rate.

Month	River flow [l/s]
January	121
February	84
March	78
April	165
May	169
June	264
July	334
August	365
September	393
October	461
November	360
December	224

At first the values obtained for the day of measurements were assumed to be the averages for the whole month, then these values for the flow rate were compared to the reference river to obtain the linear correlation coefficients and estimate the flow rate for the other months of the year. The required residual flow rate computed according to [36] as well as the design flow rate of a cross flow turbine adaptable to seasonal variations of the flow is reported in the figure below.

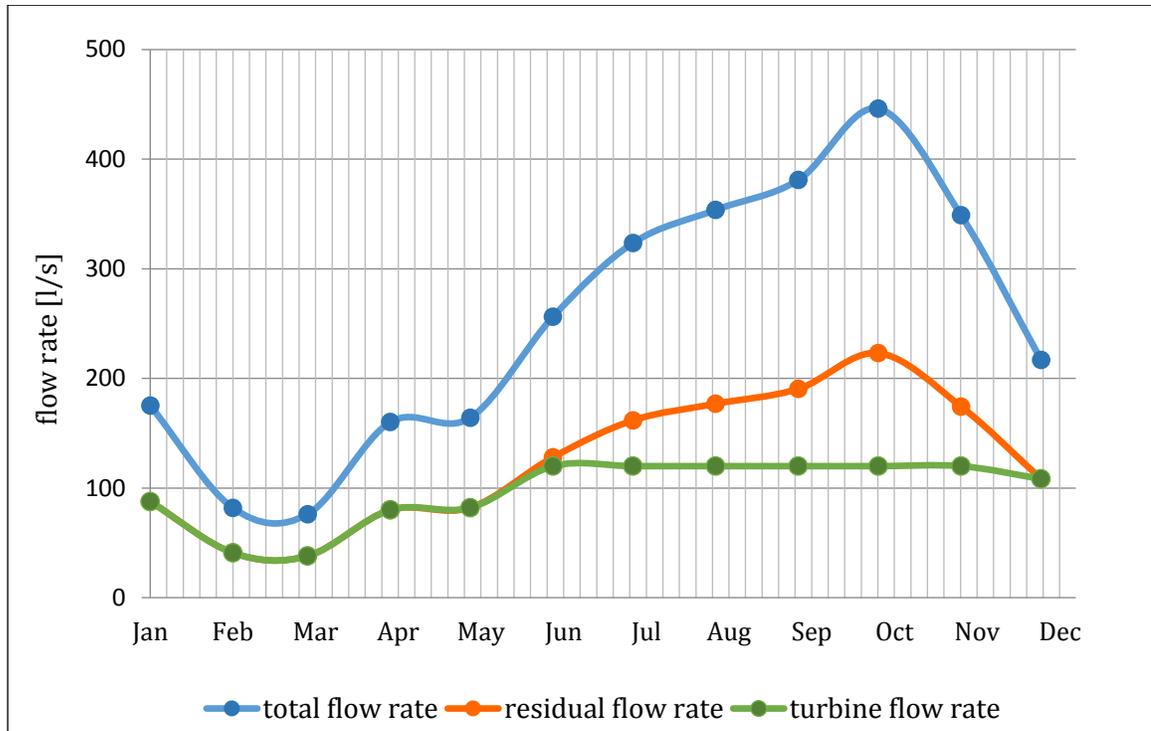


Figure 4. 7: Total and residual flow rate of the river, turbine flow rate along one year.

Considering a minimum flow equal to 35 l/s kept in the river, the minimum residual flow rate was registered in March correspondent to 43 l/s, this leads to a theoretical available power equal to 14.6 kW. Considering a capacity factor equal to 55% according to [89] and an overall efficiency of the hydropower system equal to 50% the annual energy production amounts to 140.7 GJ.

4.2.2 Wind and solar

The data regarding wind and solar potential were acquired for the months of May, June, July, August and October.

Wind

The average wind speed measured at the study area for the data acquisition period is shown in Chart 4.8.

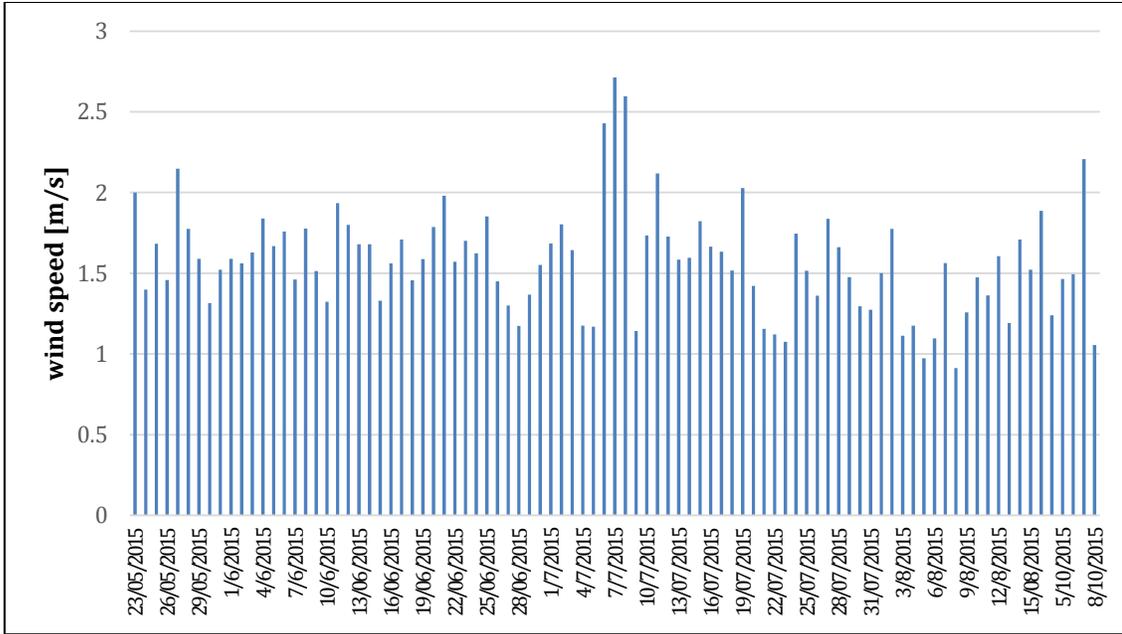


Chart 4. 8: Daily average wind speed registered in the study area.

The average wind speed was in the range between 0.5 and 2.7 m/s and it was higher within the day between 12 p.m. and 3 p.m. along the whole data collection period there were not wind gusts in the study area.

Chart 4.9 represents the wind rose obtained using the number of observations with average wind speed greater than 0.5 m/s in each direction sector.

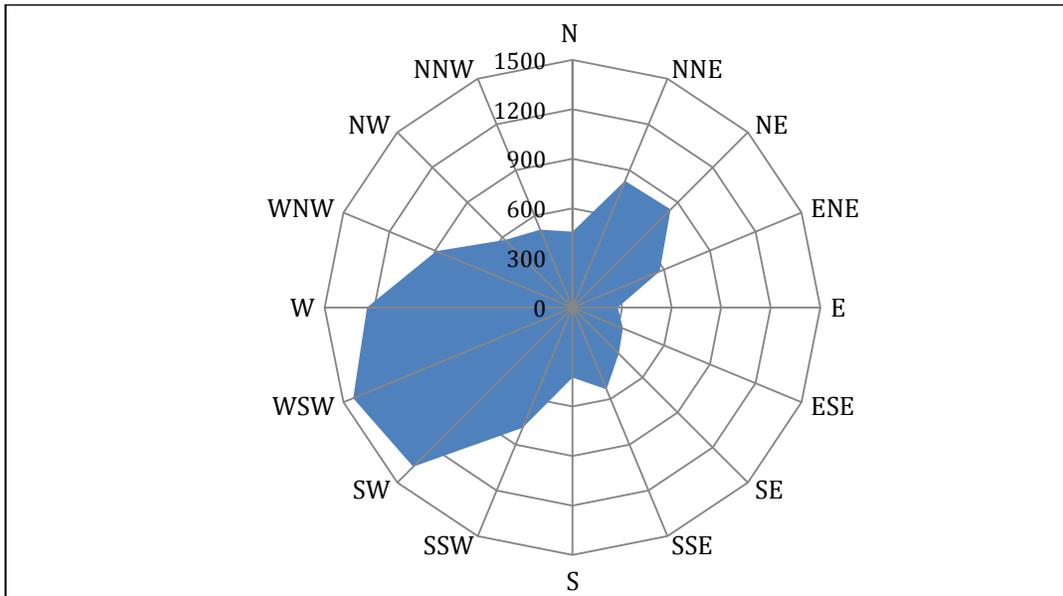


Chart 4. 9: Distribution of the wind direction in form of a wind rose.

As shown in Chart 4.9 the wind blows mainly between West and Southwest direction and the dominant direction is West-Southwest with a number of observation of almost 1500. Wind frequency distribution was obtained by estimating the Weibull shape and scale parameters as explained in Paragraph 3.2.2. The values obtained with the different approaches for each parameter are reported in Table 4.5.

Table 4. 5: Weibull parameters according to: Weibull probability plotting, Justus and Lysen.

	Weibull probability plotting	Justus	Lysen
Shape parameter	1.356	1.713	1.713
Scale parameter	0.547	1.755	1.122

The Weibull probability density function obtained with *Justus* approach is reported in the following chart.

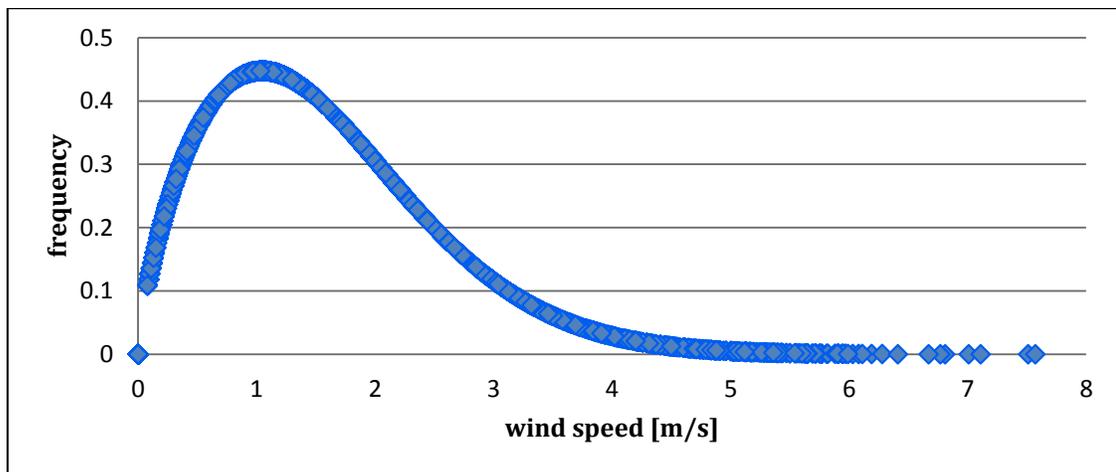


Chart 4. 10: Frequency of wind speed according to Weibull probability density function.

As shown in Chart 4.9 the most frequent wind speeds are around 1 m/s with a frequency equal to 0.45, while wind speeds above 3 m/s were rare in the study area during the data collection period. This was a first indication of the unfavorable wind conditions for wind power applications. The wind speed data for each month of the year, obtained by comparison with NASA (Appendix C.3) data are reported in Table 4.6.

Table 4. 6: Measured and estimated monthly average wind speed

	Measured wind speed [m/s]	Estimated wind speed [m/s]	
		Log law	Power law
January		1.99	1.94
February		2.03	1.99
March		1.93	1.89
April		1.75	1.71
May	1.77	1.73	1.69
June	1.61	1.85	1.80
July	1.64	1.78	1.74
August	1.33	1.85	1.80
September		1.73	1.69
October	1.55	1.50	1.46
November		1.60	1.57
December		1.70	1.66
Annual average		1.78	1.75

The measured data for the months of May, June, July, August and October, as well as the estimated values according to the log law, that shows better accuracy respect to the power law for anemometer height below 100 meters, are compared with NASA data in Chart 4.11.

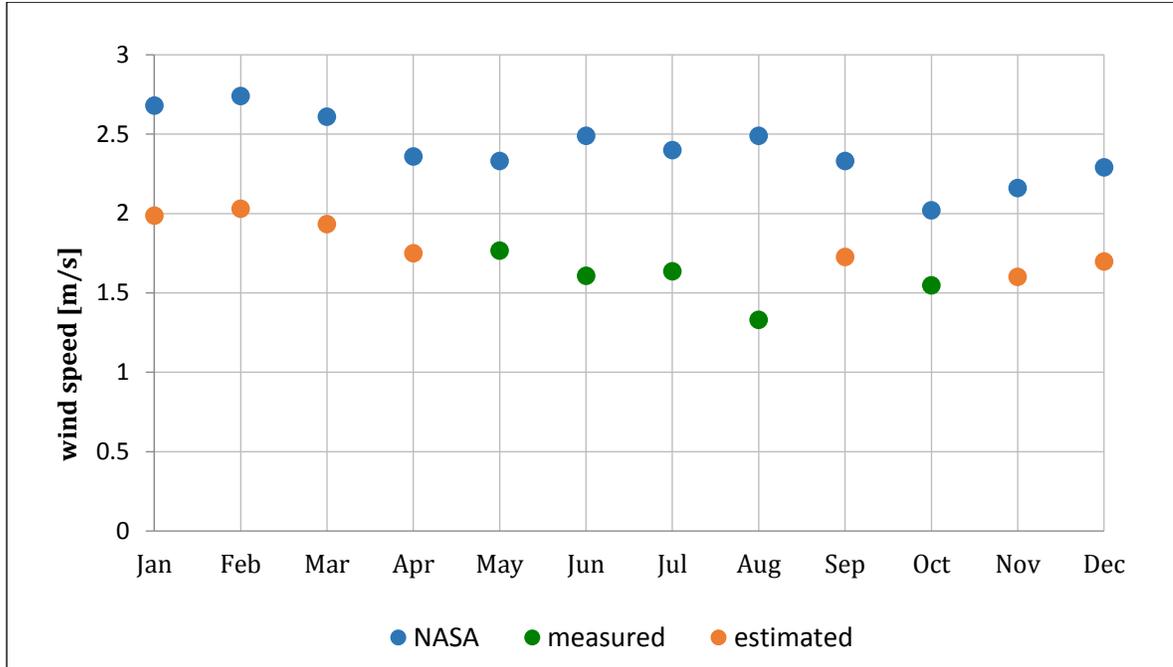


Chart 4. 11: Monthly average wind speed: NASA (blue), measured (green) and estimated values with log law (orange).

Adopting the maximum coefficient equal to 0.596 in the application of Betz law [42] the power production per unit of swept area was equal to 2.13 W/m^2 , assuming a capacity factor equal to 7% [87] the annual energy production was 4.7 MJ/m^2 .

Solar

The average insolation measured in the study area for the data collection period is reported in Chart 4.12.

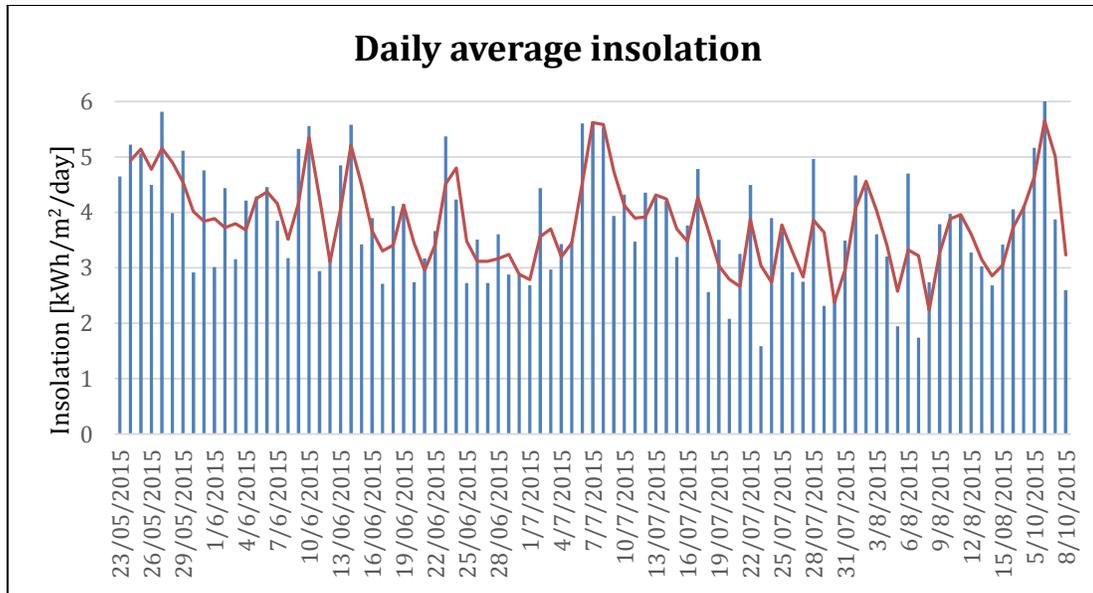


Chart 4. 12: Daily average insolation registered in the study area.

