POLITECNICO DI MILANO

Scuola di Ingegneria Industriale e dell'Informazione

Corso di Laurea Magistrale in
Ingegneria Energetica

LOAD CURVE MODELLING FOR E-COOK CONCEPT IMPLEMENTATION IN A SOLAR POWERED MINI-GRID: RESIDENTIAL AND INSTITUTIONAL CASE STUDIES IN TANZANIA

Relatore: Prof. Emanuela COLOMBO
Correlatore: Ing. Francesco LOMBARDI

Tesi di Laurea di:
Marco Sacchi, matricola 853291

Anno Accademico 2017 – 2018

"For too long, cooking has been a silent killer in developing countries around the world. Finally we are seeing momentum around this issue."

Kofi Annan

Acknowledgements

Per primo vorrei ringraziare Francesco che mi ha costantemente supportato e spronato durante questo lavoro di tesi.

Un ringraziamento speciale alla mia famiglia che mi ha permesso di frequentare il Politecnico di Milano e non mi ha mai fatto mancare nulla nel corso di questo lungo ed arduo percorso formativo.

Grazie a Luca, Nico e Robi che sono stati il mio faro ed esempio da seguire in questi anni di Università.

Grazie a Rocco, con il quale ho condiviso ogni singolo momento al Politecnico di Milano, dal primo all'ultimo giorno.

Grazie infine a Fede e Carlo, miei compagni di viaggio in Africa, che mi hanno insegnato, tra le altre cose, che si può essere dei professionisti rinomati in Italia ma avere la voglia di dare il proprio contributo in paesi come la Tanzania.

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Abbreviation Index

AC	Alternate Current
ASM	Advanced Storage Module
BOS	Balance Of System
CEFA	Comitato Europeo per la Formazione e l'Agricoltura
DC	Direct Current
DOD	Depth Of Discharge
GHI	Global Horizontal Irradiance
HAP	Household Air Pollution
HOMER	Hybrid Optimization Model for Multiple Energy Resources
ICS	Improved Cooking Stoves
IEA	International Energy Agency
INDC	Intentionally Nationally Determined Contribution
IRR	Internal Rate of Return
LCCM	Levelized Cost of Cooking a Meal
LCOE	Levelized Cost Of Electricity
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
MATLAB	Matrix Laboratory
MPPT	Maximum Power Point Tracker
NASA	National Aeronautics and Space Administration
NGO	Non-Government Organization
NPC	Net Present Cost
NPV	Net Present Value
O&M	Operation & Maintenance
OPzS	Ortsfest PanZerplatte Flussig
PBT	Payback Time
PV	Photovoltaic
PWM	Pulse Modulated Width
SDG	Sustainable Development Goals
SEI	Stockholm Environment Institute
SSA	Sub-Saharan Africa
TAHEA	Tanzania Home and Economics Association
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization

WEO	World Energy Outlook
WHO	World Health Organization

Nomenclature

A_{PV}	Area of the PV array
E_L	Daily energy required
η_{inv}	Inverter efficiency
η_B	Battery efficiency
η_{cc}	Solar charge controller efficiency
η_{PV}	PV module efficiency
γ	PV module temperature coefficient
T_{op}	Temperature reached during operation
T_{STD}	Temperature in standard conditions
I_{STD}	Standard solar irradiation
P_{PV}	PV array peak power
$P_{PV,nom}$	PV module nominal power
B_C	Battery pack capacity
N_C	Number of continuous cloudy days
$B_{C,nom}$	Nominal battery capacity
V_{sys}	System voltage
$V_{B,nom}$	Nominal battery operating voltage
$V_{MAX,CC}$	Solar charge controller maximum admissible voltage
$V_{OC,PV}$	PV module open circuit voltage
$P_{MAX,CC}$	Solar charge controller maximum admissible power
$I_{in,CC}$	Solar charge controller input current
$I_{SC,PV}$	PV module short circuit current
$I_{MAX,CC}$	Solar charge controller maximum admissible current
$P_{B,out}$	Battery pack output power
R_0	Battery series resistance
I	Current
k_T	Rate of increase of Time-and-temperature degradation variable
N	Battery’s number of cycles
$C_{ann,tot}$	System total annualized cost
E_{served}	Total electrical load served
C_{fuel}	Fuel price

E_u	Useful energy required for cooking a meal
η_{stove}	Stove efficiency
$C_{stove,t}$	Stove purchase cost
Ml_t	Meal cooked in one year
r	Real interest rate
f	Inflation rate
i	Nominal interest rate
CF_t	Cash flow occurred in time t
SV_f	Salvage value

Abstract

Nowadays, around 1.1 billion people around the world don't have access to electricity while an estimated 2.8 billion rely on the traditional use of solid biomass to cook their meals, most of them living in rural areas in developing countries. This situation hampers economic growth, social development and has a dramatic impact on health and environment.
The aim of this thesis work is to investigate the techno-economic feasibility of the *e-cook concept* implementation in a solar powered mini-grid, as a solution for access to clean cooking; and to explore its actual potential in developing countries, also given the scarce presence of similar studies in the literature. The analysis was conducted for the village of Kidegembye and for Mama Kevina Hope Center in Tanzania, representative of a residential and institutional case study respectively.
Load profiles for mini-grid design have been modelled with a new method, proposed within this thesis work, based on cooking cycles defined on local cooking habits.
Moreover, a performance analysis on different fuels for cooking, and a thorough comparison between electricity and LPG have been carried out.
According with the results, the *e-cook* solution, for access to clean cooking, should not be abandoned a priori but rather constitutes a valid alternative especially compared to LPG.

Keywords: access to energy, e-cook, load modelling, off-grid energy systems, rural electrification.

Sommario

Al giorno d'oggi, 1.1 miliardi di persone nel mondo non hanno accesso all'energia elettrica mentre 2.8 miliardi utilizzano biomassa solida per cucinare. Questa situazione ostacola la crescita economica, lo sviluppo sociale e ha conseguenze drammatiche sulla salute della popolazione e dell'ambiente.

L'obbiettivo di questa tesi è di verificare la fattibilità tecno-economica dell'*e-cook concept* che utilizza l'elettricità come vettore energetico pulito per cucinare in una mini-grid a fonte solare e di constatare il suo effettivo potenziale nei paesi in via di sviluppo, vista anche la mancanza di studi simili in letteratura.

L'analisi è stata condotta per il villaggio di Kidegembye e per il centro di accoglienza Mama Kevina Hope Center in Tanzania, rappresentativi di un caso residenziale e di uno istituzionale.

Le curve di carico necessarie al design della mini-grid sono state modellate tramite un nuovo metodo, proposto in questa tesi, basato su dei cicli di cottura definiti dalle abitudini alimentari locali.

Si sono poi svolte un'analisi delle prestazioni dei diversi combustibili utilizzati per attività di cottura e un confronto approfondito tra elettricità e LPG.

Dai risultati è emerso che la soluzione *e-cook* non deve essere abbandonata a priori ma costituisce invece una valida alternativa, specialmente se comparata a LPG.

Parole chiave: accesso all'energia, e-cook, modellazione curve di carico, sistemi energetici off-grid, elettrificazione rurale.

Extended summary

The aim of this thesis work is to investigate the techno-economic feasibility of the e-cook concept implementation in a solar powered mini-grid, and to explore its actual potential in developing countries, also given the scarce presence of similar studies in the literature. The analysis was conducted for the village of Kidegembye and for Mama Kevina Hope Center in Tanzania, representative of a residential and institutional case study respectively.

Introduction

Nowadays, around 1.1 billion people around the world don't have access to electricity while an estimated 2.8 billion rely on the traditional use of solid biomass to cook their meals [1], most of them living in rural areas in developing countries. This situation hampers economic growth, social development and has a dramatic impact on health and environment. According to International Energy Agency (IEA) access to energy is the «golden thread that weaves together economic growth, human development and environmental sustainability» and it is defined as: «a household having reliable and affordable access to both clean cooking facilities and to electricity […] ».

Significant progress has been made in recent years in electricity access, with nearly 1.2 billion people who have gained access to electricity with a rate of more than 100 million people per year from 2000 to 2012. However, in sub-Saharan Africa still 590 million people remain without access to electricity. Regarding access to clean cooking instead, still around 2.8 billion people, 38% of the global population and almost 50% of the population in developing countries, rely on solid biomass to cook their meals [1]. The IEA defines "access to clean cooking" as «*a household primarily relying on cooking facilities which are used without harm to the health of those in the household and which are more environmentally sustainable and energy efficient than biomass cookstoves and the three-stone fires currently used in developing countries*». The only regions in the world where progresses have been made on access to clean cooking are China and Indonesia, especially thanks to targeted policies focused mainly on the use of LPG. In India the number of households without access to clean cooking today is more than double that without electricity [2]. Sub-Saharan Africa is the region showing the least progress on clean cooking where almost 80% of the population still cooks with solid biomass. Most of the population without access to clean cooking is indeed concentrated in sub-Saharan Africa and in developing Asia (Figure 1). Furthermore, in many developing countries, cooking-related energy represents over 90% of total primary energy demand of a household. Accordingly, attempting to scale up renewable electricity supply without focusing on the cooking sector is therefore thoroughly inadequate, as it leaves much of the energy supply mix as well as many of the most significant challenges untouched [3].

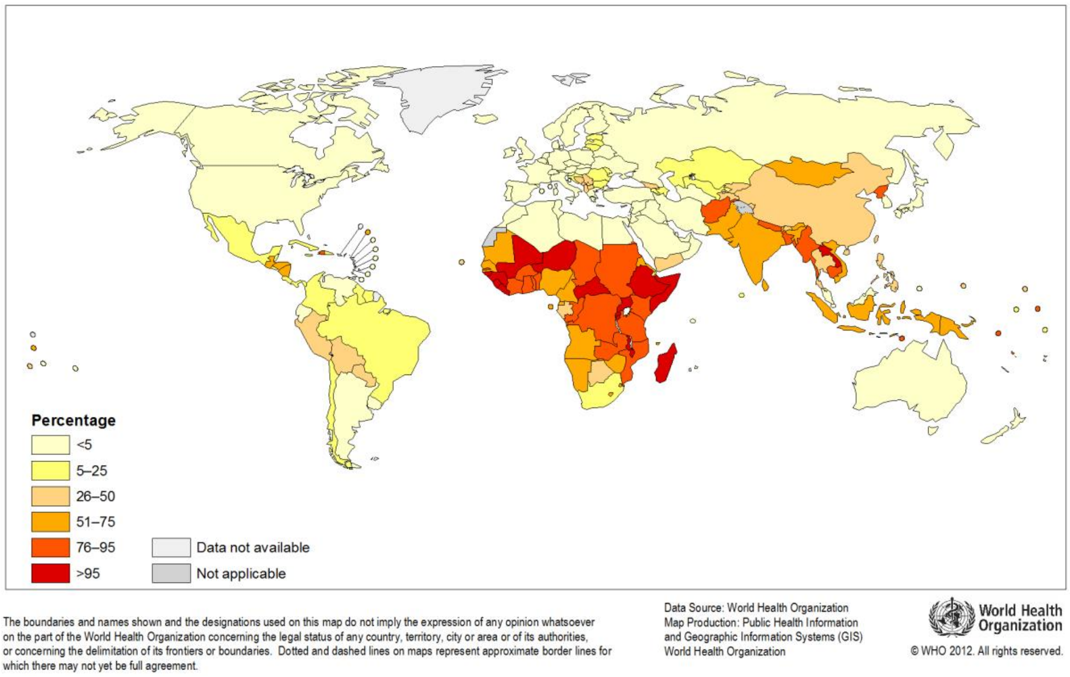


Figure 1 Population using solid fuels worldwide (%) (WHO) [4]

Burning traditional biomass fuels such as firewood, charcoal or animal dung in inefficient cookstoves has a dramatic impact on population's health, local and global environment and socio-economic development of communities. The act of combustion releases toxic pollutants into the air, leading to levels of household air pollution (HAP) which often far exceed World Health Organization (WHO) guidelines. HAP is driving a global health emergency and it is recognized by the WHO as the single most important environmental risk factor worldwide. Based on estimates of solid fuel use for cooking in 2012, exposure to HAP causes 4.3 million premature death each year, exceeding deaths attributable to malaria or tuberculosis. Moreover, unsustainable firewood and charcoal use is also recognized to be the single largest source of greenhouse emissions in many countries while it also leads to deforestation, soil erosion and loss of biodiversity whereas most areas deforested are rarely replanted resulting in a further negative impact. Additionally, according to the World Bank, collecting firewood for cooking forces especially woman and children to spend from eight to nine hours each week in this task, limiting their opportunities to go to school, improve their education or engage in other more productive activities.

The e-cook concept

The e-cook concept exploits electricity as a clean fuel for cooking providing for the use of electric cooking appliance such as induction stoves.

The possibility of guaranteeing access to clean cooking through the e-cook concept is strongly linked to the high emerging potential of decentralized systems such as mini-grids to produce electricity at relatively low cost, in developing countries and especially in rural areas far from the national grid. The e-cook concept presents two main challenges in cultural and technical terms. From the cultural point of view an immediate transition from a traditional way of cooking with solid biomass to whichever kind of modern cooking technology is unimaginable. The transition is certainly more likely to be gradual, yet it is crucial to provide clean and modern alternatives for achieving access to clean cooking as soon as possible. From the technical point of view implementing highly energy-consuming appliances, such as induction cook-stoves, in solar powered mini-grid seems an impossible challenge. However, photovoltaic systems are well known to be an interesting electricity supply solution, especially in sub-Saharan Africa where solar resource is abundant. Furthermore, continuous decrease of components cost, such as solar PV modules and batteries, and their increasing performances are beginning to make solar the most cost-effective solution for electricity production in many regions of the world. These improvements can therefore foster the diffusion of the e-cook concept as a clean cooking options.

Methodology

Decentralized energy systems, like mini-grids, are off-grid systems locally-based and need oriented, i.e. usually designed to satisfy specific local energy needs and relying on local energy resources [5]. For this reason, load demand assessment in rural electrification project is strictly required to allow the optimal sizing of the system. The first challenge, of implementing e-cook concept in off-grid systems, concerns modelling of load profiles that also consider loads deriving from electric cooking appliances, such as induction stoves. For this purpose, in the literature, it is usually defined a fixed energy consumption specific to a meal in order to present a study as general as possible [6],[7]. However, a new method is proposed in this thesis work in which load profiles are modelled based on cooking cycles defined on local cooking habits.
For load curve modelling LoadProGen software (Load Profile Generator), developed by the group of the UNESCO Chair in Energy for Sustainable Development in collaboration with group of Power Systems – Department of Energy of Politecnico di Milano has been used. However, LoadProGen was born as a support tool for the formulation of load profiles to be employed in the design process of off-grid systems for rural electrification. Load profiles modelling considering also energy needs for cooking purposes is therefore out of its features. Hence, a new methodology for cooking cycle modelling and implementation in LoadProGen have been presented.

Induction stove modelling and cooking habits assessment

Firstly, for the residential case study, single cooker induction stoves have been modelled as an input for LoadProGen. To do this, information taken from induction stoves' manual and

datasheet have been summarized to form a simplified model with three levels of power: 500 W (low), 1500 W (medium), 2000 W (high). Regarding the institutional case study, given the number of inhabitants in the center, and that the whole meals are usually prepared in the same kitchen, an induction kitchen has been considered rather than a single induction cooker. Since more than two cookers are rarely used and given the higher power levels needed for meals preparation in the center, the induction kitchen has been modelled as an appliance with fixed power rate of 3 KW providing a conservative scenario.
Then, an assessment on local cooking habits has been carried out. Local cooking habits means main local dishes, their preparation in terms of cooking methods and timings, but also the number of meal consumed per day and the time in the day in which they are prepared.

Cooking cycles modelling

Starting from cooking habits assessment and through the specific model for induction stove, cooking cycles have been modelled for both case studies. To reflect the highly random nature of cooking activities, specific scripts (FP_random_cycle, LD_random_cycle available in Annex C) have been developed in MATLAB simulating different cooking cycle preparation. In these scripts every cooking task timing, correspondent to a different power level, has been randomized between a minimum and a maximum timing considered for the specific task. The union of each single randomized task forms a random cooking cycle.
According with the induction kitchen model for Mama Kevina, cooking cycles modelling for this case study is limited to the randomization of preparation length of each task with a fixed power. The obtained cooking cycles for lunch/dinner provides a comprehensive solution based on local habits as it represents a general preparation of a main dish and of a side dish. Furthermore, according with local cooking habits, lunch is prepared immediately after breakfast and kept warm in specific pots or ovens. Consequently, a full preparation random cycle has been modelled as a combination between a breakfast and a lunch cycle.

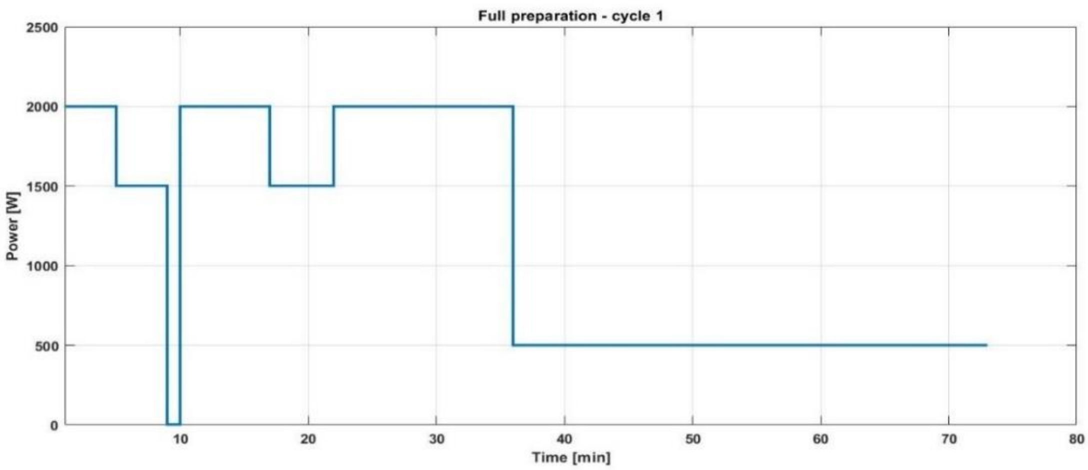


Figure 2 Full preparation random cycle example for a household in Kidegembye village

Similar cooking cycles have been modelled with the same method to simulate fuel stacking phenomenon. In this cooking cycles the main traditional preparations have been considered to be carried out in the traditional way, hence with traditional biomass fuel. For secondary preparation, induction cookers usage has been considered instead. An example of a full preparation random cycle for a household in Kidegembye village is depicted in the figure below.

Cooking cycles implementation in LoadProGen

In order to implement in LoadProGen the modelled cooking cycles, an artificial appliance for each meal preparation has been defined as an input for the software. Consequently, for breakfast and lunch preparation, an appliance characterized by full preparation randomized cycle has been considered (Cooking_FP). For dinner preparation an appliance characterized by lunch/dinner randomized cycle has instead been considered (Cooking_LD). Moreover, for the residential case study, for each meal preparation (breakfast + lunch or dinner) and for every single household a different cooking cycle has been randomized. Through this additional randomization it has been possible to better reflect the uncertainty on households' habits and to avoid the definition of too specific cooking cycles. Regarding Mama Kevina Hope Center, a random cooking cycle has been generated for each meal preparation.

Load curve scenarios

From cooking cycles implementation in LoadProGen, different load curve scenarios have been modelled. The reference case is the *Base load* scenario in which only conventional electric loads such as lighting or basic entertainment (TV, radio) have been considered. *Full cooking* scenario represents instead the reference case of a complete transition from traditional biomass fuels to e-cook. In this scenario clean cooking access is fully achieved and it is the starting point for the design of an e-cook mini-grid. Furthermore, in order to simulate effects on the mini-grid of the gradual transition from traditional way of cooking with solid biomass to induction cooking technology the *Fuel stacking* scenario has been modelled considering specific cooking cycles. Another interesting scenario, is given by the possible *Behavioural change* in terms of meal preparation windows, induced by reduced cooking timings obtained through induction technology. The new meals preparation windows will likely be placed just before meal time. Finally, *Peak-shifting* scenario has been modelled simulating the effect of a demand-side management technology implemented in the mini-grid to smooth power peaks.

Preliminary system design and HOMER optimization

Starting from the load curve modelling it has been possible to develop a preliminary system design, based on classic sizing techniques. The main component of a solar mini-grid as the

PV array, batteries, solar charge controller and the system converter has been presented and sized. Preliminary system design has been carried out only for base load and full cooking scenario. In fact, sizing the e-cook mini-grid on fuel stacking load profiles for example would mean having an undersized system instead in the full cooking scenario. Effects of future possible behavioural changes have been therefore investigated on the mini-grid sized for the full cooking scenario.
A more sophisticated system design optimization has been subsequently carried out through HOMER-Energy software, considering preliminary system design as a starting point and reference case. Moreover, through the preliminary analysis, electrical coupling between main components of the mini-grid has been verified. Since batteries represent the most critical, sensitive and expensive system component, HOMER Advanced Storage Module has been used to precisely investigate batteries performances. For each scenario of both case studies, many simulations comparing lead-acid and Li-ion batteries have been carried out. For all these simulations the result was always in favour of lead-acid technology confirming why it is still the market leader technology.

Cooking solutions performance analysis

Finally, a comparison of different cooking solutions including firewood, charcoal, kerosene, LPG and e-cook from the economic and environmental point of view has been carried out. Levelized cooking cost per month has been defined as the monthly expenditures for energy related to cooking activities in $/month. For the case study referred to Kidegembye village, from the monthly income per household, it has been possible to calculate the percentage of the cooking cost respect to income. Levelized cost of cooking a meal has been defined as the cost for cooking a “standard” meal with a certain fuel-technology combination [8]. It was introduced in 2016 by Fuso Nerini in his article “The cost of cooking a meal. The case of Nyeri County, Kenya”. Furthermore, in order to compare the two modern fuel or rather electricity and LPG, *Payback Time* (PBT) and *Internal Rate of Return* (IRR) have been calculated for a twenty years project lifetime for both the case studies. Finally, savings of the e-cook solution, in terms of non-renewable fuel saved, have been presented.

Results

One load curve per day of the year has been simulated through LoadProGen for each scenario. To highlight the huge impact of induction cookers, mean load curve of base load and full cooking scenarios have been plotted in the same graph for both case studies (Figure 3 and Figure 4). It’s evident from these graphs how challenging is trying to guarantee access to clean cooking through the e-cook concept. However, with this thesis work, the challenge has been accepted and satisfying results have been provided despite the e-cook solution is usually abandoned a priori in the literature.

For the residential case study, the peak power of the mean load curve passed from around 6 kW for the base load scenario to around 30 kW for the full cooking scenario. Consequently, the optimal size of the mini-grid passed from 11.55 kW to 37.40 kW and the initial investment cost increased from around 31000 $ to around 113000 $.

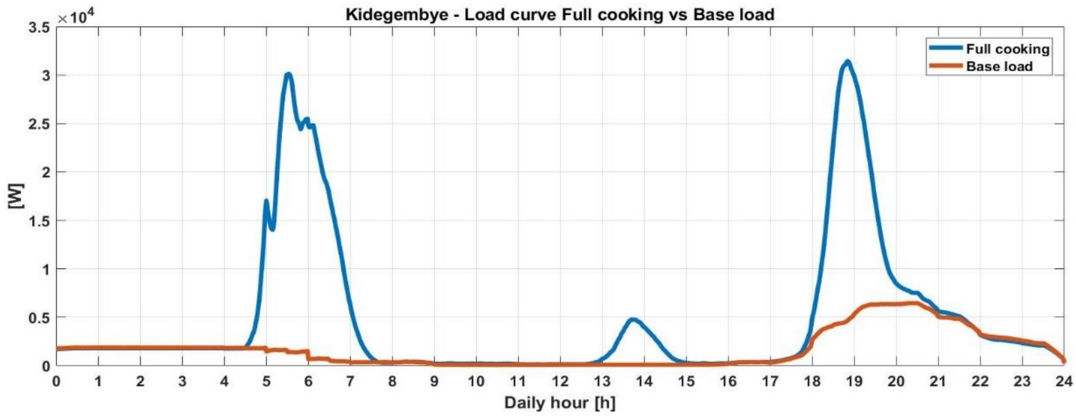


Figure 3 Kidegembye village – comparison between full cooking and base load scenario

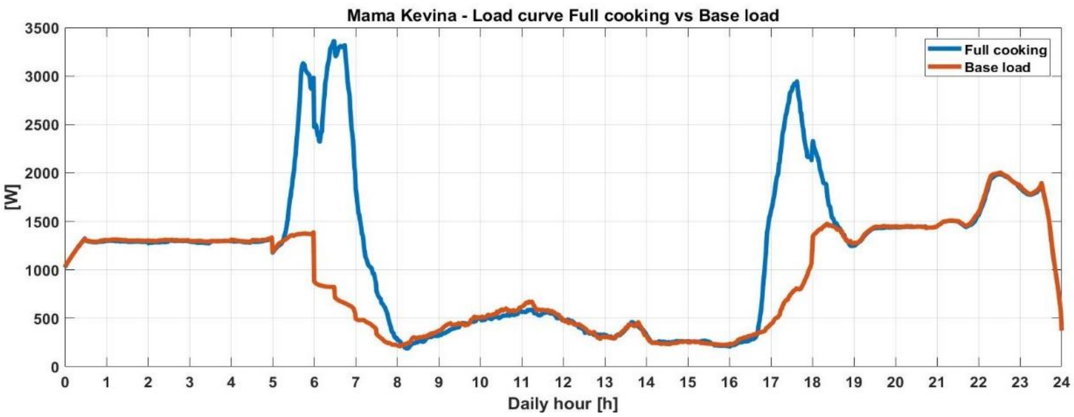


Figure 4 Mama Kevina Hope Center – comparison between full cooking and base load scenario

Regarding the institutional case study, induction kitchen has less impact on load profiles since highly energy consuming appliances, such as washing machine, iron or fridge, are already present. In addition, a sort of economy of scale is provided since one appliance is used to cook for a bigger group of people. The peak power of the mean load curve passed indeed from around 2 kW for the base load scenario, to around 3.5 kW for the full cooking scenario. Accordingly, the size of the mini-grid passed from 7.7 kW to around 9.6 kW and the initial investment cost increased from around 21000 $ to around 25000 $. The potential of e-cook solution for the "institutional" case study, representing a wide number of similar structure all around Africa, is therefore evident.
Effects of cultural barriers, leading to phenomena as fuel stacking, on the e-cook mini-grid has been analysed for the residential case study. Therefore, operations of the optimal mini-

grid designed for the full cooking scenario have been simulated with instead fuel stacking conditions. The consequent reduction in daily energy demand increased the effective autonomy of battery in the system, indeed it passed from 74.2 hours to 93.7 hours. Moreover, expected battery lifetime consequently grew from 16.1 years to 18.8 years. As the mini-grid components were the same of the full cooking scenario the purchase costs remained unchanged. However, the increased lifetime of the battery pack allowed to postpone its replacement and therefore to gain a higher salvage. For this reason, the NPC reduced from around 137000 $ to 127000 $ while the LCOE instead grew from 0.2369 $/kWh to 0.2741 $/kWh because reduction in energy request is more significant than NPC reduction.

Furthermore, effects of the possible behavioural changes on the e-cook mini-grid have been investigated. Therefore, operations of the optimal mini-grid designed for the full cooking scenario have been simulated with instead “behavioural change” conditions. Estimated daily energy demand remained almost unchanged respect to full cooking scenario, as expected. However, the different load profile with less energy request during early morning and with a peak window during the PV array most productive period (i.e. lunch time), changed the battery state of charge throughout the year. Despite a slight reduction in number of equivalent cycle per year, the battery expected lifetime remained 12 years. This is related to the crucial effect of temperature on battery lifetime, the variable which triggers battery replacement was indeed time and temperature degradation factor. Since the system design was the same as the full cooking scenario and the battery lifetime remained unchanged any variations in cost were reported. For these reasons the e-cook mini-grid, designed for full cooking scenario, can stand cooking habits variations without any penalization.

In order to pursue the thesis’ aim, a performance analysis on different fuels for cooking has been carried out. Results have been presented in a range between a *pessimistic scenario* and an *optimistic scenario*. The first represents the combination of long cooking preparation (high cook), low efficiency of the utilized stove and high fuel price (higher value in box plots). The *optimistic scenario* represents instead the combination of short cooking preparation (low cook), high efficiency of the utilized stove and low fuel price (lower value in box plots). Hence, all the plausible casuistries are expected to be included within these extreme scenarios. Providing a range of cost, rather than an absolute value, gave the possibility to carry out a comprehensive comparison between all the cooking technologies. The first performance indicator computed was the levelized cooking cost per month which represents monthly expenditure for fuel. Economic convenience of firewood and charcoal appeared evident in both case studies. However, the e-cook solution represented a valid alternative since its costs were comparable with the kerosene solution and even lower than the LPG one (Figure 5 and Figure 6).

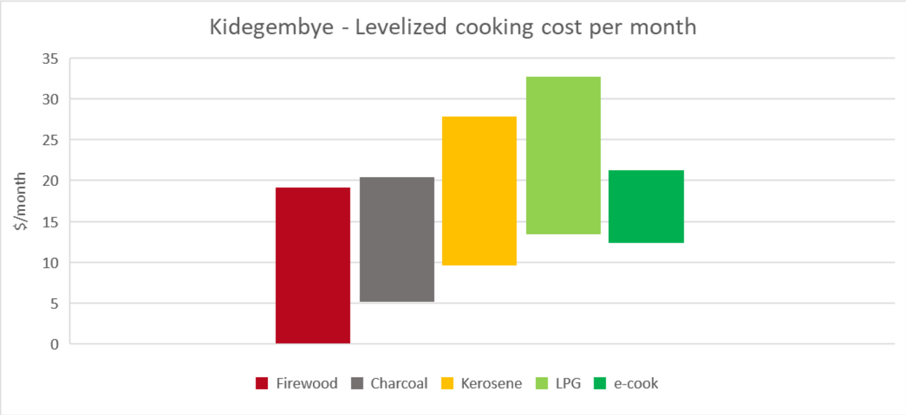


Figure 5 Kidegembye levelized cooking cost per month ($/month)

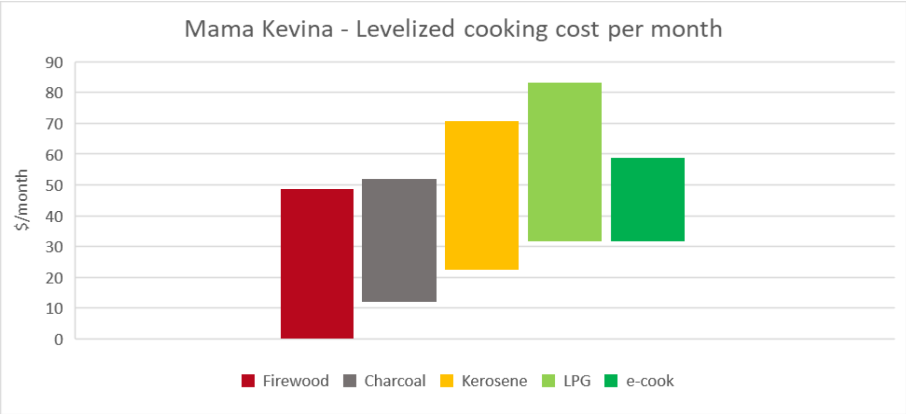


Figure 6 Mama Kevina Hope Center levelized cooking cost per month ($/month)

Moreover, Levelized Cost of Cooking a Meal (LCCM), has been computed to provide a second proof of the e-cook solution cost-effectiveness. Since Fuso Nerini's values were computed for a household of five people in Kenya, a country bordering Tanzania, with similar cooking habits, a comparison has been carried out with the residential case study (Figure 7).

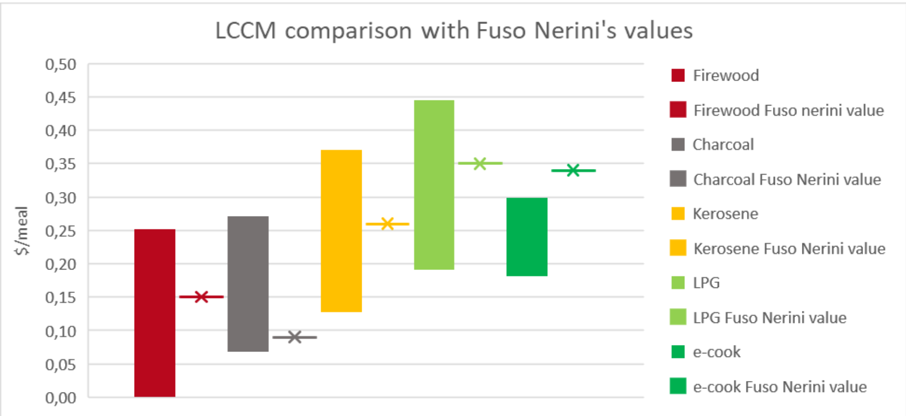


Figure 7 Levelized cost of cooking a meal comparison between Kidegembye case study and Fuso Nerini's values

For each fuel/technology combination, Fuso Nerini's values were within the LCCM calculated range, apart from the e-cook solution. This difference was mainly due to the fact that Fuso Nerini referred the e-cook scenario to an electric stove with an efficiency equal to 70% rather than an induction stove with 90% efficiency. Moreover, Fuso Nerini provided a single value for each fuel/technology combination. Within this thesis work instead, a range of results have been presented, to provide a more comprehensive evaluation. Furthermore, the e-cook solution was confirmed as a valid alternative, as for levelized cooking cost per month, its costs were comparable with the kerosene solution and even lower than the LPG one. In addition, a thorough comparison has been carried out between the two main alternative for access to clean cooking, represented by electricity and LPG. To quantify the e-cook cost-effectiveness, Pay Back Time (PBT) and Internal Rate of Return (IRR) of the e-cook solution has been calculated. Given the high volatility of LPG price, since this fuel is strongly linked to economic and geopolitical factors, different price scenarios has been considered. Results have been therefore presented in a range from the average actual price of LPG found in literature and a future possible 40% increment in its price. Considering that with e-cook access to electricity, besides access to clean cooking, is provided, for the LPG solution has been considered to install a solar powered mini-grid sized to satisfy only the base load. For the residential case study, it resulted 7.63 to 11.23 years of PBT with a IRR of 8.58% to 14.35%. For the institutional case study instead, it resulted 5.20 to 7.70 years of PBT with a IRR of 18.07% to 24.87%. This specific economic analysis confirmed the cost-effectiveness of the e-cook solution with respect to the LPG one. PBT and IRR reported values for the institutional case are highly interesting and provide a reference for possible future development of the e-cook concept in similar contexts. In addition, the actual added value of e-cook solution is the use of electricity as a clean and renewable fuel. Hence, compared to all other solutions the e-cook one presented savings in terms of non-renewable fuel consumption.

Conclusions

Achieving sustainable cooking is one of the greatest challenges of our time and connects many Sustainable Development Goals (SDGs). The e-cook concept, as an option for access to clean cooking, is often abandoned a priori because, according with IEA: «*it requires a large amount of power, which means that is not suitable for off-grid power supply and is relatively expensive».* Within this thesis work, through a techno-economic analysis of the e-cook concept, its cost-effectiveness was instead proved. Accordingly, the e-cook solution should not be abandoned a priori but rather constitutes a valid alternative especially compared to LPG. Moreover, the crucial added value of the e-cook solution is guaranteeing access to electricity and to clean cooking at the same time and in a clean and renewable way.

Introduction

The aim of this thesis work is to investigate the techno-economic feasibility of the e-cook concept implemented in a solar powered mini-grid, and to explore its actual potential in developing countries, also given the scarce presence of similar studies in the literature. The analysis was conducted for the village of Kidegembye and for Mama Kevina Hope Center in Tanzania, representative of a residential and institutional case study respectively. Load profiles for mini-grid design have been modelled with a new method based on cooking cycles defined on local cooking habits. Through this new method, starting from simple field data, it's possible to consider load deriving from cooking activities within the load modelling process.

Chapter 1 is dedicated to an introduction to the very current problem of access to energy (electricity and clean cooking) with a specific focus on the case studies context, represented by sub-Saharan Africa. Furthermore, the not well known but dramatic impacts of cooking with traditional biomass are highlighted. Finally, an overview of the modern cooking technology is presented.

Chapter 2 Focuses entirely on the e-cook concept presentation. Main components of an e-cook solar powered mini-grid are therefore presented with a brief market summary for each of them.

Chapter 3 is dedicated to the presentation of methodologies used within this thesis work. The new method for load curve modelling based on cooking cycles defined on local cooking habits is explained.

Chapter 4 Presents results of the residential case study represented by Kidegembye village.

Chapter 5 Presents results of the institutional case study represented by Mama Kevina Hope Center.

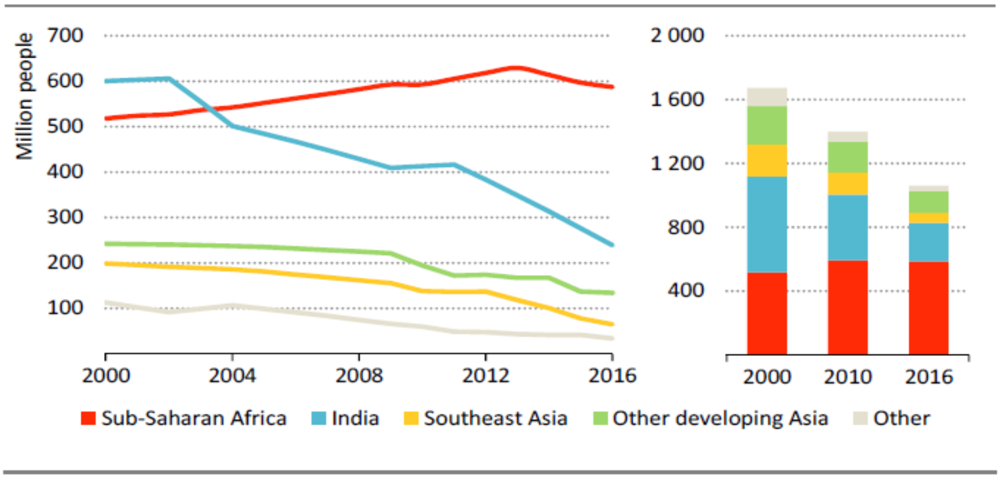
Chapter 6 is dedicated to conclusions and possible future developments.

1. Access to energy

Nowadays, around 1.1 billion people around the world don’t have access to electricity while an estimated 2.8 billion rely on the traditional use of solid biomass to cook their meals [1], most of them living in rural areas in developing countries. This situation hampers economic growth, social development and has a dramatic impact on health and environment.
In 2015, 193 countries joined the United Nations Sustainable Development Goals (SDGs) which include a target to ensure access to affordable, reliable, sustainable and modern energy for all by 2030 (SDG7) [9]. According to International Energy Agency (IEA) access to energy is the «*golden thread that weaves together economic growth, human development and environmental sustainability*» and it is defined as: «*a household having reliable and affordable access to both clean cooking facilities and to electricity […]*» where access to clean cooking facilities means possibility to use modern fuels and technologies as opposed to the traditional cookstoves used in developing countries. Energy access indeed is fundamental for achieving many other sustainable development goals related with poverty reduction, improvements in health and gender equality.

1.1 Access to electricity

Significant progress has been made in recent years in electricity access (Figure 1.1), with nearly 1.2 billion people who have gained access to electricity with a rate of more than 100 million people per year from 2000 to 2012. The electrification rate in developing countries in Asia reached 89% in 2016, up from 67% in 2000, China reached full electrification in 2015 and half a billion people gained access to electricity in India since 2000. In Latin America 97% of the population now has access to electricity and most of the population that lack access live in rural areas far from the grid. In sub-Saharan Africa 43% of the population now has access to electricity with 26 million people gaining access annually since 2012 and for the first time in 2014, electrification rate in sub-Saharan Africa outpaced population growth [1].



Note: Other includes Middle East, North Africa and Latin America.

Figure 1.1 Population without access to electricity by region [1]

1.1.1 A focus on Africa

African electric energy access is shown in Figure 1.2, in which the complicated situation in sub-Saharan Africa is highlighted. Even though the number of people without access to electricity in sub-Saharan Africa stopped increasing in 2013, still 590 million people remain without access in that region, more than a half of the total global population without access to electricity. Over 80% of those live in rural areas where the electrification rate is less than 25%, compared with 71% in urban areas [1].

Furthermore, the ones who have access to electricity must face an unreliable and unaffordable service. This is due to frequent outages from the production side, losses in the transmission and distribution side that are often two times the world average, and expensive electricity tariffs, among the highest in the world. These aspects, combined with the remoteness of rural areas, make conventional electrification by the expansion of the national grid too expensive. Moreover, sub-Saharan Africa is rich in renewable resources, especially sun, and is therefore the perfect place where to implement decentralized energy systems, either stand-alone or mini-grids, based on renewable resources. Decentralized systems are indeed defined as off-grid systems that are locally-based and need oriented, i.e. usually designed to satisfy specific local energy needs and relying on local energy resources [5]. They certainly represent one of the most appropriate solutions to the rural electrification issue, both as a first step in the electrification process or as a building-block for future grid development [10]. In the Energy for All Case, an energy scenario proposed by the IEA in the World Energy Outlook 2017: «*decentralized technologies play a key role in delivering universal access, especially in remote and rural communities with more than three-quarters of the additional connections needed provided by off-grid and mini-grid systems*».

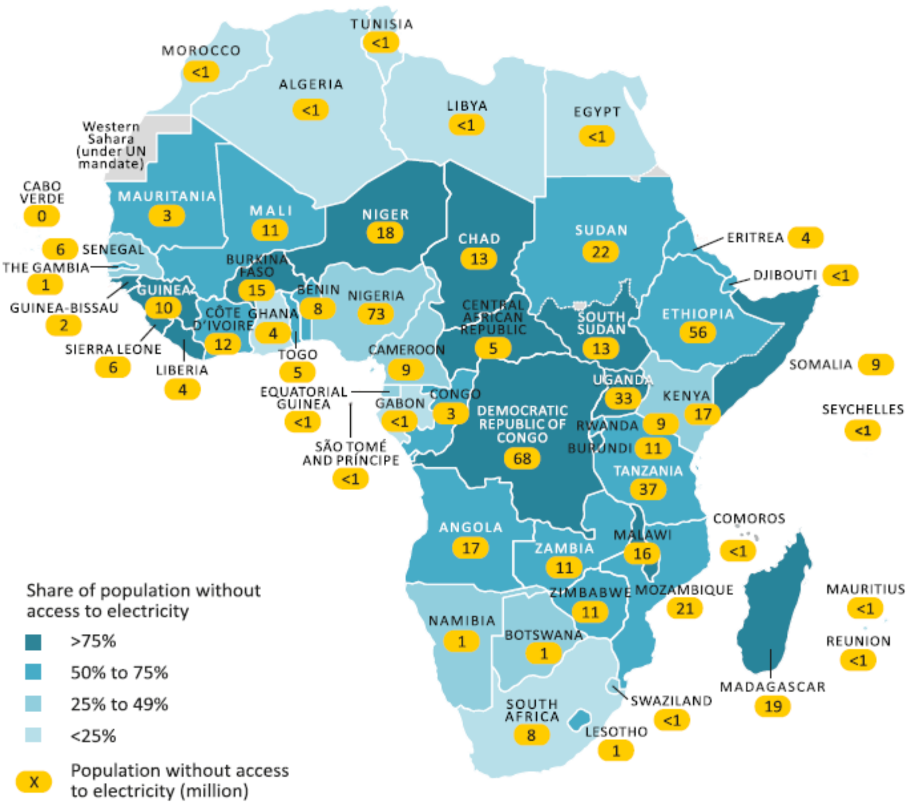


Figure 1.2 Population without access to electricity in Africa by country [1]

1.2 Access to clean cooking

Today around 2.8 billion people, 38% of the global population and almost 50% of the population in developing countries, lack access to clean cooking [1]. The IEA defines “access to clean cooking” as «*a household primarily relying on cooking facilities which are used without harm to the health of those in the household and which are more environmentally sustainable and energy efficient than biomass cookstoves and the three-stone fires currently used in developing countries*».

The majority of the people who do not have access to clean cooking rely on traditional biomass fuels such as firewood, charcoal or animal dung burned in traditional stoves, causing serious adverse consequences for the health, the environment and the social and economic development of the population. A further 120 million people use kerosene for cooking and 170 million use coal [3]. Most of the population without access to clean cooking, relying on solid fuels, is concentrated in sub-Saharan Africa and in developing Asia (Figure 1.3).

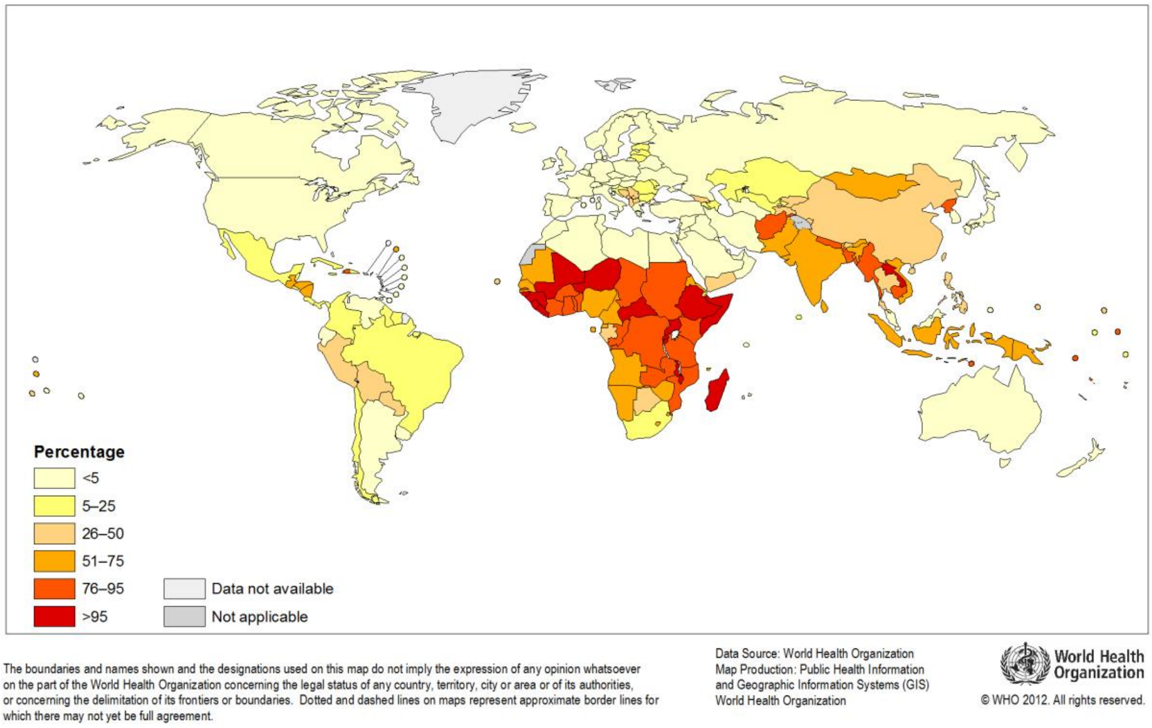


Figure 1.3 Population using solid fuels worldwide (%) [4]

The only regions in the world where progresses have been made on access to clean cooking are China and Indonesia, where the number of people cooking with solid fuels has declined respectively by 200 million and 100 million since 2000, especially thanks to targeted policies focused mainly on the use of LPG (Liquefied Petroleum Gas). However, in developing Asia, 1.65 billion people rely on biomass for cooking with an increase of 160 million people since 2000 [1]. In India, an estimated 780 million people rely on biomass for cooking and the number of households without access to clean cooking today is more than double that without electricity [2]. Sub-Saharan Africa is the region showing the least progress on clean cooking where almost 80% of the population still cooks with solid biomass, a number that has increased by 240 million since 2000 to reach around 780 million [1].

1.2.1 A focus on Africa

African access to clean cooking is shown in Figure 1.4 and, as for electricity, the worst situation is clearly concentrated in sub-Saharan Africa. In this region about 780 million people, almost four-fifths of the population and over 90% of the total population without clean cooking access, rely on solid biomass for cooking. This number has grown by nearly 50% since 2000, as population growth has outpaced the number of people gaining access to clean cooking [1].

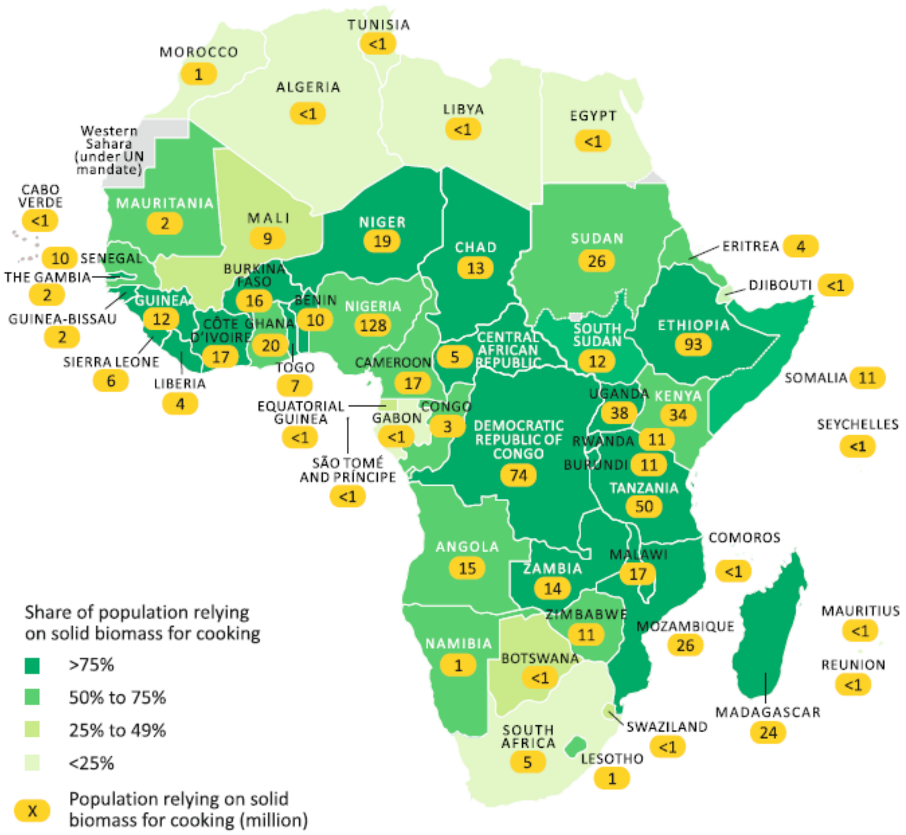


Figure 1.4 Population relying on solid biomass for cooking in Africa by country [1]

The use of biomass is deeply rooted in rural areas where about 93% of households rely on firewood, charcoal, dung and agricultural residues for their daily cooking needs [11].

Some countries like Cameroon, Ghana and Rwanda have programmes to promote the use of LPG as it has been done in China and Indonesia, and LPG is the most widely used modern cooking fuel but even this extends to just 7% of all households in sub-Saharan Africa and only 2% of rural households [1]. In Tanzania, 96% of the nearly 50 million inhabitants cook with solid biomass, specifically 77.6% cook with firewood and 19% with charcoal while just 0.3% cook with LPG and 0.2% with electricity [12].

1.2.2 The impact of cooking with traditional biomass fuels

Burning traditional biomass fuels such as firewood, charcoal or animal dung in inefficient cookstoves has a dramatic impact on population’s health, local and global environment and socio-economic development of communities.

The act of combustion releases toxic pollutants into the air, leading to levels of household air pollution (HAP) which often far exceed World Health Organization (WHO) guidelines. HAP is driving a global health emergency and it is recognized by the WHO as the single most important environmental risk factor worldwide. Based on estimates of solid fuel use for cooking in 2012, exposure to HAP causes 4.3 million premature death each year, exceeding deaths attributable to malaria or tuberculosis. The main diseases related to HAP are stroke, ischaemic heart disease, lung cancer and chronic obstructive pulmonary disease. Because of the greater involvement in daily cooking, women – and consequently children – are more exposed to HAP, rather than men: 60% of all premature death attributable to HAP occur in women and children. In addition to indoor air pollution, burning traditional biomass fuels releases emissions of some of the most important contributors to global climate change: carbon dioxide, methane, black carbon (which results from incomplete combustion) and other short-lived climate pollutants [13]. HAP indeed accounts for 12% of ambient air pollution globally and up to 30% of ambient air pollution in South Asia and China [3].

Unsustainable firewood and charcoal use is therefore recognized to be the single largest source of greenhouse emissions in many countries while it also leads to deforestation, soil erosion and loss of biodiversity whereas most areas deforested are rarely replanted resulting in a further negative impact. The production and use of solid fuel for cooking consumes more than 300 million tonnes of wood annually in SSA resulting in the highest average per-capita wood consumption in the world [14]. Considering also the strong population growth expected in the country, the problem becomes extremely serious. According to the World Bank, collecting firewood for cooking forces especially woman and children to spend from eight to nine hours each week in this task, limiting their opportunities to go to school, improve their education or engage in other more productive activities. Moreover, women involved in this task are at risk of head and spinal injuries, pregnancy complications from the strenuous task of carrying heavy loads of firewood or other fuels and may also suffer from gender-based violence, animal attacks, dehydration and skin disorders; the relationship between access to clean cooking and gender equity is therefore evident.

Key facts about the use of traditional biomass for cooking are summarized in Table 1.1.

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Table 1.1 Key facts regarding use of traditional biomass for cooking

2.8	Billion	People relying on traditional biomass for cooking in the world (IEA WEO2017, [1])
4.3	Million	Deaths per year attributable to Household Air Pollution worldwide (WHO, [13])
300	Million tonnes	Yearly firewood consumption in Sub-Saharan Africa (SEI, [14])
8-9	Hours	On average per week, spent for collecting fuel in SSA (World Future Council, [3])

1.2.3 Pathways to clean cooking access

So far, most of the developing countries efforts have been focused on guaranteeing access to electricity as highlighted in sub-section 1.1. Investments in access to clean cooking are, in fact, still at a low level compared to investments in access to electricity. The statistic related to clean cooking access are indeed generally much more discouraging than those of electricity access, and the two issues don't go hand to hand even though access to electricity may potentially ensure access to modern and clean cooking through the use electric cooking devices. For instance, in Nigeria and Ghana, two of the more electrified country in SSA, 60 to 70% of the population still relies on traditional biomass fuels for cooking. As recently reported by Hivos [3]: *«The cost of renewable energy and storage technologies keeps decreasing at a rapid pace. While we witness the global uptake and enormous cost reduction of renewable electricity, it would be a mistake not to embark the cooking sector on this journey».*

Moreover, in many developing countries households, cooking-related energy use represents over 90% of total primary energy demand. Accordingly, attempting to scale up renewable electricity supply without focusing on the cooking sector is therefore thoroughly inadequate, as it leaves much of the energy supply mix as well as many of the most significant challenges untouched [3]. Achieving sustainable cooking is one of the greatest challenges of our time and connects many sustainable development goals (SDGs), as highlighted in Figure 1.5. For this reason, new thinking around the question of cooking is strongly needed. Access to clean cooking can improve health and life expectancy through reduction of HAP (SDG3), relieve women from the inconvenient task of collecting fuel and therefore increasing their economic opportunity (SDG5), enhance the transition from traditional biomass to modern and sustainable fuels (SDG7, SDG11) and reduce deforestation rate and greenhouse gas emissions (SDG13).

Figure 1.5 Connection between access to clean cooking and SDGs [13]

However, there are many crucial barriers to the transition towards more sustainable cooking technologies, foremost several cultural and behavioural barriers linked to cooking habits, tradition and preferences. Cooking is indeed deeply rooted in people's way of life and cooking choices and behaviours are strongly tradition-based and location-specific. Moreover, the high upfront cost of alternatives, including both the cooking appliances and the fuel cost, combined with the availability in many regions of free firewood, is hindering the transition. It is estimated that around only 50% of households in sub-Saharan Africa pay something for their cooking fuels, whilst the remaining 50% gather firewood directly from the surrounding forests [6]. Making new cooking technologies affordable, especially in rural and remote areas where income levels are quite low, requires therefore the possibility to pay in instalments in order to at least overcome the upfront cost barrier. Other barriers are the lack of familiarity with the use of new cooking technologies and the "fuel stacking" problem (IEA 2016), which occurs when households continue to use, or partially use, traditional cooking technologies and fuels also when the new ones are available. This highlights the fact that the transition to sustainable cooking is likely to be a gradual process. Increasing access to clean cooking means guaranteeing access to both modern and clean fuel and cookstoves, and there is no single technology that can solve entirely the problem.

The development of all new technologies identified as helpful in fostering clean cooking access process must be carried out and targeted policies are strongly needed to promote their use. Every sub-Saharan African country submitted an INDC (Intentionally Nationally Determined Contribution) as part of the Paris Agreement in 2015 [15] and many of these include specific targets on electricity and clean cooking access. This represents a crucial step forward in the growing awareness of the importance of access to electricity and clean cooking in the region.

1.2.4 Overview of modern cooking technologies

So far, most of the efforts in the cooking sector in Sub-Saharan Africa have been focusing on the promotion of improved cookstove technologies (ICS) rather than on a fundamental transition of the fuel usage. An improved cookstove is a stove with higher efficiency and lower level of emission with respect to the traditional one; these improvements are achieved through the implementation of a number of design features, such as a closed combustion chamber, and optimised airflow circulation or the presence of a chimney. These technologies can certainly play an important role in addressing the challenge of sustainable cooking, but they represent, at best, an interim solution. The harvesting of wood and production of charcoal, in fact, continue to have significant negative impacts on the environment and on human health and what is more virtually no improved cookstove available on the market is able to meet WHO standards for exposure to HAP. Moreover, improvements in terms of emission achievable through ICS have been overestimated by laboratory tests that do not reflect real-life conditions [16].

As highlighted in paragraph 1.2 the only progress in access to clean cooking have been registered thanks to targeted policies on LPG usage. However, in sub-Saharan Africa, progresses are far to be met: in 2015 only 7% of the population has access to LPG [1]. The latter is commonly considered as a “clean” fuel because, when properly used and maintained, LPG stoves produce very low levels of direct emissions. However, the main concerns about LPG are availability and affordability. LPG is indeed transported and sold pressurized in cylinders and therefore needs some distribution infrastructure which needs to reach also the most remote rural areas. In addition, the upfront cost of the stove and the need to continuously buy fuel could undermine the affordability of the solution. Moreover, the use of LPG is unsustainable in the long-term from the environmental point of view, as it is a non-renewable fossil fuel, and from the economic point of view because its price is strongly linked to economic and geopolitical factors.

Biogas is a promising alternative that produces low levels of emissions, similarly to LPG, is a renewable fuel and has no negative climate impact. It is produced in biodigesters from organic material like crop residues and food waste through anaerobic digestion and the remaining slurry is a valuable fertilizer. However, biodigesters require a substantial upfront investment cost that can range from 100$ to 1000$ depending on the size, making them unaffordable for many rural households, and the proper installation and the maintenance of the system are also critical, especially in remote rural areas [3]. Moreover, while the fuel, represented by waste, in rural areas is typically free and abundant, the biodigesters need also a reliable supply of water that in some cases could be a problem.

Another kind of clean cooking technology is represented by solar-thermal cooking systems, such as solar-box and parabolic cookers, where the energy from the sun is directly exploited to cook. These systems are really simple, affordable and have no environmental impact. The solar-box is very easy to be built and it’s made of cheap materials, but cooking is very slow, and the maximum reachable temperature is relatively low limiting the cooking options [17]. On the other hand, parabolic cookers are more powerful, but the cooking power cannot be controlled, and its usage is limited to clear sky days [18]. For these reasons solar-thermal cooking systems have found little success so far.

The cleanest fuel at point-of-use, in term of emission, is electricity, whether used to power electric devices such as induction stoves (*e-cook* concept). Considering the recent progress in access to electricity, discussed in sub-section 1.1, and the huge potential of decentralized energy systems such as mini-grids, the e-cook concept could make a big contribution to the challenge of access to clean cooking. For these reasons the e-cook concept is examined in detail in Chapter 2.

1.3 Case studies

African continent and especially Sub-Saharan Africa are in the foreground when it comes to access to energy, as highlighted in sub-sections 1.1.1 and 1.2.1. For this reason, it is of great interest and of extreme necessity to investigate feasible solutions for enhancing access to electricity, to clean cooking and more in general to access to energy in these contexts. This thesis work refers to two case studies located in Tanzania: the small village of Kidegembye in Njombe region and the second one related to a personal field experience in Mama Kevina hope center in Same region.

Tanzania is located in East Africa and borders Kenya and Uganda in the north; the Democratic Republic of Congo, Burundi and Rwanda in the west; Zambia, Malawi and Mozambique in the south and the Indian Ocean in the east (Figure 1.6). It has a population of about 55.57 million people with an annual growth of about 3%, 67.7% of the population lives in rural areas working in the agriculture sector. Tanzania is particularly representative of African problems in terms of access to electricity and to clean cooking as depicted in Table 1.2. Most of the population lives in rural areas without access to electricity and relies almost exclusively on solid fuels. The percentage of the population using modern fuels for cooking amounts to only 0.5% (0.3% electricity, 0.2% LPG) while almost the entire population relies on firewood and charcoal for cooking [19].

Population	Around 56 million
Access to electricity (% of population)	15.5%
Access to electricity in rural area (% of rural population)	4%
Access to electricity in urban area (% of urban population)	41.1%
Percentage of population using solid fuels for cooking	96%
Number of death per year from HAP	Around 20000
Urban population using solid fuels	84.7%
Rural population using solid fuels	>95%
Population using wood for cooking	77.6%
Population using charcoal for cooking	19%
Population using gas for cooking	0.2%
Population using electricity for cooking	0.3%

Table 1.2 Tanzania by numbers [12], [19], [21]

Figure 1.6 Map of Tanzania [20]

1.3.1 Kidegembye - Njombe region

The small village of Kidegembye is located in the Njombe region is in the southern part of Tanzania, it counts thirty-three households for a total of 174 inhabitants and it has been recently electrified by the national grid extension.
In a master thesis developed at Politecnico di Milano University by Berti [22], [23], an assessment of energy needs and consumptions of the village was carried out in order to provide an estimate of the electrical energy demand for a rural electrification project conducted by CEFA, a non-Government Organization (NGO). For the scope Berti's study, it was sufficient to consider only the actual electric appliances present in the village, without considering the energy related to cooking needs. However, the aim of this thesis work is to investigate the techno-economic feasibility of the e-cook concept. For this reason, the energy assessment of the village carried out by Berti has been taken as a reference case (base load scenario).
In order to provide an estimate of the electrical energy consumption of the Kidegembye village, questionnaires were addressed to households (Annex B). The Questionnaires are composed of two sections: the first one concerns questions about general information like composition of the family, employment, income and expenditure of households; the second one concerns questions about electric device usage. Number and type of electric devices used in the house, the average daily use, the minimum functioning time and the functioning windows for each appliance have been asked to households (data required by LoadProGen for load curve estimation, as further discussed in section 3.1).
This case study wants to be representative of a wide number of similar small rural villages around Tanzania.

1.3.2 Mama Kevina hope center - Same region

Mama Kevina hope center is a residential structure for children with mild to severe disabilities and a point of reference for children with serious neurological diseases. In January 2018 I've been in the center for volunteering with the association *Hands for Africa – Hands for Osteopathy* and I took the opportunity to collect data for the study and to form a field experience-based case study. Mama Kevina is run by Christian sisters and it hosts twenty to thirty people all year long.
The centre has 3 main buildings: the first one is the dormitory, living room and toilets for the children; in the second one there is the kitchen, the dining hall and the sister's head office; the third one is the dormitory and living room for the sisters (Figure 1.7). The other smaller buildings are the guest house, the garage, the therapeutic room, the millstone house, the craftsman house and the guardian room.

It is a small-scale scenario and it is labelled as “institutional case” since the habits, in terms of electric appliance usage and cooking habits, are less random with respect to the village case study.
In order to estimate the electrical energy consumption of the centre, during my stay, I counted the number and type of electric devices used in the buildings and asked for the average daily use, the minimum functioning time and the functioning windows for each appliance. In addition, in order to collect reliable data about cooking habits in the center, I personally assisted the chef in Mama Kevina more than once.
This case study wants to be representative of a wide number of similar structure present all around the country and more generally in Africa.

Figure 1.7 Mama Kevina hope centre satellite view

2. The *e-cook* concept

Cooking with traditional biomass fuels has a dramatic impact on population's health, local and global environment and socio-economic development of communities as underlined in sub-section 1.2.2. Achieving sustainable cooking is therefore one of the greatest challenges of our time and connects many sustainable development goals (SDGs), as highlighted in Figure 1.5. Clean and modern solutions are strongly needed to promote access to clean cooking and some of them have been presented in sub-section 1.2.4. However, the e-cook concept which exploits electricity as a clean fuel for cooking is often abandoned a priori because «*it requires a large amount of power, which means that is not suitable for off-grid power supply and is relatively expensive* » [1]. The aim of this thesis work is therefore to provide a techno-economic analysis of the e-cook solution and to investigate its actual potential in developing countries, also given the scarce presence of similar studies in the literature.

The e-cook concept is strongly linked to the high emerging potential of decentralized systems such as mini-grids to produce electricity at relatively low cost in developing countries and especially in rural areas far from the national grid. This solution provides for the use of electricity to power electric cooking appliances such as induction stoves. These devices are highly energy-consuming with a nominal power around 2 kW per cooker, and very far from the culture and habits of most developing countries. These two factors highlight the main challenges of e-cook concept in technical and cultural terms.

From the cultural point of view an immediate transition from a traditional way of cooking with solid biomass to whichever kind of modern cooking technology is unimaginable. The transition is certainly more likely to be gradual, yet it is crucial to provide clean and modern alternatives for achieving access to clean cooking as soon as possible.

From the technical point of view photovoltaic systems are well known to be an interesting electricity supply solution, especially in sub-Saharan Africa where the solar resource is abundant. Furthermore, the continuous decrease of the components cost, such as solar PV modules and batteries, and their increasing performances are beginning to make solar the most cost-effective solution for electricity production in many regions of the world [24]. These improvements can therefore foster the diffusion of the e-cook concept as a clean cooking options.

The main components of a solar mini-grid system are described in the next sub-sections in order to provide a technical overview, but firstly the induction stove, the appliance on which the e-cook concept is based, is presented.

2.1.1 Induction stove

The major components in an induction stove are the induction coil and the ceramic plate. The principle of operation of an induction stove is based on the high frequency oscillating magnetic field generated by an alternating electric current which flows through the induction coil. The magnetic field penetrates the ferrous cookware and sets up an eddy current that generates heat at the base of the metallic cookware which is further transferred to its content.

The working principle of an induction stove is depicted in Figure 2.1.

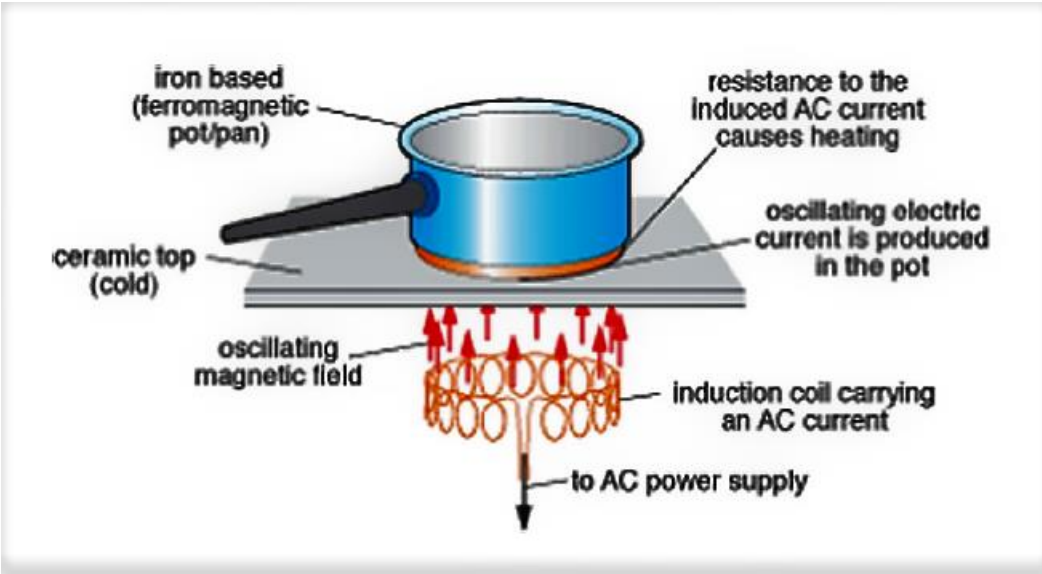


Figure 2.1 Working principle of an induction stove [25]

Induction stoves can be used for all cooking purposes, with the only restriction being the use of ferro-magnetic cookware. Depending on the meal, these kind of appliances reportedly utilize between 28% and 79% of the total energy required to prepare the same meal with traditional electric stove [26]. The efficiency of induction stoves is indeed very high and around 90% [27].

To identify the induction stoves models for the study, a brief market survey has been conducted for both single induction cooker and induction cooktop with four cookers (induction kitchen).

Single induction cooker's survey results are presented in Table 2.1, the analysis showed that most of the induction stoves available on the market have a nominal power of 2000 W and different features such as regulation systems on temperature or power or both. The appliances present on Tanzanian e-commerce website such as *Zudua* or *Jumia* have also specific cooking programs such as *“deep fry, heat milk, chapati”* where chapati is a very common type of bread in East-Africa. In addition to this they also have a display area where the instantaneous power consumption is shown. However, due to the lack of reliable data on power and dimensions of the appliances available on Tanzanian market the *Aigostar Blackfire 30IAV* (Amazon choice for single induction cookers) has been chosen. This product, manufactured by Aigostar company, has a maximum power consumption of 2000 W and an operating voltage of 220-240V with manual power or temperature control options. The criteria for the selection were based on its cost, comparable to the Tanzanian market, its dimensions, compatible also with big pots and pans, its features, its user friendliness thanks to its very simple design and on its Amazon rate [28].

Product	**Power [W]**	**Price [$]**	**Features**	**Available on**
Aigostar Blackfire 30IAV	2000	61.53	10 Power&Temperature levels	Amazon
Aicok induction cooker	2000	63.83	10 Temperature levels	Amazon
Severin KP 1071	2000	85.26	10 Temperature levels	Amazon
Casa induction cooker	1900	66.56	Specific programs & power consumption display	Zudua e-commerce website (TZ)
Casa induction cooker 2	1900	62.11	Specific programs & power consumption display	Zudua e-commerce website (TZ)
Geepas Induction cooker	2000	65.22	Specific programs & power consumption display	Jumia e-commerce website (TZ)

Table 2.1 Summary of the market survey on single induction cookers

Results of the survey on induction kitchen are depicted in Table 2.2, the analysis has been conducted on induction kitchen with four cookers and it showed that most of the appliances have a total maximum power around 7000 W. This power is usually subdivided in two cookers of 2000 W and the other two of 1500 W. All the products are available on Amazon, a lack of presence of induction kitchen on the local Tanzanian market has emerged from the survey. The *Candy CI 640 CBA/1* has been chosen for the study since it has the important features of a 3 kW limiter in order to limit energy consumption and because it has a reasonable price compared to the market average.

Figure 2.2 Aigostar Blackfire 30IAV [28]

Product	Maximum power [W]	Price [$]	Features
Viesta I4Z	7000	321.36	2x2000W+2x1500W
Klarstein Virtuosa	7000	368.34	2x2000W+2x1500W
CANDY CI 640 CBA/1	6800	341.32	3kW limiter
HOTPOINT IKID 640 F	6400	428.86	2x1800W+2x1400W
WHIRLPOOL ACM806/NE	7000	436.22	2.5-4-6kW limiter
Bosch PIE611B10J	7200	414.16	3kW limiter

Table 2.2 Summary of the market survey on induction kitchen

2.1.2 PV array

PV technology provides clean and sustainable energy which draws upon the planet's most plentiful and widely distributed renewable energy resource. This technology has the potential to strongly contribute to the achievement of many sustainable development goals such as global access to energy, sustainable communities and climate action.

The global PV market has grown rapidly in the last decade: cumulative global installed PV capacity grew from 6.1 GW at the end of 2006 to 291 GW at the end of 2016. However, the market for solar PV is still focused on a narrow range of OECD countries, while in Africa is widely dominated by South Africa which account for nearly 65% (1361 MW) of the continent's cumulative installed capacity in 2015 [29].

The bulk of PV production capacity is situated in Asia, where China is the world leader in PV production. Crystalline silicon-based photovoltaics continues to dominate the market and in the last decade huge improvements have been made in terms of efficiencies which have increased from about 12% to a range of 17% to 19%. In addition, solar PV module prices declined by around 80% between 2009 and 2015 [24]. Is therefore evident that technical improvements and price decline are making solar the most cost-effective solution for electricity production in many regions of the world.

To identify the PV module model for the mini-grid system a brief market survey has been conducted (Table 2.3). In the analysis a wide number of manufacturers from different countries have been investigated for PV module with peak power between 240 W and 345 W and for both polycrystalline and monocrystalline technology. An average market price of 0.822 $/W and an average efficiency of 17.03% resulted from the survey. The *QCELLS 275W* with monocrystalline technology has been selected for the mini-grid as it has the lowest price with an efficiency of 16.50%, just slightly above the average and it has a not too high coefficient of reduction of the power with the temperature.

Main parameters of the *QCELLS 275* are depicted in Table 2.4 and the datasheet is available in Annex A.

Product	Technology	Pmax [Wp]	Efficiency [%]	Price [$]	$/W
HANWHA SOLAR 240W	poly	240	14.50	139.97	0.583
TRINA SOLAR 255W	poly	255	15.60	151.00	0.592
TALESUN 320W	poly	320	16.50	199.97	0.625
CSUN 305W	poly	305	15.75	197.97	0.649
SOLARWORLD 285W	mono	285	17.00	193.97	0.681
TRINA SOLAR 320W	poly	320	16.50	222.00	0.694
SERAPHIM 340W	mono	340	17.52	249.97	0.735
CANADIAN SOLAR 295W	mono	295	18.02	219.97	0.746
CANADIAN SOLAR 300W	mono	300	18.33	233.97	0.780
CANADIAN SOLAR 275W	mono	275	16.80	227.97	0.829
MITSUBISHI 265W	mono	265	16.10	221.97	0.838
QCELLS 275W	mono	275	16.50	155.97	0.567
QCELLS 290W	mono	290	17.40	245.97	0.848
QCELLS 300W	mono	300	18.00	253.97	0.847
SOLAR STAR 270W	poly	270	18.49	229.97	0.852
MITSUBISHI 275W	mono	275	16.70	235.97	0.858
SUNIVA 275W	mono	275	16.73	239.97	0.873
JA SOLAR 315W	poly	315	16.25	280.00	0.889
SUNIVA 325W	mono	325	16.66	297.97	0.917
SUNIVA 335W	mono	335	17.18	307.97	0.919
SOLARWORLD 345W	mono	345	17.29	329.97	0.956
SOLARWORLD 315W	mono	315	16.03	315.97	1.003
PANASONIC 315W	mono	315	18.80	329.97	1.048
SOLARWORLD 295W	mono	295	17.59	319.97	1.085
PANASONIC 325W	mono	325	19.40	372.97	1.148
			17.03		**0.822**

Table 2.3 Summary of the market survey on PV module [30]–[33].