Sun light was available for approximately twelve hour a day in the experimental period which coincided with the rainy season in the study area. Peaks values for global solar radiation had a value of 20.2 MJ/m²/day. The following regression approaches [46], [47] were adopted to scale the collected with the NASA data (Appendix C.3) in order to compared estimated annual values:

- Rogers approach, applied according to Equation 3.29 to obtain the slope m equal to 1.19 and the intercept q equal to -1.16;
- Derrick's approach, expressed in Equation 3.30, to obtain a equal to 0.60 and b equal to 1.29;

The monthly average insolation obtained by applying all the regression approaches is reported in Table 4.7.

Table 4. 7: Measured and estimated monthly average insolation.

	Measured Insolation [kWh/m ²]	Estimated Insolation [kWh/m ²]	
		Roger's	Derrick's
January		6.14	6.25
February		6.20	6.31
March		5.38	5.42
April		4.80	4.80
May	4.60	4.58	4.58
June	3.79	4.10	4.09
July	3.68	3.61	3.60
August	3.44	3.50	3.50
September		3.85	3.84
October	4.33	4.05	4.04
November		5.04	5.05
December		5.73	5.79
Annual average		4.75	4.74

The values obtained with the two approaches were compared to the measured ones in the same months: the trend obtained with Rogers and Derricks approach was similar.

The comparison between NASA, measured and the estimated insolation data, is reported in Chart 4.13.

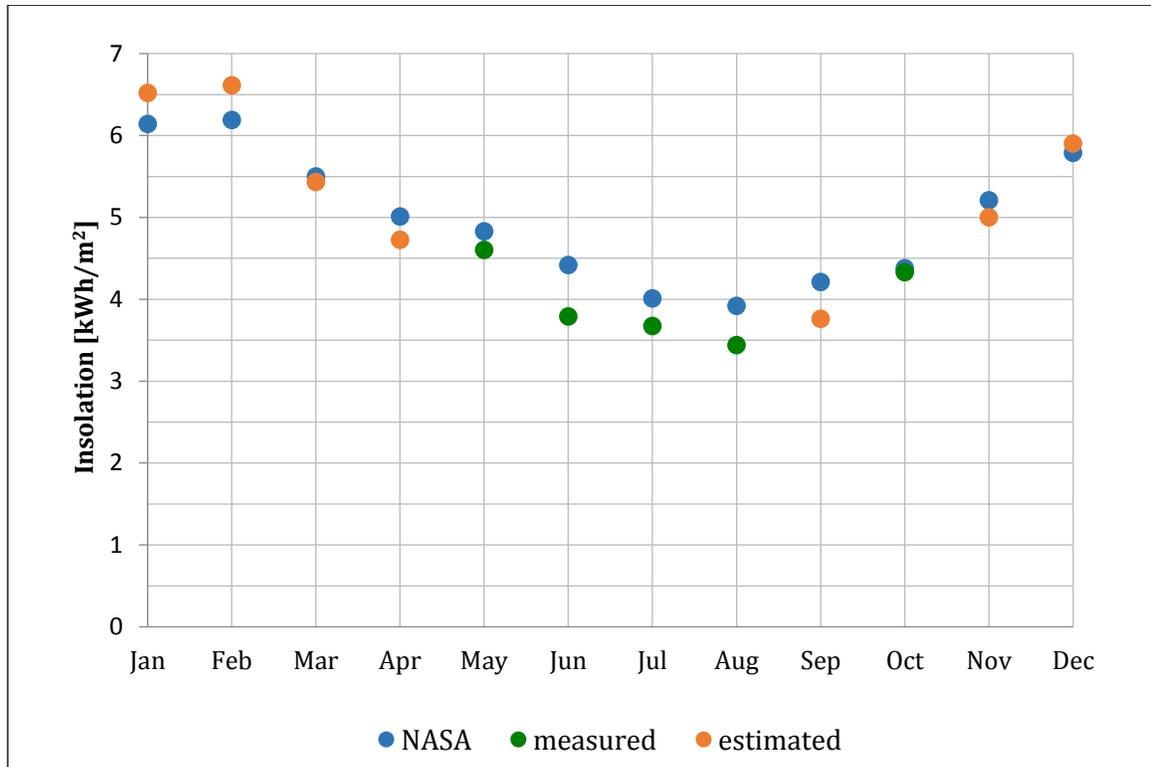


Chart 4. 13: Monthly average insolation: measured (green), estimated (orange) and NASA (blue).

The values of insolation measured on site and estimated with exponential regression were lower with respect to the NASA value from March to November, while in the months of December, January and February, in the dry season, when the solar radiation is stronger, the estimated values were higher than the NASA data.

Solar average annual potential is equal to 17.3 MJ/m^2

4.2.3 Biomass

Biodegradable materials that could be used to feed an anaerobic digester for biogas production were identified in each energy driver and their potential were computed as explained in Paragraph 3.2.3.

Domestic

Biodegradable material availability was very limited in the domestic energy driver due to the restricted number of households. The human waste biogas potential was not taken into consideration based on the limited number of households in the study area.

Regarding the kitchen waste the collection and disposal facilities were both managed by the public institution in which the households were present, therefore the kitchen waste were merged with the one of the public energy driver and accounted in that section of the results.

By analyzing the answer given in the questionnaire it was possible to establish that none of the households have animals or farms, therefore for this specific driver the biogas potential from animal dung and agricultural waste account to zero.

Public

The largest biodegradable material availability is attributed to the public energy driver, where all the four sources of biogas feedstock were present, i.e. human waste, animal dung, kitchen and agricultural waste.

Regarding the estimation of human waste production as bio-digester feedstock in Table 4.8 are reported the daily average number of times that the flush and pit toilets were used, in each unit of the public energy driver.

Table 4. 8: Daily average number of times of toilet use in the public energy driver.

	flush urine	flush faeces	pit urine	pit faeces
STCMC	160	59	13	13
Convent and Postulancy	34	76	0	20
SAJOCAH	49	39	40	6
Total	243	174	52	39

The school was not in session during the period of the field study. Therefore for SJCHS has been considered the number of students equal to 300 of which on average 80% from the school admission register are children below sixteen years old. For SAJOCAH the number of children varies along the year but it can be assumed around the 30% of the total number of patients, according to the register of the hospitalized patients. For children half waste production respect to the adults has been taken as approximation, according to [67].

The available biogas potential in each unit was estimated considering the contribution of faeces and urines in flush toilets where it was possible to adapt the current piping system to converge the human waste. Biogas potential could be substantially increased in case of using human waste coming from the pit toilets that represent 25% of the total human waste production. Taking into account a frequency of urination equal to 5 motions per person per day and a frequency of defecation equal to 1.4 motion per person per day [68], the share between adults and children and the data obtained according to [48] and to [49] the biogas production was estimated and it is reported in Table 4.9.

Table 4. 9: Human waste and biogas estimated production in the public driver.

Unit	Mass of urine [kg/month]	Mass of wet faeces [kg/month]	Biogas production [Nm³/month]
STCMC	1249.0	177	33.1
Convent and Postulancy	265.2	228	22.1
SAJOCAL	319.8	97.5	12.6
SJCHS	7020	756	167.3
Total	8854.0	1258.5	235.1

The unit that shows the highest potential is SJCHS, where the number of students is high and constant when the school is in session, moreover is expected an increase in the number of students due to expansion plans.

Animals were present only in the public energy driver with a quite constant number along the year. The following species of animals were identified: fowls, pigs, cows and goats. The animal breeding locations were two: inside SAJOCAL and Postulancy and outside in the cow bush, about 2 kilometers away from the study area, where 40 cows and 10 goats were bred. The biogas assessment has been restricted to the animals present in the proximity of the users and organized by unit.

In the public energy driver the biogas production was computed applying Equation 3.32 with manure yield for each species of animal and the corresponding biogas yield

according to [50]. In Table 4.10 are reported the different types of animals present in each unit, their average number and the corresponding expected biogas production.

Table 4. 10: Number of animals and estimated biogas production in the public driver.

Unit	Species of animal	Average number	Biogas production [Nm ³ /month]
SAJOCAH	Pigs	38	437.8
	Fowls	800	236.0
Postulancy	Pigs	16	184.4

The total expected biogas production in the public energy driver in one month corresponds to 858.2 Nm³, of which 78.5% is related to the animals bred in SAJOCAH and 21.5% to the animals in the Postulancy.

The kitchen total waste production in the public energy driver was estimated by direct measurements. The average mass of waste production in each unit of the public energy driver is reported in Chart 4.14.

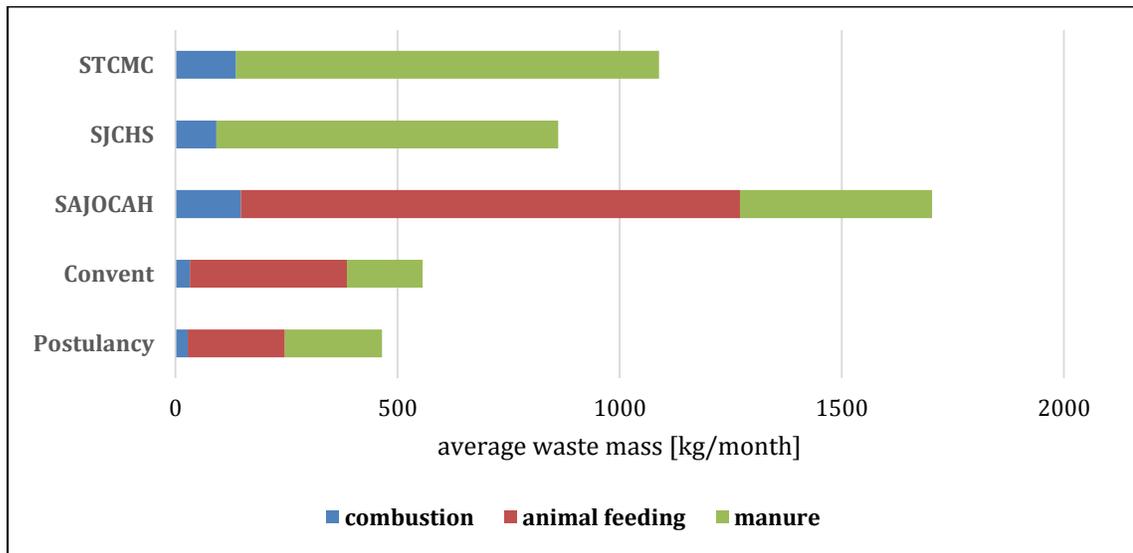


Chart 4. 14: Mass of waste for combustion, animal feeding and manure.

Kitchen waste composed by biodegradable material was the sum of waste gathered for animal feeding and manure. In the assessment of biogas potential a conservative strategy was adopted: only the fraction for manure was considered in the biogas production estimation. Kitchen waste used for animal feeding was an important and free resource in

the study area, therefore its competitive use for biogas production was not considered. Using as percentage of total solids 20% and of volatile solids 60% taken as the mean of the ranges and using as biogas yield $0.35 \text{ Nm}^3/\text{kg}_{\text{vs}}$, [51] the potential biogas production in a sample month using waste intended for manure is shown in the following table.

Table 4. 11: Average manure mass and corresponding biogas production of the public driver.

Unit	Manure waste mass [kg/month]	Biogas [Nm^3/month]
SJCHS	769.3	32.3
SAJOCAH	432.3	18.2
Postulancy	218.6	9.2
Convent	170.0	7.1
STCMC	952.5	40.0
Total	2542.6	106.8

The total production of biogas from kitchen waste was $106.8 \text{ Nm}^3/\text{month}$, the highest biogas production was obtained for SJCHS equal to approximately one third of the total. Agricultural waste was considered deriving from maize production. A maize yield between 9 and 30 t/ha/year [52] and biogas yield of $530 \text{ Nm}^3/\text{t}$ according to [53] were considered in the application of Equation 3.32. Results for each unit of the public energy driver are reported in Table 4.12.

Table 4. 12: Estimated production of maize and biogas.

Unit	Dedicated area [m^2]	Maize production [kg/month]	Biogas yield [Nm^3/month]
SAJOCAH	1234.6	92.6 – 308.7	48.2 – 160.5
SJCHS	1010.5	75.8 – 252.6	39.4 – 131.4
Convent	805.4	60.4 – 201.4	31.4 – 104.7
STCMC	185.1	13.9 – 46.3	7.2 – 24.1
Postulancy	102.0	7.7 – 25.5	4.0 – 13.3
Total	3337.7	250.3 – 834.4	130.2 – 433.9

The total biogas production from agricultural waste varies between 130.2 Nm³/month and 433.9 Nm³/month. The highest production is related to SAJOCAH followed by SJCHS, in accordance to larger farms dedicated to maize cultivation.

Section 4.2.3 is summarized in Table 4.13 where for each unit of the study area are reported the value for the feedstock resources and the biogas potential respectively (for the agricultural waste the average has been considered).

Table 4. 13: Summary of the resources available (a) and biogas potential (b) in each unit.

Unit	Resource [kg/month]			
	Human waste (faeces + urine)	Animal waste	Agricultural waste	Kitchen waste
SAJOCAH	417.3	1332.1	205.8	432.3
SJCHS	7776.0	0	168.4	769.3
Convent and Postulancy	493.2	284.0	151.2	388.6
STCMC	1426.0	0	30.9	952.5

Unit	Biogas potential [Nm ³ /month]				
	Human waste (faeces +urine)	Animal waste	Agricultural waste	Kitchen waste	Total
SAJOCAH	12.6	673.8	109.1	18.2	809.0
SJCHS	167.3	0	89.3	32.3	285.0
Convent and Postulancy	22.1	184.4	80.1	16.3	240.5
STCMC	33.1	0	16.3	40.0	149.8
Total	235.1	858.2	294.8	106.8	1494.9

Considering the biogas LHV equal to 30 MJ/Nm³, the potential of the biogas sources was 44.85 GJ/month.

4.2.4 Conventional: electricity grid and primary fuels

As shown in section 4.1 the energy sources in the study area were electricity from the national grid and fuels, namely kerosene, LPG, diesel and firewood. The evaluation of

these sources of energy was performed in order to investigate the main issues related to their use and the possibility to mitigate them.

The supply of electricity was evaluated in terms of reliability and affordability in order to elaborate a more reliable solution to supply electrical energy based on local RES, while the supply of kerosene, LPG and diesel was evaluated in terms of availability and affordability.

For each identified unit in the study area, a separate meter was present: three-phase meters for SAJOCAH, SJCHS, STCMC and the Convent, while for the Postulancy the meter was single phase. The results obtained from section on “*Electricity supply*” of the questionnaire and related to power shortage frequency and duration, as well as damages caused by voltage fluctuation are reported in the following paragraphs.

The reported frequency of power shortages in five categories of increasing frequency is shown in Chart 4.15.

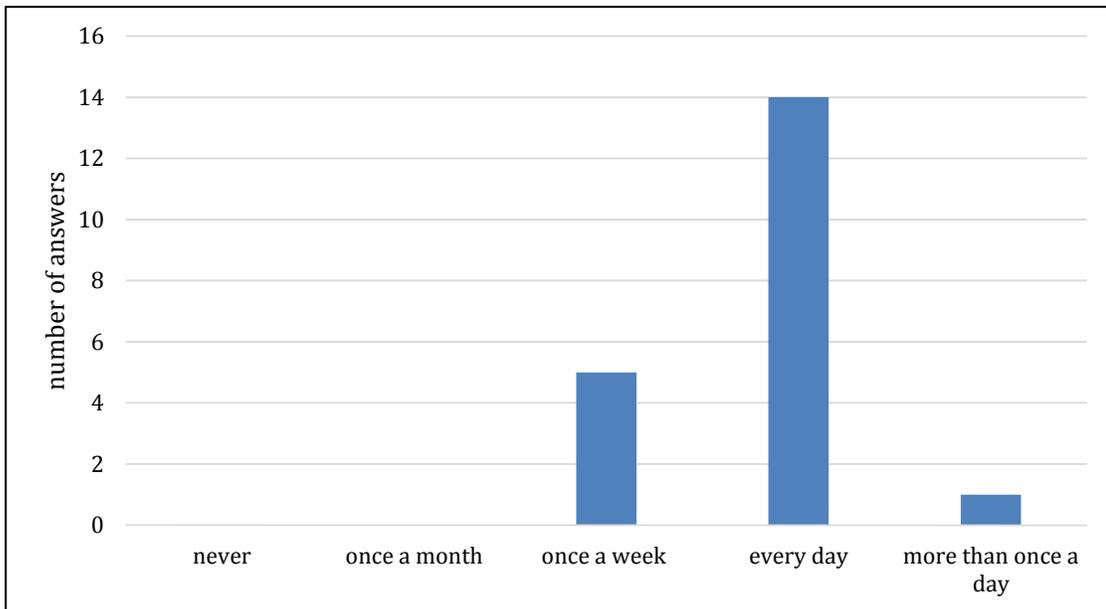


Chart 4. 15: Power shortage frequency according to 20 answers given by interviewees

Power shortages occur frequently, according to 70% of the interviewees every day, moreover none of the answers reported a frequency below once a week.