QCELLS 275W 60cells		
Power	W	275
Nominal voltage	V	20
Efficiency @STD	-	16.5%
T coefficient γ	-	-0.4%
T_STD	°C	25
V_oc @STD	V	38.72
I_sc @STD	A	9.35

Table 2.4 QCELLS 275 main parameters

2.1.3 Batteries

Battery technology is a wide field, there are many different cell type and within any one broad type there are many different chemistries, each of which has different functional characteristics. Detailed discussion of different battery types is out of scope for this thesis work hence the analysis has been restricted to lead-acid and Lithium-ion (Li-ion) batteries. In the last years efforts in battery development have been focused mainly on Lithium-ion technology because of the nascent electric vehicle market which requires high energy density [6]. The higher energy and power densities are the reason why Li-ion batteries are already widely dominating the consumer electronics market such as cell phones, laptop computers and many other portable electronic devices. The renewable energy sector is only expected to benefit from the development of the Li-ion batteries in the near future but will not be the driving objective of industries [34].

The relevant features of Li-ion batteries for the renewable energy sector are high efficiency, high cycle life in deep discharge applications also with high operation temperature and no need of maintenance. These characteristics have the potential to increase efficiency, lifespan and reliability of decentralized systems such as solar powered mini-grid.

However, energy storage in off-grid PV systems is currently dominated by lead-acid batteries as they represent, at the moment, the most cost-effective solution [7]. The lead-acid battery is the oldest and most mature technology that has been used for energy storage applications, with low investment cost, lowest self-discharge of all rechargeable battery system and relatively ease of maintenance they provide a cost-competitive and proven solution to a range of storage requirements [35].

To identify the battery model for the mini-grid system a brief market survey has been conducted (Table 2.5). Both lead-acid and Li-ion technology have been investigated from the main manufacturer company. The system voltage has been chosen to be 48 V in order to reduce current and therefore size of the cables and power losses and to install a 48 V DC inverter which will be safer and more reliable compared to the 12 or 24 V DC one [6], [36]. OPzS acronym is used to refer to a flooded type of tubular-plated, lead acid, deep cycle battery and it stands for Ortsfest (stationary) PanZerplatte (tubular plate) Flussig (flooded) [37].

The choice of the battery model, for each case study and relative scenarios, has been made within the HOMER Optimized system design.

Considerations about the implications of battery type for the system will be widely discussed in sub-section 3.2.2 and 3.3.2.

Product	Technology	V	Capacity [Ah]	Capacity [kWh]	Price [$]	Efficiency
Hoppecke 10 OPzS solar 1520	Lead Acid	48	1520	72960	12027.8	0.86
Hoppecke 11 OPzS solar 1670	Lead Acid	48	1670	80160	13224.4	0.86
Hoppecke 12 OPzS solar 1820	Lead Acid	48	1820	87360	14237.2	0.86
Hoppecke 12 OPzS solar 2170	Lead Acid	48	2170	104160	16660	0.86
Hoppecke 14 OPzS solar 2540	Lead Acid	48	2540	121920	20649.6	0.86
Hoppecke 16 OPzS solar 2900	Lead Acid	48	2900	139200	23042.7	0.86
Hoppecke 18 OPzS solar 3250	Lead Acid	48	3250	156000	25865	0.86
Hoppecke 20 OPzS solar 3610	Lead Acid	48	3610	173280	28045	0.86
Hoppecke 22 OPzS solar 3980	Lead Acid	48	3980	191040	30376	0.86
Hoppecke 24 OPzS solar 4340	Lead Acid	48	4340	208320	32616.6	0.86
HP Solar One SO-6-125-33	Lead Acid	48	1992	95616	24640	0.85
OutBack EnergyCell 2700RE	Lead Acid	48	2288	109824	28638	0.9
Outback Power Nano-Carbon 2200NC	Lead Acid	48	1855	89040	24800	0.95
Simpliphi PHI 3.4	Li-ion	48	67	3.44	3490	0.98
LG RESU6.4	Li-ion	48	63	3.2	6167.3	0.95
LG RESU10	Li-Ion	48	189	8.5	5830	0.95
Tesla Powerwall 2CC	Li-ion	48	280	13.5	7299	0.918
Discovery 42-48-6650	Li-ion	48	130	6.656	7406	0.95

Table 2.5 Summary of the market survey on batteries [30], [38]–[41]

2.1.4 Solar Charge controller

A controller is needed to manage the interaction between the PV modules and the batteries, to block reverse current, to protect the batteries from overcharging or over-discharging, to protect batteries from over-heating and to maximize the output of the PV module.

There are two main type of solar charge controller: the traditional Pulse Width Modulated (PWM) solar charge controller and the Maximum Power Point Tracker (MPPT) solar charge controller. The PWM is a time-tested technology, it’s cheap and reliable but it is only available in small sizes respect to MPPT and has limited capacity for system growth. The MPPT solar charge controller it’s more expensive than the PWM but offers a potential increase in charging efficiency up to 30% respect to the PWM, offers the possibility to have a PV array with higher input voltage than battery bank and has great flexibility for system growth [42]. For these reasons MPPT solar charge controller has been chosen as reference technology for the system.

To identify the solar charge controller model for the mini-grid system a brief market survey has been conducted investigating a wide number of manufacturers from different countries (Table 2.6).

The *Magnum PT-100 MPPT* has been selected for the mini-grid as it has a high value of maximum PV array short circuit current accepted and a reasonable price. Main parameters of the *Magnum PT-100 MPPT* are depicted in (Table 2.7) and the datasheet is available in Annex A.

Product	**Max PV voltage [V]**	**Max PV I_sc [A]**	**Pmax [W]**	**Efficiency**	**Price [$]**
Magnum PT-100 MPPT	187	100	6600	0.98	752
OutBack FM80-150 MPPT	150	80	4000	0.975	488
Morningstar TS-MPPT-60	150	60	3200	0.99	598
MorningstarTS-MPPT-60-600V-48	525	60	3200	0.979	1359
Conext XW MPPT 60A	140	60	3500	0.98	547
Steca Tarom MPPT 6000	180	60	3600	0.989	850
OutBack FLEXmax100	290	100	6000	0.988	968
Victron Energy Smart MPPT 150/100	150	70	5800	0.98	785
Schneider XANTREX XW MPPT 80 600	550	80	4800	0.96	1350

Table 2.6 Summary of the market survey on solar charge controller [30], [40]–[42]

Magnum PT-100 MPPT		
Max voltage	V	187
Max current	A	100
Max power	W	6600
Efficiency	-	98%

Table 2.7 Magnum PT-100 MPPT main parameters

2.1.5 System inverter

The system inverter converts the DC current from the battery bank into AC current that runs every electric appliance in the households. In order to select the inverter for the system a brief market survey has been conducted (Table 2.8). Every system inverter has a nominal input voltage equal to the battery bank voltage 48 V DC. The choice of the system inverter model, for each case study and relative scenarios, has been made within the HOMER Optimized system design.

Product	Pmax [W]	Efficiency	Price [$]	[$/W]
Magnum MS4348PE	4300	0,91	2175,2	0,506
Schneider Conext SW 4048	3800	0,94	1592,5	0,419
Schneider Conext XW6848NA	6800	0,95	3093,7	0,455
Radian GS8048A	8000	0,93	4331,5	0,541
Victron Quattro	12000	0,96	5747,5	0,479
Outback Power VFXR-3048E	3000	0,93	1569,3	0,523

Table 2.8 Summary of the market survey on system inverter [32], [43], [44]

3. Methodology

3.1 Load curve modelling

The aim of this thesis work is to investigate the techno-economic feasibility of the e-cook concept implemented in a solar powered mini-grid. Decentralized energy systems, like mini-grids, are off-grid systems locally-based and need oriented, i.e. usually designed to satisfy specific local energy needs and relying on local energy resources [5]. For this reason, load demand assessment in rural electrification project is strictly required to allow the optimal sizing of the system. The first challenge of implementing e-cook concept in off-grid systems concerns modelling of load profiles that also consider loads deriving from electric cooking appliances such as induction stoves. For this purpose, in the literature, it is usually defined a fixed energy consumption specific to a meal in order to present a study as general as possible [6],[7]. However, a new method is proposed in this thesis work in which load profiles are modelled based on cooking cycles defined on local cooking habits. Local cooking habits means main local dishes, their preparation in terms of cooking methods and timings, but also the number of meal consumed per day and the time in the day in which they are prepared.
For load curve modelling LoadProGen software, presented in the next sub-section, has been used.

3.1.1 Introduction to LoadProGen software

The LoadProGen (Load Profile Generator) software has been developed by the group of the UNESCO Chair in Energy for Sustainable Development in collaboration with group of Power Systems – Department of Energy of Politecnico di Milano, which is currently continuing its development. It is based on a mathematical procedure devoted to formulating daily load profiles for off-grid consumers in rural areas of developing countries. The mathematical procedure is based on input data that can be reasonably surveyed and/or assumed in rural areas, and it is based on a stochastic bottom-up approach with correlations between load profile parameters in order to build up the coincidence behaviour of electrical appliances [45].

The LoadProGen input data requirement are presented in Table 3.1 where appliances' functioning times and windows are the most significant data since they determine the daily electric energy consumption and the coincidence behaviour of the appliances respectively.

$\boldsymbol{i}$	Type of electrical appliances (e.g. light, radio, tv)
$\boldsymbol{j}$	Specific user class (e.g. household, dormitory, kitchen)
$\boldsymbol{N_j}$	Number of user within class j
$\boldsymbol{n_{ij}}$	Number of appliances i within class j
$\boldsymbol{P_{ij}}$	Nominal power rate [W] of appliance i within class j
$\boldsymbol{h_{ij}}$	Overall time each appliance i within class j is on during a day [min]: *functioning time*
$\boldsymbol{w_{F,ij}}$	Period(s) during the day when each appliance i within class j can be on: *functioning windows*
$\boldsymbol{d_{ij}}$	Functioning cycle [min], i.e. minimum continuous functionating time once appliance ij is on
$\boldsymbol{Rh_{ij}}$	% random variation of functioning time appliance ij
$\boldsymbol{Rw_{ij}}$	% random variation of functioning windows appliance ij

Table 3.1 Input data LoadProGen [45]

In LoadProGen, in order to consider a degree of uncertainty in the values of functioning time $\mathrm{h_{ij}}$ and functioning windows $\mathrm{w_{F,ij}}$ random parameters $\mathrm{Rh_{ij}}$ and $\mathrm{Rw_{ij}}$ are introduced respectively. They set the maximum percentage of functioning time and functioning windows subject to random variations.
Another important feature of LoadProGen is the definition of a *peak window,* i.e. a functioning window which results to be embraced by most of the appliances hence defining a possible maximum power peak.
Given all the input data the load profile of each appliances ij is computed by defining, in a stochastic manner, the times t_{ij} the appliance ij is switched on within the vector of the daily minute [1:1440]. Hence, having the switching on times t_{ij} and the functioning cycles d_{ij}, the load profile of each appliance is defined. Then, the daily load profile of the user class j results from the aggregation of single appliance profile ij. Accordingly, the overall daily load profile results from the aggregation of the user classes' profile j [45].

LoadProGen was born as a support tool for the formulation of load profiles to be employed in the design process of off-grid systems for rural electrification. Load profiles modelling considering also the energy needs for cooking purposes is therefore out of its features. Therefore, in the next sub-sections, methodologies for cooking cycle modelling and implementation in LoadProGen have been presented.

3.1.2 Induction stove modelling and cooking habits assessment

In this sub-section basis for cooking cycles modelling have been provided.

Firstly, single cooker induction stove has been modelled as an input for LoadProGen. To do this, information taken from induction stoves' manual and datasheet, as the ones depicted in Table 3.2, was summarized to form a simplified model with three levels of power: 500 W (low), 1500 W (medium), 2000 W (high) . This model has been used for cooking cycles modelling within the Kidegembye village case study.

Power level	Watts	Cooking level
1-2	100-300	Simmer-keep warm
3-4	300-700	Low
5-6	700-1000	Medium-low
7-8	1000-1500	Medium-High
9-10	1500-2000	High

Table 3.2 Summary of user manual and datasheet for single cooker induction stove [46]

Power level	Watts	Cooking level
1-4	500	Low
5-8	1500	Medium
9-10	2000	High

Table 3.3 Simplified model for a single cooker induction stove

Regarding Mama Kevina Hope Center, given the number of inhabitants in the center, and that the whole meals are usually prepared in the same kitchen, an induction kitchen has been considered rather than a single induction cooker. Moreover, bigger pots and pans are used and for this reason, it's plausible that higher power levels are needed for meals preparation in Mama Kevina rather than in the village. In order to take in to account these considerations, and to provide a conservative scenario, the induction kitchen has been modelled as an appliance with fixed power rate of 3 kW (*Candy CI 640 CBA/1* with 3 kW power limiter). This assumption is reasonable also given the fact that more than two preparations at the same time are rarely carried out. Thus, power level of two cookers is around 3 kW.

Then, cooking habits assessment has been first carried out with the information given by Lorenzo Berti who personally spent a month in the village of Kidegembye. These have been further complemented by Fabrizio Colombelli, Energy Program Manager of CEFA-Tanzania.

Hence, the "Household Food and Nutrition Security Baseline Survey for Dodoma, Iringa, Njombe, and Singida" by Tanzania Food and Nutrition Centre and TAHEA (Tanzania Home Economics Association) has been consulted [47]. In addition, Prof. Pietro D'Alessio, Professor of "Prodotti e cucine del Mondo" for the gastronomic science degree course in the "Università degli studi di Parma" has been consulted. As last, my field experience confirmed the obtained information and contributes to precisely define cooking habits in Mama Kevina hope centre. This information was crucial for the cooking cycle modelling and represent the starting point of the load curve modelling process.

In Tanzania, especially in poor rural areas, the diet is restricted and limited to a small number of dishes which are prepared with locally available ingredients. For breakfast milk or tea are usually consumed with Chapati (a very popular type of bread in East Africa) or fruits. For lunch or dinner, the most common main dish is certainly Ugali which is made of maize flour cooked in boiling water. As rice, it goes with vegetables, beans and rarely meat. Cooking habits in Mama Kevina Hope Center are not far from typical Tanzanian tradition. For breakfast the chef usually prepares porridge and chapati bread for the day. For lunch or dinner, preparations are limited to ugali with vegetables/beans or rice with vegetables/beans and sometimes soup. In Table 3.4 Tanzanian main dishes are depicted and combined with corresponding timings and induction cooker power levels according with the simplified model. Table 3.4 represents the starting point for cooking cycle modelling for Kidegembye village. In Table 3.5 instead, Mama Kevina main preparations and corresponding timings are depicted.

Breakfast	**Timing [min]**	**Power [W]**	**Power level**
Latte/The	4-6	2000	HP
Chapati	4-6	1500	MP
Lunch/Dinner	**Timing [min]**	**Power [W]**	**Power level**
Ugali	20-30	500	LP
Rice	20-30	500	LP
Soup	20-40	500	LP
Vegetables/potatoes	5-10	1500	MP
Water boiling	15-25	2000	HP

Table 3.4 Summary of Tanzanian cooking habits with corresponding timings and induction cooker power levels

Breakfast	**Timing [min]**
Porridge	20-30
Chapati	10-15
Lunch/Dinner	**Timing [min]**
Ugali	20-30
Rice	20-30
Soup	20-40
Vegetables/potatoes	5-10
Water boiling	15-25

Table 3.5 Mama Kevina main preparations and corresponding timings

3.1.3 Cooking cycles modelling

Starting from cooking habits assessment and through the specific model for induction stove, cooking cycles have been modelled for both case studies.

LoadProGen allows to generate a fixed functioning cycle of a generic appliance instead of defining the functioning time and functioning cycle input parameters. Hence, whenever an appliance characterized by a fixed functioning cycle is on, its load profile will be determined by the specified fixed functioning cycle. However, while it’s possible to consider a degree of uncertainty on functioning windows of this fixed functioning cycle, it is not possible to randomize its length in terms of time.

To better reflect the highly random nature of cooking activities, specific scripts (FP_random_cycle, LD_random_cycle available in Annex C) have been developed in MATLAB to bypass this software limit, simulating different cooking cycle preparation. In these scripts every cooking task timing has been randomized between a minimum and a maximum timing considered for the specific task (Table 3.4, Table 3.5). The union of each single randomized task forms a random cooking cycle.

According with the induction kitchen model for Mama Kevina, cooking cycles modelling for this case study is limited to the randomization of the preparation length within the functioning windows of the induction kitchen.

For the Kidegembye village case study instead, given cooking habits information and the simplified model for a single cooker induction stove, cooking cycles have been generated from the MATLAB scripts.
Hence, for breakfast the cooking cycle has been modelled as a combination of two tasks. The first is related to boil water for tea or heat up milk, and it takes 4-6 minutes with the induction cooker at high power (HP). The second task is Chapati preparation which takes 4-6 minutes with the induction cooker at medium power (MP). Accordingly, breakfast total preparation time will vary between 8-12 minutes (Table 3.4). Two examples of the randomization process on breakfast cooking cycles are shown in Figure 3.1 and Figure 3.2. From these two examples, it can be noticed how the length of each single task varies between its bounds and total preparation timing varies consequently.

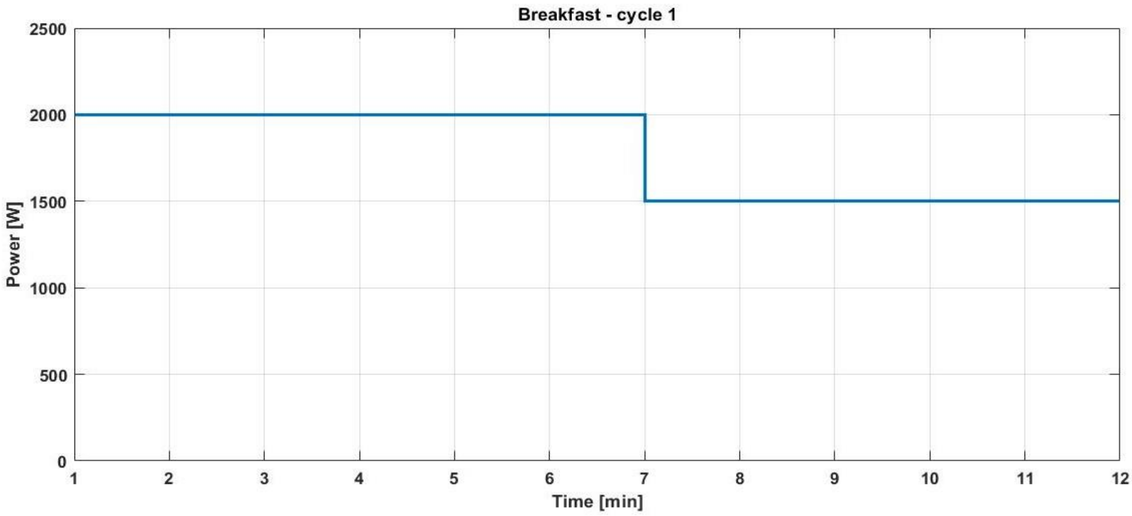


Figure 3.1 Breakfast randomized cycle 1

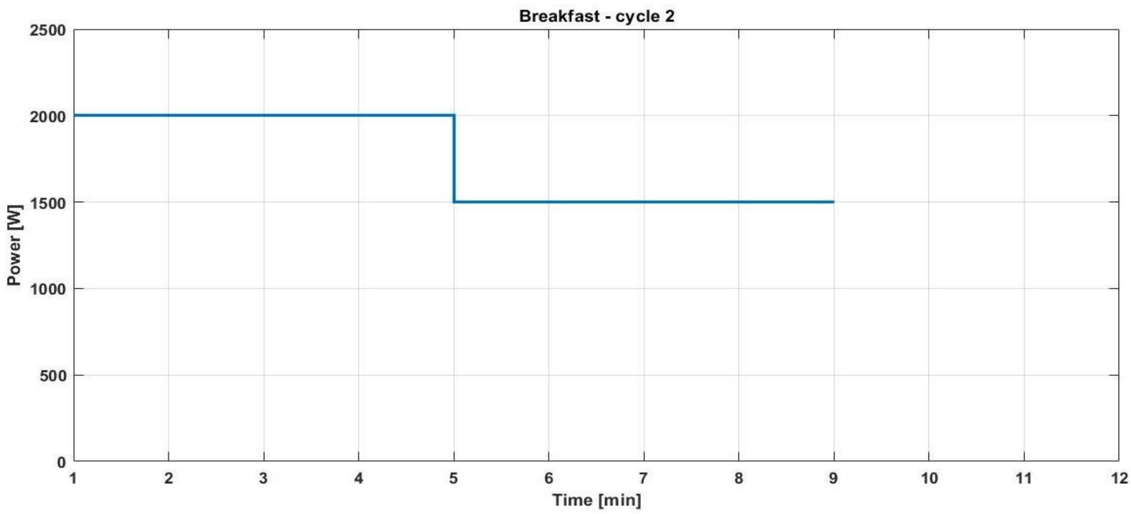


Figure 3.2 Breakfast randomized cycle 2

Then, lunch and dinner have been indiscriminately modelled as a combination of four tasks. Firstly, water or oil are boiled for vegetables preparation. This task accounts for 4-8 minutes in the total preparation time and it needs the induction cooker to work at high power. Then vegetables are cooked with a 4-6 minutes preparation timing accordingly with TAHEA (Tanzania Home Economics Association) [47]. Subsequently, the main dish preparation is carried out with water boiling first which accounts from 10-15 minutes in the total preparation time, and it needs the induction cooker to work at high power. Finally, rice, ugali or soup are cooked with a 20-40 minutes preparation timing. Accordingly, lunch or dinner total preparation time will vary between 38-69 minutes. The combination of these four tasks provides a comprehensive cooking cycle based on local habits as it represents a general preparation of a main dish and of a side dish. Two examples of the randomization process on lunch/dinner cooking cycles are shown in Figure 3.3 and Figure 3.4.

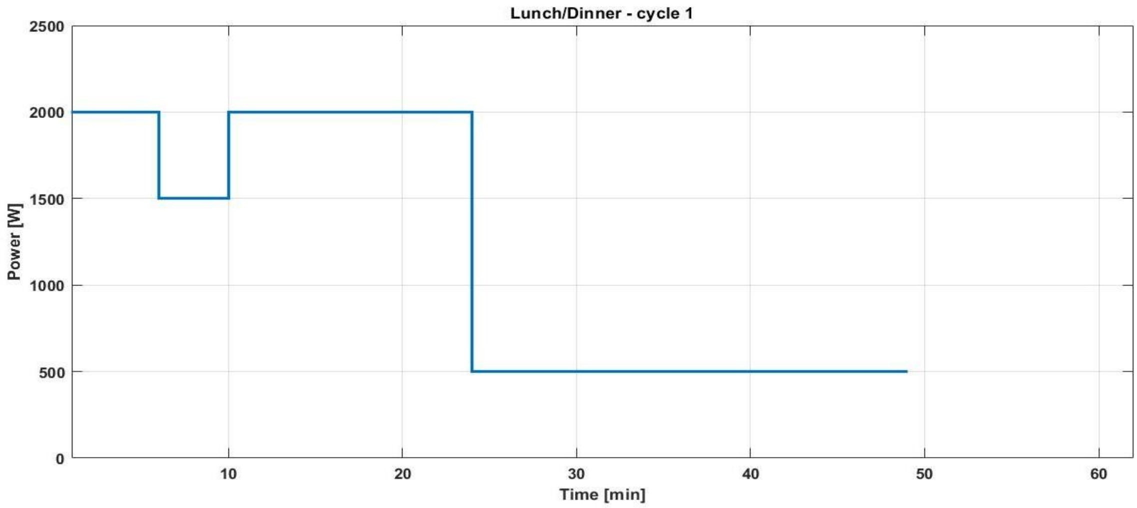


Figure 3.3 Lunch/dinner randomized cycle 1

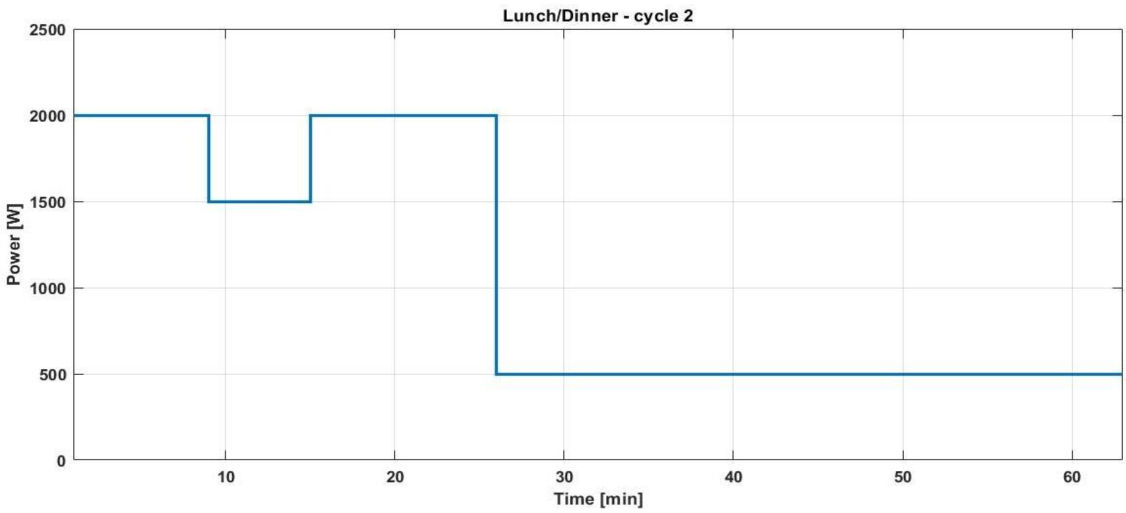


Figure 3.4 Lunch/dinner randomized cycle 2

However, according with local cooking habits, lunch is prepared immediately after breakfast and kept warm in specific pots or ovens. Moreover, in rural areas, the majority of people is employed in the agricultural sector. For these people is usual to cook lunch after breakfast and bring it to the fields [47]. Consequently, a full preparation random cycle has been modelled as a combination between a breakfast and a lunch/dinner cycle. Between the two cycles a delay of 1-15 minutes has been taken into account in order to consider time for the effective consumption of breakfast and for general preparation tasks. Moreover, relying on full preparation cycle rather than separately on breakfast and lunch cycle avoids senseless overlapping between the two tasks. This would be impossible since the cooker is just one per household in the Kidegembye village. Two examples of the randomization process on full preparation cooking cycles are shown in figures below.

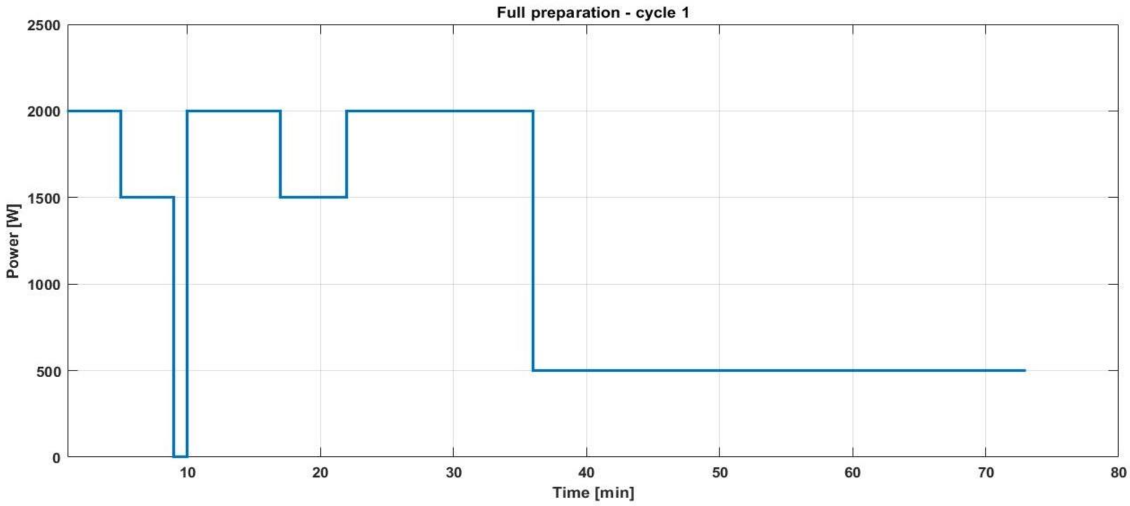


Figure 3.5 Full preparation randomized cycle 1

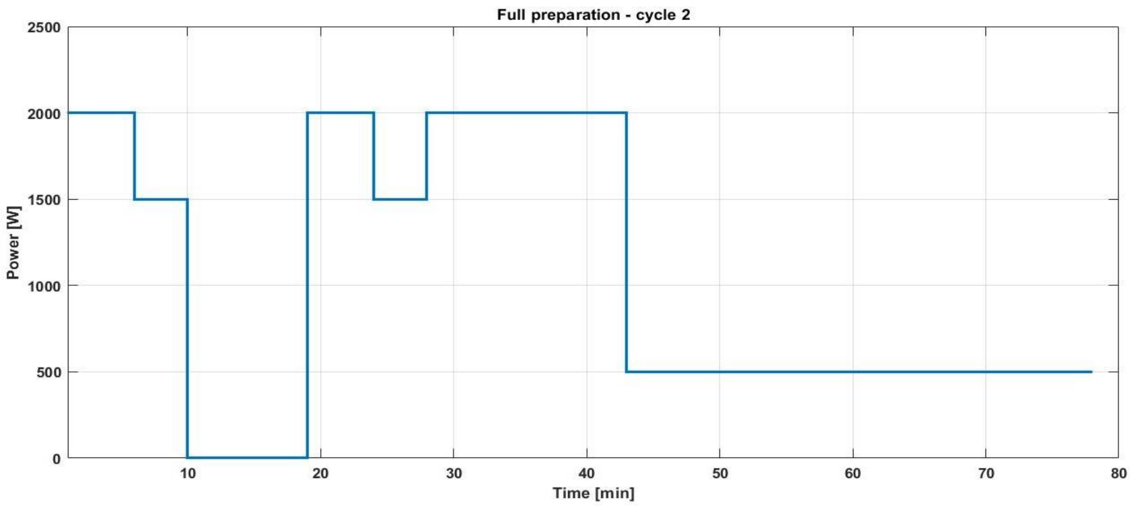


Figure 3.6 Full preparation randomized cycle 2

Transition from traditional way of cooking with solid biomass to whichever kind of modern cooking technology is more likely to be gradual as mentioned before. According with IEA, “fuel stacking” phenomenon is probable to occur whenever a new cooking technology is provided. In order to consider this phenomenon, specific cooking cycles have been modelled.
The main preparation, as ugali and rice, are more likely to be prepared in the traditional way, hence with traditional biomass fuel. Also for Chapati preparation, traditional cooking method has been considered as it is a very traditional type of bread. For secondary preparation, as vegetables or side dishes more in general, induction cookers usage has been considered instead. The resulting full preparation cooking cycle and dinner cooking cycle are depicted respectively in Figure 3.7 and Figure 3.8.

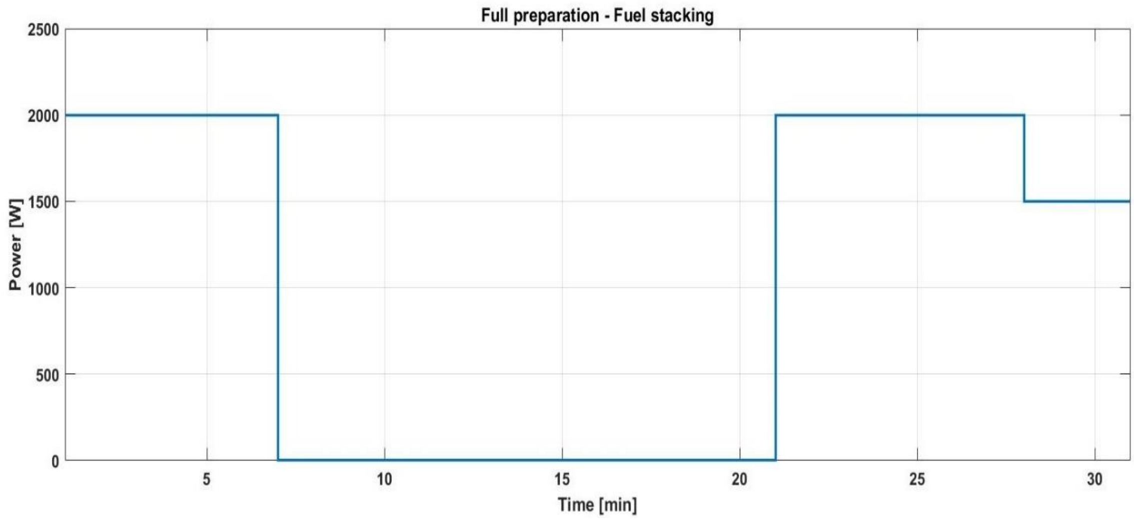


Figure 3.7 Fuel stacking - full preparation randomized cycle

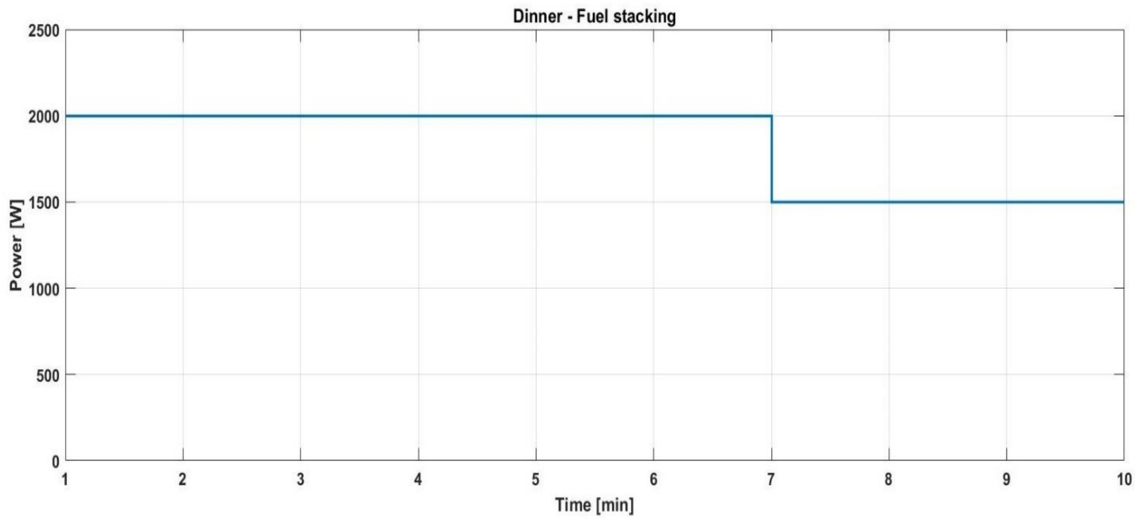


Figure 3.8 Fuel stacking - lunch/dinner randomized cycle

3.1.4 Cooking cycles implementation in LoadProGen

In order to implement in LoadProGen cooking cycles modelled in the previous sub-section, an artificial appliance for each meal preparation has been defined as an input for the software. Consequently, for breakfast and lunch preparation, an appliance characterized by full preparation randomized cycle has been considered (Cooking_FP). Then, for dinner preparation an appliance characterized by lunch/dinner randomized cycle has instead been considered (Cooking_LD). An example of LoadProGen input is depicted in Table 3.6.

Type of electrical appliance *(i)*	**Nominal appliance power rate [W] *(P_{ij})***	**functioning cycle [min] *(d_{ij})***	**Starting time Win 1 [min] *[1-1440]***	**Ending time Win 1 [min] *[1-1440]***	**Starting time Win 2 [min] *[1-1440]***	**Ending time Win 2 [min] *[1-1440]***
Cooking_FP	2000	Cycle1	285	450	0	0
Cooking_D	2000	Cycle2	780	900	1080	1200

Table 3.6 Example of cooking cycle implementation in LoadProGen

Cycle 1 and Cycle 2 correspond to full preparation randomized cycle and lunch/dinner randomized cycle respectively.

Moreover, for the village case study, for each meal preparation (breakfast + lunch or dinner) and for every single household a different cooking cycle has been randomized. Through this additional randomization it has been possible to better reflect the uncertainty on households' habits and to avoid the definition of too specific cooking cycles.

To do this was necessary to develop a MATLAB script (Figure 3.9). Within this script, for each of the thirty-three household in the village, one full preparation randomized cycle and one lunch/dinner randomized cycle has been generated for each iteration.