In Chart 4.16 is reported the average duration of power shortages in a week categorized according to the five possible answers.

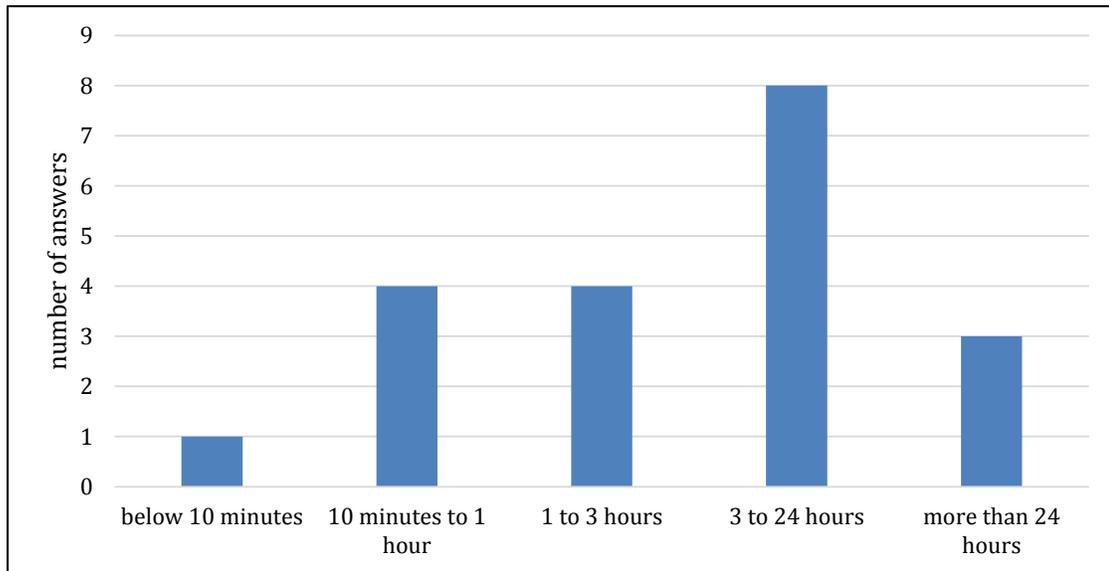


Chart 4. 16: Average power shortage duration in a week, according to the interviewees.

According to 40% of the interviewees the duration of power shortage ranges in a week was between 3 and 24 hours. The estimation of power shortage duration was more challenging with respect to its frequency since part of the interviewees were working in the study area, so they were present only for a part of the day. Moreover estimation of time was more difficult for the interviewees than counting the number of power shortages. The most common issue reported from the interviewees related to the power shortage was the lack of water since the water supply was based on electric pumps.

The results from the “*blackout registration*” checklists (Appendix C.5), submitted as explained in the Paragraph 3.1.2, are presented in Chart 4.17.

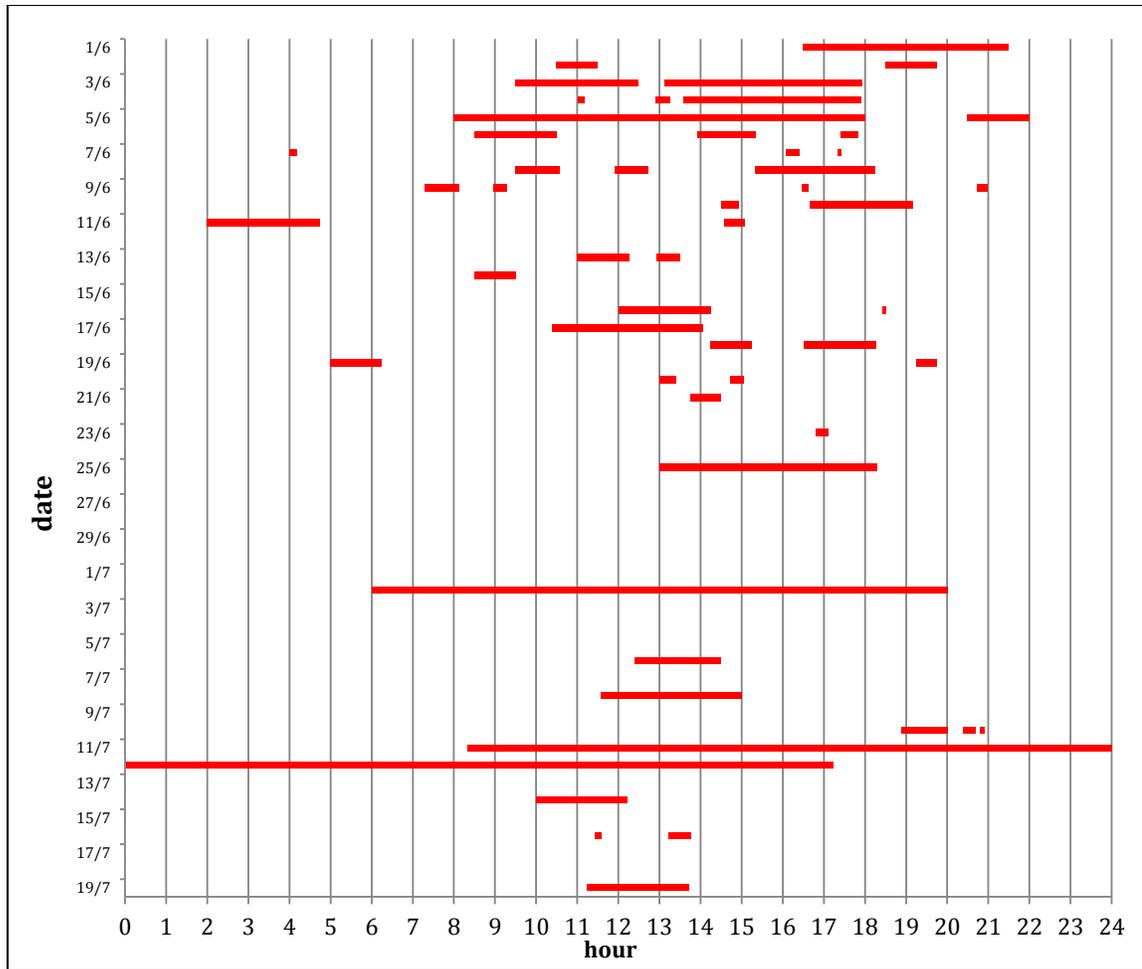


Chart 4. 17: Occurrence of power shortages in the study area (1st of June -19th of July).

In the chart above are shown, for every day of the registration period, the power shortages occurring along the day. The high frequency of power shortages estimated with the questionnaires was confirmed, since out of 49 days of registration there were 30 days with at least one power shortage and 17 with more than one power shortage per day. Power shortage duration was variable: for 5 days the total power shortage duration was below one hour; for 16 days ranged between 1 and 4 hours and for 9 days it was above 4 hours. A peculiar case was registered in the 11th of July when the power shortage started at 8.20 a.m. and lasted until the following day at 5.14 p.m., i.e. a duration of almost 33 hours.

Presence of voltage fluctuation and its consequences were analyzed through the questionnaires: all the interviewees have experienced voltage fluctuation, in particular

high voltage levels were recognized due to issues caused to the appliances. The high tension, greater than 240 V has caused damages to the electric appliances connected to the grid. Serious damages were reported in the laboratory of STCMC throughout the years and in SJCHS where 10 laptops were damaged in the last academic year and not repaired, making difficult the classes held in the computer lab. Moreover many other appliances were damaged, mostly refrigerators and televisions. In order to limit the damages voltage regulators were used extensively in the study area. However, for particular devices used to perform surgical operations in the Theatre voltage regulators were not sufficient to guarantee proper functioning of the appliances.

Electricity tariffs applied by the utility company to medium voltage level customers are reported in Appendix C.6, the tariffs varied with the class of consumption. Since every unit has a different electricity meter the electricity tariff was not the same for all the study area, it ranges from 79 FCFA/kWh to 99 FCFA/kWh [69].

Comparison between electricity tariffs in Cameroon, Nigeria [70], Italy and average of European Union [71] is reported in Table 4.14 in c€/kWh for the same consumption classes present in the study area.

Table 4. 14: Average electricity tariffs in Cameroon, Nigeria, Italy and EU by consumption classes

	Cameroon [c€/kWh]	Nigeria [c€/kWh]	Italy [c€/kWh]	Average EU [c€/kWh]
Class 1 (110 to 400 kWh/month)	12.04	9.13	14.27	15.74
Class 2 (400 to 1000 kWh/month)	15.09	9.11	15.04	13.97

The electricity tariffs in Cameroon were higher than the ones present in Nigeria, neighbor country, and comparable to the Italian and European tariffs despite the lower GDP.

Data regarding the electrical energy consumption in the study area were acquired from the electricity bills of every month, since 2012 for SJCHS and since 2010 for all the other units. The expenditures for electricity of the facilities in the study area are reported as averages in Table 4.15.

Table 4. 15 Average monthly electricity expenditures (FCFA) for the years 2010-2015.

	2010	2011	2012	2013	2014	2015
Convent	207,625	219,854	148,408	165,699	157,779	202,026
SJCHS			149,513	198,397	156,181	192,641
STCMC	89,734	118,622	124,750	152,589	159,905	148,900
SAJOCAH	129,065	158,862	154,083	127,223	110,763	117,763
Postulancy	19,770	18,072	21,350	32,492	26,297	33,212
Total	446,194	515,410	598,104	676,400	610,925	694,542

Diesel, LPG and kerosene are currently used in the study area and from the questionnaires it was possible to assess their consumption, cost and availability. Although diesel, LPG and kerosene were supplied at the local market, only kerosene could be directly purchased. While LPG and diesel need to be either ordered, and thus an extra transportation cost was charged, or bought directly from Bamenda, i.e. at a distance of about 15 km from the study area. Apart from the distance that needed to be covered, the buyer was often facing fluctuations of the fuels' prices, as it was testified by interviewees. From the lists of expenditures of STCMC of the last two years, the price instability of the fuels was confirmed. Kerosene and gas stoves were not being used, even if available, and firewood was preferred instead. The explanation given was the high cost of the conventional fuels, 15 FCFA/MJ for LPG, 14 FCFA/MJ for kerosene respect to firewood 4-8 FCFA/MJ.

4.3 Energy efficiency

4.3.1 Electrical

An evaluation of the mini grid of the study area was performed in terms of complexity, automation and efficiency. The mini grid was without an emergency line to serve the high priority loads, i.e. theatre, maternity department, physiotherapy treatment area and workshops. The current wiring system was constructed without a specific design: cables were added if needed without evaluating the optimal setup from an economic and technical point of view. Besides, the mini grid was old while regular and proper maintenance interventions was lacking: in case of fault only the affected part was

maintained. Maintenance can be performed only by the technicians of the study area since the wiring scheme was not mapped. Moreover, only a few protective devices and no automatic switches were present. In case of power shortages back-up generators need to be connected and switched on and off manually. Safety lights were switched on and off manually according to a scheduled plan regardless of the amount of natural light available. Additionally, some cables were observed that connected households in the surrounding area to the wiring system of the study area, contributing to “non-technical” losses.

All the units present in the study area, namely STCMC, SAJOCAH, SJCHS, Convent and Postulancy, present a different meter for the electricity withdrawn from the grid. The current wiring schemes obtained for SAJOCAH, SJCHS, STCMC, Convent and Postulancy are presented in the figure below.

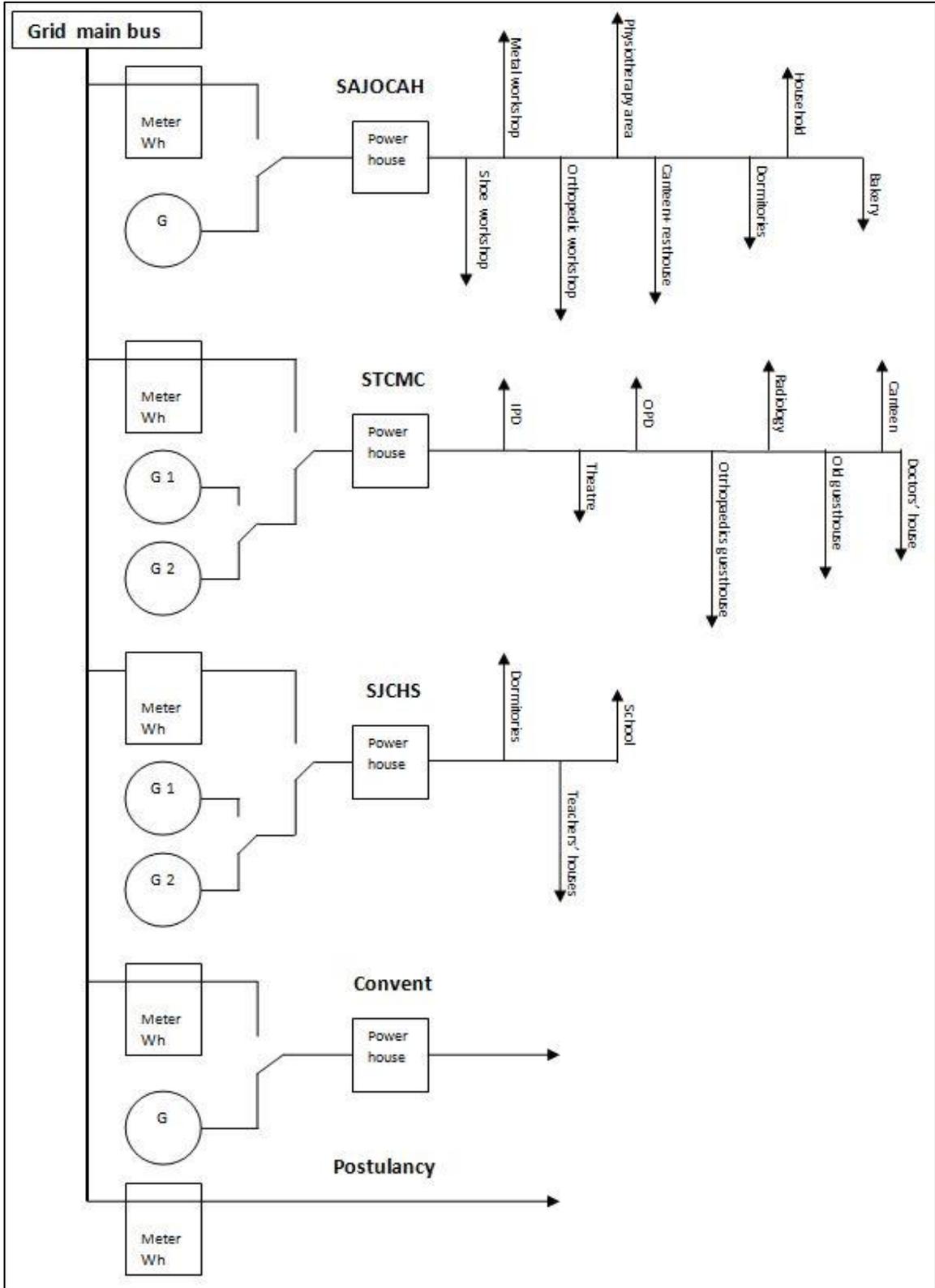


Figure 4. 8 Current wiring scheme of the study area. Source: Authors

4.3.1 Efficiency of conversion of cooking technologies

In this paragraph are presented the results obtained for the field assessment of technologies converting the firewood energy content in thermal energy related to public and artisan energy driver. In the domestic energy driver the only firewood stove type present was a three stone fire stove that was tested on site.

Public

The efficiency of conversion, as results from the experimental test performed on- field , in the actual conditions of use of the stoves in the public energy driver are reported in the following table:

Table 4. 16: Type of stoves and corresponding efficiency in the public driver.

Unit	Type of stove	η conversion [%]
SAJOCAH	Modified Plancha	20
SJCHS	Multi-pot brick Rocket	17
Convent	ICS 2 pots	20.8
Postulancy	ICS 3 pots	15.2

The average conversion efficiency in SAJOCAH and Postulancy increases up to 24.3 % and 17.4 % respectively if the doors of the combustion chamber were kept closed.

Artisan

The efficiency of the 3SF present in STCMC canteen, shown in Figure 4.9, was assessed through a WBT and the obtained value equal to 13%. This value was then assumed as the conversion efficiency of all the 3SF present within the study area.

The efficiency of the bakery oven was estimated, according to Equation 3.32, equal to 6.6%. During the interview with the baker revealed many issues related to the oven, especially because of the shared combustion and baking chamber and the difficulties to control of the temperature.

5. ENERGY SOLUTION PLANNING

Energy solution planning was proposed to obtain a more sustainable energy system for the study area taking into consideration technical, environmental and economic aspects. The following chapter is divided into two sections to take into account the two faces of energization: access to reliable electricity and access to modern and clean technologies for cooking.

5.1 Electrical solution planning

5.1.1 The mini grid

An improvement of the mini grid was proposed by redesigning it for better energy management. In Figure 5.1 is shown the proposed design of the mini grid for the whole study area.

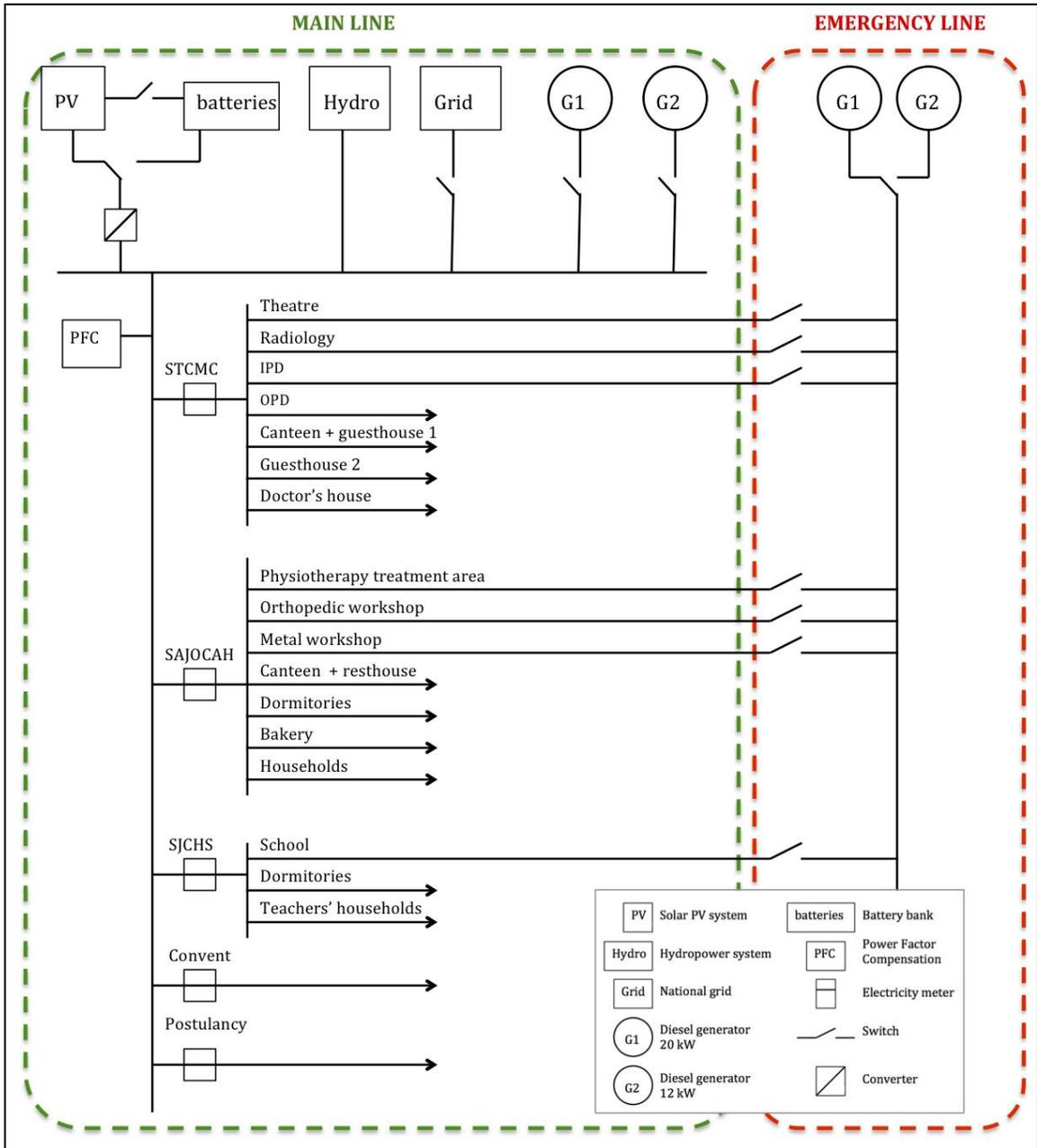


Figure 5. 1: Suggested wiring scheme of the study area including an emergency line. Source: Authors

The level of automation can be increased by installing automatic switches when a supply system is connected to make easier and faster the connection and the switch to emergency line. In order to reduce the electricity consumption it was suggested the installation of: solar light detecting sensors for the automatic operation of the safety lamps and time-

regulated switches for the automatic operation of the lamps according to the hour of the day.

Another way to improve the electrical energy efficiency was by applying demand side management, not only by reducing the daily average consumption, as achieved by installing automatic sensors, but also through load shifting. The healthcare and education services of the public energy driver were of high priority, while the artisanal activities were associated to the specific working hours of the personnel. The units where changes in the daily schedule were feasible and can be accepted by the consumers were the religious institutions within the public energy driver, i.e. Convent and Postulancy. The daily electricity consumption for lighting and running of appliances in the Convent and Postulancy is shown in Figure 5.2.

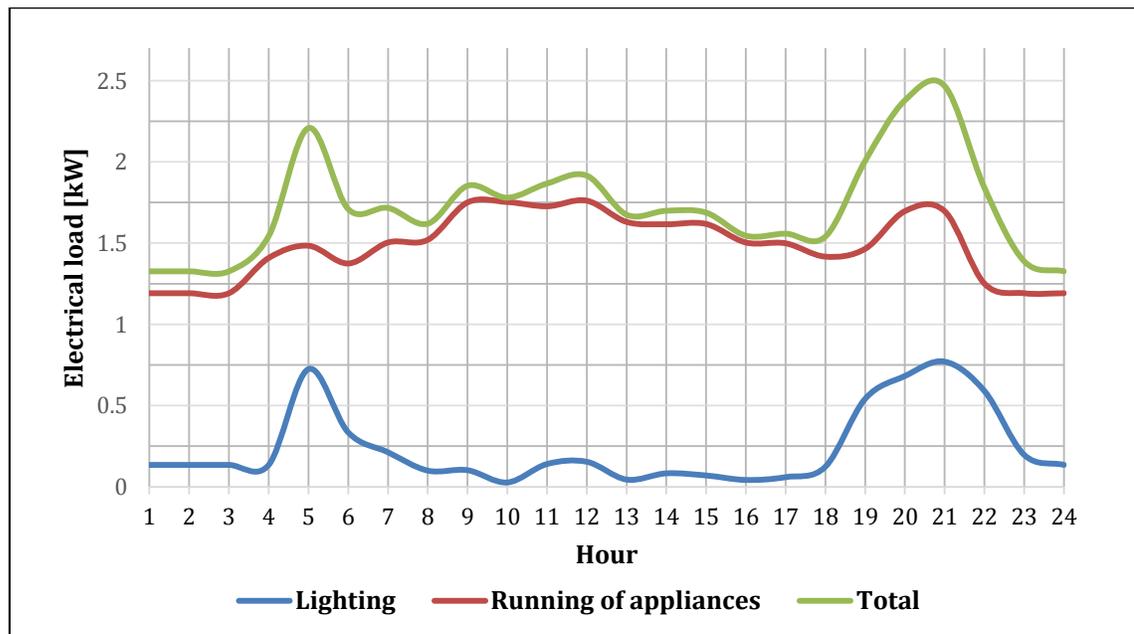


Figure 5. 2: Daily electricity consumption in the Convent and Postulancy.

As shown in the graph, two peaks occur during the day, one in the early morning and one in the afternoon. Since they consisted mainly of the demand for lighting, load shifting was not a feasible solution in this case; the automatic sensors presented before can contribute to the reduction of the amount of electrical energy consumed in these time windows. A high electricity consumption for running of appliances in the religious institutions was observed from 9 a.m. to 3 p.m., when there was highest total energy

demand in the public and the artisan energy drivers, as shown in Figures 4.2 and 4.4, mainly due to the high energy consuming appliances in the Theatre and the SAJOCAH workshops. In the religious institutions load shifting was suggested by moving the running of washing machines and the ironing to off-peak hours, namely after 2 p.m.

5.1.2 Electrical system

A centralized system for the supply of electricity in the study area was designed and simulated according to the mini grid proposed above.

In Figure 5.3 is presented a graph with the total load curve of the study area in a typical weekday on which the selection of type of component and size to be installed was based. The peak load, was about 30.2 kW and occurred between 10 and 11 am, while the base load was about 5 kW.

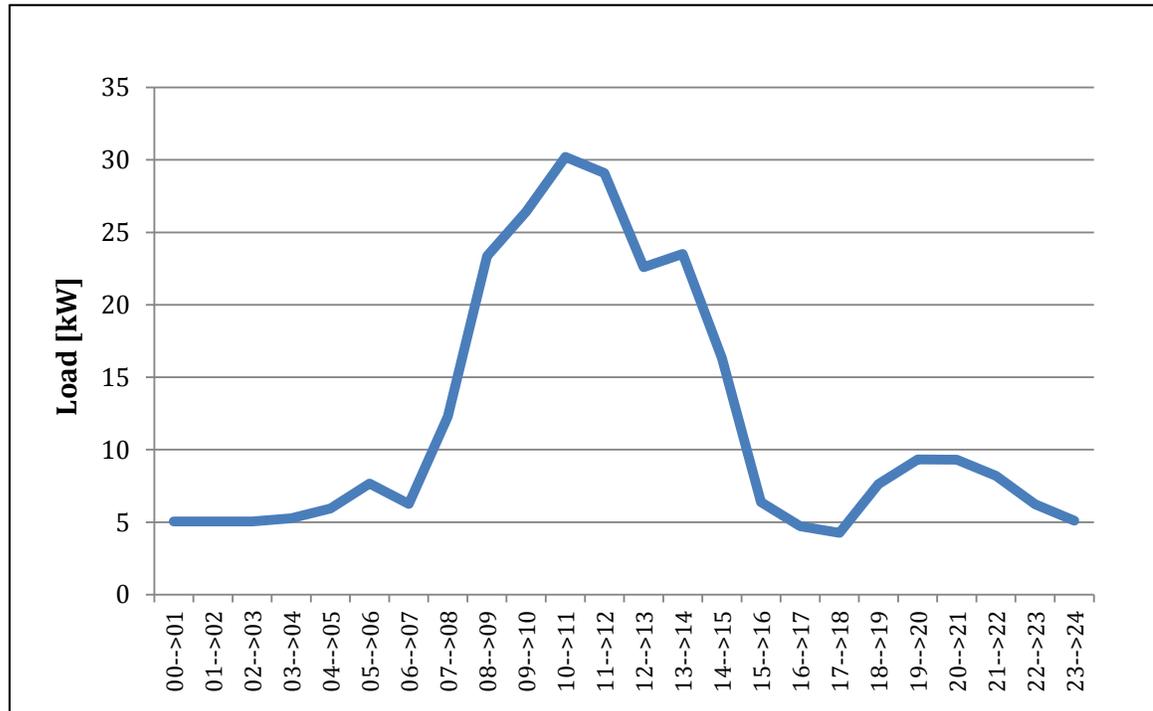


Figure 5. 3: Electrical load curve estimated for the study area.

Figure 5.3 together with the availability of RES computed in Chapter 4.2 was used for the design of the electrical power supply system. The RES taken into consideration were hydro, solar photovoltaic and wind turbines.

The power production of the hydro system ranges between 8.8 kW at minimum turbine partial load in March and 27.5 kW in the months from June to November at full load of the turbine. Considering an average of 18 kW and a capacity factor of 55% the energy resource per year is 314 GJ per year. The demand was equal to 291 GJ per year. Therefore the hydropower seems to be enough to cover the energy demand of the study area.

Since the peak load, as shown in Figure 5.3, is present between 8 a.m. and 3 p.m., when the solar resource reaches its maximum potential, a PV system has been considered to cover from 15% to 30% of the peak load. The sizes of PV system simulated are equal to 5 kW (15% of the peak load), 8 kW (25% of the load) and 10 kW (30% of the load).

Wind resource has a low potential, since the average wind speed, estimated in Chapter 4.2, was 1.8 m/s. The wind potential was 4.7 MJ/m². Even considering the wind turbine Honeywell 6500 [72], [73] suitable for low wind speed and with low cut-in velocity, the installation of a wind was not considered as favorable due to the cost of installation, 6500\$ for each turbine.

Two diesel generators were available in SJCHS, both of size equal to 12 kW, bought in 2014 each of them able to cover 40% of the electric load, these were used in the simulation to ensure system stability of the system.

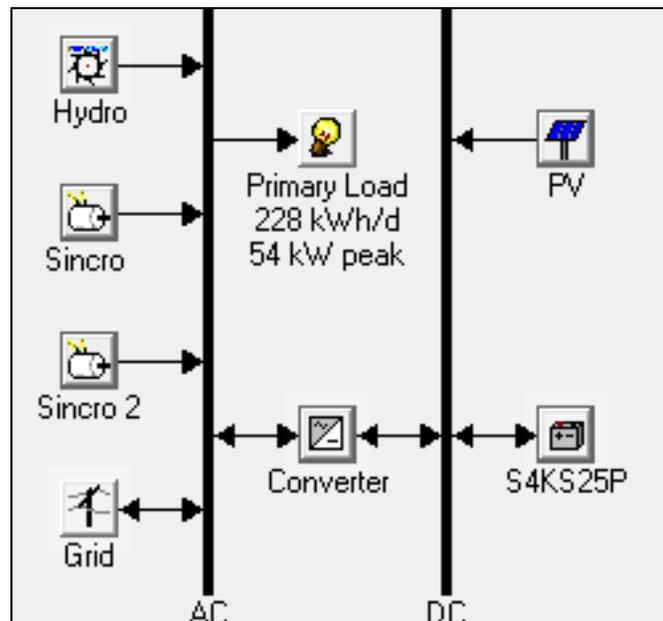


Figure 5. 4: System architecture

Two scenarios were taken into consideration for the simulations with HOMER®, each one with different system configuration. The first scenario was the "*Off-grid*" where the supply was based on the renewable energy sources locally available. In the second one, the "*Grid-RES*" scenario, the system included the national electricity grid.

All the components considered for the simulation are presented in Figure 5.4. In the AC bus the electric load, a hydro turbine the two diesel generators and the grid are connected, while to the DC bus are connected the photovoltaic system and the battery bank. Finally, a converter connects the two buses.

Both seasonal and weekly variability were taken into account in order to simulate the changes in electric load throughout the year according to the real electricity consumption. For the seasonal variability, SJCHS was assumed closed for the months of June, July and August while a medical mission of volunteers from abroad was assumed to be realized twice a year, for two weeks in February and two weeks in October. Regarding the weekly variability two profile days for each month were taken into consideration, according to HOMER® limitations, for weekdays and weekend. The weekday was estimated as an average of all the different profile working days, while the weekend profile day was created according to the electricity consumption for Sundays. For random variation of the load noise levels were added: 15% daily and 20% hourly.

The characteristics of the components that were taken into consideration as input data for the simulation of the systems are presented in the following paragraphs. Cost inputs were assumed based on information from market research [63] considering a mark-up for the local market based on the scientific papers of Bekele [20] and Nfah [22].

A cross flow turbine with design flow rate of 120 l/s was selected due to its capacity of adapting to variable flow rate from 30% to 100% of the design one [75],[76].

The turbine efficiency considered is 82% and the available head amounts to 39 m giving the nominal size of the system equal to 37.6 kW. Pipe head losses are assumed equal to 40% due to the large distance between the intake and the powerhouse location. The hydropower system capital, replacement and O&M cost as well as the expected lifetime of the system are presented in Table 5.1.

Table 5. 1: Costs and lifetime of the hydropower system.

	Capital cost [\$]	Replacement cost [\$]	O&M cost [\$/yr]	Lifetime [yr]
Hydropower system	80000	15000	50	25

The capital cost of the hydropower system includes the cost of civil and electric connection works, while the replacement cost is based on the hydropower turbine.

For the solar photovoltaic the cost input data per unit of nominal size are reported in Table 5.2, according to the electric load were simulated PV system with size equal to 5 kW, 8 kW and 10 kW.

Table 5. 2: Costs and lifetime of the PV system per unit of installed power.

	Capital cost [\$/kW]	Replacement cost [\$/kW]	O&M cost [\$/yr]	Lifetime [yr]
PV system	2500	2000	30	20

For the PV system a ground reflectance of 20% and a PV panel with derating factor of 80% are considered as default values in Homer®. PV system is to be mounted without a tracking system at a slope of 5.9 degrees (equal to the latitude of the site). Due to the intermittency of the RES generation a battery bank is required in order to guarantee that the electrical load is continuously satisfied even in case of sudden changes in the weather conditions. Energy produced and not consumed immediately is stored and utilized to cover the load in a different time of the day when the production is lower.

The type of batteries was chosen based on a feasibility study in Ethiopia [20] among the models present in HOMER® dataset. Surrrette 4KS25P is the chosen model, manufactured by Rolls/Surrrette, with 4 Volt nominal voltage and every string consisting of 6 batteries. A number of strings ranges from 0 to 10 was considered in the simulation. Both load following and cycle charging dispatch strategies were simulated.

The lifetime and costs of the batteries are presented in Table 5.3.

Table 5. 3: Costs and lifetime of the battery bank.

	Capital cost [\$/string]	Replacement cost [\$/string]	O&M cost [\$/yr]	Lifetime [kWh]
Battery bank	1100	1100	10	10494

Since PV system generate in DC while the load is served in AC a converter is required. The converter considered is assumed to operate with the same capacity as inverter and rectifier with efficiencies of 90% and 80% respectively. Based on the load characteristics converters of capacity equal to 5 kW, 10 kW and 15 kW were simulated. Costs and lifetime of the converter are presented in Table 5.4.