Regarding Mama Kevina Hope Center, a random cooking cycle has been generated for each meal preparation.

```
num_str=13:78;
lett='B%d:CS%d';
m=365;
Loadcurve=zeros(m,1440);
save Loadcurve
for k=1:m
    for n=1:66
        range(1,n)=compose(lett,num_str(1,n),num_str(1,n));
        if floor(n/2)*2==n
            LD_random_cycle
            xlswrite('C:\Users\Marco\Desktop\Tesi\LoadProGen 2.0\input_LoadProGen\Configuration',LD,string(range(1,n)))
        else
            FP_random_cycle
            xlswrite('C:\Users\Marco\Desktop\Tesi\LoadProGen 2.0\input_LoadProGen\Configuration',FP,string(range(1,n)))
        end
    end
 save k
 load_excel
 LoadProGen_main
 load('Loadcurve.mat')
 load k
 load('C:\Users\Marco\Desktop\Tesi\LoadProGen 2.0\output_LoadProGendaily_load_profiles.mat')
 Loadcurve(k,:)= All_lc;
 save('Loadcurve.mat')
 k
end
```

Figure 3.9 MATLAB script random_cycle_advance_v2

3.1.5 Load curve scenarios

From cooking cycles implementation in LoadProGen, different load curve scenarios have been modelled.

The reference case is the *Base load* scenario in which only conventional electric loads such as lighting or basic entertainment (TV, radio) have been considered. Base load scenario is the starting point for the design of a conventional mini-grid for rural electrification. Data for base load curve modelling for Kidegembye village have been taken from Berti’s thesis. Within his thesis work surveys about electric appliances and their utilization were conducted in the village of Kidegembye and are available in Annex B. The main appliances are indoor/outdoor lights, charger, radio and TV.
Data for base load curve modelling for Mama Kevina has been taken from surveys about electric appliances and their utilization conducted during my stay. The main appliances are indoor/outdoor lights, charger, radio, TV, fans, fridge, iron and washing machine (detailed data available in Annex B). With respect to the village case study, there is already the presence of a highly energy-consuming appliance as the washing machine.

Full cooking scenario represents instead the reference case of a complete transition from traditional biomass fuels to e-cook. In this scenario clean cooking access is fully achieved and it is the starting point for the design of an e-cook mini-grid.

For Kidegembye case study, starting from base load curves, full cooking load curves have been simulated by adding one induction cooker per household. Input for the induction cookers are depicted in Table 3.7 where Cooking_FP is the artificial appliance for breakfast and lunch preparation while Cooking_D is the artificial appliance for dinner preparation. According with local cooking habits, dinner is usually prepared just before its consumption. However, preparing dinner just after lunch it's also possible. To model this phenomenon, two functioning windows have been provided for dinner preparation, the first just after lunch and the second in the late afternoon.

Type of electrical appliance *(i)*	**Nominal appliance power rate [W] *(P_{ij})***	**functioning cycle [min] *(d_{ij})***	**Starting time Win 1 [min] *[1-1440]***	**Ending time Win 1 [min] *[1-1440]***	**Starting time Win 2 [min] *[1-1440]***	**Ending time Win 2 [min] *[1-1440]***
Cooking_FP	2000	Cycle1	285	450	0	0
Cooking_D	2000	Cycle2	780	900	1080	1200

Table 3.7 Kidegembye – Full cooking scenario - LoadProGen input for the single induction cooker

For Mama Kevina, starting from base load curves, full cooking load curves have been simulated by adding the induction kitchen. Inputs for this appliance are depicted in Table 3.8. Where "Induction kitchen B+L" refers to breakfast and lunch preparation while "Induction kitchen D" to dinner preparation.

Type of electrical appliance *(i)*	**Nominal appliance power rate [W] *(P_{ij})***	**functioning cycle [min] *(d_{ij})***	**Starting time Win 1 [min] *[1-1440]***	**Ending time Win 1 [min] *[1-1440]***
Induction kitchen B+L	3000	Cycle1	330	480
Induction kitchen D	3000	Cycle2	1005	1110

Table 3.8 Mama Kevina - Full cooking scenario - LoadProGen input for the induction kitchen

In order to simulate effects on the mini-grid of the gradual transition from traditional way of cooking with solid biomass to induction cooking technology the *Fuel stacking* scenario has been modelled. For the institutional case study, represented by Mama Kevina Hope Center, given the continuous presence of people from the Hands for Africa – Hands for Osteopathy association and given the fact that a small number of people is responsible for cooking, the transition could instead be immediate. For this reason, fuel stacking scenario has been modelled just for the Kidegembye village case study. In addition, a growing percentage of penetration in the use of induction cookers as primary cooking technology has been considered to simulate future developments. For households which use induction cookers as primary technology, complete cooking cycles have been considered. For the remaining percentage of household, induction cookers are used as secondary technology, therefore fuel stacking cooking cycles have been considered (Figure 3.7 and Figure 3.8).

Another interesting scenario, is given by the possible *Behavioural change* in terms of meal preparation windows, induced by the reduced meal preparation timings thanks to the induction technology. As mentioned before indeed, in context like rural Tanzania, people usually prepare lunch immediately after breakfast. The main reason in doing this is related to the time spent in preparing fire. Providing induction stoves makes therefore plausible a shift in the meals preparation windows that will likely take part just before meal time. While a similar shift in a village is unlikely to rapidly happen, in a structure like Mama Kevina where a restricted group of people is responsible of cooking, is more plausible.
In order to evaluate impacts on the mini-grid of this possible behavioural change a specific scenario has been carried out only for the Mama Kevina institutional case study.
Input for the induction kitchen, relatively to this scenario, are depicted in Table 3.9. To simulate the effects of the behavioural change, a functioning window has been added before lunch time, consequently morning functioning window has been reduced. Getting used to the new and quicker technology may also lead to a reduction in cooking functioning windows. For this reason, in the evening it has been reduced by 15 minutes.

Type of electrical appliance *(i)*	**Nominal appliance power rate [W] *(P_{ij})***	**functioning cycle [min] *(d_{ij})***	**Starting time Win 1 [min] *[1-1440]***	**Ending time Win 1 [min] *[1-1440]***
Induction kitchen B	3000	Cycle1	360	420
Induction kitchen L	3000	Cycle2	630	720
Induction kitchen D	3000	Cycle3	1020	1110

Table 3.9 Mama Kevina - Behavioural change - LoadProGen input for the induction kitchen

Finally, *Peak-shifting* scenario has been modelled. One of the main technical problems in an e-cook mini-grid is the simultaneous use of highly energy-consuming appliances such as induction stoves during meal preparation windows. In order to smooth these power peaks, demand-side management component is installed in the mini-grid [48].
Demand side management technologies are increasingly studied and implemented in e-cook mini-grid [6], [48]. These technologies encourage users to distribute the use of large appliances, as induction cookers, more evenly throughout the day, allowing power-limited systems to provide reliable, long-term renewable electricity to villages and communities.

Moreover, is possible to reduce brownouts by using a low-cost device that communicates the state of the grid to its users.

In article [48], a demand side management technology has been tested in a small village in Buthan, accompanied by an extensive education program. Following the installation, the occurrence and average length of severe brownouts, which had been caused primarily by electric cooking appliances during meal preparation, decreased by over 92%. Moreover, load curve showed a slight change after the installation of the technology (Figure 3.10). Within the article indeed, 42% of respondents stated they intentionally cooked either earlier or later than their normal cooking time at least once a week.

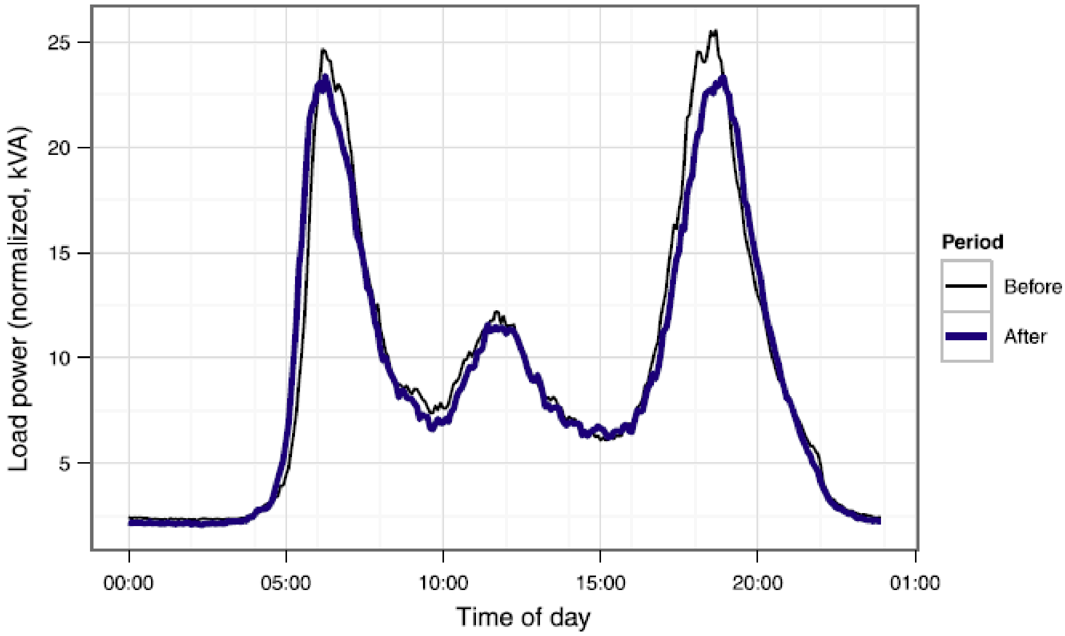


Figure 3.10 Mean load power consumption throughout the day before and after installation of demand side management technology [47]

Given the potential benefits for the mini-grid achievable through the installation of a demand side management technology, *Peak shifting* load curves have been modelled for Kidegembye village.

Input for the induction cookers, relatively to this scenario, are depicted in Table 3.10. To simulate the effects of demand side management technology, functioning windows of induction cookers have been widened by 30 minutes.

Type of electrical appliance *(i)*	**Nominal appliance power rate [W] *(P_{ij})***	**functioning cycle [min] *(d_{ij})***	**Starting time Win 1 [min] *[1-1440]***	**Ending time Win 1 [min] *[1-1440]***	**Starting time Win 2 [min] *[1-1440]***	**Ending time Win 2 [min] *[1-1440]***
Cooking_FP	2000	Cycle1	285	480	0	0
Cooking_D	2000	Cycle2	765	915	1065	1215

Table 3.10 Kidegembye - Peak shifting scenario - LoadProGen input for the single induction cooker

3.2 Preliminary system design

Starting from the load curve modelling it is possible to develop a preliminary system design, based on classic sizing techniques. A more sophisticated system design optimisation has been subsequently carried out through the HOMER-Energy software (sub-section 3.3.1), considering preliminary system design as a starting point and reference case. Moreover, this preliminary analysis wants to provide a method for the electrical coupling between main components of the mini-grid and give an idea of the system layout. This method for electrical coupling has been exploited for the coupling of the resulting components from HOMER optimized system design.

The main components of a solar powered mini-grid are depicted in Figure 3.11 and have been presented in sub-section 2.1.2, 2.1.3, 2.1.4 and 2.1.5.

In this sub-section a method widely used in literature [49]–[53] for the sizing of each component is presented.

Sizing the e-cook mini-grid on fuel stacking load profiles for example, it would mean having an undersized system instead in the full cooking scenario. For this reason, preliminary system design has been carried out only for the Base load and Full cooking scenarios for both case studies.

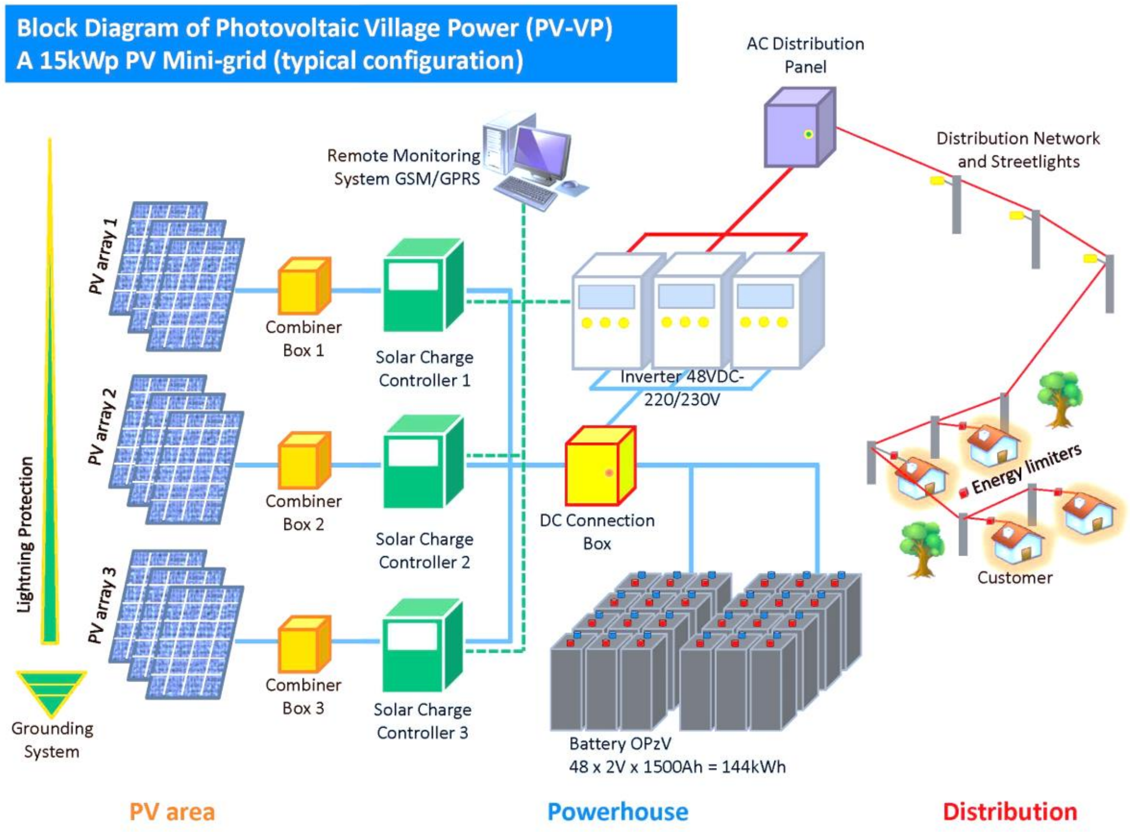


Figure 3.11 Typical layout of a solar powered mini-grid [54]

3.2.1 PV array

Power output of a PV module depends primarily on incident solar radiation and on operating temperature. Manufacturers report rated or nominal peak power output in Watts produced under standard test conditions of 1000W irradiance per square meter of panel area and at 25 °C. The first step for sizing the PV array is therefore a solar resource assessment in order to collect data about solar radiation for the case studies' sites. Monthly average solar global horizontal irradiance (GHI) data have been downloaded from the NASA surface meteorology and solar energy database [55]. Monthly average values are calculated for a period of twenty-two years between July 1983 and June 2005 and therefore represent reliable data unaffected by yearly variations.

The PV power (P_{PV}) must be calculated to meet the required daily load energy given by load profiles. The total area of the required PV array (A_{PV}) in square meters can be calculated as follows [49]–[53]:

$$A_{PV} = \frac{E_L}{GHI \times \eta_{inv} \times \eta_{cc} \times \eta_B \times \eta_{PV} \times [1 + \gamma \times (T_{op} - T_{STD})]} \qquad 3.1$$

Where:

- E_L is the daily energy required in kWh/day;
- GHI is the lower value of monthly average solar global horizontal irradiance in kWh per square meter per day;
- $\eta_{inv}, \eta_{cc}, \eta_B$ are the efficiencies of other system components respectively inverter, solar charge controller and battery.
- η_{PV} is the PV module efficiency computed at standard conditions;
- γ is the temperature coefficient of solar panel and must be considered as the PV module output is affected by its surface temperature;
- T_{op} and T_{STD} are respectively temperature reached during operation and temperature in standard conditions.

Therefore, using standard solar irradiation I_{STD} as 1000 W/m^2 the PV array peak power in W can be calculated as follows [49]–[53]:

$$P_{PV} = A_{PV} \times I_{STD} \times \eta_{PV} \qquad 3.2$$

Finally, is possible to compute the number of PV modules in the PV array:

$$\# \, modules = \frac{P_{PV}}{P_{PV,nom}} \qquad 3.3$$

Where P_{nom} is the nominal power of a single module computed in standard conditions. Number of modules in series or parallel will be determined by the coupling with MPPT.

3.2.2 Battery

The role of batteries in off-grid systems such as mini-grids is mainly to store electric energy for night time supply or for period when there is no sunlight during the day. However, e-cook requires a much higher power level, and much more stored energy than is necessary for night time lighting.

The capacity of storage batteries B_C in kWh can be calculated as follows [49]–[53]:

$$B_C = \frac{E_L \times N_C}{DOD \times \eta_{inv} \times \eta_B} \qquad 3.4$$

Where:

- N_C is the number of continuous cloudy days;
- DOD is the depth of discharge of the battery which is a crucial parameter for battery lifetime.

Therefore, is possible to compute the number of batteries composing the battery pack:

$$\# \, batteries = \frac{B_C}{B_{C,nom}} \tag{3.5}$$

Where $B_{C,nom}$ is the nominal capacity of a single battery in kWh.
Therefore, in order to define the layout of the battery pack, it is possible to compute the number of batteries in series and in parallel:

$$\# \, batteries \; in \; series = \frac{V_{sys}}{V_{B,nom}} \tag{3.6}$$

$$\# \, batteries \; in \; parallel = \frac{\# \, batteries}{\# \, batteries \; in \; series} \tag{3.7}$$

When connecting two batteries in series the voltage doubles while the capacity remains unchanged, connecting two batteries in parallel instead the capacity doubles, and the voltage remains unchanged. Finally, the actual autonomy of the battery pack in hours can be computed as follows:

$$Autonomy_{Eff} = \frac{\#batteries \times B_{C,nom} \times DOD \times \eta_B \times \eta_{inv}}{E_L \times 24} \tag{3.8}$$

3.2.3 Solar charge controller

In order to compute the number of solar charge controller needed, it is necessary to calculate the number of PV modules accepted by each solar charge controller.
To do this, first the number of modules accepted in series has been calculated from the maximum admissible voltage by solar charge controller $V_{MAX,CC}$ and from the open circuit voltage of the module $V_{OC,PV}$:

$$\# \, modules \; in \; series \; accepted = \frac{V_{MAX,CC}}{V_{OC,PV}} \tag{3.9}$$

Therefore, the number of modules accepted in parallel has been calculated from the maximum admissible power by solar charge controller and from the power of the string of module in series:

$$\#modules\ in\ parallel\ accepted = \frac{P_{MAX,CC}}{\#\ modules\ in\ series\ accepted \times P_{PV,nom}} \quad 3.10$$

The total number of PV modules accepted by a single solar charge controller is the product between number of modules in series accepted by number of modules in parallel accepted. The current in input in the solar charge controller can be computed as further confirmation of correct coupling between PV array and solar charge controller from the number of modules in the parallel string and from the short circuit current of a single module:

$$I_{in,CC} = \#\ modules\ in\ parallel\ accepted \times I_{SC,PV} \quad 3.11$$

This value must be lower than the maximum admissible current in input in the solar charge controller $I_{MAX,CC}$.
The number of solar charge controllers needed to control the entire PV array is therefore calculated by dividing total number of modules by number of modules accepted by a single solar charge controller. These calculations are part of the electrical coupling part and for this reason have been carried out only after the HOMER optimized system design.

3.2.4 System inverter

Preliminary sizing of the system inverter has been carried out considering the PV array peak power P_{PV}. Power rate of the inverter has been chosen 10% lower than this value as suggested in literature [56].

3.3 HOMER Optimized system design

Optimized system design has been carried out through HOMER pro® micro grid software (Hybrid Optimization Model for Multiple Energy Resources) by HOMER energy [57]. Preliminary design has been used to define electric coupling of the mini-grid components and to give a first idea of the system sizing. Through HOMER's optimization algorithm it has been possible to simulate numerous system configurations and to select the best in terms of life cycle cost considering the system operations for each time step.

The aim of this thesis work is to verify techno-economic feasibility of a solar powered e-cook mini-grid. Hence, since the type of mini-grid has already been decided, HOMER software has been chosen as it provides a highly detailed technical level for each component of the system. Moreover, through the Advanced Storage Module (3.3.2) it has been possible to precisely investigate batteries performances as they represent the most important and sensitive system component.

3.3.1 Introduction to HOMER software

The HOMER Pro® microgrid software by HOMER Energy is the global standard for optimizing microgrid design in all sectors [57].
HOMER simulates the operation of a system by making energy balance calculations in each time step (interval) of the year. For each time step, HOMER compares the electric demand in that time step to the energy that the system can supply in that time step and calculates the flow of energy to and from each component of the system. For systems that include batteries, HOMER also decides in each time step whether to charge or discharge the batteries. It then determines whether a configuration is feasible (i.e. whether it can meet the electric demand under the specified conditions) and estimates the cost of installing and operating the system over the lifetime of the project. The system cost calculations account for costs such as capital, replacement, operation and maintenance (O&M), and interest [58].

The first step is to define the electric load of the system by importing the load profiles modelled for the considered scenario. HOMER then compute an average daily load profile, a monthly profile and a yearly profile. For this reason, one load curve per day of the year has been modelled through LoadProGen. HOMER also calculates the average daily energy request in kWh/day and the power peak in kW.

The second step is to carry out a resource assessment for the location of case studies. Monthly average solar global horizontal irradiance (GHI) data have been downloaded from the NASA surface meteorology and solar energy database as for preliminary system design. Monthly average values are calculated for a period of twenty-two years between July 1983 and June 2005 and therefore represent reliable data unaffected by seasonality. HOMER then calculates average daily radiation in kWh per square meter per day and compute a monthly profile of the GHI.
Temperature resource has been downloaded from the MERRA-2 (global) dataset, freely available online at Renewables Ninja [59]. Temperature values for each location have been

measured with a one-hour time step for the year of 2014. Homer then calculates average monthly temperatures and their profile throughout the year.

Given electric load demand and resource assessment a power source is needed. For this thesis work the power source is the PV array since only solar powered mini-grid have been investigated, because solar resource is the most available around the world especially in developing countries. For a single PV module HOMER requires as inputs the capacity in kW, purchase, replacement and operation and maintenance (O&M) costs. In addition, lifetime of the PV module in years and derating factor are required. The photovoltaic (PV) derating factor is a scaling factor that HOMER applies to the PV array power output to account for reduced output in real-world operating conditions compared to conditions under which the PV panel was rated. The derating factor site specific and is used to account for such factors as soiling of panels, wiring losses, shading, aging and so on, its reference value in HOMER is 80%.

In order to consider temperature effect on the PV array HOMER requires as inputs the temperature effects on power in %/°C (temperature coefficient γ), nominal operating cell temperature (NOCT) and efficiency at standard test conditions.

Is then possible to specify MPPT solar charge controller parameters directly from the PV input page in HOMER by the “explicitly model Maximum Power Point Tracker” command. As for PV module, HOMER requires as inputs the size in kW, purchase, replacement and O&M costs of the solar charge controller. In addition, lifetime in years and efficiency are required.

Considering the strong influence of temperature on battery system, the HOMER advanced storage add-on module has been downloaded and presented in the next sub-section. In contexts such those of the case studies, or rather, sub-Saharan Africa, temperature effects on battery system can indeed play a crucial role in technology selection and sizing process.

The last component for which HOMER requires inputs is the system converter. Inputs are the same as for solar charge controller, or rather, capacity in kW, purchase, replacement, O&M costs, lifetime in years and efficiency.

Finally, the economic inputs have been inserted in the HOMER specific section. US Dollar ($) has been selected as currency for the project. Moreover, in Tanzania, since August 2017, the nominal discount rate has been settled to 9% [60], while the inflation rate have been oscillating around 5% since 2014 [61].

For each component, replacement and O&M costs have been considered for a project lifetime of 20 years. Replacement costs have been evaluated equal to the purchase costs in order to not make assumption about future price development. Reference values for O&M costs instead have been taken from the literature [62]–[64].
For the PV modules, MPPT solar charge controllers and system inverter O&M costs have been considered equal to 1.5% of the specific purchase cost. For batteries instead, 22 $/kW per year has been taken as reference value for lead-acid O&M costs.
Moreover, for the PV modules a 25 years lifetime has been considered as it represents the most common value derived from the brief market survey conducted on PV modules. For MPPT solar charge controller and system converter a 15 years lifetime has been considered for the same motivation. As for batteries instead, lifetime has been computed by HOMER as explained in sub-section 3.3.2.
Furthermore, a 5% annual capacity shortage has been considered acceptable for the mini-grid. HOMER defines capacity shortage as a shortfall that occurs between the required operating capacity and the actual amount of operating capacity the system can provide. An annual capacity shortage greater than zero has been selected to avoid the mini-grid sizing on the worst conditions of the year in terms of peak load or unfavourable external conditions.
In addition, given the size of the mini-grid it has been possible to consider BOS costs. These costs can be divided into main components as mounting, installation, cabling and infrastructure. Within this thesis work it has been considered 90 $/kW for mounting, 60 $/kW for installation, 60 $/kW for wirings and 55 $/kW for infrastructure [65].

3.3.2 HOMER Advanced Storage Module

The Advanced Storage Module (ASM), based on the HOMER *Modified Kinetic Battery Model*, adds a series resistance, temperature effects on capacity, temperature effects on degradation rate, and cycle-by-cycle degradation based on depth of discharge. The HOMER Modified Kinetic Battery Model is in turn based on the *Kinetic Battery Model*. HOMER uses the Kinetic Battery to determine the amount of energy that can be absorbed by or withdrawn from the storage bank each time step. The Kinetic Battery model is a two-tank model with kinetics that match lead acid battery behaviour. The first tank contains "available energy," or energy that is readily available for conversion to DC electricity. The second tank contains "bound energy," or energy that is chemically bound and therefore not immediately available for withdrawal [58]. The two-tank model is represented in Figure 3.12.

Figure 3.12 Two-tank model representation [58]

Three parameters are used to describe this two-tank system. The maximum (or theoretical) storage capacity which is the total amount of energy the two tanks can contain. The capacity ratio which is the ratio between the size of the available energy tank and the combined size of both tanks. The rate constant is related to the conductance between the two tanks and is therefore a measure of how quickly the storage can convert bound energy to available energy or vice versa [58].

The time step to time step behaviour of the battery in simulation is governed by the *functional model* represented in Figure 3.13, where KiBaM stands for Kinetic Battery Model. In the functional model, the discharging losses are modelled with a series resistor. The output power of the battery bank for a given current (I) is defined by the following relation:

$$P_{B,out} = V_{B,nom}I - R_0 I^2 \qquad 3.12$$

Where $P_{B,out}$ is the output power and R_0 is the series resistance. Therefore, $R_0 I^2$ represents the loss in the resistor. The circuit behaviour also leads to a maximum possible output power: at higher currents, the term I^2 begins to dominate and the output power actually decreases with increasing current.

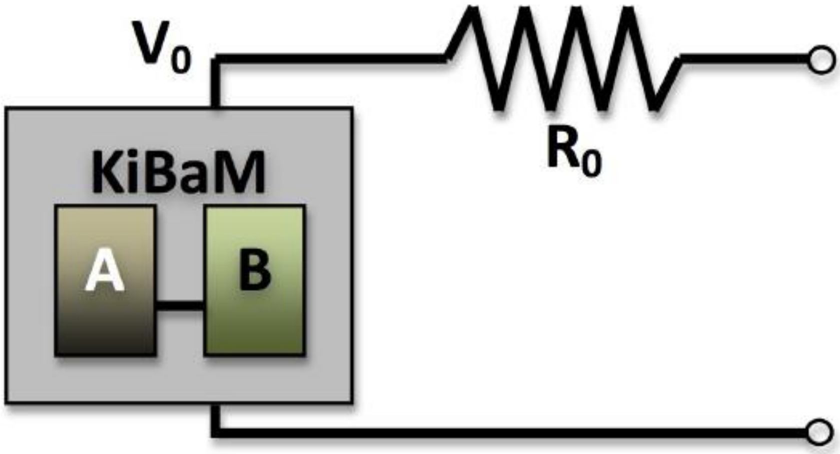


Figure 3.13 Functional model representation [58]

Therefore, in the Modified Kinetic Model, with respect to the Kinetic Battery Model, there is a maximum discharge power limit imposed by the circuit model, which is found calculating the current that gives the maximum value of the output power.
When specifying the functional model for a battery in the HOMER storage library the capacity curve of the selected battery has to be inserted as an input (Figure 3.14). From the capacity curve HOMER calculates parameters used to describe the Kinetic Battery Model such as maximum capacity in Ah, rate constant in 1/hour, capacity ratio and the effective series resistance in Ohm.

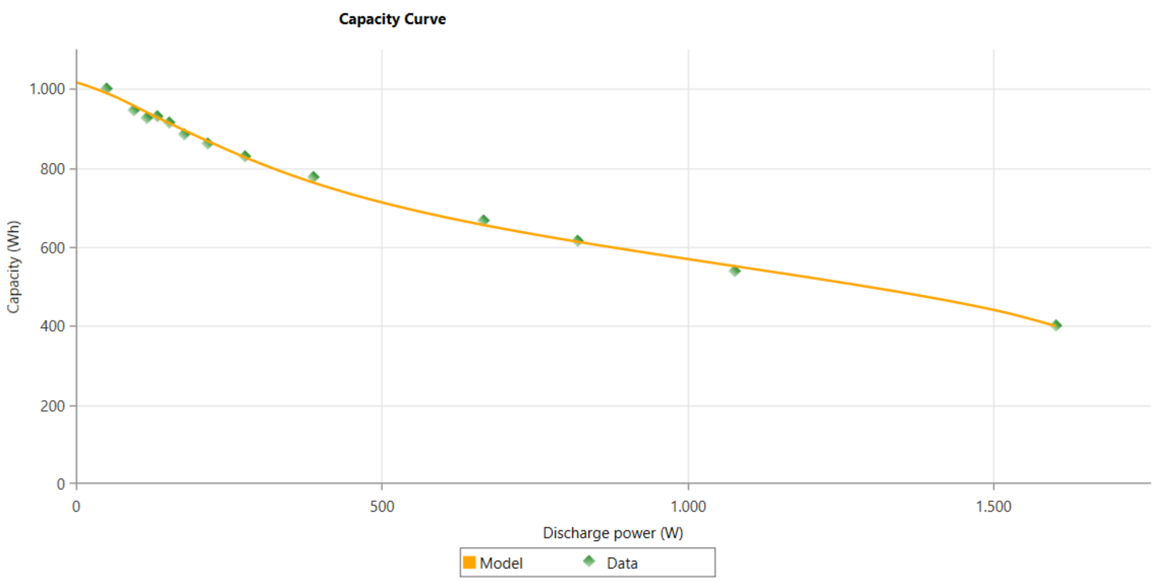


Figure 3.14 Capacity curve for a 1 kWh generic lead-acid battery

In addition, by the HOMER ASM, temperature effects on capacity and on degradation rate of the battery bank can be considered.
Firstly, the storage component temperature is modelled as a lumped thermal capacity. It's possible to specify the thermal conductance to ambient in W/K, the mass of the component in kg and the specific heat capacity in joules per kg per K. Given the lack of information on the thermal conductance to ambient, the specific heat capacity has been chosen equal to zero as suggested by HOMER in similar cases. Hence, the battery internal temperature will follow the temperature resource exactly.
In each time step of the simulation, any energy dissipated by the effective series resistance is converted into heat and increases the bulk temperature of the storage bank.
The temperature of the storage component can be plotted in the HOMER time series results viewer. This is the temperature used to calculate temperature effects on capacity and on degradation rate of the battery bank.

To consider temperature effect on battery capacity, it's possible to specify a relative capacity versus temperature curve in the HOMER storage library (Figure 3.15.). This curve is calculated from data on relative capacity (percent of nominal) versus temperature, then the Modified Kinetic Model fits a quadratic function to compute the curve. Moreover, temperature effect on battery capacity is modelled modifying the minimum state of charge of the battery respect to the current temperature of the battery pack.

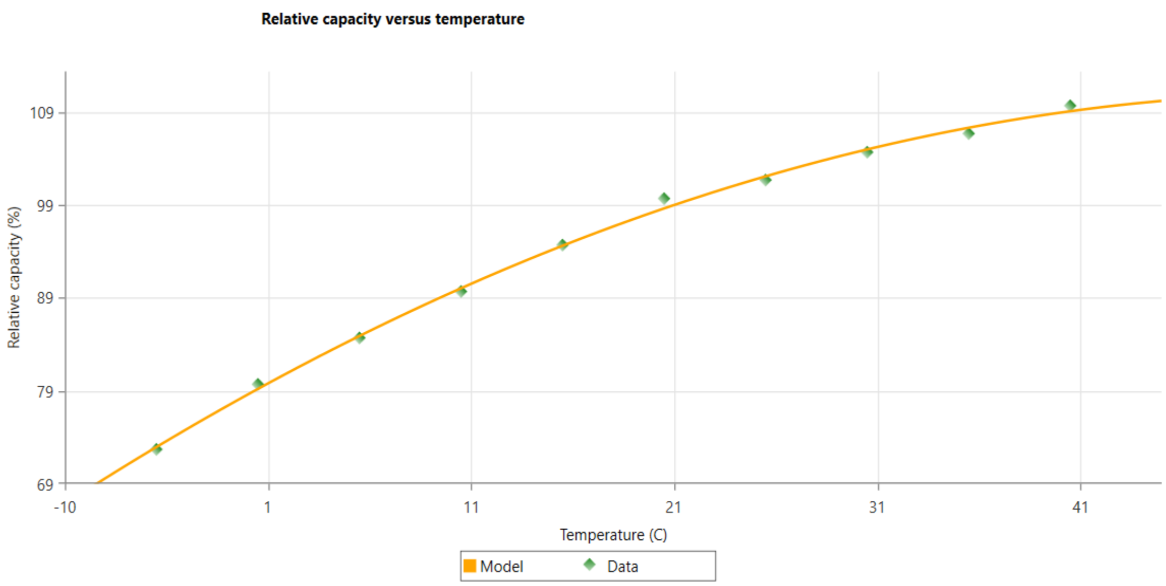


Figure 3.15 Relative capacity versus temperature curve for a generic 1 kWh lead-acid battery

The Modified Kinetic Model tracks functional degradation using two variables that increase as the battery degrades over its life. One tracks time and temperature over the battery's lifetime (Figure 3.16), and the other tracks the wear from cycles, adjusted for depth of discharge (Figure 3.17). Functional degradation is modelled as a gradual decrease in storage capacity and increase in series resistance.

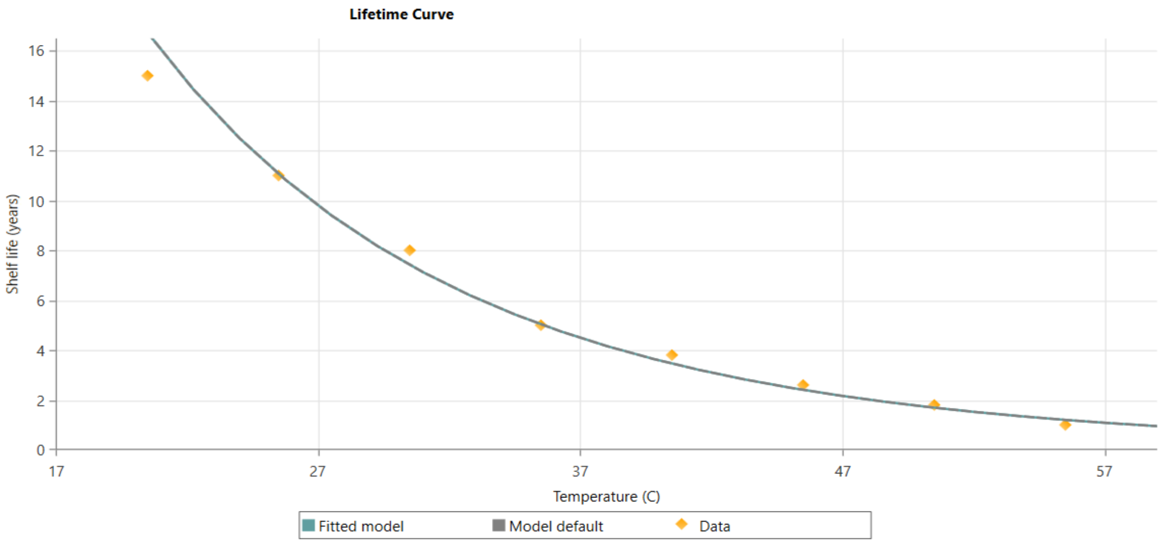


Figure 3.16 Lifetime curve over temperature for a generic 1 kWh lead-acid battery

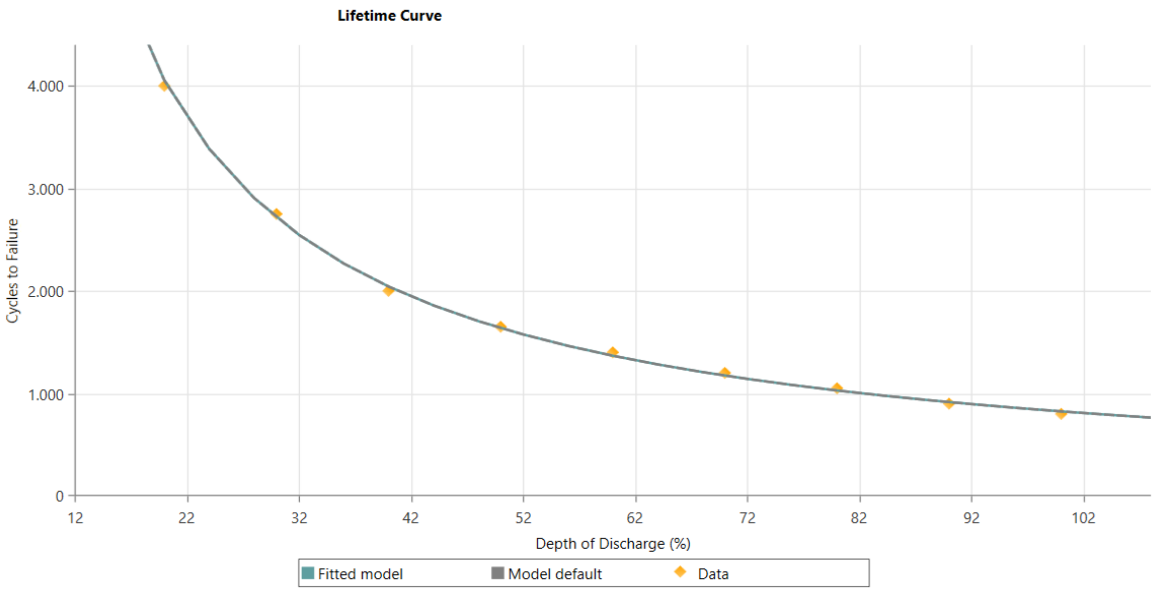


Figure 3.17 Lifetime curve over number of cycles for a generic 1 kWh lead-acid battery

The first degradation variable (calendar degradation) increases with each time step regardless of whether the storage component is being used or is idle. The rate of increase of this variable depends only on temperature, as described in the following equation [58]:

$$k_T = B \times e^{-\frac{d}{T}} \quad 3.13$$

Where k_T is the rate of increase of the time-and-temperature degradation variable, B and d are constants fit to data, and T is the temperature in kelvins. These constants are calculated from the shelf life versus temperature curve computed in the HOMER storage library (Figure 3.16).

The second degradation variable (cycle degradation) tracks the cycle fatigue on the battery. The relationship between cycles to failure and depth of discharge (DOD) is described by the following equation [58]:

$$\frac{1}{N} = A \times DOD^{\beta} \quad 3.14$$

In the above equation, N is the number of cycles, D is the depth of discharge (a fractional number between 0 and 1), and A and β are fitted constants. These constants are calculated from the cycles to failure versus depth of discharge curve computed in the HOMER storage library (Figure 3.17). In addition, during simulation, HOMER effectively adjusts the minimum state of charge (considered equal to 20% as a reference value for lead-acid technology) up or down based on the current temperature of the battery pack. Hence the number of charge/discharge cycles before the battery end of life can slightly differ from the specified value.

The battery is considered dead and is instantly replaced at its end of life. It's possible to specify how to calculate the battery end of life in the HOMER storage library. The two options are: "sum of calendar and cycling degradation" and "calendar or cycling degradation whichever is greater". The second option has been chosen since the battery end of life effectively occurs when the battery capacity decreases by the degradation limit. This is defined as the percent degradation in capacity that triggers replacement of the component [58]. By choosing "Calendar or cycling degradation,
whichever is greater", then the battery will be replaced when either the time-and temperature degradation variable or the cycle degradation variable equals the degradation

limit (whichever happens first). From HOMER output it's possible to check which of the two variables reached first the degradation limit within the simulation. In the plot section of the output, is therefore possible to obtain a graph showing the decrease in battery capacity in % throughout the year, an example is reported in Figure 3.18.

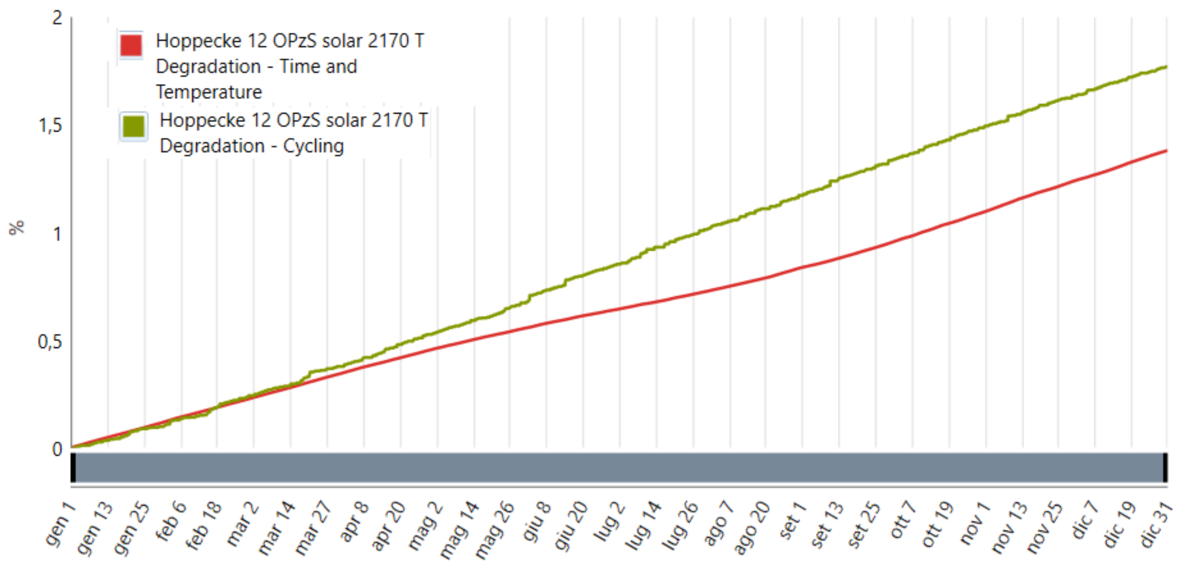


Figure 3.18 Example of battery degradation variable profile from HOMER ASM output

Finally, in the HOMER storage library is possible to specify purchase, replacement and O&M costs and also the string size in V, the initial and the minimum state of charge of the battery.

For each scenario of both the case studies, many simulations comparing lead-acid and Li-ion have been carried out. For all these simulations the result was always in favour of lead-acid technology confirming why it is still the market leader technology. The much higher purchase cost of Li-ion batteries didn't pay back in the project lifetime also considering all the potential benefits of this technology as negligible O&M, high cycle lifetime in deep discharge applications and lower temperature effect on performances. Within lead-acid technology, OPzS batteries resulted most cost-effective options as they are characterized by long service life and excellent capacity performance while operating in high temperature conditions.

3.3.3 Levelized cost of electricity (LCOE)

The most important performance parameter computed by HOMER is the levelized cost of electricity in $/kWh. This will be crucial for the cost assessment of the e-cook solution in

the result section. HOMER defines the levelized cost of electricity as the average cost per kWh of useful electrical energy produced by the system.
To calculate the LCOE, HOMER divides the annualized cost of producing electricity by the total electric load served, using the following equation [58]:

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \quad 3.15$$

Where $C_{ann,tot}$ is the total annualized cost of the system in \$/year and E_{served} is the total electrical load served.

3.4 Cooking solutions performance analysis

In this section, a method for the comparison of different cooking solutions including firewood, charcoal, kerosene, LPG and e-cook from the economic and environmental point of view is presented.
In order to compare different solutions a reference quantity has to be defined. According to the literature *Useful energy* has been defined as energy going into the pot and food [6], [8].
In this thesis work, cooking cycles have been modelled starting from local cooking habits and from the simplified model for a single cooker induction stove. For this reason, useful energy has been calculated as the product between electric energy request for cooking in a day and the efficiency of the induction stove. Then, dividing useful energy value by the efficiency of other cooking technologies the primary energy required for each cooking solution has been calculated.
Moreover, in the load curve modelling process, time length of each cooking task has been randomized between a minimum and a maximum value. Starting from these values it has been possible to define two different cooking scenarios:

- *low cook scenario* in which the time length of every cooking task has been considered equal to the minimum value;
- *high cook scenario* in which the time length of every cooking task has been considered equal to the maximum value.

Through the definition of these two different scenarios, it has been possible to present results of each analysis as a range rather than an absolute value.

3.4.1 Levelized cooking cost per month

Levelized cooking cost per month is defined as the monthly expenditures for energy related to cooking activities in $/month. For the case study referred to Kidegembye village, from the monthly income per household, it has been possible to calculate the percentage of the cooking cost respect to income.

For each solution, cooking cost per month has been calculated for both low cook and high cook scenarios constituting the basic analysis.
For the e-cook solution, cooking cost per month has been determined by multiplying the electricity request per month in kWh/month by the levelized cost of electricity in $/kWh computed by HOMER software.
For the other solutions, firstly the primary energy required has been calculated according to the stove efficiency value. Then, fuel quantity per month required to satisfy cooking needs has been determined through the lower calorific value (LHV) of the fuel. Consequently, cooking cost per month has been calculated through the fuel price.
In addition, for the charcoal solution, firewood per month required to produce the request quantity of charcoal has been determined through the conversion factor between firewood and charcoal [66].
Fuso Nerini's stove efficiency values have been considered for the basic analysis [8]. The lower calorific values of each fuel has been instead taken from "The engineering toolbox" online platform [67]. Moreover, for the Kidegembye village basic analysis, the specific cost of firewood has been considered equal to the Fuso Nerini's value i.e. 0.092 $/kg [8]. The price of charcoal equal to 0.31 $/kg, has been instead taken from a recent article of a famous Tanzanian newspaper [68]. The value of Kerosene, equivalent to 0.9 $/l, has been taken from a recent article published by CNBC [69]. Finally the reference price for LPG has been considered equal to 2.2 $/kg, value presented in Leach-Oduro's article [6]. For Mama Kevina case study, fuel prices have been instead taken from a survey conducted in Same during my stay in January 2018, results are depicted in Table 3.11.

Fuel prices in Same	
Firewood [$/kg]	0,112
Charcoal [$/kg]	0,266
Kerosene [$/l]	1,253
LPG [$/kg]	2,72

Table 3.11 Fuel prices in Same (January 2018)

Moreover, in order to avoid presenting too specific results a sensitivity analysis on stove efficiencies has been carried out for levelized cooking cost per month. For each solution a minimum and a maximum value of efficiency have been considered giving rise to two additional scenarios for both low cook and high cook: *low efficiency* and *high efficiency* scenarios. A lower efficiency value and an upper one has been supposed for each technology, apart from the induction cookers for which literature agrees on the 90% value [2], [26], [70]. For the firewood cooking technology, three stone fire has been considered as it represents the most used in rural areas in Tanzania. For this technology a range between 11% and 15.7% has been taken into account [71], [72]. Then, for charcoal traditional stoves, efficiency values between 20% and 26% are reported, while for kerosene they varies in a 37% - 45% range [8], [72]. Finally for LPG stoves efficiencies from 53% to 60.4% have been considered [8], [71].

Finally, considering the instability of fuel prices, a sensitivity analysis on this variable, combined to the sensitivity analysis on stove efficiency, has been carried out. For each fuel a minimum and a maximum price have been considered giving rise to two other scenarios: *low price* and *high price*. Combining the two sensitivity analysis, it has been possible to obtain a *pessimistic scenario* represented by the combination of high cook – low efficiency – high price and an *optimistic scenario* represented by the combination of low cook – high efficiency – low price. Hence, all the plausible casuistries are expected to be included within these extreme scenarios. Providing a range of cost, rather than an absolute value, makes possible to carry out a comprehensive confront between all the cooking technologies.
Regarding firewood the lowest price is represented from gathered firewood which is for free, while the highest value is 0.112 $/kg (actual value in Same in January 2018). For charcoal a range between 0.199 $/kg and 0.40 $/kg has been considered [6], [8], while for kerosene prices vary from 0.9 $/l [69] to 1.253 $/l (actual value in Same in January 2018). Finally, for LPG prices vary between 2.2 $/kg [8] to 2.720 $/kg (actual value in Same in January 2018).

3.4.2 Levelized cost of cooking a meal (LCCM)

Levelized cost of cooking a meal is defined as the cost for cooking a “standard” meal with a certain fuel-technology combination [8]. It was introduced in 2016 by Fuso Nerini in his article “The cost of cooking a meal. The case of Nyeri County, Kenya”. The LCCM model in the article was used to compare different cooking solutions in the case study area. Since the scope of this thesis is to confront e-cook with other solutions, LCCM has been selected as a comparison parameter within the performance analysis.

LCCM is defined by the following equation [8]:

$$LCCM = LCCM_{fuel} + LCCM_{stove} = \frac{C_{fuel} \times E_u}{\eta_{stove}} + \frac{\sum_{t=1}^{n} \frac{C_{stove,t} + O\&M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Ml_t}{(1+r)^t}} \quad 3.16$$

Where:

- C_{fuel} is the fuel price in \$/kWh;
- E_u is the useful energy required for cooking a meal in kWh/meal;
- η_{stove} is the stove efficiency;
- $C_{stove,t}$ is the stove purchase cost occurred in the year t in \$;
- $O\&M_t$ are the operation and maintenance cost related to the stove occurred in the year t in \$/year;
- Ml_t are the amount of meals cooked in the time unit (1 year);
- n is the stove lifetime in years;
- r is the real interest rate.

The real interest rate is defined as [58]:

$$r = \frac{i - f}{1 + f} \quad 3.17$$

Where i is the nominal interest rate and f is the inflation rate. By defining the real interest rate also inflation has been taken into account.
Therefore, in order to determine the useful energy required for cooking a meal E_u, useful energy defined in 3.4 has been divided by the number of meals per day.
In Tanzania, as in most parts of the world, people usually eat three meals per day, however, it's common that all three are not fully cooked meals [8], [47]. For example, for breakfast, the only energy consumption is due to boiling water for tea or for chapati preparation which cannot be considered as a full cooked meal. Moreover, leftovers from lunch are usually consumed for dinner with a simply reheating process that can't neither be considered as a full cooked meal. In order to account for these variations 2.5 meals per day have been considered for the case study set Kidegembye. According with Mama Kevina Hope Center cooking habits, three meals per day have been considered instead.

In addition, also for the LCCM sensitivity analysis on stove efficiency and fuel&stove price, have been carried out. Therefore, as for the cooking cost per month, combining the two sensitivity analysis, it has been possible to obtain a *pessimistic scenario* represented by the combination of high cook – low efficiency – high price and an *optimistic scenario* represented by the combination of low cook – high efficiency – low price.
Moreover, price of the different stoves must be defined. Regarding firewood, three stone fire has been identified as a reference technology, and since it is usually hand made its price has been considered equal to zero US dollars. For charcoal traditional stoves instead, Leach-Oduro value of 10$ has been taken into account [6] while for kerosene 15$ has been taken as reference value on the local market (Jumia e-commerce website). Also for LPG cooker, price value has been considered equal to Leach-Oduro's one that is 51.6$ for the Kidegembye village while for Mama Kevina a LPG kitchen has been considered with a price of 92.93$. Finally, for induction cooker a 10$ reference value for specific pots and pans (Jumia e-commerce website) has been added to the *Aigostar Blackfire 30IAV* and */1* price (sub-section 2.1.1). Accordingly, for induction kitchen a 30$ reference value for specific pots and pans (Jumia e-commerce website) has been added to the *Candy CI 640 CBA* price.

Results for each cooking solution have been therefore presented included in a range between the pessimistic scenario and the optimistic scenario.
Finally, a comparison with Fuso Nerinis' results has been carried out.

3.4.3 Comparison between two modern technology: electricity versus LPG

The two main alternatives for access to clean cooking are globally represented by electricity and LPG. As highlighted in section 2, electricity is often abandoned a priori, while for LPG is rarely mentioned that it is unsustainable in the long-term. In fact, from the environmental point of view LPG is a non-renewable fossil fuel, and from the economic point of view its price is strongly linked to economic and geopolitical factors.

In order to compare these two different solutions, *Payback Time* (PBT) and *Internal Rate of Return* (IRR) have been calculated for a twenty years project lifetime for both the case studies. Payback time is defined as the length of time required to recover an investment cost. Internal rate of return is instead a discount rate that makes the *net present value* NPV of all cash flows of the project equal to zero. Since there aren't revenues in the considered project *Net Present Cost* (NPC) is defined instead of NPV for both the solutions. NPC has been computed to determine PBT and IRR.

Considering that with e-cook access to electricity, besides access to clean cooking, is provided, for the LPG solution it has been considered to install a solar powered mini-grid sized to satisfy only the base load. Consequently, the two different solutions can be compared as they provide both access to clean cooking and to electricity.

The following equation defines the net present cost:

$$NPC = I_0 + \sum_{t=1}^{n} \frac{CF_t - SV_f}{(1+r)^t} \qquad 3.18$$

Where:

- I_0 is the investment cost considering purchase of mini-grid components and cooking stoves;
- CF_t are the cash flows occurred year by year, they consider fuel expenditure, O&M and replacements costs;
- SV_f is the salvage value i.e. the value remaining in the mini-grid components at the end of the project lifetime;
- r is the real interest rate defined by 3.17;
- n is the project lifetime.

Defining the difference between the NPC of the LPG solutions and the e-cook as:

$$\Delta NPC = NPC_{LPG} - NPC_{e-cook} \qquad 3.19$$

ΔNPC is a straight line in the NPC-years plane. The value of ΔNPC will be negative, respect to the NPC axes, until the LPG solution is favourable. The PBT is the interception of the straight line with the year axes and after its value the e-cook solution will be favourable.
Calling i the year in which the NPC of the LPG solution becomes greater than the NPC of the e-cook solution ($\Delta NPC > 0$) and i-1 the year before that, is possible to define slope and intercept as:

$$m = \frac{\Delta NPC_i - \Delta NPC_{i-1}}{i-(i-1)} = \Delta NPC_i - \Delta NPC_{i-1} \qquad 3.20$$

$$q = \Delta NPC_{i-1} - m \times (i-1) \qquad 3.21$$

The PBT can be therefore calculated as the ratio between the intercept q and the slope m of the straight line.

$$PBT = -\frac{q}{m} \tag{3.22}$$

Internal rate of return has been calculated, through excel solver, as the discount rate that makes the ΔNPC equal to zero at the end of the project lifetime.

3.4.4 Savings of e-cook solution

Comparing e-cook solution with the others only from the economic point of view it wouldn't be complete. The actual added value of e-cook solution is indeed the use of electricity as a clean and renewable fuel. Electricity is the cleanest fuel at point-of-use and it is renewably generated from the solar powered mini-grid. Hence, compared to all other solutions the e-cook one presents savings in terms of non-renewable fuel consumption.

For each non-renewable fuel solution, the fuel quantity consumed throughout a year has been calculated as explained in 3.4.1, and consequently the e-cook savings have been determined.

4. Results – Kidegembye

In this section results referred to the village of Kidegembye are presented. Methodologies and calculation procedures for obtaining the results have been presented in section 3.

4.1 Load curves

The first step for the techno-economic assessment of an e-cook mini-grid is load curve modelling. In this sub-section load curves modelled for the village of Kidegembye are presented.

4.1.1 Base load

Data for Base load curve modelling has been taken from Berti's thesis. Within his thesis work surveys about electric appliances and their utilization were conducted in the village of Kidegembye and are available in Annex B. The main appliances are indoor/outdoor lights, charger, radio and TV. One load curve per day of the year has been simulated through LoadProGen. In the figure below mean load curve and the load curve correspondent to the maximum power peak have been plotted.

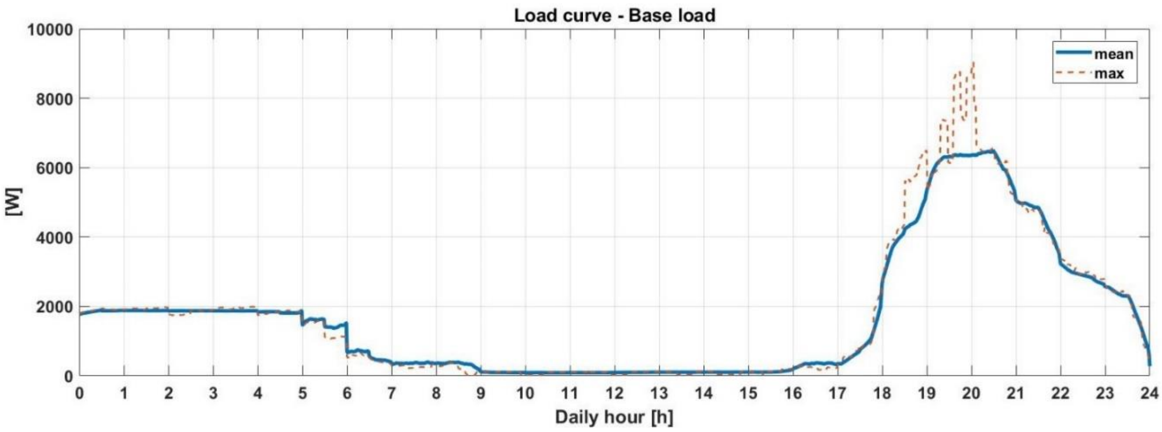


Figure 4.1 Kidegembye Load curve - Base load

4.1.2 Full cooking

Starting from base load curves, full cooking load curves have been simulated by adding one induction cooker per household. Input for the induction cookers are depicted in Table 4.1 where "Cooking_FP" refers to the full preparation cycle while "Cooking_D" to the dinner preparation.

One load curve per day of the year has been simulated through LoadProGen. In Figure 4.2 mean load curve and the load curve correspondent to the maximum power peak have been plotted.

Type of electrical appliance *(i)*	Nominal appliance power rate [W] *(P_{ij})*	functioning cycle [min] *(d_{ij})*	Starting time Win 1 [min] *[1-1440]*	Ending time Win 1 [min] *[1-1440]*	Starting time Win 2 [min] *[1-1440]*	Ending time Win 2 [min] *[1-1440]*
Cooking_FP	2000	Cycle1	285	450	0	0
Cooking_D	2000	Cycle2	780	900	1080	1200

Table 4.1 LoadProGen input - Kidegembye load curve - Full cooking

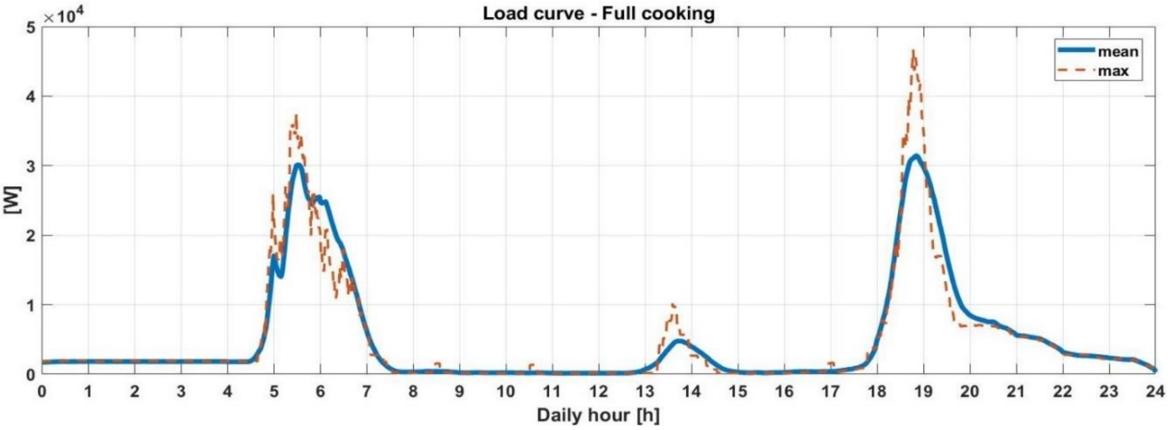


Figure 4.2 Kidegembye load curve - Full cooking

To highlight the huge impact of induction cookers, mean load curve of base load and full cooking scenarios have been plotted in the same graph (Figure 4.3).

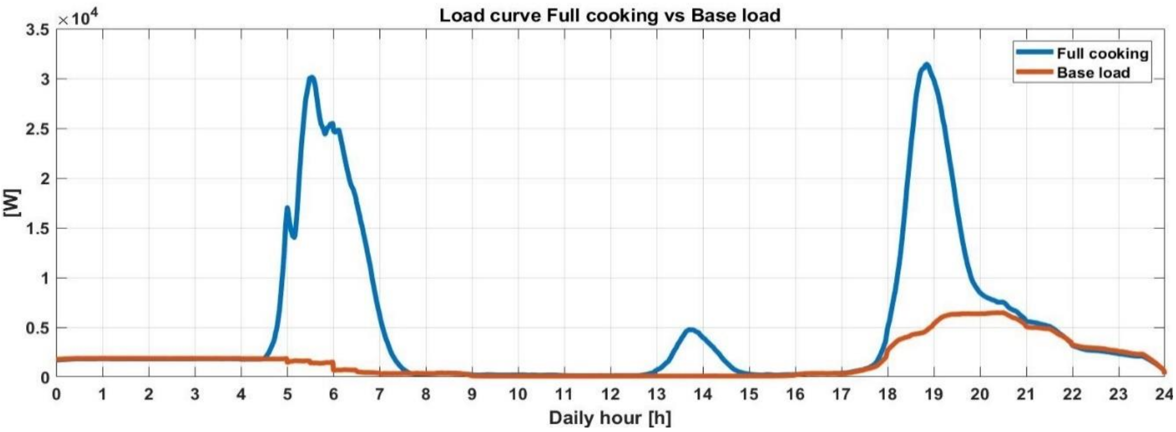


Figure 4.3 Kidegembye load curve - Full cooking vs Base load

The peak power of the mean load curve passed from around 6 kW for the base load scenario to around 30 kW for the full cooking scenario. It's evident from this graph how challenging is trying to guarantee access to clean cooking through the e-cook concept. However, with this thesis work, the challenge has been accepted and satisfying results have been provided despite the e-cook solution is usually abandoned a priori in the literature.

4.1.3 Fuel stacking

Transition from traditional way of cooking with solid biomass to whichever kind of modern cooking technology is likely to be a gradual process. For this reason, the *Fuel stacking* scenario has been modelled.
One load curve per day of the year has been simulated through LoadProGen for this scenario. In the figure below mean load curve and the load curve correspondent to the maximum power peak have been plotted.

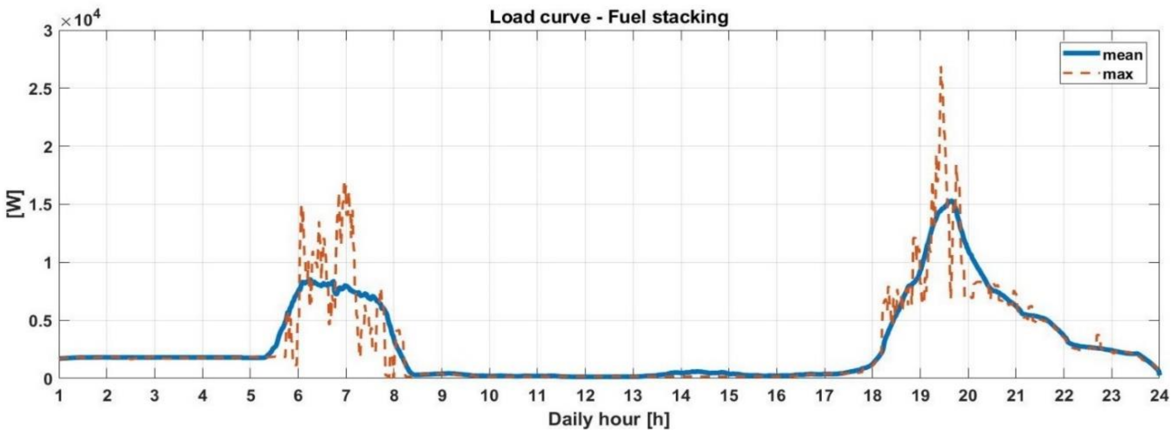


Figure 4.4 Kidegembye load curve - Fuel stacking

In addition, a growing percentage of penetration in the use of induction cookers as primary cooking technology has been considered to simulate future developments (Figure 4.5). For households which use induction cookers as primary technology, complete cooking cycles have been considered. For the remaining percentage of household, induction cookers are used as secondary technology, therefore fuel stacking cooking cycles have been considered. One load curve per day of the year has been simulated through LoadProGen for each penetration level, results are depicted in Figure 4.5.

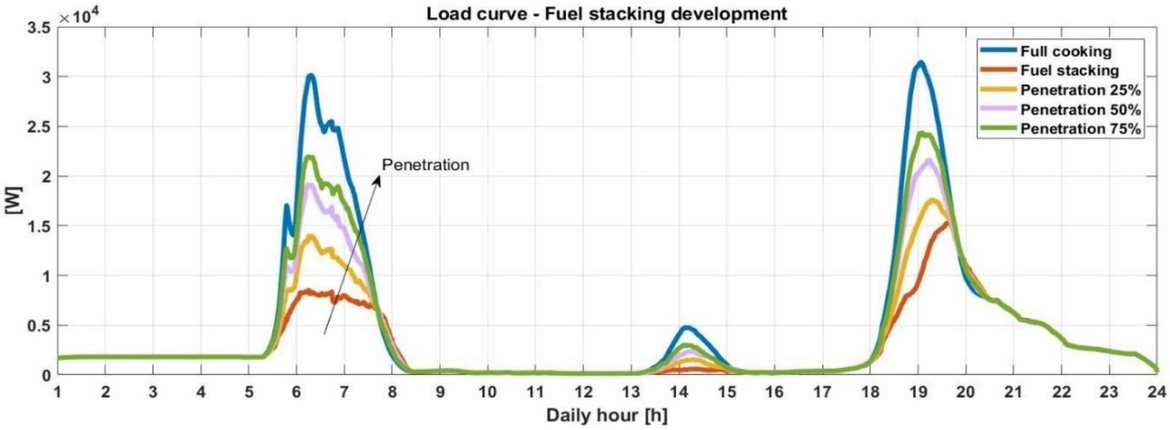


Figure 4.5 Kidegembye load curve - Fuel staking development

4.1.4 Peak shifting

Given the potential benefits for the mini-grid achievable through the installation of a demand side management technology, *Peak shifting* load curves have been modelled for Kidegembye village.

Input for the induction cookers, relatively to this scenario, are depicted in Table 4.2. To simulate the effects of demand side management technology, functioning windows of induction cookers have been widened by 30 minutes.

Type of electrical appliance *(i)*	Nominal appliance power rate [W] (P_{ij})	functioning cycle [min] (d_{ij})	Starting time Win 1 [min] *[1-1440]*	Ending time Win 1 [min] *[1-1440]*	Starting time Win 2 [min] *[1-1440]*	Ending time Win 2 [min] *[1-1440]*
Cooking_FP	2000	Cycle1	285	480	0	0
Cooking_D	2000	Cycle2	765	915	1065	1215

Table 4.2 LoadProGen input – Kidegembye load curve – Peak shifting

One load curve per day of the year has been simulated through LoadProGen. In Figure 4.6, mean load curve and the load curve correspondent to the maximum power peak have been plotted.

Furthermore, to highlight the potential of demand side management technology, mean load curve of full cooking and peak shifting scenarios have been plotted in the same graph (Figure 4.7).

As expected, the peak of the mean load curve passed from around 32 kW for the full cooking scenario to around 27 kW for the peak shifting scenario.

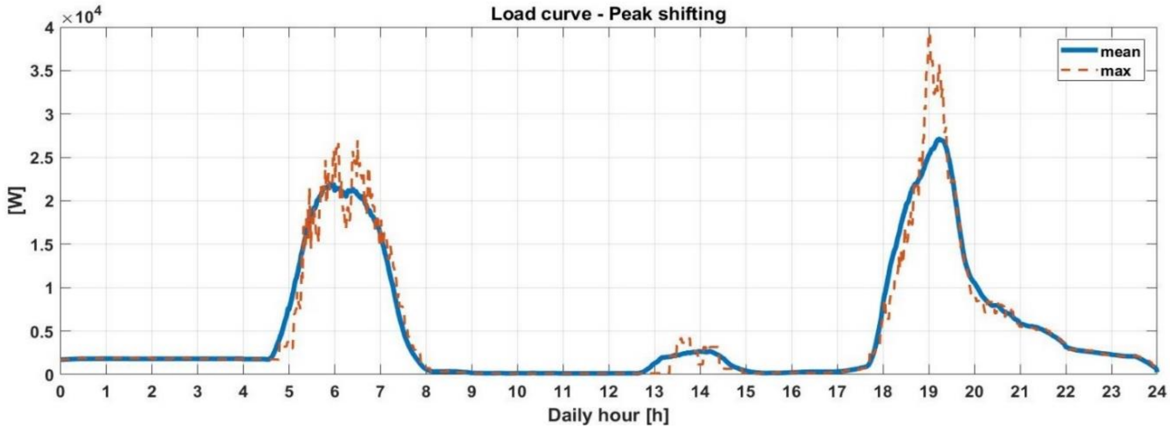


Figure 4.6 Kidegembye load curve - Peak shifting

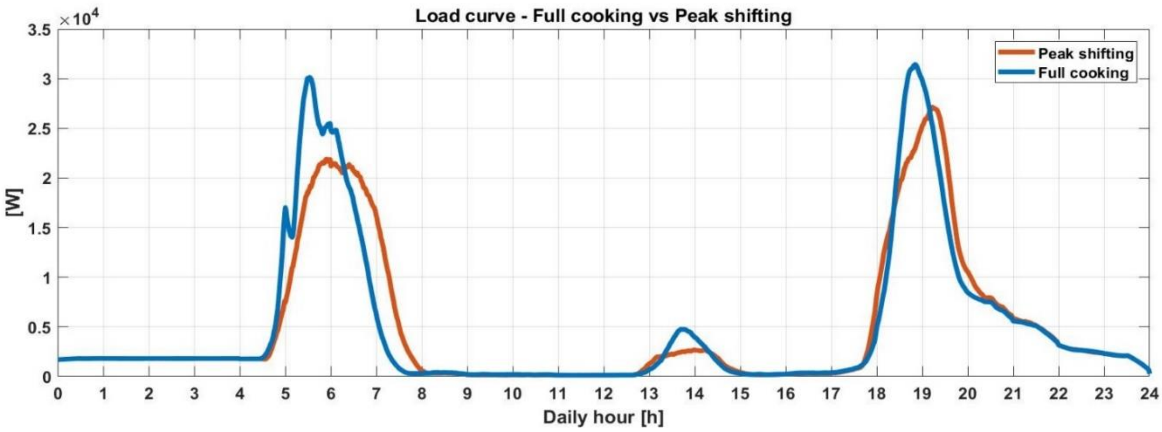


Figure 4.7 Kidegembye load curve - Full cooking vs Peak shifting

4.2 Preliminary system design

Starting from the load curve modelling it has been possible to develop a preliminary system design, based on classic sizing techniques presented in sub-section 3.2.

4.2.1 Resource assessment

The first step for the preliminary system design is the resource assessment. Monthly average solar global horizontal irradiance (GHI) for Kidegembye are depicted in Figure 4.8.

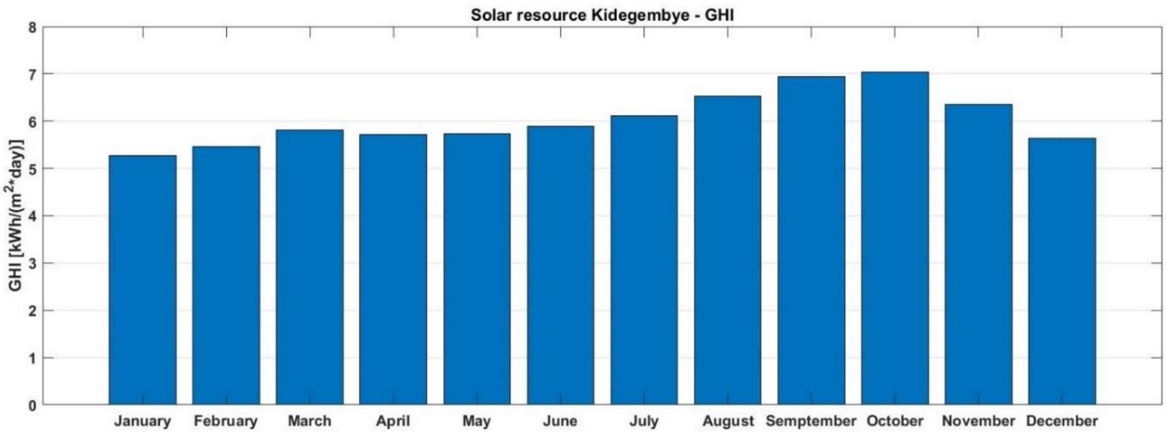


Figure 4.8 Kidegembye - solar resource (GHI) [55]

Temperature profile, hour by hour throughout the whole year, is depicted in Figure 4.9.

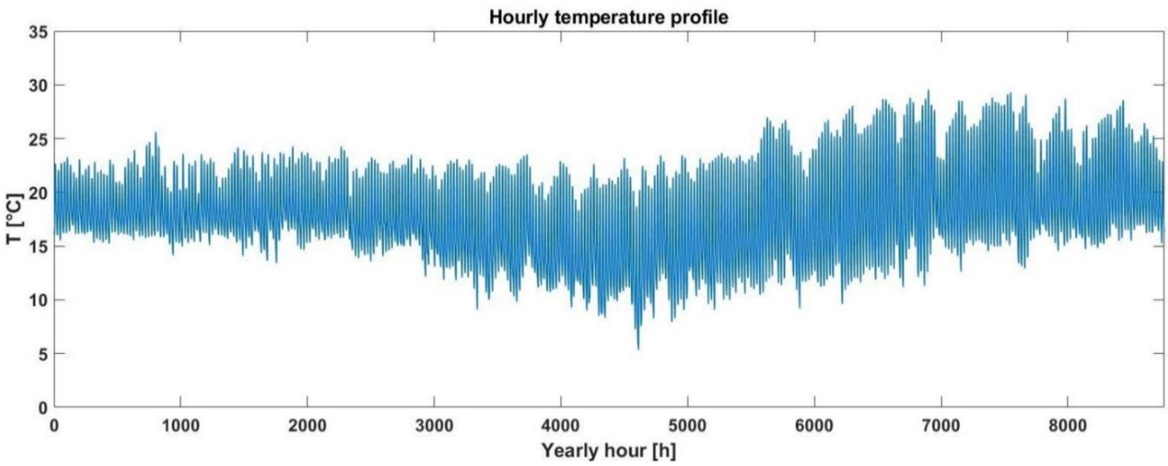


Figure 4.9 Kidegembye - temperature profile [59]

4.2.2 Base load

For the base load scenario, the estimated daily energy demand resulting from load curves is equal to 39.87 kWh per day. Then, considering the worst case, the global horizontal solar radiation (GHI) is equal to 5.27 kWh per square meter per day.