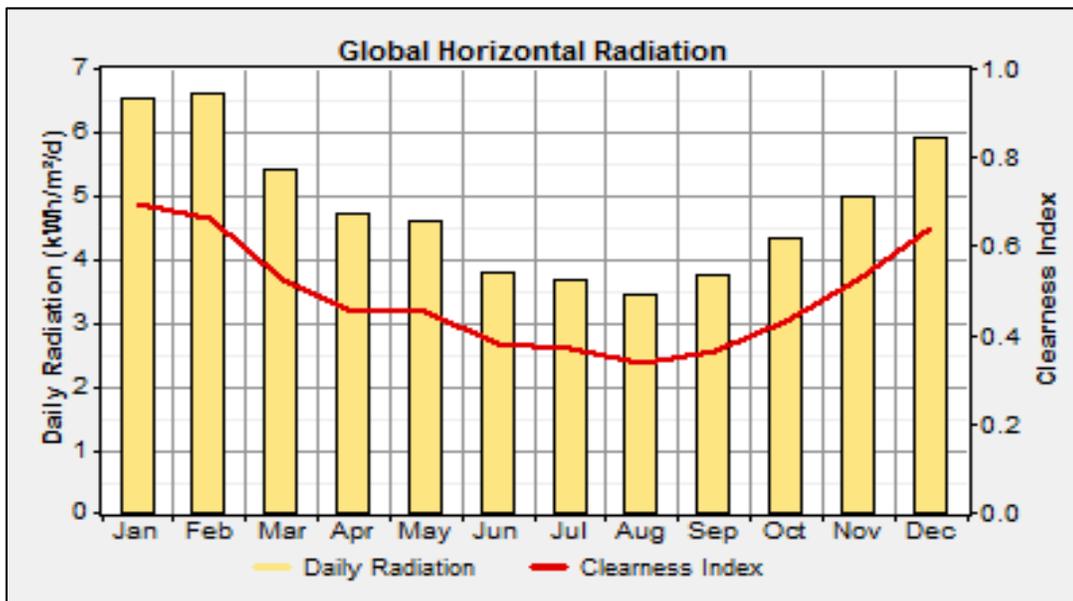
Table 5. 4: Cost and lifetime of the converter.

	Capital cost [\$/kW]	Replacement cost [\$/string]	O&M cost [\$/yr]	Lifetime [yr]
Converter	1000	1000	30	15

In the study area are currently present six diesel generators used as backup, two were taken into consideration for the system due to their suitable size, equal to 12 kW, and better general condition. Since they were bought in 2014 the residual lifetime was estimated equal to 40000 hours, the capital cost was considered null and the replacement cost assumed equal to \$7000.

The solar resource inputs consist of twelve average monthly values for solar radiation throughout a year as well as the latitude of the site. The solar radiation values presented in Figure 5.5 include monthly averages estimated as explained in Chapter 3.2.

Figure 5. 5: Monthly average solar radiation and clearness index respect to the study area.



The average stream flow available to the hydro turbine each month is given as HOMER® input regarding the hydro resource. The variation of the flow during a whole year is shown in Figure 5.6. Besides, a minimum residual flow equal to 35 l/s is considered.

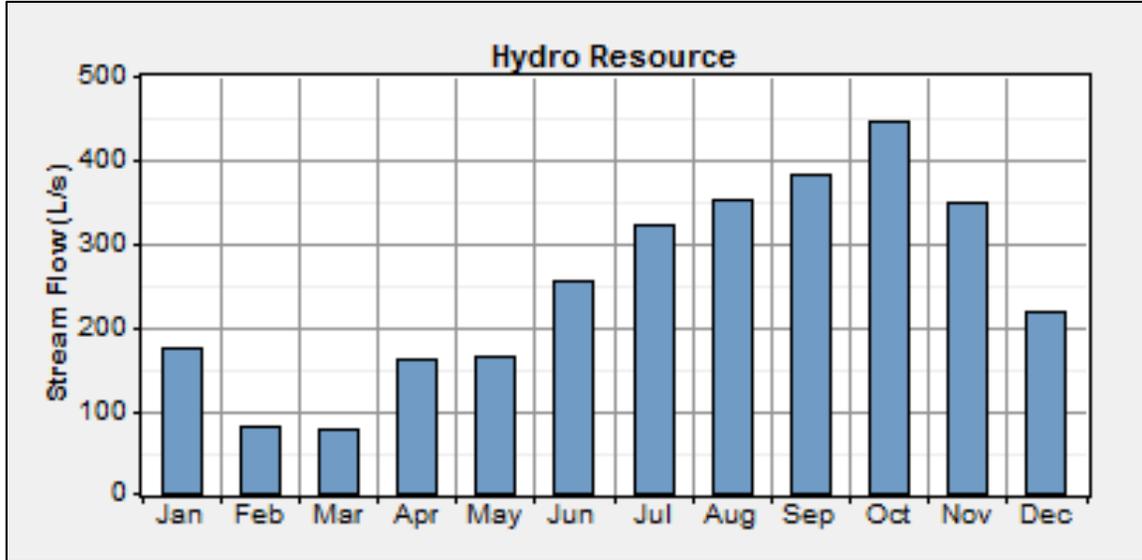


Figure 5. 6: Monthly average stream flow available to the hydro turbine

The price for the diesel is estimated based on data on the expenses found on bills and receipts and is assumed equal to 0.81 \$/l. The limit for the maximum consumption of diesel is considered 1000 l/year, equivalent to the actual annual consumption for electricity production within the study area. In residential sector the maximum allowable annual capacity shortage is set to 10% according to [77] in this study a more stringent limit, equal to 5% was assumed due to the sensibility of the electric load in the public sector.

Off-grid

The system configuration obtained by the software simulation for the Off-grid system are presented in the following figure, where they are categorized by type of component included and listed in ascending order of total net present cost (NPC).

	PV (kW)	Hydro (kW)	gen1 (kW)	gen2 (kW)	S4KS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)
	5	37.6	12	12	6	10	CC	\$ 109,100	729	\$ 116,185	0.148
	5	37.6	12		6	10	CC	\$ 109,100	1,026	\$ 119,062	0.152
	5	37.6		12	6	10	CC	\$ 109,100	1,026	\$ 119,062	0.152
		37.6	12	12	18	10	CC	\$ 109,800	1,049	\$ 119,988	0.152
		37.6	12		18	10	CC	\$ 109,800	1,345	\$ 122,865	0.156
		37.6		12	18	10	CC	\$ 109,800	1,345	\$ 122,865	0.156
	5	37.6			18	15	CC	\$ 127,300	840	\$ 135,458	0.175

Figure 5. 7: Optimization results for the Off-grid option.

The optimal solution suggested by HOMER® for the Off-grid scenario includes the hydropower system, a PV system of size equal to 5 kW and both diesel generators currently present in the study area, six batteries and a 8 kW converter. The dispatch strategy selected is cycle charging, meaning that when a generator runs, it runs at full power and charges the batteries. The net present cost of the off-grid solution amounts to \$116185, with a LCOE equal to 0.148 \$/kWh and an operating cost of 729 \$/yr. The NPC for all the components of the optimal solution is reported in Figure 5.8.

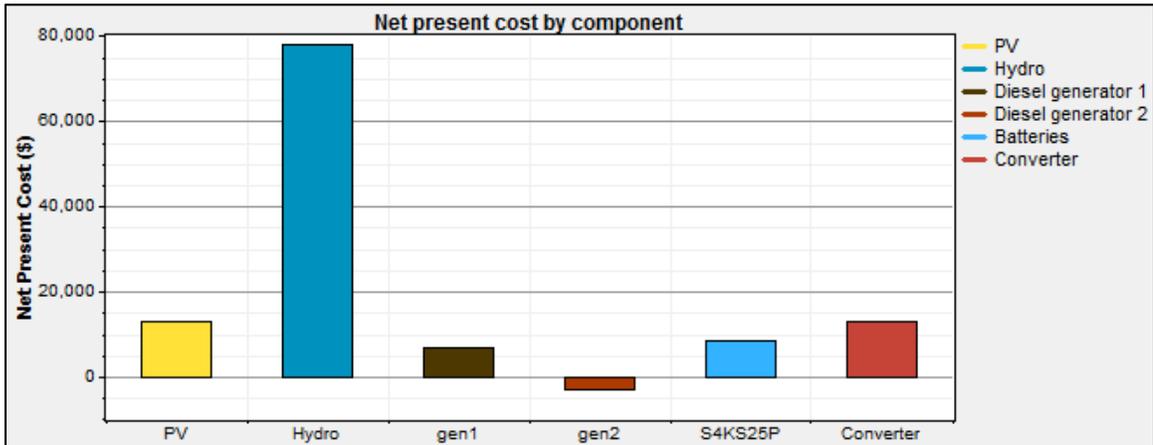


Figure 5. 8: Net present cost by component of the Off-grid system (namely hydro and PV systems, two diesel generators (gen1 and gen2), battery bank (S4KS25P) and converter).

The main contribution to the NPC is represented by the hydropower system, due to its large capital cost in the year of construction, corresponding to 67.1 % of the total net present cost of the system.

The production of electricity is shared between the hydropower system, the PV system and the diesel generators. The annual production from the hydropower system is equal to

639.2 GJ/yr, corresponding to 94% of the total production, while 25.6 GJ/yr are produced by the PV system, corresponding to 4% and 12.2 GJ/yr by back-up generators. The total electrical production that amounts to 677GJ/yr satisfies therefore the total electrical demand of 291 GJ/yr. The excess of electricity produced by the energy system reaches a high value of 378 GJ/yr due to continuous hydroelectric power production compared to a high difference between peak and base loads to be satisfied, as shown in the figure in Appendix E.1. The monthly average electricity production by source along the year is shown in Figure 5.9.

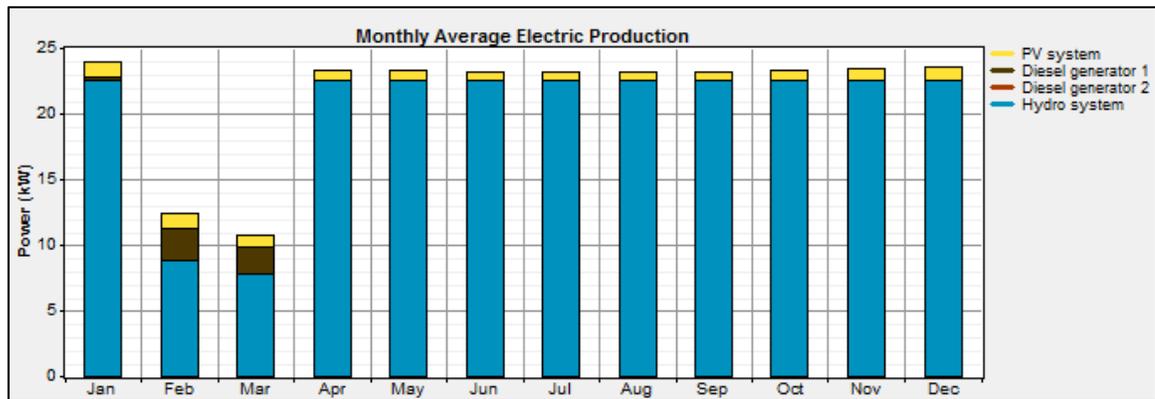


Figure 5. 9: Monthly average electricity production of the Off-grid system.

Figure 5.9 shows that the hydro system reaches its maximum power output, equal to 22.6 kW, during the period from April to January. On the other hand, in March, in the end of the dry season, the hydropower output reaches its lowest value. The maximum output of the PV system reached in the month of the dry season, from December to March, was equal to 4.86 kW. In order to satisfy the electrical demand during the months of February and March the maximum values for electrical power output of the diesel generator were observed equal to 12 kW.

Electrical load, electricity production by hydropower system, PV system and diesel generators as well as the battery discharge power of a sample day in March are shown in Figure 5.10. This day was chosen in the month of minimum hydropower production to show the mix of sources used along the 24 hours to cover the primary load.

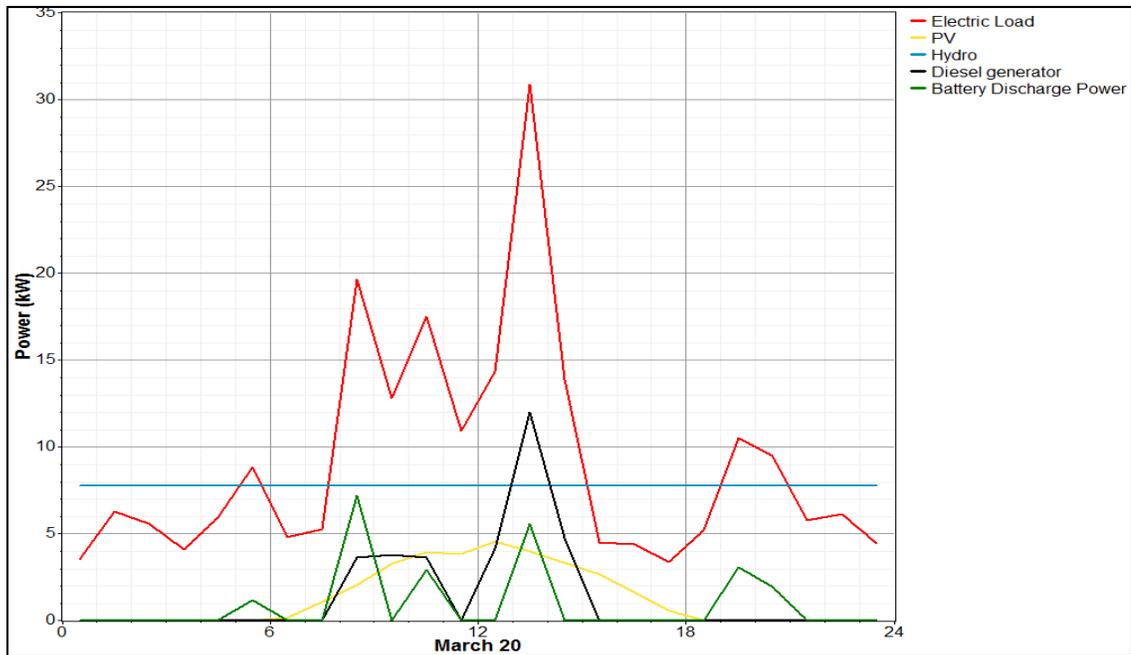


Figure 5.10: Electrical load and power production for the Off-grid system (by hydro system, PV system, generator and battery discharge) for a sample day.

The hydropower production is constant along the day and equal to 8.8 kW. When electric load exceeds the hydropower production, power from the PV system and diesel generator covers part of the load from 8 a.m. to 3 p.m. The energy stored in the batteries from the production in excess is used to meet the highest peaks along the day.

Grid-RES

The second scenario analyzed includes the same piece of equipment simulated in the Off-grid configuration as well as the national electricity grid.

The same inputs regarding resources, sizes and cost characteristics of the equipment (PV, hydro turbine, wind turbine, batteries and converter) were simulated. The electricity from the grid is provided from the national utility company applying a single tariff, i.e. there are no different tariffs according to the hour and the type of the day (Weekday or Holiday). In the study area a tariff equal to 99 FCFA/kWh was chosen to perform the simulation according to class of consumption of the study area. The national grid was considered as capable of absorbing the excess electricity, produced from the local RES-

based power systems, in case of need and providing the electricity to cover the peak demand.

The system configurations obtained for the Grid-RES system are presented in the following figure.

	PV (kW)	Hydro (kW)	gen1 (kW)	gen 2 (kW)	S4KS25P	Conv. (kW)	Disp. Strgy	Grid (kW)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)
		37.6	12	12			CC	1000	\$ 80,000	1,069	\$ 90,383	0.049
		37.6	12				CC	1000	\$ 80,000	1,365	\$ 93,260	0.051
		37.6		12			CC	1000	\$ 80,000	1,365	\$ 93,260	0.051
		37.6					CC	1000	\$ 80,000	1,662	\$ 96,137	0.052
		37.6	12	12	6	5	CC	1000	\$ 91,600	788	\$ 99,255	0.056
		37.6	12		6	5	CC	1000	\$ 91,600	1,084	\$ 102,132	0.057
		37.6		12	6	5	CC	1000	\$ 91,600	1,084	\$ 102,132	0.057
		37.6			6	5	CC	1000	\$ 91,600	1,381	\$ 105,009	0.059
	5	37.6	12	12		5	CC	1000	\$ 97,500	884	\$ 106,085	0.057
	5	37.6	12			5	CC	1000	\$ 97,500	1,180	\$ 108,962	0.058

Figure 5. 11: Optimization results for the Grid-RES scenario

The optimal system configuration includes centralized national electricity grid, hydropower system and diesel generators that were already present in the study area therefore they do not introduce an extra capital cost. The net present cost of the grid connected solution was equal to \$90383, with a LCOE equal to 0.049 \$/kWh, therefore convenient compared to the electricity grid tariff equal to 0.165 \$/kWh. The operating cost of the system corresponds to 1069 \$/year. The contribution of each component of the optimal solution to NPC is shown in Figure 5.12.