The total area of the required PV array has been calculated through equation 3.1 and it resulted 67.3 square meters. For this calculation parameters of *QCELLS275* and *Magnum PT-100 MPPT* have been considered, while efficiency of inverter and battery have been chosen equal to 94% and 86% respectively as reference values. Finally, the temperature reached during operation has been hypothesized equal to 60 °C.
Then, through equation 3.2 PV array peak power resulted 11.10 kW.

Therefore, the total capacity of the batteries required has been calculated through equation 3.4 considering two continuous cloudy days and a depth of discharge equal to 80% as reference value. It resulted 123.30 kWh or 2568.73 Ah considering a 48 V DC system voltage.

Finally, considering the power rate of the inverter 10% lower than the PV array peak power it resulted 9.99 kW.

4.2.3 Full cooking

For the full cooking scenario, the estimated daily energy demand resulting from load curves is equal to 116.53 kWh per day. Then, as for the base load scenario, the global horizontal solar radiation (GHI) has been considered equal to 5.27 kWh per square meter per day.

The total area of the required PV array has been calculated through equation 3.1 and it resulted 194.62 square meters considering the same parameters as for the base load scenario. Then, through equation 3.2 PV array peak power resulted 32.11 kW.

Therefore, the total capacity of the batteries required has been calculated through equation 3.4 considering the same parameters as for the base load scenario. It resulted 356.58 kWh or 7428.73 Ah considering a 48 V DC system voltage.

Finally, considering the power rate of the inverter 10% lower than the PV array peak power it resulted 28.90 kW.

		Base load	Full cooking
PV_Area	m^2	67.30	194.62
P_PV	kW	11.10	32.11
Battery capacity	kWh	123.30	356.58
Battery capacity	Ah	2568.73	7428.73
P_inverter	kW	9.99	28.90

Table 4.3 Comparison between Base load and Full cooking preliminary system design

4.3 HOMER optimized system design

Starting from the preliminary system design, optimized sizing of each component has been carried out through HOMER software.

4.3.1 Base load

Starting from load curves of the base load scenario (sub-section 4.1.1), resource assessment conducted for Kidegembye village (sub-section 4.2.1) and from the relative preliminary system design (sub-section 4.2.2) the optimized system design has been carried out through HOMER software. The resulting schematic system layout is depicted in Figure 4.10.

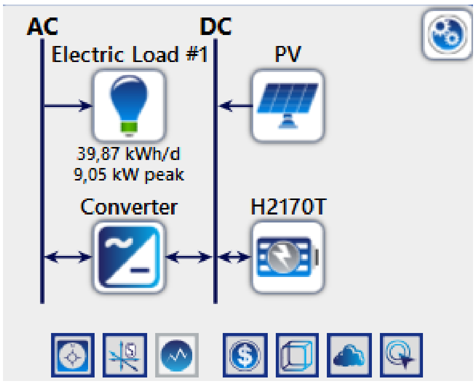


Figure 4.10 Kidegembye - Base load - HOMER schematic system layout

The PV array size resulted 11.55 kW meaning 42 *QCELLS275W* modules. From the electrical coupling between *QCELLS275W* and *Magnum PT-100* MPPT solar charge controller maximum 4 modules in series and 6 in parallel resulted, providing maximum 24 modules per controller. Hence, two *Magnum PT-100* are needed. The PV array power output throughout the year is depicted in Figure 4.11.

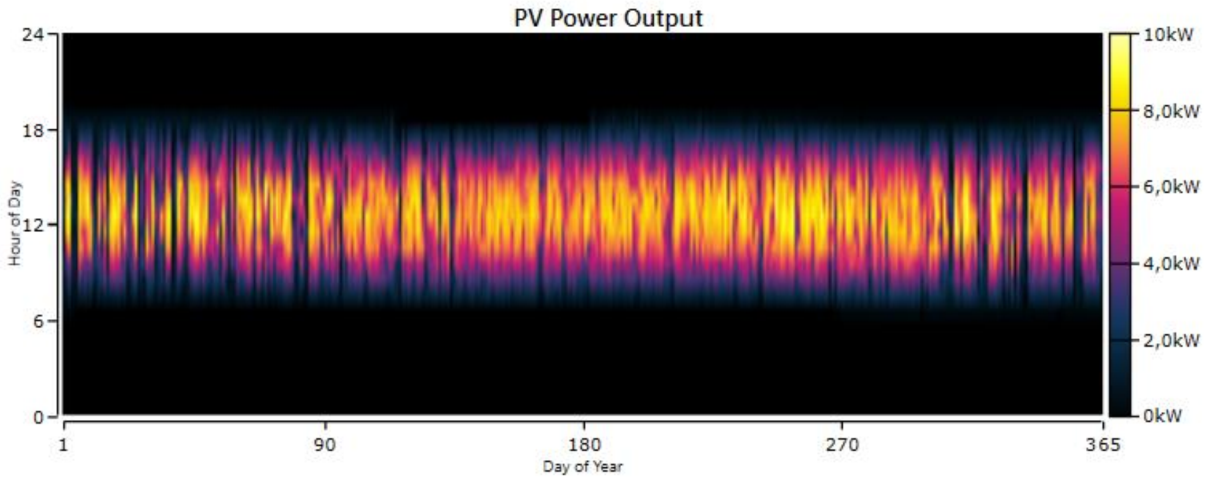


Figure 4.11 Kidegembye - Base load - PV array power output

The *Hoppecke 12 OPzS solar.power 2170* with a 2170 Ah nominal capacity resulted the best option for the mini-grid (datasheet in Annex A). The effective autonomy of the battery in the system is 50.2 hours. Battery expected lifetime is 11.1 years considering 105 cycles per year and 80% maximum DOD accepted. Battery's state of charge throughout the year is depicted in Figure 4.12.

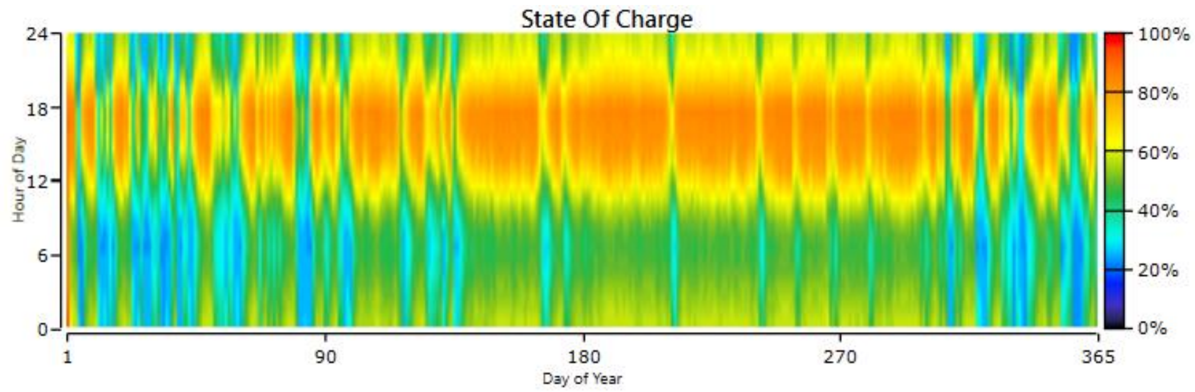


Figure 4.12 Kidegembye - Base load - battery state of charge

Considering that the minimum state of charge rarely reaches 20%, and that the manufacturer expects 1500 cycles with a DOD equal to 80%, the effect of temperature on the battery lifetime is evident.

However, the variable which triggers the battery replacement, reaching first the degradation limit, is the cycle degradation, as highlighted in Figure 4.13.

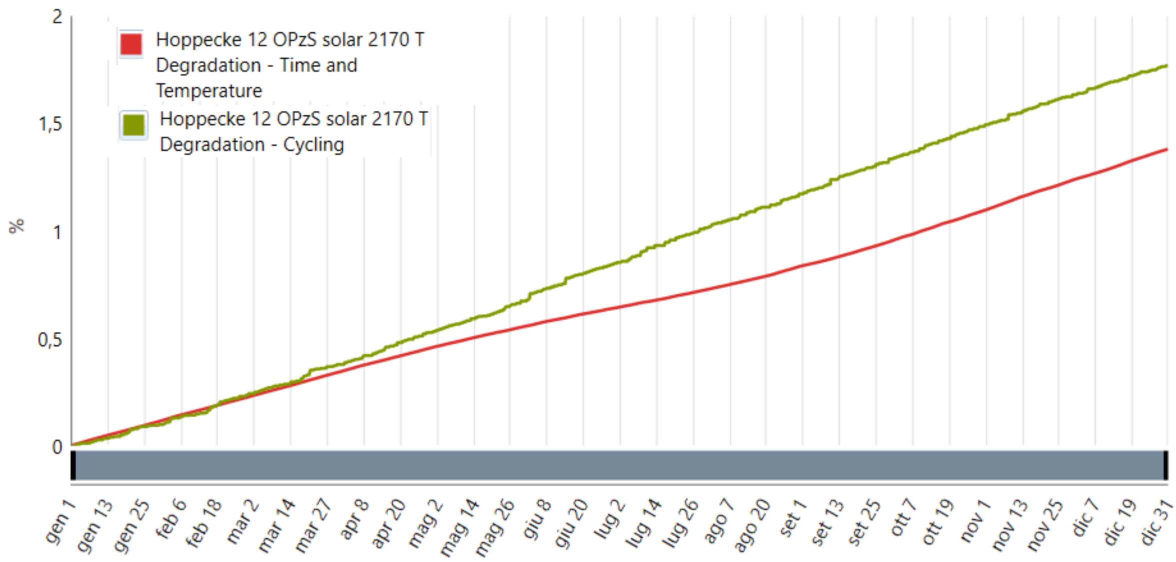
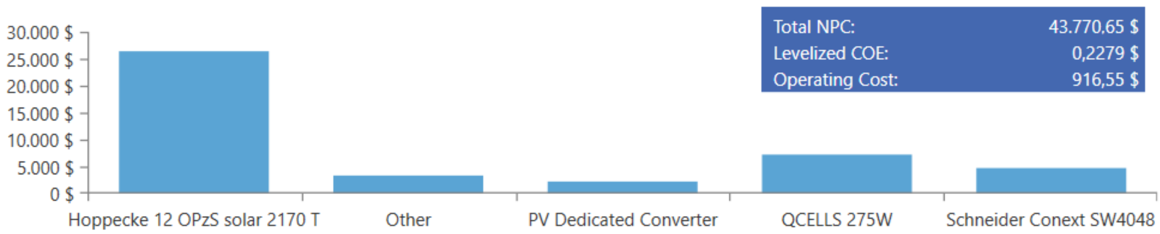


Figure 4.13 Kidegembye - Base load - Battery degradation factors

The optimal solution for system inverter turn out to be two *Schneider Conext SW4048* (datasheet in Annex A) with a 7.6 kW total power rate, representing the most cost-effective solution.

The resulting net present cost structure for the mini-grid in the base load scenario is presented in Figure 4.14.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Hoppecke 12 OPzS solar 2170 T	16.659,00 $	11.006,06 $	304,09 $	0,00 $	-1.546,13 $	26.423,02 $
Other	3.221,75 $	0,00 $	0,00 $	0,00 $	0,00 $	3.221,75 $
PV Dedicated Converter	1.504,00 $	858,40 $	311,83 $	0,00 $	-474,69 $	2.199,54 $
QCELLS 275W	6.531,97 $	0,00 $	1.354,58 $	0,00 $	-618,49 $	7.268,06 $
Schneider Conext SW4048	3.185,00 $	1.817,82 $	660,71 $	0,00 $	-1.005,25 $	4.658,29 $
System	31.101,72 $	13.682,28 $	2.631,22 $	0,00 $	-3.644,56 $	43.770,65 $

Figure 4.14 Kidegembye - Base load - HOMER cost structure

The economic relevance of the battery within the mini-grid, accounting for around 60% of the total cost, therefore appears evident. The total NPC resulted 43770.65 $ while the levelized cost of energy (LCOE) resulted 0.2279 $/kWh. The entry "other" is referred to BOS costs.

4.3.2 Full cooking

Starting from load curves of the full cooking scenario (sub-section 4.1.2), resource assessment conducted for Kidegembye village (sub-section 4.2.1) and from the relative preliminary system design (sub-section 4.2.3) the optimized system design has been carried out through HOMER software. The resulting schematic system layout is depicted in Figure 4.15.

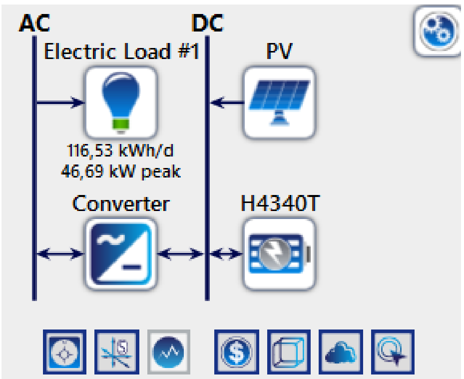


Figure 4.15 Kidegembye – Full cooking - HOMER schematic system layout

The PV array size resulted 37.4 kW meaning 136 *QCELLS275W* modules. From the electrical coupling between *QCELLS275W* and *Magnum PT-100* MPPT solar charge controller maximum 4 modules in series and 6 in parallel resulted, providing maximum 24 modules per controller. Hence, six *Magnum PT-100* are needed. The PV array power output throughout the year is depicted in Figure 4.16.

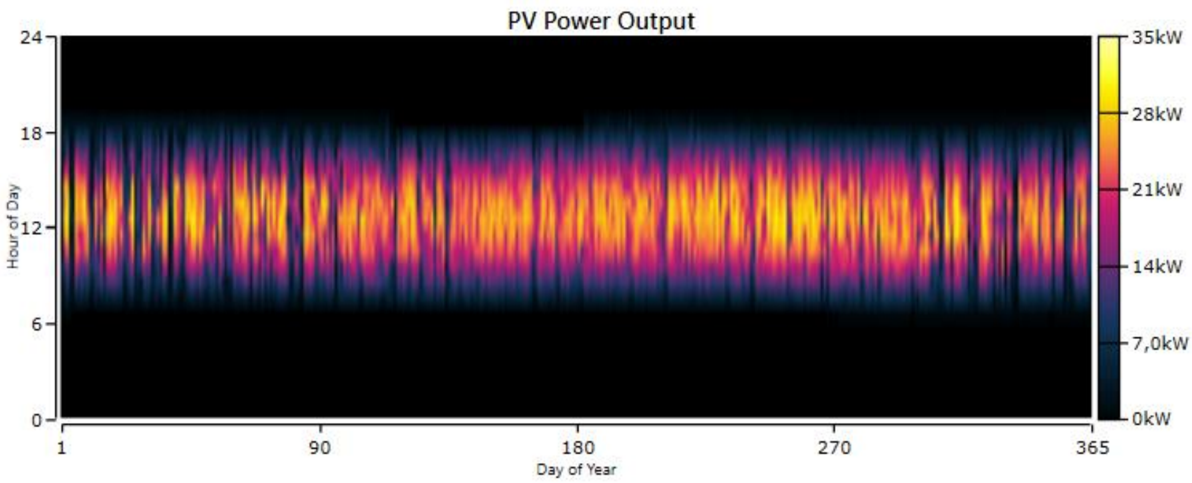


Figure 4.16 Kidegembye - Full cooking - PV array power output

The combination of two *Hoppecke 24 OPzS solar.power 4340* connected in parallel with a 8680 Ah total nominal capacity resulted the best option for the mini-grid (datasheet in Annex A). The effective autonomy of the battery pack in the system is 74.2 hours. Battery pack expected lifetime is 16.1 years considering 73 cycles per year and 80% maximum DOD accepted. Batteries' state of charge throughout the year is depicted in Figure 4.17.

Figure 4.17 Kidegembye - Full cooking - Batteries state of charge

It can be notice that with respect to the base load case the optimal sizing of the battery results over-sized for most of the year and with a higher autonomy. This is due to the need of satisfying a high and concentrated energy request also during the most unfavourable period represented by January.

Then, considering that the minimum state of charge rarely reaches 20%, and that the manufacturer expects 1500 cycles with a DOD equal to 80%, the effect of temperature on the battery pack lifetime is evident.

However, as for the base load scenario, the variable which triggers the battery replacement, reaching first the degradation limit, is the cycle degradation, as highlighted in Figure 4.18.

The optimal solution for system inverter turn out to be four *Schneider Conext XW6848NA* (datasheet in Annex A) with a 27.2 kW total power rate, representing the most cost-effective solution.

The resulting net present cost structure for the mini-grid in the base load scenario is presented in Figure 4.19.

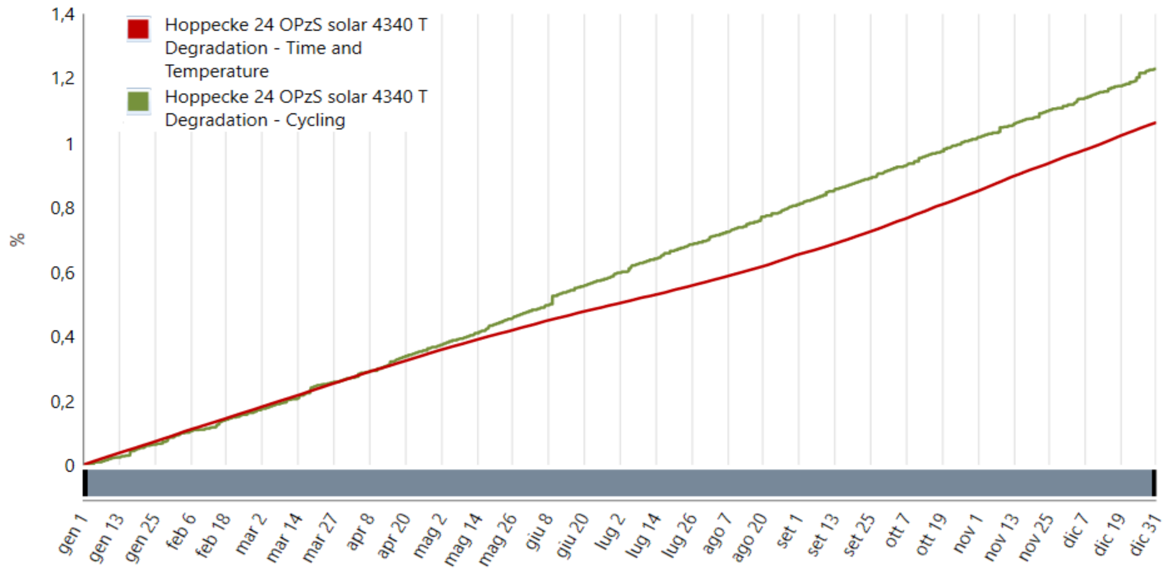
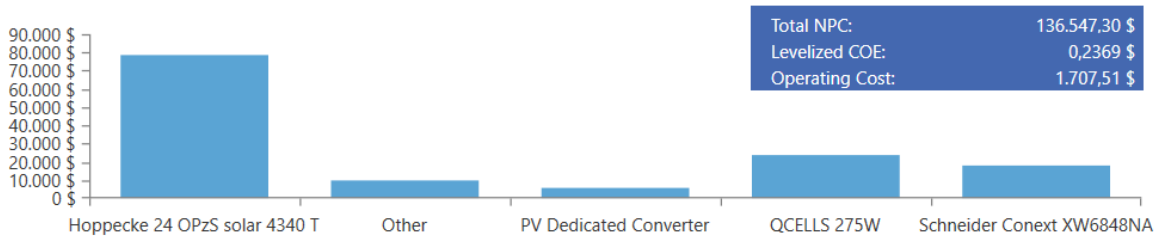


Figure 4.18 Kidegembye - Full cooking - Battery degradation factors



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Hoppecke 24 OPzS solar 4340 T	65.233,20 $	35.725,93 $	1.266,14 $	0,00 $	-23.412,02 $	78.813,24 $
Other	9.958,00 $	0,00 $	0,00 $	0,00 $	0,00 $	9.958,00 $
PV Dedicated Converter	4.170,18 $	2.380,11 $	864,63 $	0,00 $	-1.316,19 $	6.098,73 $
QCELLS 275W	21.211,92 $	0,00 $	4.380,06 $	0,00 $	-2.008,47 $	23.583,51 $
Schneider Conext XW6848NA	12.372,00 $	7.061,26 $	2.565,45 $	0,00 $	-3.904,85 $	18.093,85 $
System	112.945,30 $	45.167,30 $	9.076,28 $	0,00 $	-30.641,54 $	136.547,33 $

Figure 4.19 Kidegembye - Full cooking - HOMER cost structure

As for the base load scenario the economic relevance of the battery pack within the mini-grid, accounting for around 60% of the total cost, therefore appears evident. The NPC resulted 136547.30$, around 3 times the base load NPC, while LCOE resulted 0.2369 $/kWh. The entry “other” is referred to BOS costs.

4.3.3 Fuel stacking

As mentioned before, transition from traditional way of cooking with solid biomass to whichever kind of modern cooking technology is likely to be a gradual process. For this reason, in order to provide a complete analysis, impacts of this phenomenon on the mini-grid have been evaluated. Starting from the HOMER optimized system design for the full cooking scenario, load curves relative to fuel stacking scenario with 50% penetration of induction cookers as primary technology have been given as input in HOMER. The system design of the mini-grid is therefore unchanged respect to full cooking scenario (sub-section 4.3.2).

For the 50% penetration fuel stacking scenario, the estimated daily energy demand resulted from load curves is equal to 92.26 kWh per day while for full cooking was 116.53 kWh per day.

This reduction in daily energy demand will affect batteries operations. The effective autonomy of the battery in the system indeed increased to 93.7 hours from 74.2 hours in the full cooking scenario. Moreover, expected battery lifetime consequently grew to 18.8 years from 16.1 years considering 54 cycles per year and 80% maximum DOD accepted. Battery's state of charge throughout the year is depicted in Figure 4.20.

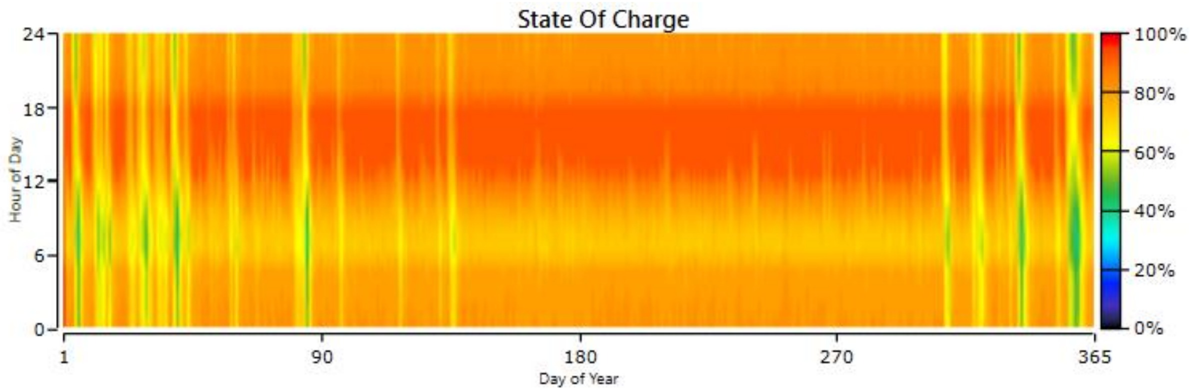


Figure 4.20 Kidegembye - Fuel stacking - Battery state of charge

It can be noticed that the optimum battery pack for the full cooking scenario resulted instead oversized for the fuel stacking one as expected. Batteries reach a 40% minimum state of charge during the year only with the worst external conditions. The reduced DOD and number of cycles equivalent brought to an increase in the battery pack lifetime value. However, it's interesting to notice how the variable which triggers the battery replacement in this case, is the time and temperature degradation rather than cycle degradation as highlighted in Figure 4.21.

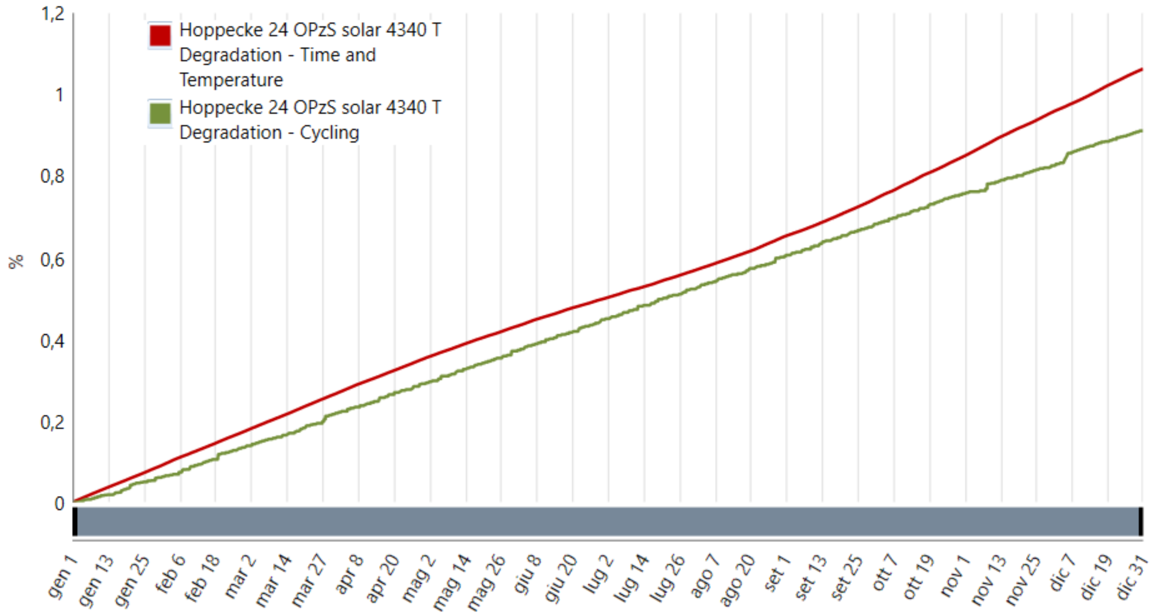
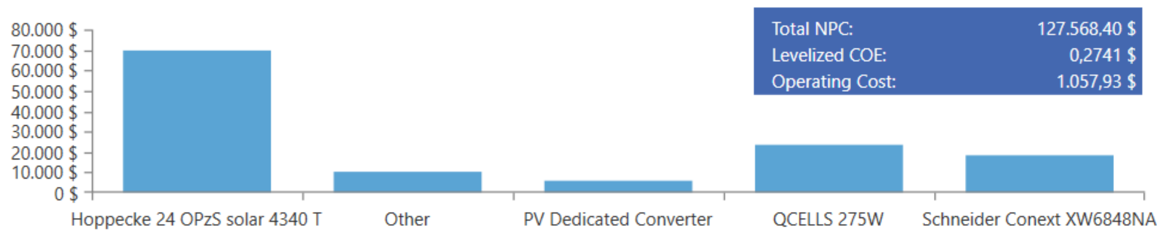


Figure 4.21 Kidegembye - Fuel stacking - Battery degradation factors

The resulting net present cost structure for the mini-grid in the base load scenario is presented in Figure 4.22.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Hoppecke 24 OPzS solar 4340 T	65.233,20 $	32.278,67 $	1.266,14 $	0,00 $	-28.943,67 $	69.834,34 $
Other	9.958,00 $	0,00 $	0,00 $	0,00 $	0,00 $	9.958,00 $
PV Dedicated Converter	4.170,18 $	2.380,11 $	864,63 $	0,00 $	-1.316,19 $	6.098,73 $
QCELLS 275W	21.211,92 $	0,00 $	4.380,06 $	0,00 $	-2.008,47 $	23.583,51 $
Schneider Conext XW6848NA	12.372,00 $	7.061,26 $	2.565,45 $	0,00 $	-3.904,85 $	18.093,85 $
System	112.945,30 $	41.720,04 $	9.076,28 $	0,00 $	-36.173,19 $	127.568,43 $

Figure 4.22 Kidegembye - Fuel stacking - HOMER cost structure

As the mini-grid components are the same of the full cooking scenario the purchase costs remain unchanged. However, the increased lifetime of the battery pack allows to postpone its replacement and therefore to gain a higher salvage. For this reason, the NPC reduced to 127568.40 $ from 136547.30 $ while the LCOE instead grew from 0.2369 $/kWh to 0.2741 $/kWh because the reduction in energy request is higher than costs reduction.

4.3.4 Peak shifting

The potential of demand side management technology has been studied. Starting from the HOMER optimized system design for the full cooking scenario, load curves relative to peak shifting scenario have been given as an input in HOMER.

On the contrary to fuel stacking scenario, the estimated daily energy demand resulted from load curves remained the same while the peak reduced from around 32 kW to around 27 kW. However, implementing demand side management technology in an already built mini-grid has slight effects visible from HOMER outputs. Indeed, all simulation results remain almost unchanged apart from a slight increase in battery lifetime that passes from 16.1 to 16.5 years. In addition, a small reduction in unmet electric load has been registered. Real benefits of demand side management technology are fully exploited only if a specific mini-grid is properly designed for the relative scenario. However, it's unsafe to size a mini-grid relying on an imaginary proper users' behaviour. Indeed, mini-grid users might not follow the expected behaviour and in such a scenario, the mini-grid would result undersized.

Demand side management technology remains an interesting technology for peak shifting and brownouts reduction, however they must be accompanied by an intensive education program.

4.4 Cooking solution performance analysis

In this section, different cooking solutions including firewood, charcoal, kerosene, LPG and e-cook have been compared from the economic and environmental point of view. For the e-cook solution the full cooking scenario has been considered as a reference scenario.

Useful energy, defined as energy going into the pot and food, and calculated from the cooking preparation cycle (sub-section 3.1.3) resulted 1.530 kWh per day and 2.655 kWh per day in the low cook and high cook scenario respectively. These values represent the useful energy required for preparing two complete meal and the breakfast for a household of five inhabitants. The range constituted by these two values is in line with the ones found in literature [6], [8].

4.4.1 Levelized cooking cost per month

Levelized cooking cost per month is defined as the monthly expenditures for energy related to cooking activities in $/month. Method for its calculation has been presented in sub-section 3.4.1 and values of stove efficiency, fuel LHV and prices are available in Annex D. Results of the basic analysis are depicted in Table 4.4.

To present the results in a more effective way a box plot has been created in Excel (Figure 4.23). Lower values are representative of the low cook scenario while higher ones are representative of the high cook scenario. Economic convenience of firewood and charcoal solutions appears evident from this first analysis, while the e-cook solution is instead comparable to the kerosene one and LPG results the most expensive option.

BASIC ANALYSIS	**Low cook**	**High cook**
e-cook		
Electricity per day [kWh/day]	1.70	2.95
Electricity per month [kWh/month]	51.71	89.73
Cooking cost per day [$/day]	0.40	0.70
Cooking cost per month [$/month]	12.25	21.26
Percentage of cooking cost on income	16.5%	28.7%
Firewood		
Primary Energy required [kWh/day]	10.93	18.96
Firewood per day [kg/day]	2.55	4.43
Firewood per month [kg/month]	77.67	134.77
Cooking cost per day [$/day]	0.24	0.41
Cooking cost per month [$/month]	7.18	12.46
Percentage of cooking cost on income	9.7%	16.8%
Charcoal		
Primary Energy required [kWh/day]	5.88	10.21
Charcoal per day [kg/day]	0.75	1.29
Charcoal per month [kg/month]	22.69	39.37
Firewood per day	6.22	10.79
Firewood per month	189.05	328.05
Cooking cost per day [$/day]	0.23	0.40
Cooking cost per month [$/month]	7.03	12.20
Percentage of cooking cost on income	9.5%	16.5%
Kerosene		
Primary Energy required [kWh/day]	4.14	7.18
Kerosene per day [l/day]	0.42	0.73
Kerosene per month [l/month]	12.83	22.27
Cooking cost per day [$/day]	0.38	0.66
Cooking cost per month [$/month]	11.55	20.04
Percentage of cooking cost on income	15.6%	27.1%
LPG		
Primary Energy required [kWh/day]	2.89	5.01
LPG per day [kg/day]	0.23	0.40
LPG per month [kg/month]	6.95	12.05
Cooking cost per day [$/day]	0.50	0.87
Cooking cost per month [$/month]	15.28	26.52
Percentage of cooking cost on income	20.6%	35.8%

Table 4.4 Kidegembye – Levelized cooking cost per month

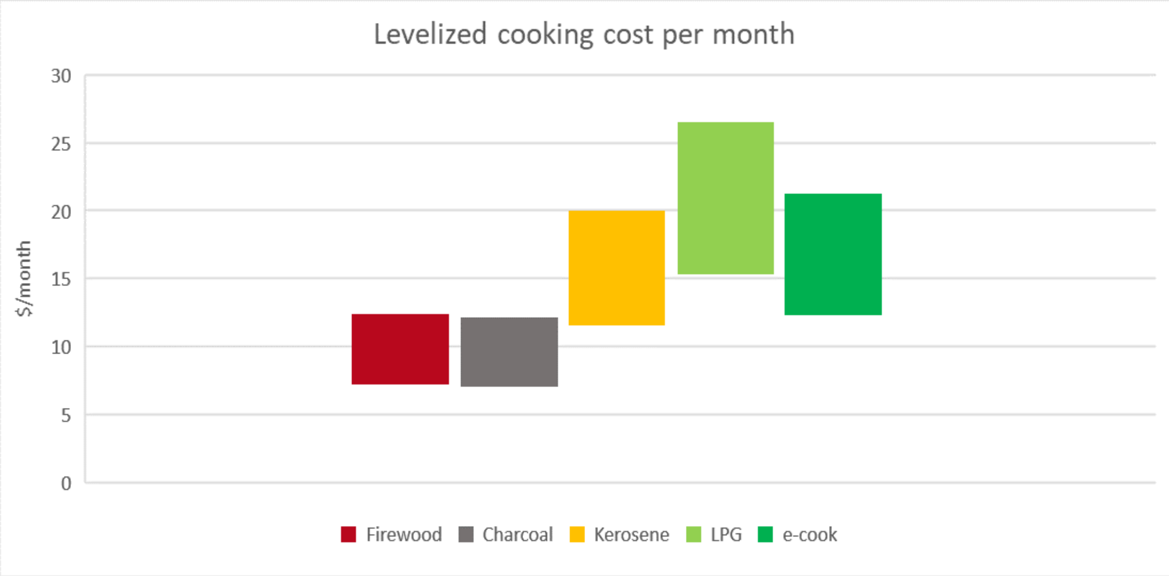


Figure 4.23 Kidegembye - Levelized cooking cost per month

In order to avoid presenting too specific results a sensitivity analysis on stove efficiencies has been carried out (Table 4.5). A lower efficiency value and an upper one has been supposed for each technology. Results are presented in a box plot (Figure 4.24) in which the lower value represent the low cook-high efficiency scenario while the upper value represents the high cook-low efficiency scenario.

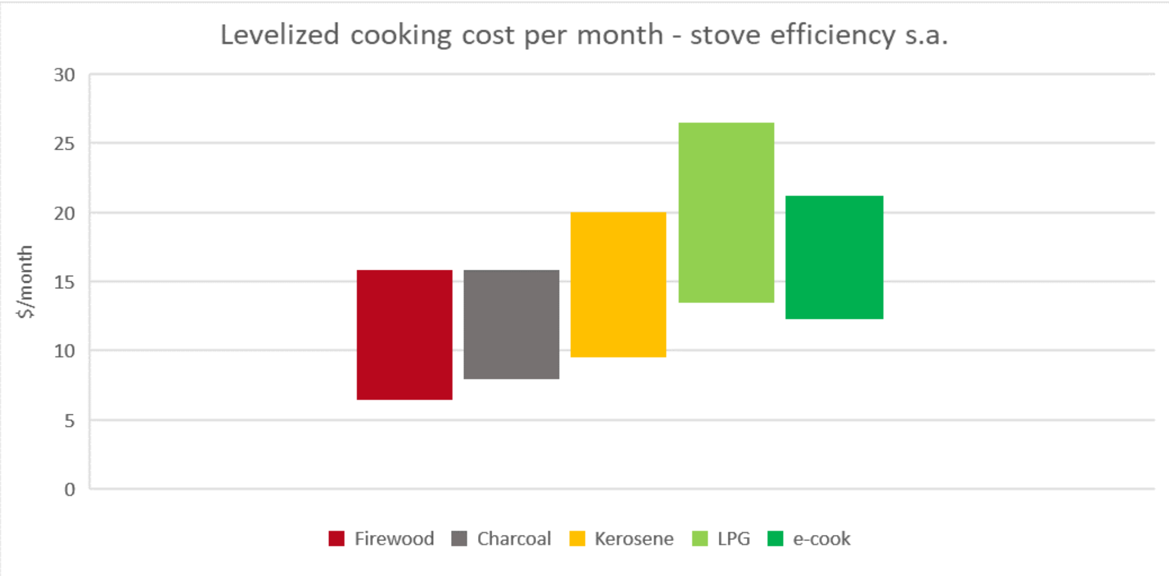


Figure 4.24 Kidegembye - Levelized cooking cost per month - stove efficiency s.a.

SENSITIVITY ANALYSIS - STOVE EFF	Low cook		High cook	
	Low efficiency	**High efficiency**	**Low efficiency**	**High efficiency**
Firewood				
Primary Energy required [kWh/day]	13.91	9.75	24.14	16.91
Firewood per day [kg/day]	3.25	2.28	5.64	3.95
Firewood per month [kg/month]	98.85	69.26	171.53	120.18
Cooking cost per day [$/day]	0.30	0.21	0.52	0.37
Cooking cost per month [$/month]	9.14	6.40	15.86	11.11
Charcoal				
Primary Energy required [kWh/day]	7.65	6.59	13.28	11.44
Charcoal per day [kg/day]	0.97	0.84	1.68	1.45
Charcoal per month [kg/month]	29.49	25.42	51.18	44.12
Cooking cost per day [$/day]	0.30	0.26	0.52	0.45
Cooking cost per month [$/month]	9.14	7.88	15.86	13.68
Kerosene				
Primary Energy required [kWh/day]	4.14	3.40	7.18	5.90
Kerosene per day [l/day]	0.42	0.35	0.73	0.60
Kerosene per month [l/month]	12.83	10.55	22.27	18.31
Cooking cost per day [$/day]	0.38	0.31	0.66	0.54
Cooking cost per month [$/month]	11.55	9.49	20.04	16.48
LPG				
Primary Energy required [kWh/day]	2.89	2.53	5.01	4.40
LPG per day [kg/day]	0.23	0.20	0.40	0.35
LPG per month [kg/month]	6.95	6.10	12.05	10.58
Cooking cost per day [$/day]	0.50	0.44	0.87	0.77
Cooking cost per month [$/month]	15.28	13.41	26.52	23.27

Table 4.5 Kidegembye - Levelized cooking cost per month - Stove efficiency s.a.

Finally, considering the instability of fuel prices, a sensitivity analysis on this variable, combined to the sensitivity analysis on stove efficiency, has been carried out (Table 4.6). Results are presented in a box plot (Figure 4.25) in which the lower value represents the optimistic scenario (low cook-high efficiency-low price) and the upper one represents the pessimistic scenario (high cook-low efficiency-high price). Therefore, all the plausible casuistries are expected to be included within this range.

SENSITIVITY ANALYSIS – STOVE EFFICIENCY & FUEL PRICE	Optimistic scenario	Pessimistic scenario
e-cook		
Electricity per day [kWh/day]	1.70	2.95
Electricity per month [kWh/month]	51.71	89.73
Cooking cost per day [$/day]	0.40	0.70
Cooking cost per month [$/month]	12.25	21.26
Percentage of cooking cost on income	16.5%	28.7%
Firewood		
Primary Energy required [kWh/day]	9.75	24.14
Cooking cost per day [$/day]	0.00	0.63
Cooking cost per month [$/month]	0.00	19.21
Percentage of cooking cost on income	0.0%	25.9%
Charcoal		
Primary Energy required [kWh/day]	6.59	13.28
Cooking cost per day [$/day]	0.17	0.67
Cooking cost per month [$/month]	5.05	20.47
Percentage of cooking cost on income	6.8%	27.6%
Kerosene		
Primary Energy required [kWh/day]	3.40	7.18
Cooking cost per day [$/day]	0.31	0.92
Cooking cost per month [$/month]	9.49	27.90
Percentage of cooking cost on income	12.8%	37.7%
LPG		
Primary Energy required [kWh/day]	2.53	5.01
Cooking cost per day [$/day]	0.44	1.08
Cooking cost per month [$/month]	13.41	32.79
Percentage of cooking cost on income	18.1%	44.3%

Table 4.6 Kidegembye – Levelized cooking cost per month – stove efficiency&fuel price s.a.

Providing a range of cost, rather than an absolute value, makes possible to carry out a comprehensive confront between all the cooking technologies. The e-cook upper value resulted comparable to the charcoal solution one and lower respect to the kerosene solution one. Its lower value is instead embraced in all the other cooking solution ranges, including firewood one.

From these results is already possible to assert that the e-cook solution should not be abandoned a priori but rather constitutes a valid alternative especially compared to LPG. Moreover, this comparison has been carried out only from the economic point of view, the crucial added value of the e-cook solution is guaranteeing access to electricity and to clean cooking at the same time.

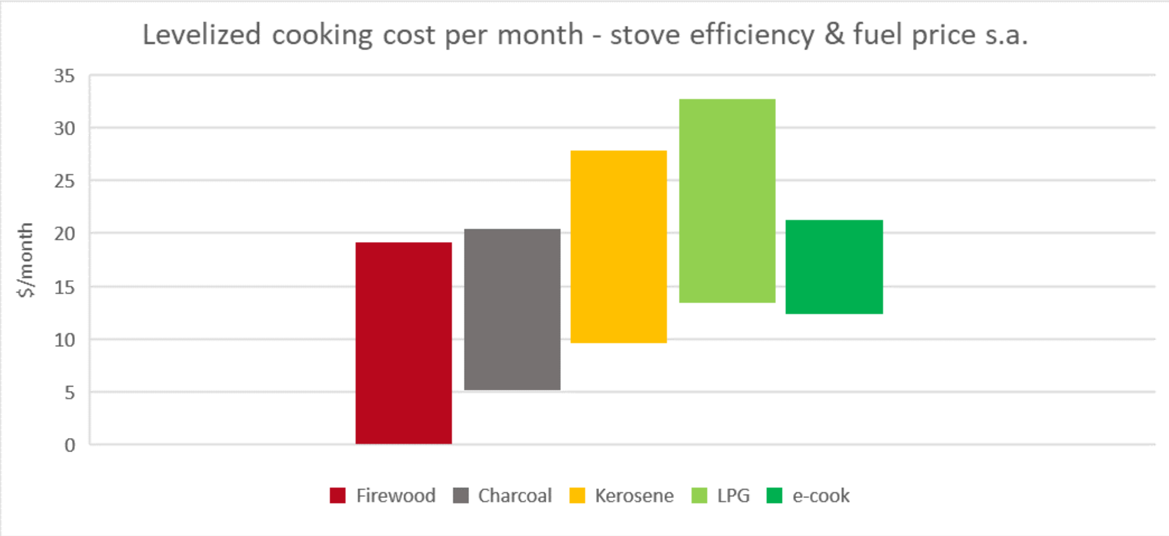


Figure 4.25 Kidegembye - Levelized cooking cost per month - stove efficiency & fuel price s.a.

4.4.2 LCCM

In this sub-section, results about levelized cost of cooking a meal (sub-section 3.4.2) have been presented. Sensitivity analysis on stove efficiency and fuel price have been carried out also for LCCM, and results have been compared with Fuso Nerini's ones.

Results about the basic analysis on LCCM are depicted in Table 4.7. Stove efficiencies and fuel prices considered are the same as the levelized cooking cost per month basic analysis. In addition, price of the different stoves has been defined.

To present the results in a more effective way a box plot has been created in Excel as for levelized cooking cost per month (Figure 4.26). Lower values are representative of the low cook scenario while higher ones are representative of the high cook scenario. Economic convenience of firewood and charcoal solutions appears evident from the box plot also for LCCM, while the e-cook solution is instead comparable to the kerosene one. LPG results the most expensive option as for levelized cooking cost per month.

Then, also for LCCM a sensitivity analysis on stove efficiency has been carried out. Efficiency values considered are the same used for levelized cooking cost per month. Results are presented in (Table 4.8) and depicted in an excel box plot (Figure 4.27).

BASIC ANALYSIS	Low cook	High cook
e-cook		
Electricity per day [kWh/day]	1.70	2.95
Electricity per meal [kWh/meal]	0.68	1.18
LCCM_fuel [$/meal]	0.161	0.280
LCCM_stove [$/meal]	0.020	0.020
LCCM [$/meal]	0.181	0.300
Firewood		
Primary Energy required [kWh/day]	10.93	18.96
Primary Energy required [kWh/meal]	4.37	7.59
LCCM_fuel [$/meal]	0.094	0.164
LCCM_stove [$/meal]	0.000	0.000
LCCM [$/meal]	0.094	0.164
Charcoal		
Primary Energy required [kWh/day]	5.88	10.21
Primary Energy required [kWh/meal]	2.35	4.08
LCCM_fuel [$/meal]	0.092	0.160
LCCM_stove [$/meal]	0.003	0.003
LCCM [$/meal]	0.095	0.163
Kerosene		
Primary Energy required [kWh/day]	4.14	7.18
Primary Energy required [kWh/meal]	1.65	2.87
LCCM_fuel [$/meal]	0.152	0.264
LCCM_stove [$/meal]	0.004	0.004
LCCM [$/meal]	0.156	0.268
LPG		
Primary Energy required [kWh/day]	2.89	5.01
Primary Energy required [kWh/meal]	1.15	2.00
LCCM_fuel [$/meal]	0.201	0.349
LCCM_stove [$/meal]	0.015	0.015
LCCM [$/meal]	0.216	0.363

Table 4.7 Kidegembye – LCCM

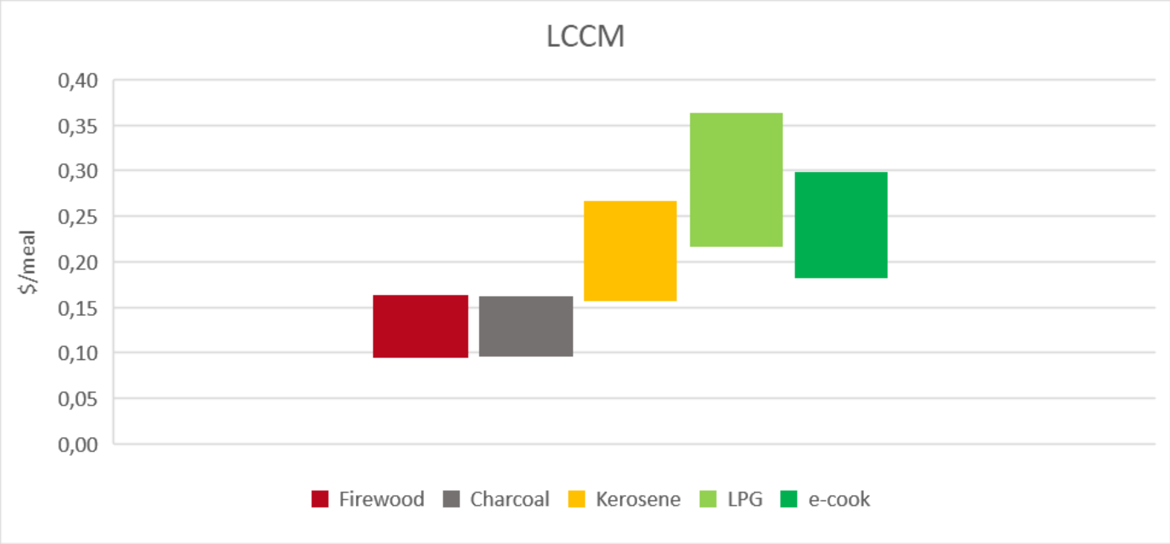


Figure 4.26 Kidegembye – LCCM

SENSITIVITY ANALYSIS - STOVE EFF	Low cook		High cook	
	Low efficiency	**High efficiency**	**Low efficiency**	**High efficiency**
Firewood				
Primary Energy required [kWh/day]	13.909	9.745	24.136	16.911
Primary Energy required [kWh/meal]	5.564	3.898	9.655	6.764
LCCM_fuel [$/meal]	0.120	0.084	0.209	0.146
LCCM_stove [$/meal]	0.000	0.000	0.000	0.000
LCCM [$/meal]	0.120	0.084	0.209	0.146
Charcoal				
Primary Energy required [kWh/day]	7.650	6.595	13.275	11.444
Primary Energy required [kWh/meal]	3.060	2.638	5.310	4.578
LCCM_fuel [$/meal]	0.120	0.104	0.209	0.180
LCCM_stove [$/meal]	0.003	0.003	0.003	0.003
LCCM [$/meal]	0.123	0.106	0.211	0.183
Kerosene				
Primary Energy required [kWh/day]	4.135	3.400	7.176	5.900
Primary Energy required [kWh/meal]	1.654	1.360	2.870	2.360
LCCM_fuel [$/meal]	0.152	0.125	0.264	0.217
LCCM_stove [$/meal]	0.004	0.004	0.004	0.004
LCCM [$/meal]	0.156	0.129	0.268	0.221
LPG				
Primary Energy required [kWh/day]	2.887	2.533	5.009	4.396
Primary Energy required [kWh/meal]	1.155	1.013	2.004	1.758
LCCM_fuel [$/meal]	0.201	0.176	0.349	0.306
LCCM_stove [$/meal]	0.015	0.015	0.015	0.015
LCCM [$/meal]	0.216	0.191	0.363	0.321

Table 4.8 Kidegembye - LCCM - stove efficiency s.a.

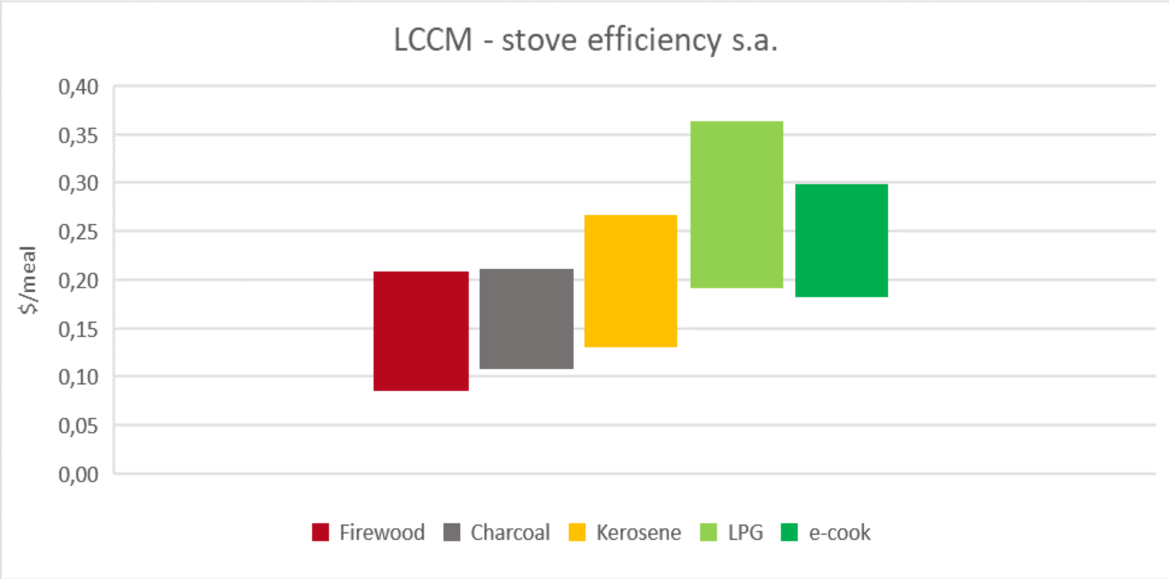


Figure 4.27 Kidegembye - LCCM - stove efficiency s.a.

In addition, considering the instability of fuel prices, a sensitivity analysis on this variable, combined to the sensitivity analysis on stove efficiency and price, has been carried out (Table 4.9). Results are presented in a box plot (Figure 4.28) in which the lower value represents the optimistic scenario (low cook-high efficiency-low price) and the upper one represents the pessimistic scenario (high cook-low efficiency-high price). Therefore, all the plausible casuistries are expected to be included within this range.

As for levelized cooking cost per month, the e-cook solution is very interesting also for LCCM indicator, thus taking into account stove related costs. Its range is slightly higher than the charcoal solution and is embraced by the kerosene one. LPG represents the most expensive alternative also for LCCM analysis as for levelized cooking cost per month.

SENSITIVITY ANALYSIS - STOVE EFF AND FUEL&STOVE PRICE	**Optimistic scenario**	**Pessimistic scenario**
e-cook		
Electricity per day [kWh/day]	1.700	2.950
Electricity per meal [kWh/meal]	0.680	1.180
LCCM_fuel [$/meal]	0.161	0.280
LCCM_stove [$/meal]	0.020	0.020
LCCM [$/meal]	0.181	0.300
Firewood		
Primary Energy required [kWh/meal]	3.898	9.655
LCCM_fuel [$/meal]	0.000	0.253
LCCM_stove [$/meal]	0.000	0.000
LCCM [$/meal]	0.000	0.253
Charcoal		
Primary Energy required [kWh/meal]	2.638	5.310
LCCM_fuel [$/meal]	0.066	0.269
LCCM_stove [$/meal]	0.001	0.003
LCCM [$/meal]	0.067	0.272
Kerosene		
Primary Energy required [kWh/meal]	1.360	2.870
LCCM_fuel [$/meal]	0.125	0.367
LCCM_stove [$/meal]	0.002	0.005
LCCM [$/meal]	0.127	0.372
LPG		
Primary Energy required [kWh/meal]	1.013	2.004
LCCM_fuel [$/meal]	0.176	0.431
LCCM_stove [$/meal]	0.015	0.015
LCCM [$/meal]	0.191	0.446

Table 4.9 Kidegembye - LCCM - stove efficiency and fuel&stove price s.a.

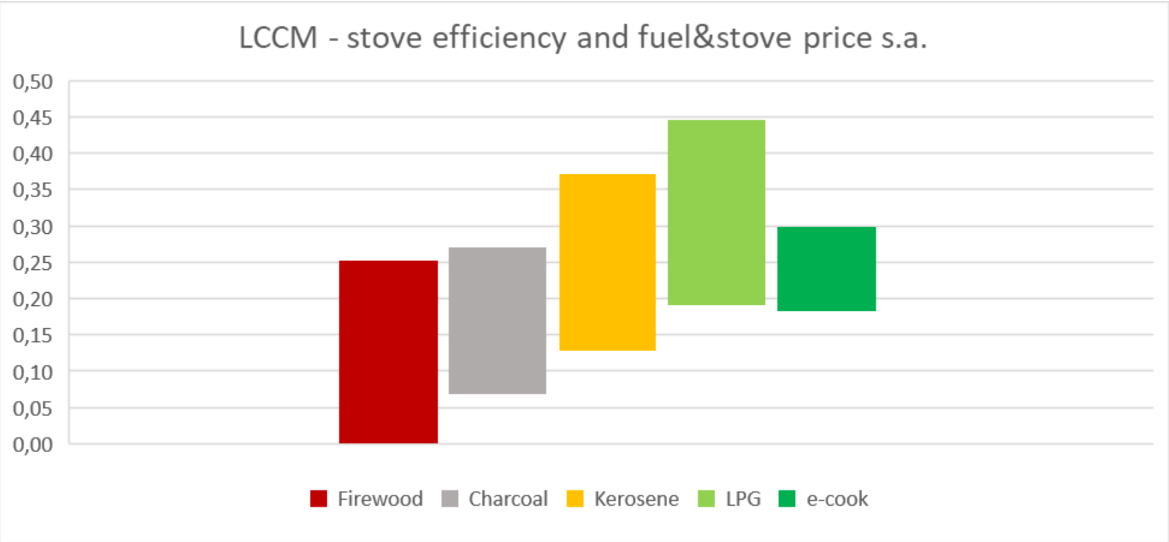


Figure 4.28 Kidegembye - LCCM - stove efficiency and fuel&stove price s.a.

Finally, a comparison between calculated LCCM values and Fuso Nerini's ones has been carried out (Figure 4.29). For each fuel/technology combination, Fuso Nerini's values are within the LCCM calculated range, apart from the e-cook solution. This difference is due to the fact that Fuso Nerini referred the e-cook scenario to an electric stove with an efficiency equal to 70% rather than an induction stove with 90% efficiency. Indeed, cost of electricity considered is equal to 0.2376 $/kWh compared with the HOMER LCOE value for full cooking scenario equal to 0.2369 $/kWh [8]. Moreover, in the article, electrical stove price is taken equal to 44 $ while the value for induction stove, considering also specific pots and pans, is around 71 $. Penalization of the e-cook solution within Fuso Nerini's article is therefore attributable to the lower efficiency of the electric stove with respect to the induction stove. For the charcoal solution Fuso Nerini's value is almost coincident with the lower bound of the LCCM calculated range because lower value of stove price and fuel price have been taken from his article.
However, within this thesis work, a range of results have been presented rather than a single value for each fuel/technology combination. In this way a more comprehensive evaluation can be made from the reported results that are likely to embrace all the possible casuistries.

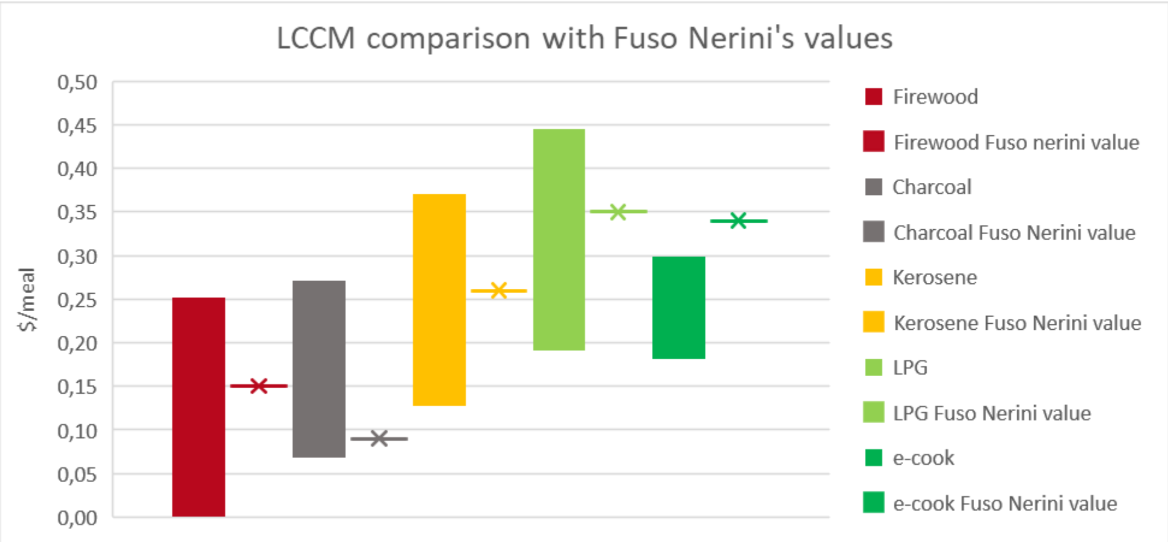


Figure 4.29 Kidegembye - LCCM - comparison with Fuso Nerini's values

4.4.3 Comparison between two modern technology: electricity versus LPG

The two main alternatives for access to clean cooking are globally represented by electricity and LPG. Results from levelized cooking cost per month and LCCM analysis showed that the e-cook solution is cost-effective with respect to the LPG one. The aim of this sub-section is to quantify, through economic indicators such as payback time (PBT) and internal rate of return (IRR) the e-cook convenience.

Data for the e-cook solution are related to the full cooking scenario. According with HOMER simulation, for the full cooking scenario, initial investment for the mini-grid construction is equal to 112945 $ while O&M costs are around 657 $/year. Replacement of inverter occurs during the 15th year of operation, battery replacement instead occurs in the 17th year. In addition, 10 years life time has been considered for induction stoves, hence replacement of these components take part in the 10th year of operation.
Data for the LPG solution are instead related to the base load scenario to meet electricity demand and to calculated LPG consumption for cooking needs. According with HOMER simulation, for the base load scenario, initial investment for the mini-grid construction is equal to 31102 $ while O&M costs are around 190 $/year. Replacement of inverter occurs during the 15th year of operation, battery replacement instead occurs in the 12th year. In addition, as for the induction stove, the life time of the LPG stove has been considered equal to 10 years. Moreover, for LPG stoves, regulators must be changed every four years for safety reasons [6].
For the LPG consumption three different scenarios have been considered. The first one is related to an average price of the fuel calculated from values available in Annex D. Furthermore, given the high volatility of LPG price, especially in rural area in sub-Saharan Africa because of the lack of a reliable transport infrastructure, two more scenarios have been presented. They represent an increase in the LPG price value of 20% and 40% respectively.

NPC profile within the project lifetime have been plotted, for each scenario, in Figure 4.30, Figure 4.31 and Figure 4.32. e-cook NPC decreasing values in the last year of the project is due to salvage.

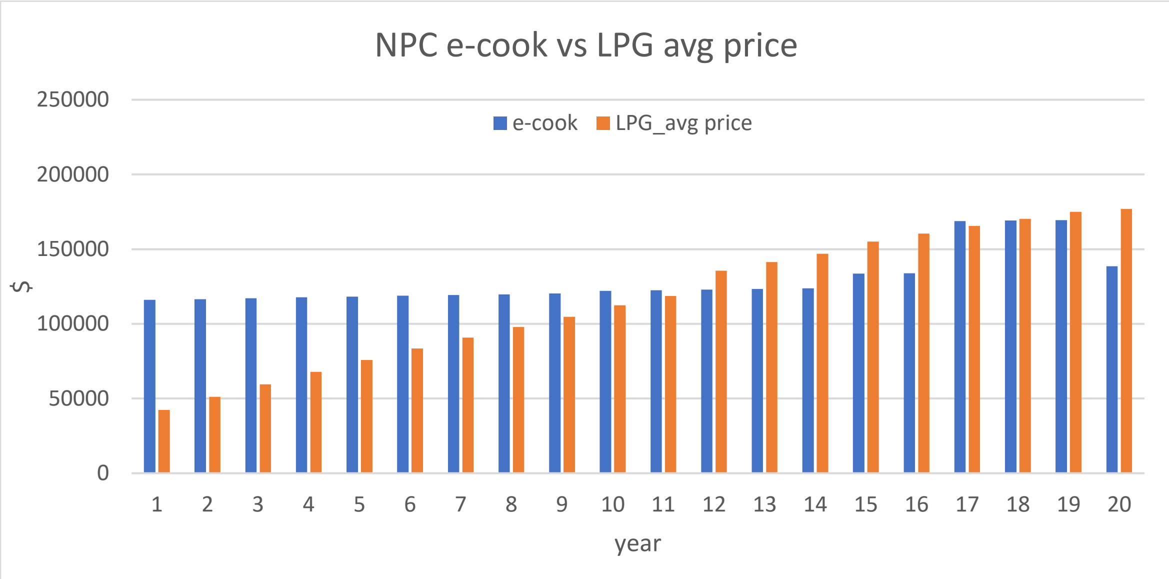


Figure 4.30 Kidegembye – NPC of e-cook vs LPG average price

PBT	**11,23**	**years**
IRR	**8,58%**	

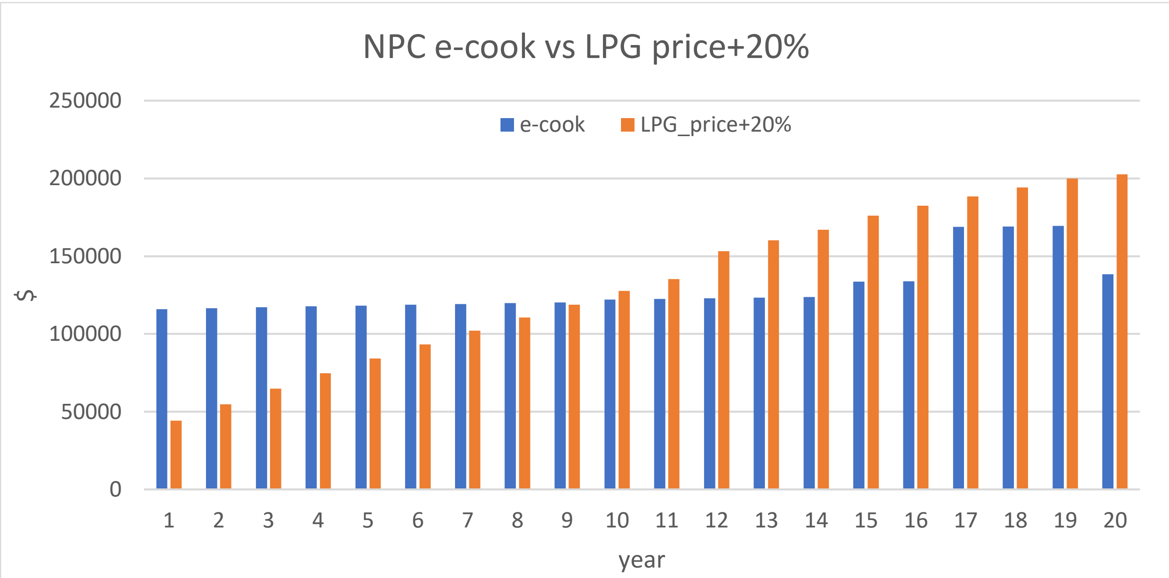


Figure 4.31 Kidegembye - NPC of e-cook vs LPG with price increased by 20%

PBT	**9,21**	**years**
IRR	**11,53%**	

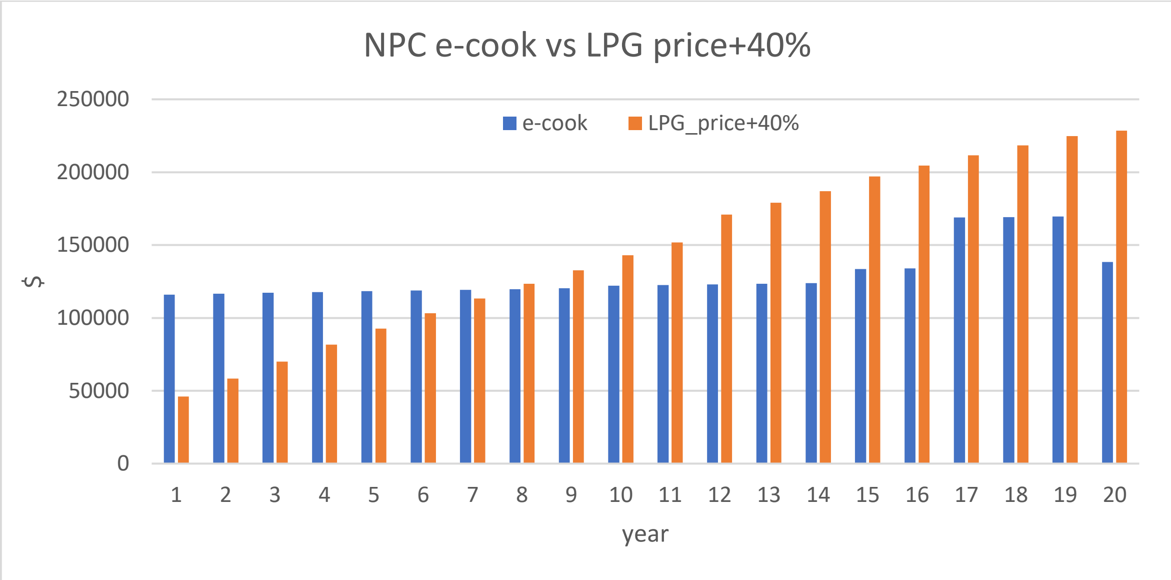


Figure 4.32 Kidegembye - NPC of e-cook vs LPG with price increased by 40%

PBT	**7,63**	**years**
IRR	**14,35%**	

The cost-effectiveness of the e-cook solution is confirmed by this basic economic analysis. PBT and IRR values obviously improve as the LPG price increases.

4.4.4 Savings of e-cook

The real added value of the e-cook solution is that energy for cooking is produced by the solar powered mini-grid. Energy is therefore produced in a clean, renewable and reliable way without any impact on health or environment and neither in socio-economic development.

In this sub-section savings of the e-cook solution are presented. Savings have been calculated for the optimistic and pessimistic scenarios and within this range all plausible casuistries are likely to be embraced.

SAVINGS e-COOK	**Optimistic**	**Pessimistic**
Saved firewood [kg/month]	69,26	171,53
Saved firewood village [ton/year]	27,43	67,93
Saved charcoal [kg/month]	25,42	51,18
Saved charcoal village [ton/year]	10,07	20,27
Saved firewood per charcoal [ton/year]	83,90	168,88
Saved kerosene [l/month]	10,55	22,27
Saved kerosene village [l/year]	4177,71	8817,03
Saved LPG [kg/month]	6,10	12,05
Saved LPG village [kg/year]	2413,87	4773,63
Saved LPG tank 15kg [#/year]	161	318

Table 4.10 Kidegembye - savings of the e-cook solution

5. Results – Mama Kevina Hope Center

In this section results referred to Mama Kevina Hope Center are presented. Methodologies and calculation procedures for obtaining the results have been presented in section 3.

5.1 Load curves

The first step for the techno-economic assessment of an e-cook mini-grid is load curve modelling. In this sub-section load curves modelled for the village of Kidegembye are presented.

5.1.1 Base load

Data for Base load curve modelling has been taken from surveys about electric appliances and their utilization conducted in Mama Kevina during my stay. The main appliances are indoor/outdoor lights, charger, radio, TV, fans, fridge, iron and washing machine (detailed data available in Annex B). With respect to the village case study, there is already the presence of a highly energy-consuming appliance as the washing machine.
One load curve per day of the year has been simulated through LoadProGen. In the figure below mean load curve and the load curve correspondent to the maximum power peak have been plotted.

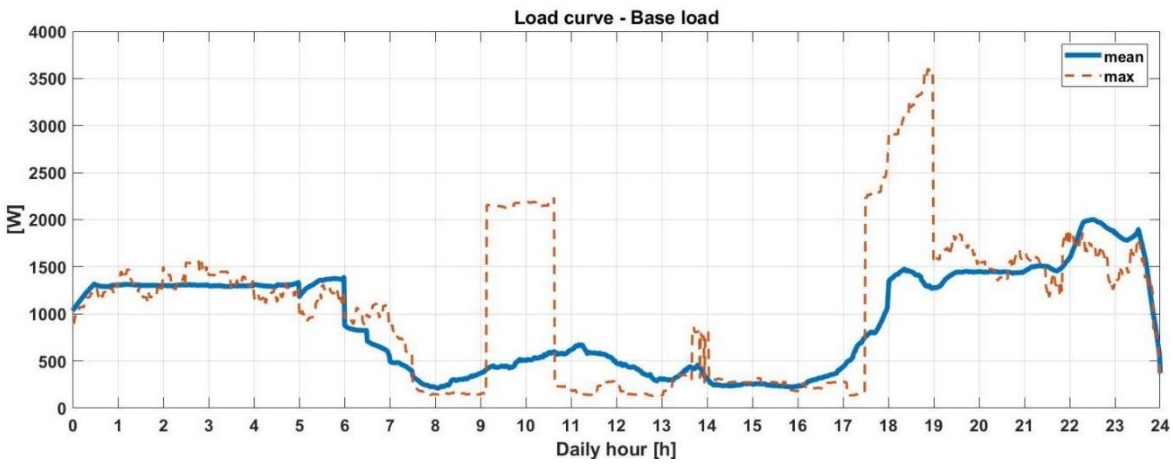


Figure 5.1 Mama Kevina load curve - Base load

The peak power around 3500 W is attributable to the usage of the washing machine during evening, when indoor/outdoor lights are on.

5.1.2 Full cooking

Starting from base load curves, full cooking load curves have been simulated by adding the induction kitchen. Inputs for this appliance are depicted in Table 5.1. Where "Induction kitchen B+L" refers to breakfast and lunch preparation while "Induction kitchen D" to dinner preparation.

One load curve per day of the year has been simulated through LoadProGen. In Figure 5.2 mean load curve and the load curve correspondent to the maximum power peak have been plotted.

Type of electrical appliance *(i)*	**Nominal appliance power rate [W] *(P_{ij})***	**functioning cycle [min] *(d_{ij})***	**Starting time Win 1 [min] *[1-1440]***	**Ending time Win 1 [min] *[1-1440]***
Induction kitchen B+L	3000	Cycle1	330	480
Induction kitchen D	3000	Cycle2	1005	1110

Table 5.1 LoadProGen input - Mama Kevina load curve- Full cooking

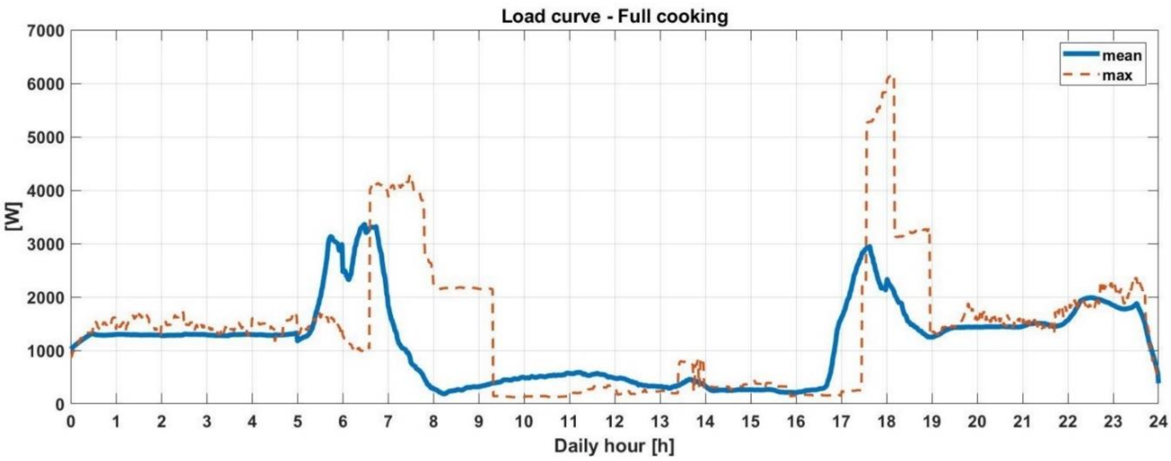


Figure 5.2 Mama Kevina load curve - Full cooking

To highlight the impact of the induction kitchen, mean load curve of base load and full cooking scenarios have been plotted in the same graph (Figure 5.3).