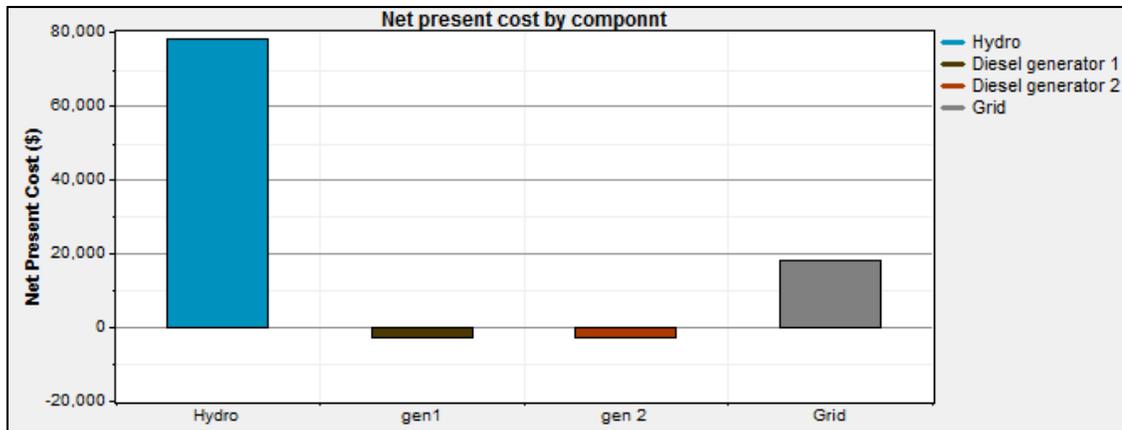


Figure 5. 12: Net present cost by component of the Grid-RES system (namely the hydro systems, the two diesel generators (gen1 and gen2) and the national electricity grid).

The NPC of the grid represents the electricity purchased along the project lifetime.

The production of electricity is shared between the hydropower system and the national grid with an annual production from hydropower equal to 639.2 GJ/yr corresponding to 94% of the total production and the purchases from the grid corresponding to the remaining 6% equal to 37.8 GJ/yr. The extra production of electricity from the hydro system was re-injected in the grid that acts like a storage device for the system. Therefore, the surplus of electricity as well as the capacity shortage were null. The average electric production along the year is reported in Figure 5.13.

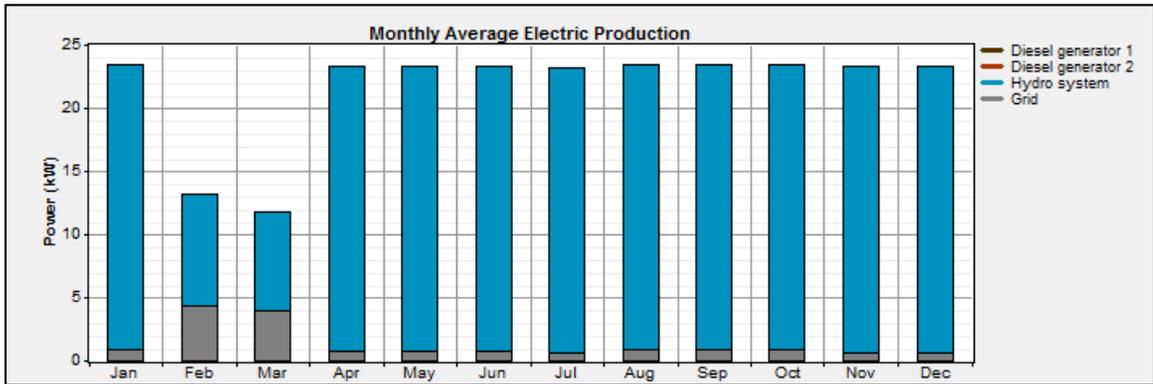


Figure 5. 13: Monthly average electricity production of the Grid-RES system.

The electricity production from the hydropower system has the same trend as in the Off-grid scenario, with lowest value in March, when the grid purchases reach the maximum corresponding to 4.1 kW to meet the load. The highest value of electricity purchase from the grid, equal to 45 kWh, is reached in February, when the hydropower production is at its minimum and the demand is maximum. For the Grid-RES system, for a sample day in March, the production from the system components as well as the demand is shown in Figure 5.14.

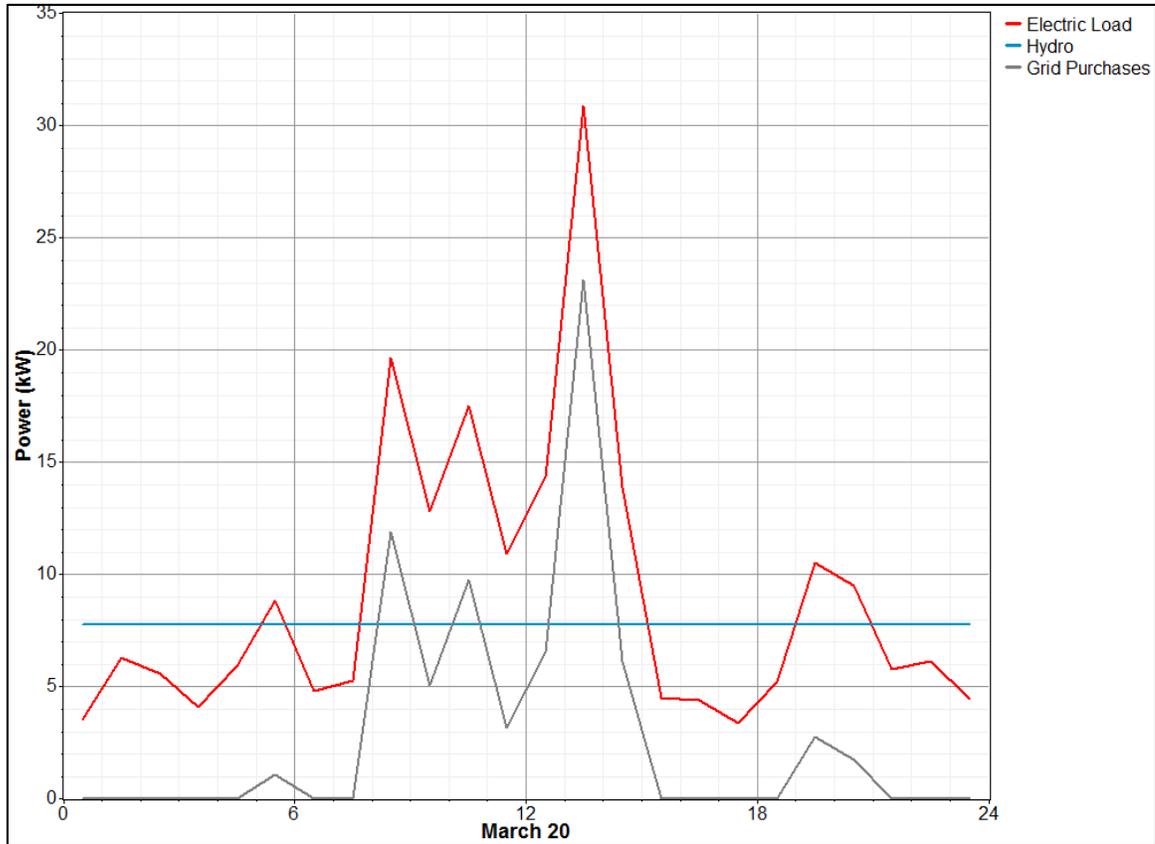


Figure 5. 14: Electrical load, hydropower output and grid purchases in a sample day

When the hydropower production is lower than the power demanded, electricity is purchased from the national grid to cover the peaks in the load instead of production from the PV system and diesel generators like in the Off grid system. The annual power output is presented in Appendix E.

Comparison of Emissions

In the framework of COP21, the equivalent emissions of CO₂ were compared for the current electricity supply system, the Off grid system and the Grid-RES system. Emissions from the national electricity grid were computed based on the mix of production, reported in Chart 1.1, and considering emissions for the power generation in the country according to IEA [78]. Emissions for the RET systems were estimated considering the specific emissions of each technology according to [5]. Emissions from

diesel generators were considered according to [79]. The carbon footprint of the three electricity supply systems are reported in the following table.

Table 5. 5: Equivalent annual CO₂ emissions from the electricity supply systems

Electricity supply system	Annual CO₂ emissions [kg_CO₂/year]
Current system: supply from the grid	9117.9
Off grid system	3468.2
Grid-RES system	2453.8

The reduction in CO₂ emissions with the shift to a new electricity supply system was large in both Grid-RES and Off grid scenario due to the high penetration of hydropower production. The emissions for Grid-RES system were lower with respect to the Off grid case since in *Grid-RES* option there was no use of diesel generators that have higher specific emissions with respect to the average specific emissions of the national electricity grid.

Sensitivity analysis

In both Grid-RES and Off grid systems the hydropower capital cost represent the highest contribution to the NPC and LCOE since it covers the highest share of the load. The LCOE values correspondent to the different investments cost of hydropower plant are reported and compared with the base case (\$80000) in Table 5.8 for Off-grid and Grid-RES options.

The difference in LCOE is proportional to the difference in capital cost for the hydropower, as shown in the table above, both in case of Off-grid and Grid-RES system, the influence of capital cost of the hydropower system is stronger in Grid-RES case.

Table 5. 6: Sensitivity analysis on hydro system capital cost for *Off grid* and *Grid-RES* option

Hydro capital cost [\$]	<i>Off grid</i>		<i>Grid-RES</i>	
	LCOE Off-grid [\$/kWh]	Δ LCOE Off-grid	LCOE Grid-RES [\$/kWh]	Δ LCOE Grid-RES
80000	0.148	-	0.049	-
70000	0.135	-8.7%	0.044	-10%
90000	0.161	+8.7%	0.055	+12.2%

In case of *off-grid* system the optimal solution includes also a PV system of 5 kW therefore the capital cost of the PV system was evaluated for the hybrid solution. Even if capital and replacement cost of the PV system are linked along the lifetime of the project (20 years) there is no replacement of the PV system due to its expected lifetime equal to 20 years. The variation of LCOE, correspondent to a variation of PV costs of $\pm 10\%$ are shown in the following table.

Table 5. 7: Sensitivity analysis on PV capital costs for the *Off grid* system

PV capital cost [\$]	LCOE [\$/kWh]	Δ LCOE
12500	0.148	-
11250	0.147	-0.7%
13750	0.150	+1.3%

Due to the small size of the PV system and the correspondent low energy production from it respect to the hydropower system, the influence of the PV capital cost on the levelized cost of electricity is negligible.

A sensitivity evaluation was performed on diesel fuel cost in a range between 0.73\$/l and 1.05\$/l in case of *Off grid* system. According to the result of the simulation, diesel generators are used in the dry season when hydropower production is at its minimum value and cannot satisfy the electricity demand of the study area especially peak load.

The LCOE values as well as the O&M cost for the system with different diesel prices are reported in the following table.

Table 5. 8: Sensitivity analysis on diesel price for *Off grid* system

Diesel price [\$/L]	O&M cost [\$/year]	ΔO&M cost	LCOE [\$/kWh]
0.81	729	-	0.148
0.73	650	-10.8%	0.147
0.89	809	+11%	0.149
0.97	889	+21.9	0.150
1.05	969	+32.9	0.151

The price of diesel fuel influences the O&M cost that varies up to 32.9%, but the influence of this cost component on the levelized cost of energy is low since diesel consumption is limited to 1000 liters per year and the major component of the LCOE is represented by the hydropower investment cost.

For the Grid-RES scenario was included as sensitivity variable the electricity tariff, since the system is connected to the grid and the national electricity company provide the power to supply the load whenever the hydropower system is not sufficient. The electricity tariffs for which the sensitivity analysis was performed are equal to 0.149 \$/kWh, 0.152 \$/kWh, 0.161 \$/kWh (base case), 0.17 \$/kWh, 0.176 \$/kWh. The tariffs are constant for all the hours of the day and corresponding to the tariffs currently applied to medium voltage customers for different classes of consumption. The evaluation was based on the levelized equivalent cost of energy and comparison of O&M costs of the system per year as shown in Table 5.9.

Table 5. 9: Sensitivity analysis on electricity tariffs for *Grid-RES* system

Electricity tariff [\$/kWh]	O&M costs [\$/year]	ΔO&M costs	LCOE [\$/kWh]
0.161	1069	-	0.049
0.149	930	-13.0%	0.048
0.152	965	-9.7%	0.049
0.17	1174	+9.8%	0.050
0.176	1253	+19.0%	0.050

The influence of the electricity tariffs is relevant for O&M cost of the system while for the LCOE is negligible since electricity purchased from the grid correspond only to 6% of the total annual supply.

The Grid-RES system is suggested between the two options considering that it has a lower NPC and LCOE since there is no investment cost for PV installation and the connection to the grid is already present in the area, also emissions of carbon dioxide are lower for this option. Moreover, in the current electric load situation there is a large amount of extra production that can be injected in the grid in Grid-RES option solving the problem of handling this electricity in excess.

5.2 Thermal solution planning

Ad-hoc solutions were suggested in accordance to the strategy proposed in the Chapter 3.4.2 to obtain a reduction of the energy consumption related to the use of firewood in public and artisan energy driver. In the study area the following energy services were identified to be satisfied mainly using firewood adopting low efficiency conversion technologies: cooking in the public and artisan energy driver, baking in the artisan driver. Water heating need in the public driver was not fulfilled.

The suggested solutions to satisfy the energy need to fulfill these services were evaluated from the technical point of view taking into account the feasibility, the adoption of RET based on biogas and solar sources and the increase in conversion efficiency of stoves and oven.

Cooking: biogas stoves

The energy required for cooking and the means of supply were analyzed separately in SJCHS and in the rest of the units.

The final energy demand for cooking amounted to 14.5 GJ/month in the public energy driver and 6.2 GJ/month in the artisan driver satisfied from firewood and LPG.

The solution suggested to reduce the firewood energy consumption and use more clean and efficient cooking facilities was the installation of biogas stoves and improvement of the efficiency of the firewood stoves.

The amount of energy production estimated from biogas was equal to 36.2 GJ/month in case of installation of a single digester to serve part of public and artisan drive (SAJOCAH, STCMC, Convent and Postulancy).

Considering an efficiency equal to 42% for biogas, according to [80], 15.2 GJ/month will be obtained from biogas which can cover 75% of the energy need for cooking (20.2 GJ/month). Therefore, it is suggested the installation of biogas stoves to substitute the currently present firewood stoves in some selected kitchens in the public and artisan driver.

Biogas stoves were selected as the best available option for these kitchens where the meals were cooked in large quantities by a limited number of persons that can be trained on the use of the new stoves. In Table 5.10 is compared the primary energy required for cooking with the current stoves and with the biogas stoves in the selected kitchens of the public and artisan driver.

Table 5. 10: PE for cooking with current and biogas stoves

Unit	Initial PE demand with firewood stoves [GJ/month]	PE demand with biogas stove [GJ/month]	Energy savings [GJ/month]
SAJOCAH kitchen	11.8	5.6	6.2
Convent kitchen	10.9	5.7	5.2
Postulancy kitchen	8.5	3.0	5.5
SAJOCAH Canteen	7.9	2.4	5.4
STCMC Canteen	3.9	1.2	2.6
Total	43.0	17.9	25.1

From the estimated biogas production (36.2 GJ/month), 17.9 GJ/month was used to meet the cooking needs in the selected kitchens. The balance equal to 18.3 GJ/month is available to meet other needs (water heating to be discussed in subsequent paragraph).

Cooking: Improved Cooking Stoves

For the kitchens of the public driver in STMC the option of substitution of 3SF with ICS was considered. Since the number of users was variable and large along the year the aim in these kitchens was to reduce the firewood consumption and improve the indoor air quality by adopting a clean and efficient cooking device. In STCMC there were two kitchens for users with four and six 3SF respectively. In these two kitchens the installation of improved stoves was suggested, based on compatibility of size and simplicity of use.

In the kitchens of STCMC was suggested the installation of ten Chitetezo stoves, an African model of ICS that can be built with local material and has been tested to reach an efficiency of 31% [90].



Figure 5. 15: Chitetezo stove. Source: cleancookstoves.

In order to provide the final energy for cooking in the these kitchens, by adopting ICS instead of 3SF, 2.4 GJ/month of primary energy from firewood will be required. This action will result in an energy saving of 3.5 GJ/month.

In SJCHS improvement to the currently used stove was evaluated to increase its efficiency and consequently reduce the firewood consumption. The current stove has two feeding openings and no chimney, the suggested modification to the current design was the relocation of the feeding openings on the outside wall of the stove and the introduction of a chimney to decrease the level of smoke in the room. In order to increase the current efficiency (17%) the combustion chamber was to be kept closed during cooking operations by adding two doors to the feeding openings. These modifications could move the efficiency of the stove towards the one of an Astra stove (40%). This would lead to reduce the primary energy consumption to 20 GJ/month.

Artisan baking

The bread production of the study area bakery was around 950 kg/week of bread loaves with a production of approximately 150 kg per day from Monday to Friday and 200 kg on Saturday. The energy required for baking can be substantially reduced by substitution of the current ovens with improved ones.

The Kigali Institute of Science, Technology and Management of Rwanda has designed a new bread oven with firewood reduction efficiency of 75% respect to traditional ovens [83] [84]. This fuel-efficient bread oven was selected since it is appropriate for institutional use and can bake 320 small loaves at a time or totally four thousand loaves in three hours. [83] [84]. The efficiency of the current ovens was estimated as 6.6% (paragraph 5.1.1) while with the improved bread oven it can arrive up to approximately 26.3%. Therefore the primary energy supply required to satisfy completely the energy need for baking amounts to 13.4 GJ/month, i.e. a reduction corresponding to 75%.

Another option considered to improve the efficiency of baking in the study area was the substitution of the actual oven with an electric one. The selection was based on the models available in the US market evaluated by the *Energy Star* and *Food service technology center* in California. The evaluated full size convection oven was a Blodgett mark V-III, with a production rate of 44 kg/hour, and an efficiency of 73% [85]. The electricity consumption, considering a 220 V feed, corresponds to 9.7 kWh. Since 3.5 hours of use are required in a weekday and 4.5 hours on Saturday to meet the current

bread production, the monthly electricity consumption for the oven accounts for 3.1 GJ/month. From the load curve obtained in paragraph 5.1.1 there are possibilities for baking to occur when excess energy is produced from the electricity supply system, for example from 3 p.m. to 7 p.m.; the implications on power installation and energy supply strategies were analyzed with Homer.

In Grid-RES system, suggested as preferable, the electricity to cover the load of the oven is purchased from the grid so it is not required a change in the system architecture. The grid purchases are equal to 46.8 GJ per year, the NPC is \$92574 per year - an increase of \$2191 (2.4%) respect to the same system without electric oven - and LCOE equal to 0.50 \$/kWh - with an increase of 0.01 \$/kWh (2%).

Considering issues related to imported technologies, i.e. local know-how in operation and maintenance and spare parts availability, the installation of improved firewood oven is suggested among the two alternatives.

Public water heating

The demand for hot water was currently satisfied in Convent and Postulancy by using electric boilers while hot water was not available for the patients of STCMC and SAJOCAH and for the students of SJCHS. Therefore, the need for water heating in the public energy driver was currently below the minimum standards prescribed by WHO [65]. The lack of hot water can cause health issues to people, especially to patients that are in poor health conditions.

The solution suggested to satisfy the hot water demand for STCMC and SAJOCAH was based on the installation of biogas boilers. The demand for hot water was computed considering the average number of patients in SAJOCAH was 80 and an average number of patients hospitalized in STCMC was 100. The total demand for hot water, computed according to Equation 3.33, was 10.5 GJ/month. To satisfy the demand for hot water using biogas boilers with an efficiency of 80% [86] 13.2 GJ/month of biogas would be required.

This amount will be met from the excess of 18.3 GJ/month after using biogas for cooking in the selected kitchens.

For the hot water demand of SJCHS students it was suggested the installation of biogas boilers and solar thermal collectors. The total final energy required for water heating, considering an average number of students of 300, corresponds to 15.7 GJ/month. Considering biogas boilers with efficiency equal to 80% the amount of biogas needed to meet the need would be 19.6 GJ/month. The biogas production for SJCHS was estimated at 8.7 GJ/month, therefore the biogas boilers can cover 43.9 % of the energy demand for hot water. The remaining 63.9% could come from solar thermal.

The size of the solar hot water production plant has been estimated according to Equation 3.34 assuming a flat thermal collector of 60% efficiency and an efficiency of the system equal to 85%. The minimum value of sun irradiation registered in August in the study area was 390.6 MJ/m²/month. The SWH obtained to satisfy the hot water demand of SJCHS was 44.2 m². This area corresponds to 15 panels with area equal to 2.99 m². The total investment cost was between 15000\$ and 20000\$, [92] therefore compatible with investments in a rural area.

5.3 Prospective energy balance

In the following paragraph is proposed a comparison of the energy supply system of the study area between two suggested systems based on *Grid-RES* and *Off grid* options. The medium and low grade energy supply for thermal purposes is realized using the same sources in both the schemes while the type and magnitude of sources for electricity supply differs. The analysis and comparison is proposed through two energy flow diagrams for the whole study area. In Figure 5.16 and 5.17 are presented the energy balances of the study area, in form of Sankey diagram, for *Off grid* and *Grid-RES* system, respectively.

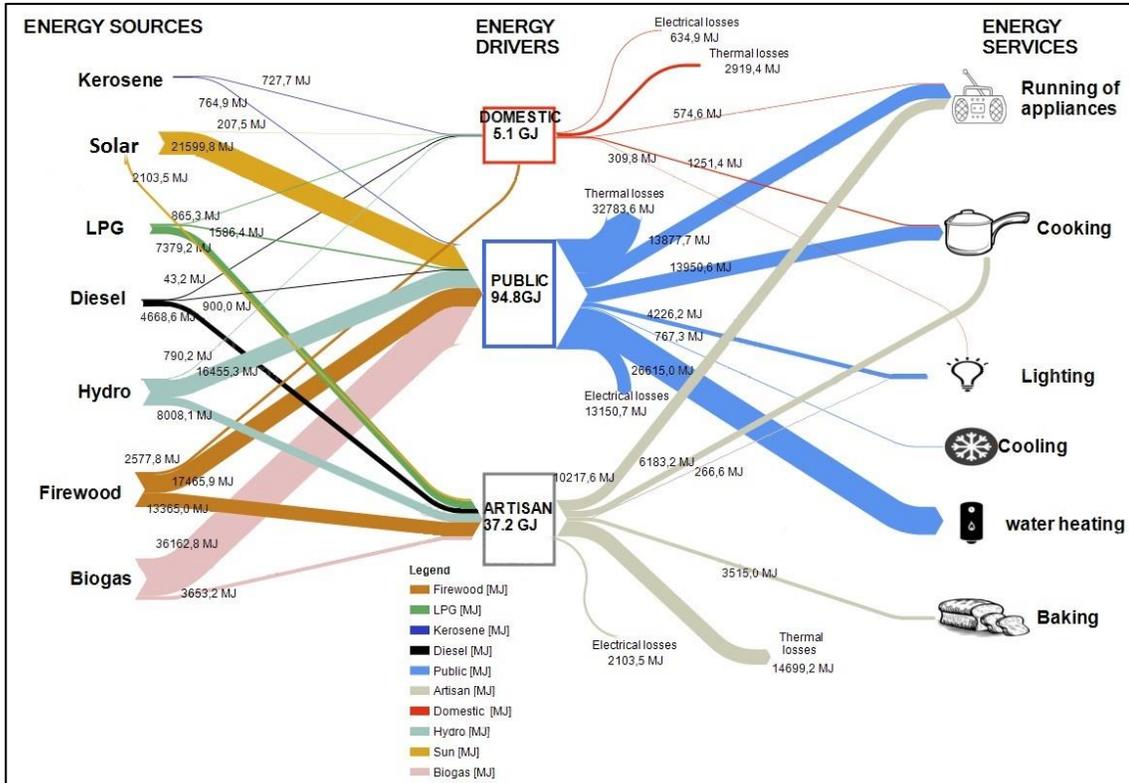


Figure 5. 16: Energy flows in the study area: Off grid option.

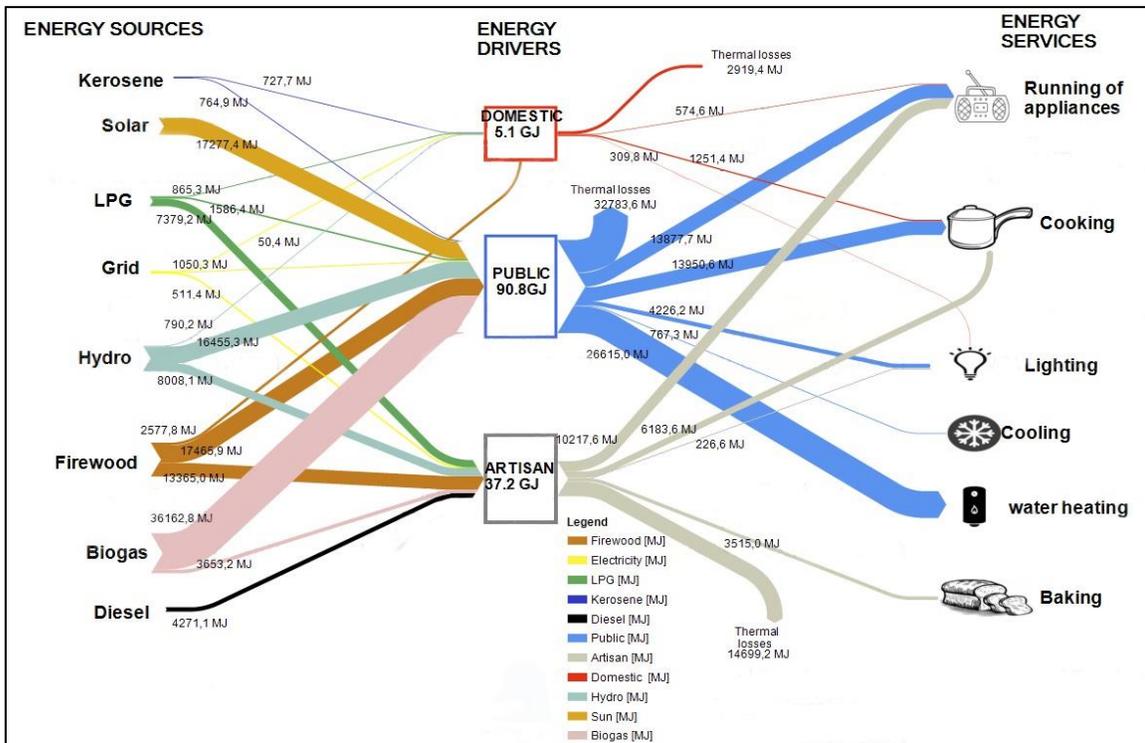


Figure 5. 17: Energy flows in the study area: Grid-RES option.

The Sankey diagrams presented in the figures above were compared with each other and with the scheme of the current energy flow in the study area. The differences are highlighted in the following paragraphs.

The energy sources according to the solution planning include three new RES, biogas, solar resource and hydro resource, as well as all the other energy sources currently present in the study area (kerosene, LPG, grid, firewood and diesel).

The consumption of firewood in the new energy balance for both scenarios was decreased by 76% in the public and by 80% in the artisan energy driver respect to the current situation. The reduction could be justified by the adoption of more efficient conversion technologies, improved stoves and improved oven and new sources to satisfy the thermal demand: biogas plant and solar thermal collectors. Primary energy from biogas supplies public and artisan energy drivers with 36.2 GJ/month and 3.6 GJ/month respectively. An amount of solar thermal energy, equal to 17.3 GJ/month, was used to produce hot water in the public energy driver, satisfying a demand that was unmet. The total primary energy for the artisan driver was 37.2 GJ/month with a reduction of 57% compared to the current consumption. For the public driver the total amount of primary energy required was 90.8 GJ/month for the Grid-RES system. Despite a reduction of the thermal losses by 46%, the total amount of PE required for the public sector has decreased of just 4% due to the very large increase of energy demand for water heating.

In the current condition minimum standards for water heating need of the study area population were not satisfied and in order to guarantee availability of hot water in the public driver 26.6 GJ/month were required, supplied by biogas boilers and solar thermal collectors.

For the suggested option, Grid-RES, the TPES was 133.1 GJ/month, corresponding to 38.15 toe/year, losses were equal to 38%, while TFC was 82.7 GJ/month corresponding to 24.99 toe/year, the increase in final consumption is attributed to an extra service provided, water heating.

6. CONCLUSION

This study was conducted to investigate improvement of access to energy in rural areas of developing countries within the theme of sustainable energization. The set objectives were fully met through the field application of the proposed planning methodology. Specifically:

- Current energy balance was obtained with a TPES equal to 53.37 toe/year and a TFC of 16.01 toe/year, energy losses were equal to 70% mainly from firewood conversion technologies. The energy sources were electricity from the national grid, firewood, LPG, kerosene and diesel. The energy drivers were domestic, public and artisan. The energy services required were lighting, powering of appliances, cooking, water heating (partially satisfied), cooling, and baking.
- The potential of the local energy sources was assessed. The hydropower resource potential was 140.7 GJ/year. The annual wind resource potential was 4.7 MJ/m². The solar annual average potential was 17.3 MJ/m². Biogas resource was equal to 44.85 GJ /month.
- Areas to improve energy efficiency were identified and strategies were proposed, specifically a mini-grid with a common bus for all the facilities was recommended to substitute the individual connections in order to improve demand side management and facilitate RES penetration. Substitution of low energy efficiency thermal conversion technologies was proposed to reduce firewood consumption. A new energy supply system Grid-RES is suggested with large RES local production, increasing reliability, affordability and sustainability of the system.
- A more sustainable energy supply network was proposed in order to guarantee access to reliable energy with complete satisfaction of the water heating energy service, adopting RETs and improving efficiency of conversion technologies; therefore in agreement with the three objectives of SE4All [94] to achieve SDG 7: energy access, renewable energy and energy efficiency.

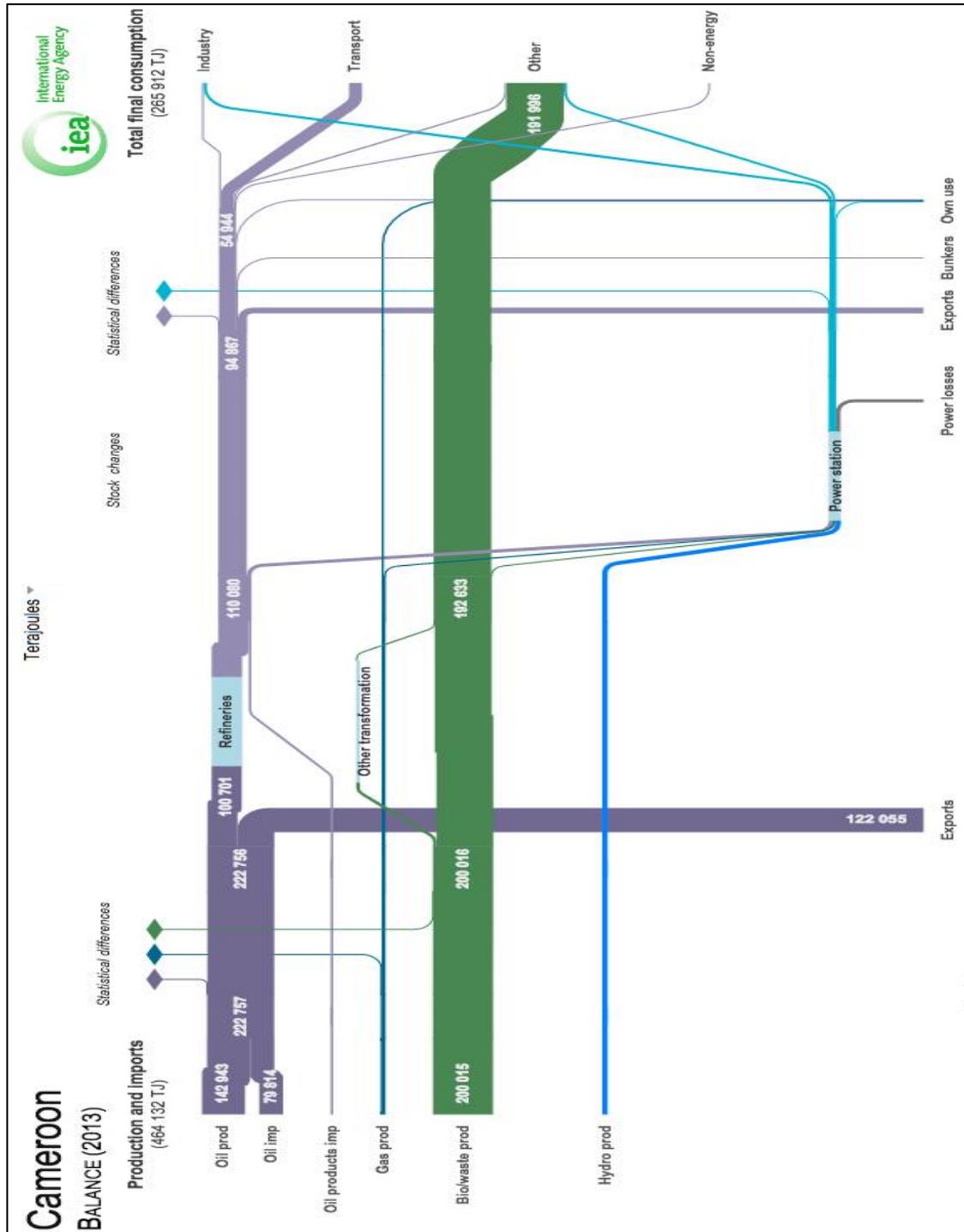
Since this research was conducted on a pre-feasibility level, some aspects need a further analysis prior to implementation: detailed investigation on the design of the hydropower

Conclusion

system, economic analysis of the thermal solution planning, and further investigation on better demand side management.

APPENDIX A

A.1 Energy balance of Cameroon in 2013.



A.2 Front page of the Cameroonian newspaper “L’Effort” of June 2015.

N° 606 (154) 068. JUNE 17 TO JULY 01, 2015
300 FCFA

L'EFFORT

CAMEROUNAIS

Catholic Weekly. Established in 1955 - Publisher: NECC / Mgr. Samuel KLEDA

FOR A BETTER FUTURE REFLECTION

"Poverty is at the very centre of the Gospel. If we remove poverty from the Gospel, you would not understand anything about the message of Jesus."

Pope Francis

Despite Energy Potentials: Cameroon Continuously Candle-powered



Cameroon has been facing acute electricity shortage for some decades now, but never before has the crisis been as serious as it is at the moment. No sector has been spared and the consequences are far reaching. Despite its vast energy potentials, many people in Cameroon are resorting to traditional sources of energy at a time energy-conscious countries are drifting more towards alternative, cleaner and renewable energy sources. Though it is taking unusually long for promises to be fulfilled and the lone electricity company is justifying its present lethargic performance, many see an absence of a political will and multinational kleptomania behind Cameroon's persistent electricity crisis. While waiting for the situation to change, if it ever does, Cameroon continues to be candle-powered.

Pgs. 6 & 7

EDITORIAL

Living In Cameroon's Dark
And Thirsty Towns Pg 3

LOCAL CHURCH

CMA Maroua Celebrates
Bishop Bruno Ateba's First
Anniversary, Implants
Branch in Mokolo Pg 8

FOCUS

The Religious Brother:
The Least Known
Form Of Consecrated
Life Pg 10

VATICAN

Pope Francis To Visit
Africa In November Pg 12

**Government Authorises Departments Of
Medicine and Pharmacy Of CATUC's
School Of Health And Medical Sciences**



Pg. 4

**Church Gears Up To
Obey Christian Cardinal
Tumi's Mother: A
Resplendent Burial**



Pg. 5

www.leffortcamerounais.com

APPENDIX B

Questionnaire administered during peer-to-peer interviews at the households.



Master thesis project:
Improvement of the energy efficiency and the energy supply of St. Theresa's Catholic Medical Centre - Mambu Bafut



Partners: Politecnico di Milano, Catholic University of Cameroon – Bamenda and St. Theresa's Catholic Medical Centre



Data collection for the electrical energy consumption assessment and the electric grid stability within the Medical Centre

INTERVIEWEE'S NAME: _____

Part 1: interviewee and family description

Age _____ Sex: M F
 Role in the family _____

Where are you working? In STCMC/SAJOCAH.
 In SJCHS.
 None of the two. Please specify:.....

Please complete the following 3 points:

- job _____
- number of working hours per week _____
- since when are you working _____

	Family member	Sex	Age	Occupation
1				
2				
3				
4				
5				
6				

Part 2: electricity supply

2.1 How often do you experience a power shortage from the main grid?

- never once a month once a week every day
 more than once a day

2.2 Please estimate the average power shortage time in one week

- below 10 minutes 10 minutes to 1 hour 1 to 3 hours
 3 to 24 hours more than 24 hours

2.3 Is this household served by an EMERGENCY GENERATOR during shortages?

- YES NO

2.4 Have you ever experienced voltage fluctuation of the grid?

- YES NO

Have they caused damages to the electrical appliances?

.....
.....

Have you managed to repair the damaged devices? If yes, at what cost?.....

Part 3: electricity consumption

Please complete the following table on end-uses of electricity in the house:

	TYPE OF DEVICE	No OF ITEMS	RATED POWER [W]	DAILY USE [hours]	OPERATING HOURS: please mark the exact hours of use with an "X"											
					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
1					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
2					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
3					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
4					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
5					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
6					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
7					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
8					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
9					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
10					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
11					00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12
					12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24

Part 4: firewood consumption

4.1 What kind of firewood stove are you using:

- I am not using firewood for cooking 3 stones fire wood oven
 improved stove other(specify)

4.2 What kinds of firewood are you mainly using?

4.3 Please express the average quantity of firewood used in one day [kg]

4.4 How many meals do you prepare per day by using firewood?

4.5 Where do you take the firewood from?

- locally not in Mambu (specify: _____)

4.6 How is it the firewood transported?

- by hands by motorbike by car by truck
other(specify)

4.7 Do you buy or collect the firewood? BUY COLLECT

If BUY, please specify the cost per kg _____ and the name of the supplier

If COLLECT

How many hours per week are spent for the collection (per person)? _____

How far do you collect it from?

- less than 1km between 1 and 2 km
 more than 2 km

4.8 Do you use wood for water heating? YES NO

If YES, please estimate the quantity:

Part 5: other primary fuels

5.1 Do you use other primary energy forms rather than firewood and electricity in your house?

- YES NO

If YES, please complete the following questions:

5.2 Please mark with an "X" the primary energy forms that are used in your house and complete the corresponding questions below

- natural gas LPG kerosene charcoal others
(specify _____)

5.3 Natural gas:

- please express the size of the gas cylinder [Liters or kg]
-

- please express the cost of one cylinder [CFA]

- how often do you have to replace the cylinder?

- where do you buy the natural gas from?
 delivered at home local market Bamenda

5.4 Liquid petroleum gas (LPG):

- please express the size of the gas cylinder [Liters or kg]

- please express the cost of one cylinder [CFA]

- how often do you have to replace the cylinder?

- where do you buy the LPG from?
 delivered at home local market Bamenda

5.5 Kerosene:

- please express the size of the kerosene bottle [Liters or kg]

- please express the cost of one bottle [CFA]

- how often do you have to refill the bottle?

- where do you buy the kerosene from?
 delivered at home local market Bamenda

5.6 Charcoal:

- please express the size of the charcoal bag [kg]

- please express the cost of one bag [CFA]

- how often do you buy charcoal?

- where do you buy the charcoal from?
 delivered at home local market Bamenda

5.7 Others: please describe the other primary energy sources including quantity consumed and cost

Part 6: biogas potential

6.1 Do you cultivate any crop ? if YES please complete the following table

YES NO

	crop type	area dedicated	sowing time	harvesting time
1				
2				
3				
4				
5				
6				

6.2 Do you breed any animal ? if YES, please complete the following table

YES NO

	animal kinds	number	With what do you feed them? (animal feed, kitchen waste etc)
1			
2			
3			
4			
5			
6			

Thank you for the cooperation!

Gloria & Malama

APPENDIX C

C.1 Checklist for electricity consumption registration

Responsible: Week →

Department: Room: Device:

Time	7.30 →8	8 →8.30	8.30 →9	9 →9.30	9.30 →10	10 →10.30	10.30 →11	11 →11.30	11.30 →12	12 →12.30	12.30 →13	13 →13.30	13.30-- >14	14-- >14.30	14.30-- >15
Mon															
Tue															
Wed															
Thu															
Fri															
Sat															

Remarks:

C.2 Typical peak power and load factors of specific electrical appliances.

Appliance	Typical peak power [W]
TV 15"	90
TV 12"	60
VHS/DVD player	15
Decoder	10
Speakers	100-500
Desktop computer	100
Laptop computer	100
Phone chargers	20
Multi-function printer	20 stand-by mode, 100 printing mode
Photocopy machine	30 stand-by mode, 100 printing mode
Scanner	50
Small radio	7

Appliance	Load Factor
AC	0.75
Amplifier	0.25
Anesthetic machine	0.75
Band saw	0.67
Boiler	0.1
Appliances based on an electric motor	0.75
Decoder	0.15
Drill	0.8
Electrosurgical generator	0.6
Fan	0.4
Freezer	0.4
Fridge	0.4
Lamp	0.4
Lathe	0.8
Oxygen concentrator	0.8
PC /laptop	0.2
Printer	0.2
Radio	0.2
Samples incubator	0.4
Scanner	0.4
Speakers	0.2
Stereo system	0.2
TV	0.15
VHS /DVD player	0.1
Washing machine	0.4
Water pump	0.1
Welding machine	0.67
X-ray monitor	0.4

C.3 NASA data on wind speed and solar radiation.

	wind speed [m/s]	solar radiation [W/m ²]
Jan	2.68	6.14
Feb	2.74	6.19
Mar	2.61	5.50
Apr	2.36	5.01
May	2.33	4.83
Jun	2.49	4.42
Jul	2.40	4.01
Aug	2.49	3.92
Sep	2.33	4.21
Oct	2.02	4.38
Nov	2.16	5.21
Dec	2.29	5.79
Average	2.40	4.96

C.4 Human waste data collection checklist

Data collection for BIOGAS potential assessment: HUMAN WASTE

Please mark with an (x) every time you use the toilet

	URINE	FAECES
Monday		
Tuesday		
Wednesday		
Thursday		
Friday		
Saturday		
Sunday		

WHY? Human waste can be used to produce gas for cooking and water heating.
 4 kg of human waste can produce 200 liters of gas which:

- Correspond to 1 kg of firewood.
- Are enough to cook 500 g of vegetables or 750 g of rice.
- Are enough to boil 5 liters of water.

Thank you !!!
 Gloria & Malama

C.5 Power shortages registration checklist.

BLACKOUT REGISTRATION				
Name:			Week →	
#	DATE	START TIME [HH:MM]	STOP TIME [HH:MM]	DURATION [MINUTES]
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

C.6 Tariffs for electricity in Cameroon fixed by the regulatory agency.

TARIFF PLAN FOR ELECTICITY CONSUMPTION IN CAMEROON AS FIXED BY THE ELECTRICITY SECTOR REGULATORY AGENCY		
MEDIUM VOLTAGE CLIENTS		
A) DOMESTIC AND RESIDENTIAL USAGE		
	Range of monthly consumption	Tariffs
1.	Consumption less than or equal to 110 kWh	50 FCFA/kWh
2.	Consumption between 111 kWh and 400 kWh	79 FCFA/kWh
3.	Consumption between 401 and 800 kWh	94 FCFA/kWh
4.	Consumption between 801 and 2000 kWh	99 FCFA/kWh
B) OTHER NONRESIDENTIAL USAGES		
	Range of monthly consumption	Tariffs
1.	Consumption less than or equal to 110 kWh	84 FCFA/kWh
2.	Consumption between 111 kWh and 400 kWh	92 FCFA/kWh
3.	Consumption between 401 and 1000 kWh	99 FCFA/kWh
C) PUBLIC LIGHTING		
Tariff	66 FCFA/kWh.	

APPENDIX D

Firewood stoves in the study area



Figure D. 1: Cook stoves present in SAJOCAH kitchen



Figure D. 2: Two-pot ICS present in the Convent



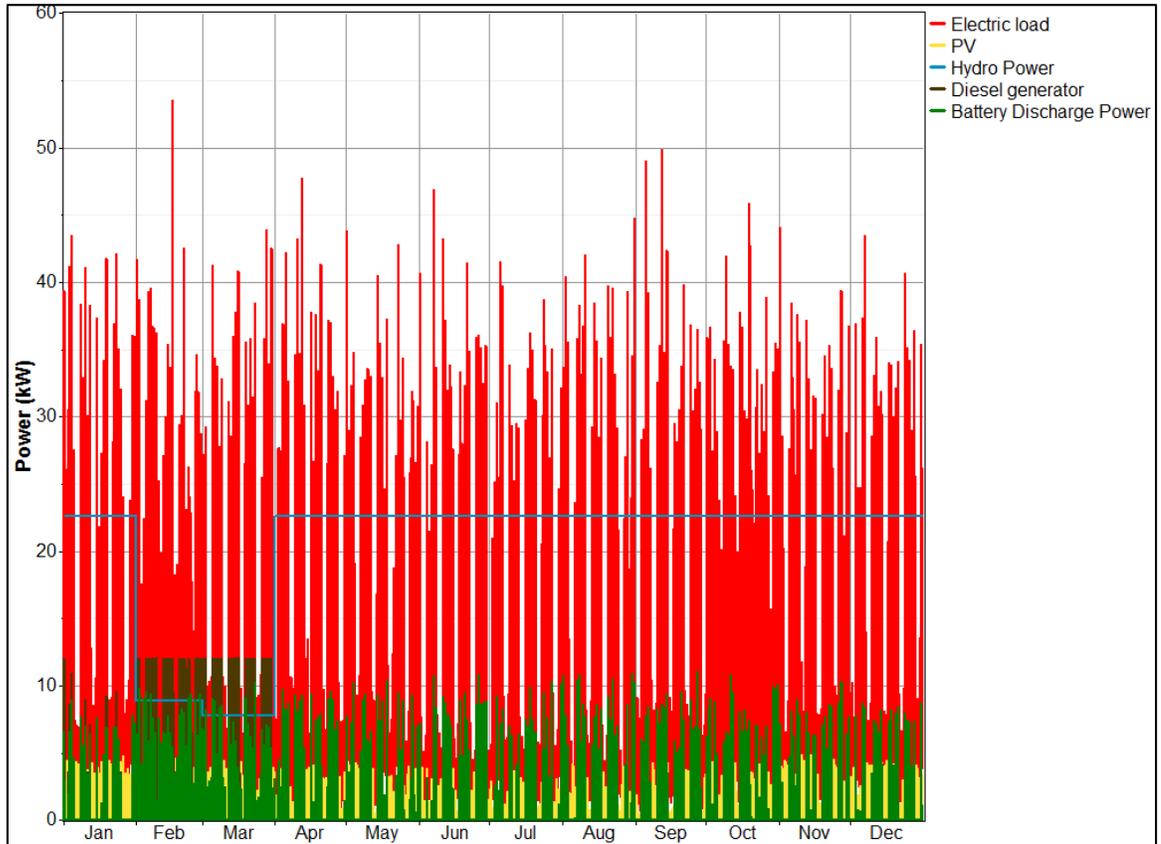
Figure D. 3: Multi-pot stove used in the kitchen of SJCHS and the level of smoke generated



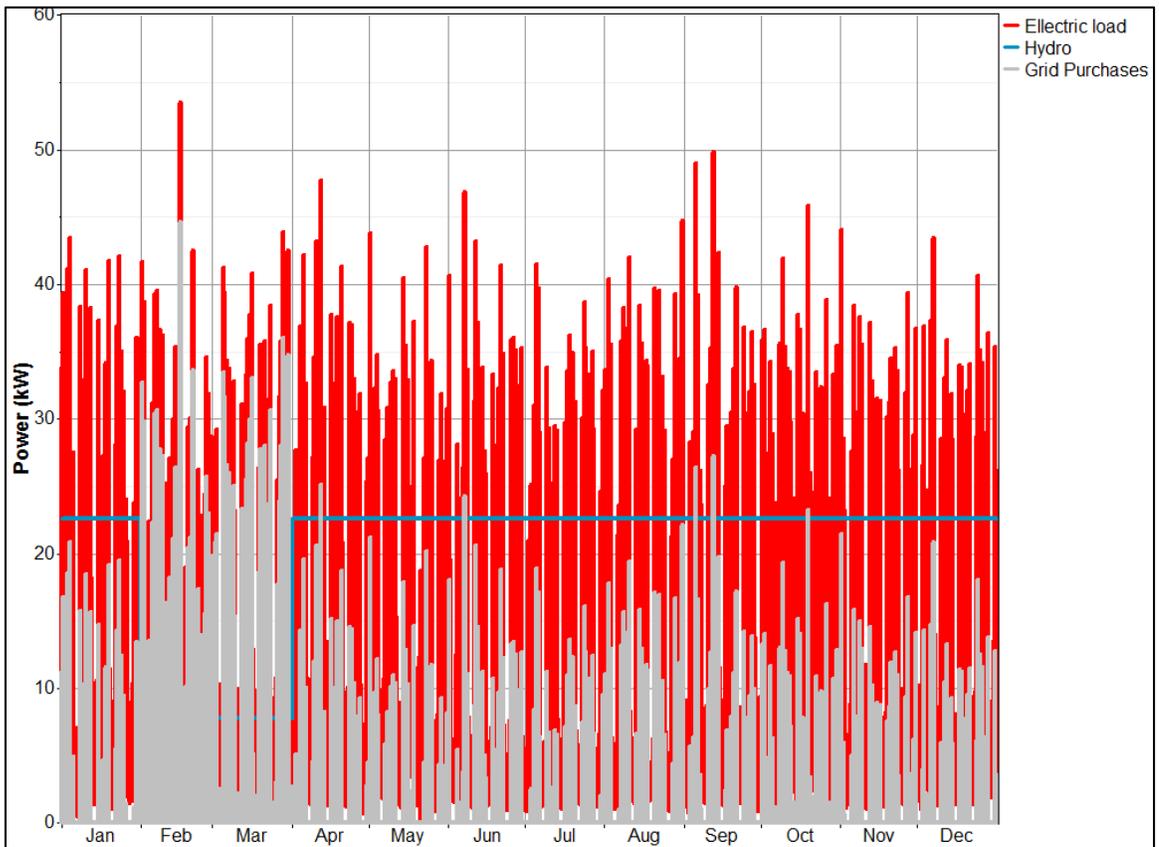
Figure D.4 (a) and (b): Three-pot ICS in the Postulancy, presenting a hole at the side

APPENDIX E

E.1 Off-grid supply system annual output



E.2 Grid-RES supply system annual output



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