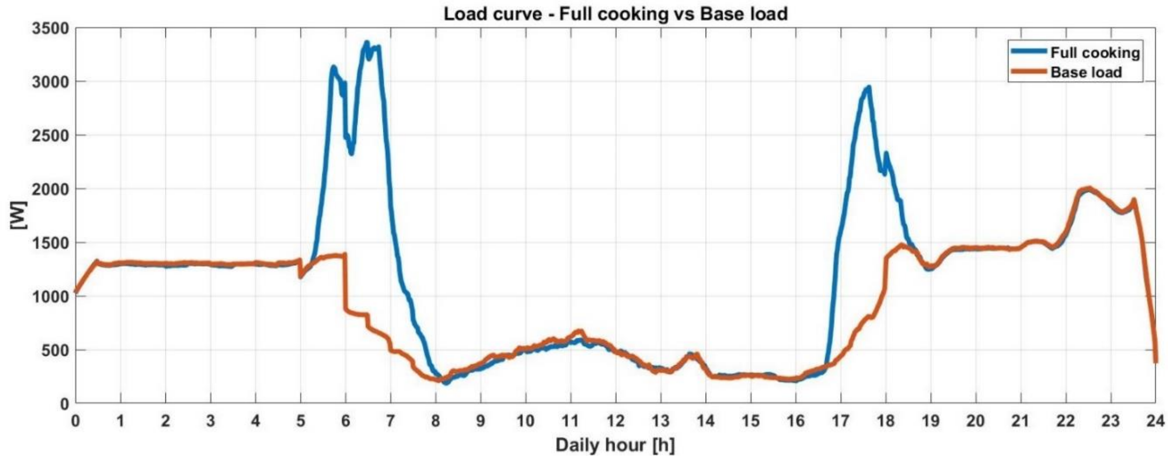


Figure 5.3 Mama Kevina load curve - Full cooking vs Base load

It can be noticed that the peak power of the mean load curve passed from around 2 kW for the base load scenario, to around 3.5 kW for the full cooking scenario. For Kidegembye village instead, it passed from around 6 kW to around 30 kW. Is therefore clear that adding an induction kitchen where highly energy-consuming appliances are already present has a far less significant impact on the mini-grid. In addition, a sort of economy of scale is provided since one appliance is used to cook for a bigger group of people. The potential of e-cook solution for the "institutional" case study, representing a wide number of similar structure all around Africa, is therefore evident.

5.1.3 Behavioural changes

Providing induction stoves makes plausible a shift in the meals preparation windows that will likely take part just before meal time. While a similar shift in a village is unlikely to happen, in a structure like Mama Kevina where a restricted group of people is responsible of cooking is more plausible.

In order to evaluate impacts on the mini-grid of this possible behavioural change a new specific scenario has been carried out.

Input for the induction kitchen, relatively to this scenario, are depicted in Table 5.2. To simulate the effects of the behavioural change, a functioning window has been added before lunch time, consequently morning functioning window has been reduced. Getting used to the new and quicker technology may also lead to a reduction in cooking functioning windows. For this reason, in the evening it has been reduced by 15 minutes.

Type of electrical appliance *(i)*	Nominal appliance power rate [W] *(P_{ij})*	functioning cycle [min] *(d_{ij})*	Starting time Win 1 [min] *[1-1440]*	Ending time Win 1 [min] *[1-1440]*
Induction kitchen B	3000	Cycle1	360	420
Induction kitchen L	3000	Cycle2	630	720
Induction kitchen D	3000	Cycle3	1020	1110

Table 5.2 LoadProGen input - Mama Kevina load curve - Behavioural change

One load curve per day of the year has been simulated through LoadProGen. In Figure 5.4 mean load curve and the load curve correspondent to the maximum power peak have been plotted. Therefore, to highlight the impact of the behavioural change, relative mean load curve has been plotted with full cooking scenario mean load curve in the same graph (Figure 5.5).

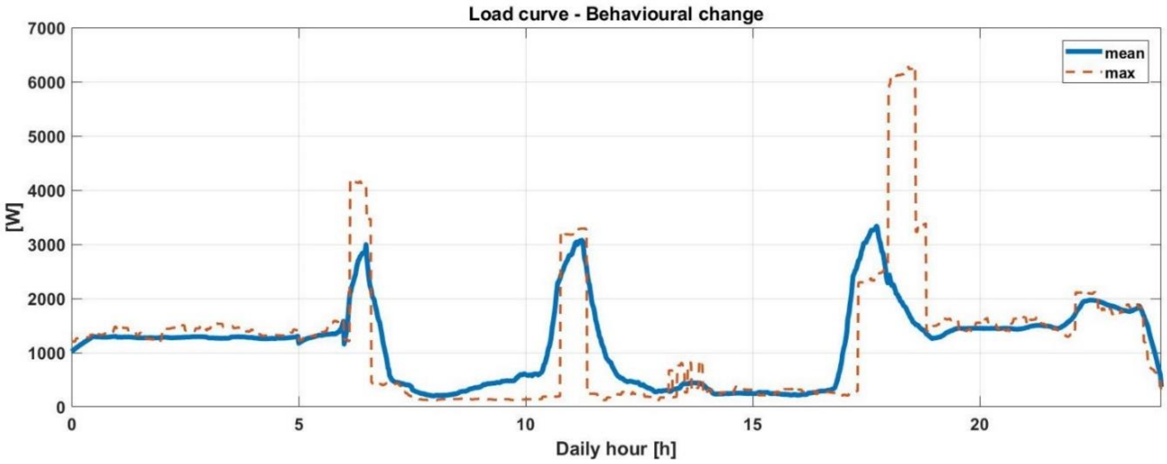


Figure 5.4 Mama Kevina load curve - Behavioural change

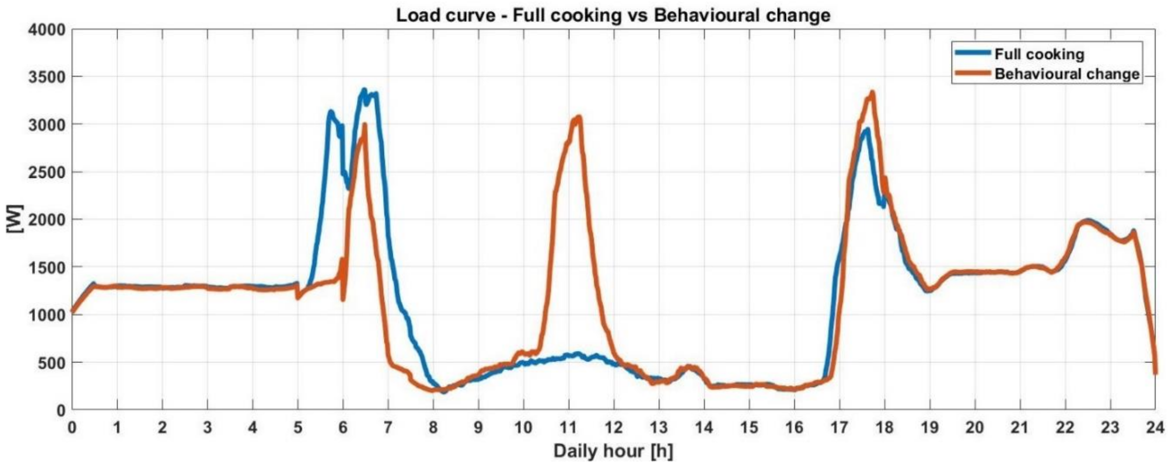


Figure 5.5 Mama Kevina load curve - Full cooking vs Behavioural change

It can be noticed that the mean load curve peak power of the two different scenario passed from the morning windows to the evening one. However, its value remains almost unchanged. Consequent to the generation of the new mid-day window, morning window resulted thinner. The mid-day window is coincident with the period of maximum productivity of the PV array and therefore some effects on batteries operations are expected.

5.2 Preliminary system design

Starting from the load curve modelling it is possible to develop a preliminary system design, based on classic sizing techniques presented in sub-section 3.2.

5.2.1 Resource assessment

The first step for the preliminary system design is the resource assessment. Monthly average solar global horizontal irradiance (GHI) for Same is depicted in Figure 5.6.

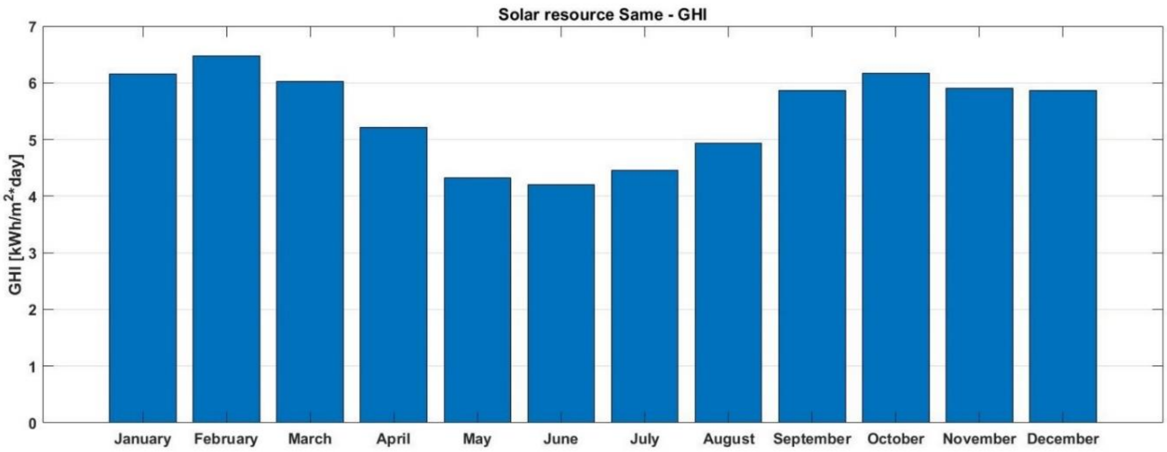


Figure 5.6 Same - solar resource (GHI) [55]

Temperature profile, hour by hour throughout the whole year, is depicted in Figure 5.7.

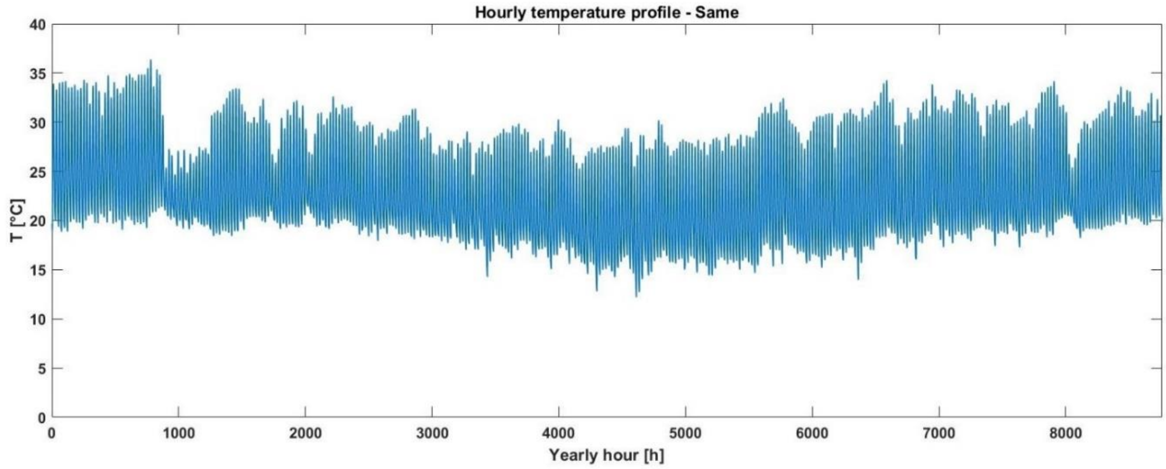


Figure 5.7 Same - temperature profile [59]

5.2.2 Base load

For the base load scenario, the estimated daily energy demand resulting from load curves is equal to 22.25 kWh per day. Then, considering the worst case, the global horizontal solar radiation (GHI) is equal to 4.2 kWh per square meter per day.

The total area of the required PV array has been calculated through equation 3.1 and it resulted 47.12 square meters. For this calculation parameters of *QCELLS275* and *Magnum PT-100 MPPT* have been considered, while efficiency of inverter and battery have been chosen equal to 94% and 86% respectively as reference values. Finally, the temperature reached during operation has been hypothesized equal to 60 °C.
Then, through equation 3.2 PV array peak power resulted 7.78 kW.

Therefore, the total capacity of the batteries required has been calculated through equation 3.4 considering two continuous cloudy days and a depth of discharge equal to 80% as reference value. It resulted 68.81 kWh or 1433.52 Ah considering a 48 V DC system voltage.

Finally, considering the power rate of the inverter 10% lower than the PV array peak power it resulted 7 kW.

5.2.3 Full cooking

For the full cooking scenario, the estimated daily energy demand resulting from load curves is equal to 27.56 kWh per day. Then, as for the base load scenario, the global horizontal solar radiation (GHI) has been considered equal to 4.2 kWh per square meter per day.

The total area of the required PV array has been calculated through equation 3.1 and it resulted 58.37 square meters considering the same parameters as for the base load scenario. Then, through equation 3.2 PV array peak power resulted 9.63 kW.

Therefore, the total capacity of the batteries required has been calculated through equation 3.4 considering the same parameters as for the base load scenario. It resulted 85.23 kWh or 1775.63 Ah considering a 48 V DC system voltage.

Finally, considering the power rate of the inverter 10% lower than the PV array peak power it resulted 8.67 kW.

In Figure 5.8 a comparison between base load and full cooking preliminary design has been carried out. In the “institutional” case study transition from a mini-grid oriented on base load scenario to a e-cook mini-grid is not so severe as for the village case study.

		Base load	**Full cooking**
PV_Area	m^2	47.12	58.37
P_PV	kW	7.78	9.63
Battery capacity	kWh	68.81	85.23
Battery capacity	Ah	1433.52	1775.63
P_inverter	kW	7.00	8.67

Figure 5.8 Comparison between Base load and Full cooking preliminary system design

5.3 HOMER optimized system design

Starting from the preliminary system design, optimized sizing of each component has been carried out through HOMER software.

HOMER inputs as project and components lifetime, economic inputs, purchase, O&M and replacement costs, capacity shortage and BOS costs have been considered equal to the Kidegembye scenario (sub-section 4.3).

5.3.1 Base load

Starting from load curves of the base load scenario (sub-section 5.1.1), resource assessment conducted for Same (sub-section 5.2.1) and from the relative preliminary system design (sub-section 5.2.2) the optimized system design has been carried out through HOMER software. The resulting schematic system layout is depicted in Figure 5.9.

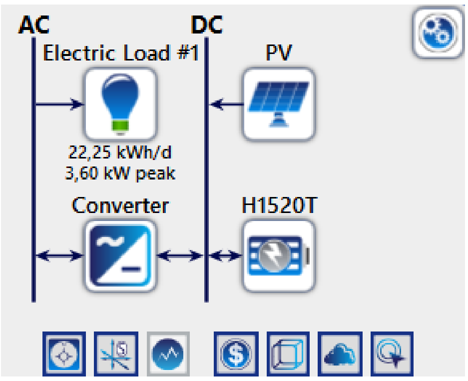


Figure 5.9 Mama Kevina - Base load - HOMER schematic system layout

The PV array size resulted 7.7 kW meaning 28 *QCELLS275W* modules. From the electrical coupling between *QCELLS275W* and *Magnum PT-100* MPPT solar charge controller maximum 4 modules in series and 6 in parallel resulted, providing maximum 24 modules per controller. Hence, two *Magnum PT-100* are needed. The PV array power output throughout the year is depicted in Figure 5.10.

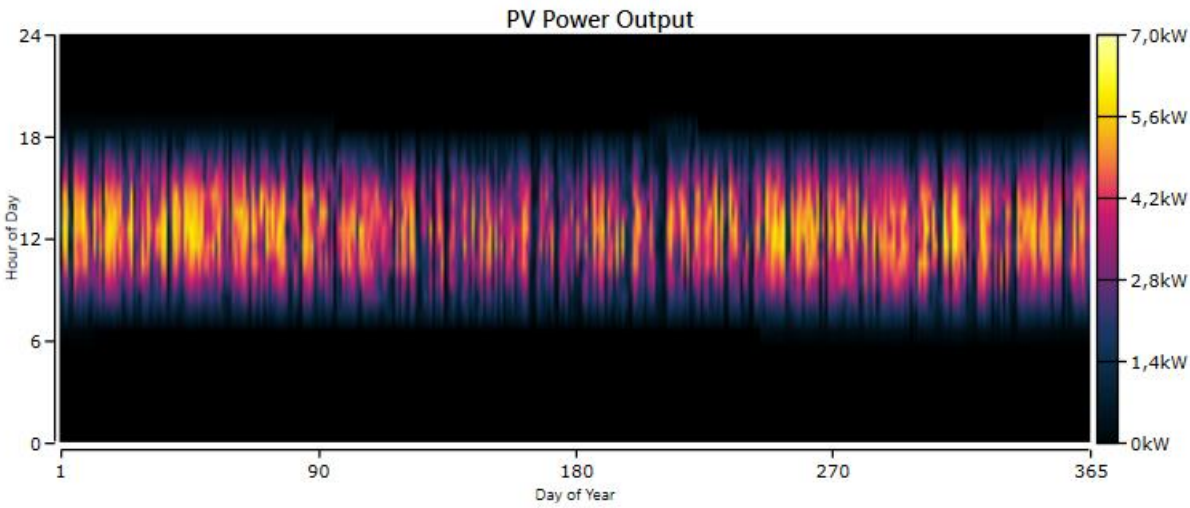


Figure 5.10 Mama Kevina - Base load - PV array power output

The *Hoppecke 10 OPzS solar.power 1520* with a 1520 Ah nominal capacity resulted the best option for the mini-grid (datasheet in Annex A). The effective autonomy of the battery in the system is 66.6 hours. Battery expected lifetime is 12 years considering 66 cycles per year and 80% maximum DOD accepted. Battery’s state of charge throughout the year is depicted in *Figure 5.11*.

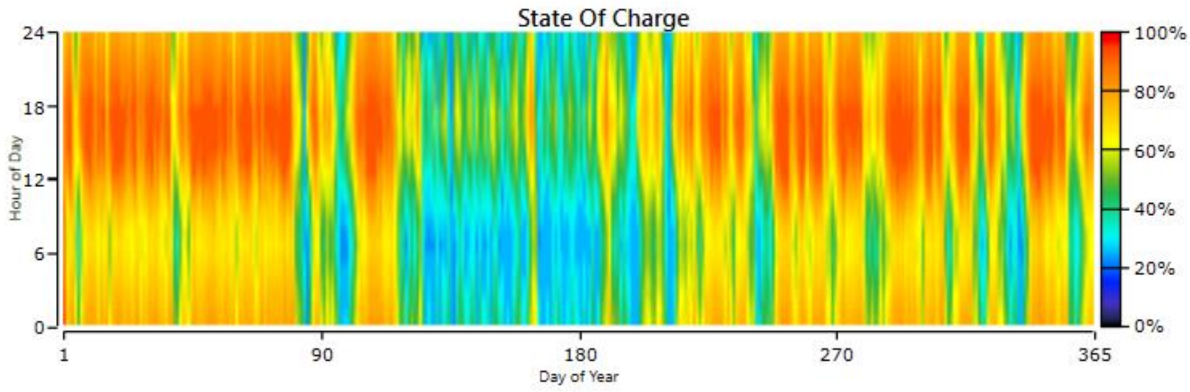


Figure 5.11 Mama Kevina - Base load - battery state of charge

Considering that the minimum state of charge reaches 20% only with worst external condition during the rainy season, and that the manufacturer expects 1500 cycles with a DOD equal to 80%, the effect of temperature on the battery lifetime is evident. The variable which triggers the battery replacement, reaching first the degradation limit, is indeed the time and temperature degradation, as highlighted in Figure 5.12. Temperature has much more effect respect to Kidegembye village since the average temperature in Same is higher (Figure 5.7).

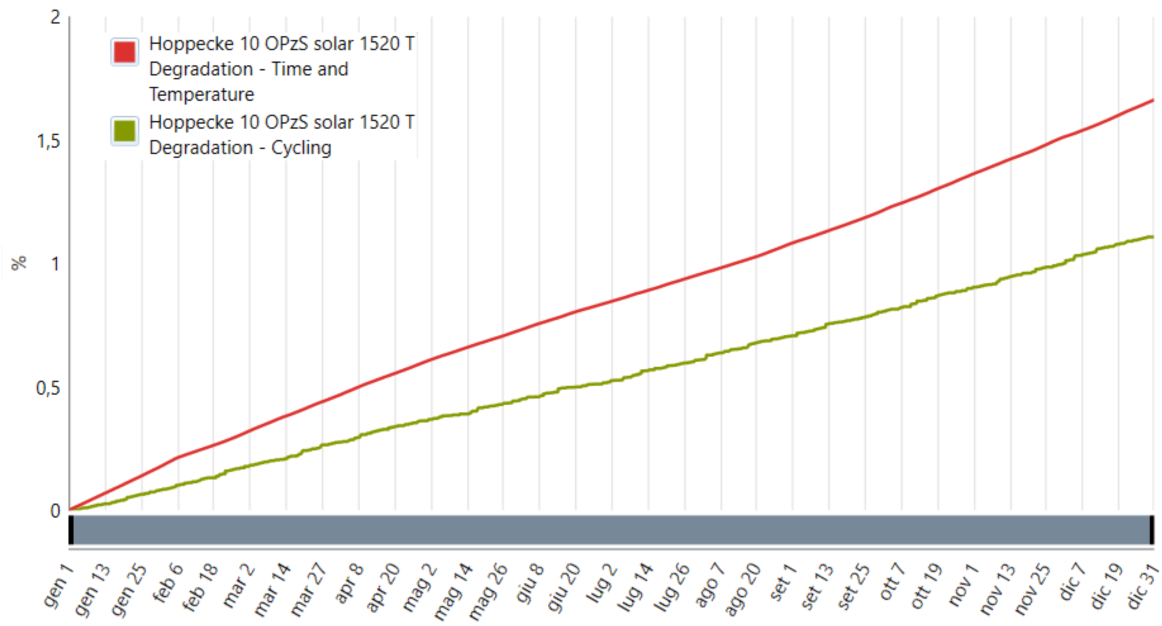
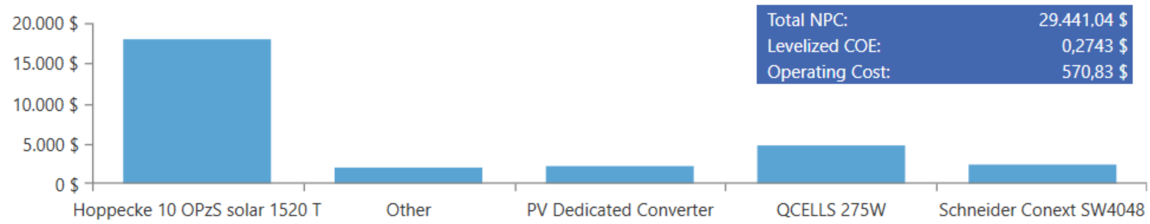


Figure 5.12 Mama Kevina - Base load - Battery degradation factors

The optimal solution for system inverter turn out to be one *Schneider Conext SW4048* (datasheet in Annex A) with a 3.80 kW total power rate, representing the most cost-effective solution.
The resulting net present cost structure for the mini-grid in the base load scenario is presented in Figure 5.13.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Hoppecke 10 OPzS solar 1520 T	12.027,80 $	7.670,82 $	221,85 $	0,00 $	-1.922,29 $	17.998,18 $
Other	2.098,13 $	0,00 $	0,00 $	0,00 $	0,00 $	2.098,13 $
PV Dedicated Converter	1.504,00 $	858,40 $	311,83 $	0,00 $	-474,69 $	2.199,54 $
QCELLS 275W	4.328,28 $	0,00 $	897,59 $	0,00 $	-409,83 $	4.816,04 $
Schneider Conext SW4048	1.592,50 $	908,91 $	330,36 $	0,00 $	-502,63 $	2.329,14 $
System	21.550,71 $	9.438,14 $	1.761,63 $	0,00 $	-3.309,44 $	29.441,04 $

Figure 5.13 Mama Kevina - Base load - HOMER cost structure

The total NPC resulted 29441.04 $ while the levelized cost of energy (LCOE) resulted 0.2743 $/kWh. The entry “other” is referred to BOS costs.

5.3.2 Full cooking

Starting from load curves of the full cooking scenario (sub-section 5.1.2), resource assessment conducted for Same (sub-section 5.2.1) and from the relative preliminary system design (sub-section 5.2.3) the optimized system design has been carried out through HOMER software. The resulting schematic system layout is depicted in Figure 5.14.

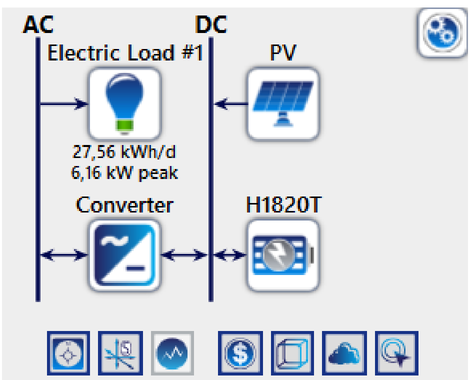


Figure 5.14 Mama Kevina - Full cooking - HOMER schematic system layout

The PV array size resulted 9.625 kW meaning 35 *QCELLS275W* modules. From the electrical coupling between *QCELLS275W* and *Magnum PT-100* MPPT solar charge controller maximum 4 modules in series and 6 in parallel resulted, providing maximum 24 modules per controller. Hence, two *Magnum PT-100* are needed. The PV array power output throughout the year is depicted in Figure 5.15.

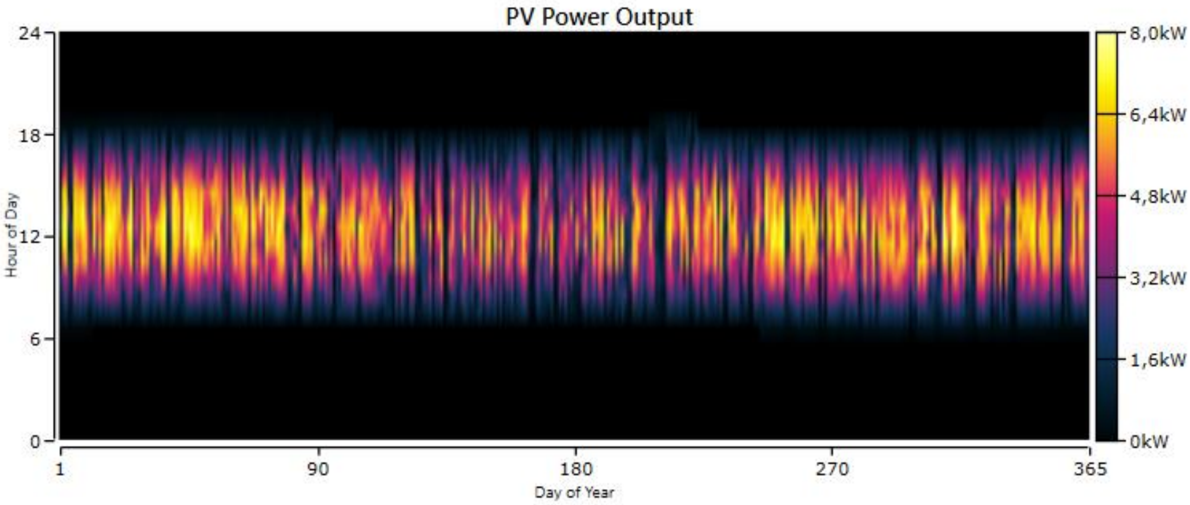


Figure 5.15 Mama Kevina - Full cooking - PV array power output

The *Hoppecke 12 OPzS solar.power 1820* with a 1820 Ah nominal capacity resulted the best option for the mini-grid (datasheet in Annex A). The effective autonomy of the battery in the system is 64.4 hours. Battery expected lifetime is 12 years considering 68 cycles per year and 80% maximum DOD accepted. Battery's state of charge throughout the year is depicted in Figure 5.16.

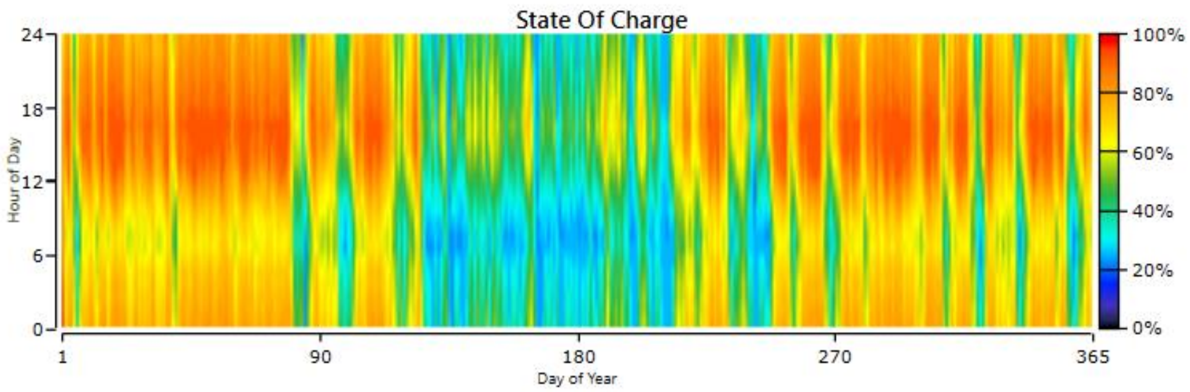


Figure 5.16 Mama Kevina - Full cooking - battery state of charge

Considering that the minimum state of charge reaches 20% only with worst external condition during the rainy season, and that the manufacturer expects 1500 cycles with a

DOD equal to 80%, the effect of temperature on the battery lifetime is evident. The variable which triggers the battery replacement, as for base load scenario, is indeed the time and temperature degradation, as highlighted in Figure 5.17.

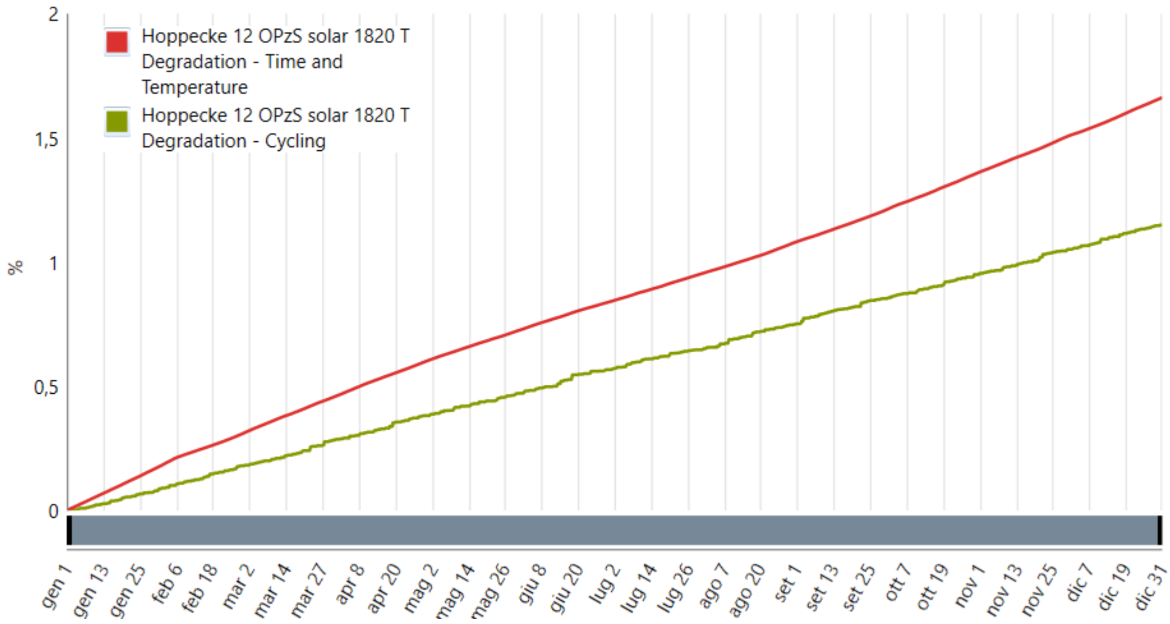
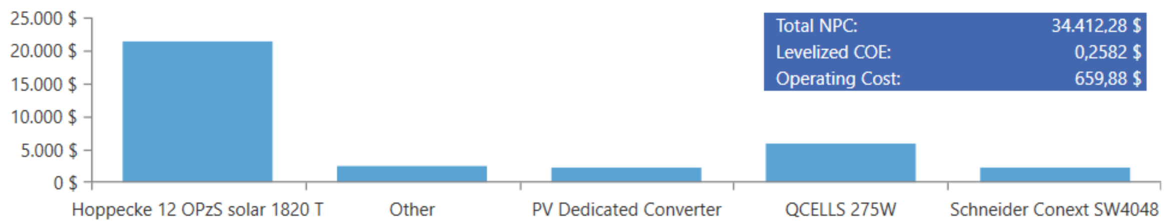


Figure 5.17 Mama Kevina - Full cooking - battery degradation factors

The optimal solution for system inverter turn out to be one *Schneider Conext SW4048* (datasheet in Annex A) with a 3.80 kW total power rate, representing the most cost-effective solution. The resulting net present cost structure for the mini-grid in the base load scenario is presented in Figure 5.18.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Hoppecke 12 OPzS solar 1820 T	14.237,20 $	9.079,89 $	280,98 $	0,00 $	-2.275,40 $	21.322,67 $
Other	2.601,36 $	0,00 $	0,00 $	0,00 $	0,00 $	2.601,36 $
PV Dedicated Converter	1.504,00 $	858,40 $	311,83 $	0,00 $	-474,69 $	2.199,54 $
QCELLS 275W	5.356,00 $	0,00 $	1.110,71 $	0,00 $	-507,14 $	5.959,57 $
Schneider Conext SW4048	1.592,50 $	908,91 $	330,36 $	0,00 $	-502,63 $	2.329,14 $
System	25.291,06 $	10.847,20 $	2.033,88 $	0,00 $	-3.759,86 $	34.412,28 $

Figure 5.18 Mama Kevina - Full cooking - HOMER cost structure

5.3.3 Behavioural change

As mentioned before, behavioural changes regarding cooking habits are plausible to take part in Mama Kevina after the installation of the induction kitchen. For this reason, in order to provide a complete analysis, impacts of this phenomenon on the mini-grid have been evaluated. Starting from the HOMER optimized system design for the full cooking scenario, load curves relative to behavioural change have been given as input in HOMER. The system design of the mini-grid is therefore unchanged respect to full cooking scenario (sub-section 5.3.2).

Regarding behavioural change scenario, the estimated daily energy demand resulted from load curves is equal to 27.72 kWh per day, almost unchanged respect to full cooking scenario as expected. However, the different load profile with less energy request during early morning change the battery state of charge throughout the year (Figure 5.19).

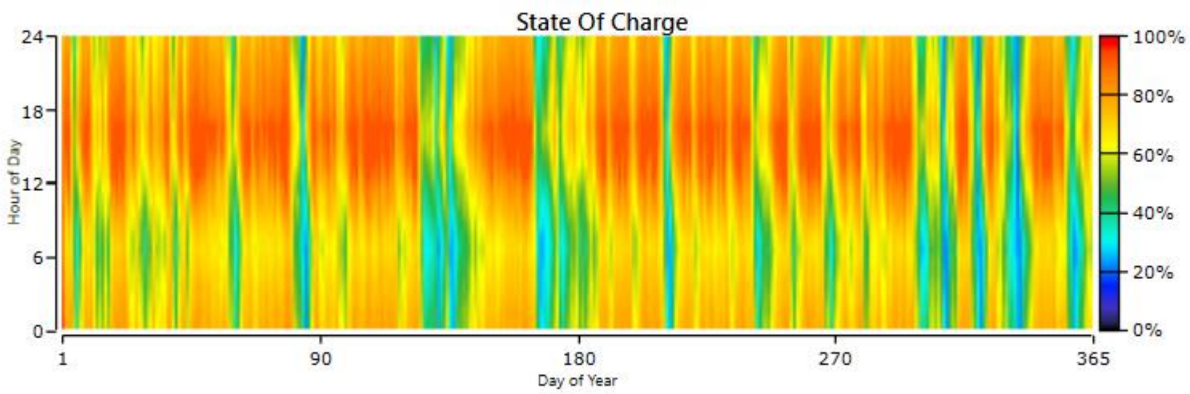


Figure 5.19 Mama Kevina - Behavioural change - battery state of charge

Despite a slight reduction in number of equivalent cycle per year, passed from 68 for full cooking scenario to 64 for behavioural change scenario, the battery expected lifetime remains 12 years. This is related to the crucial effect of temperature on battery lifetime, the variable which triggers battery replacement is indeed time and temperature degradation factor.

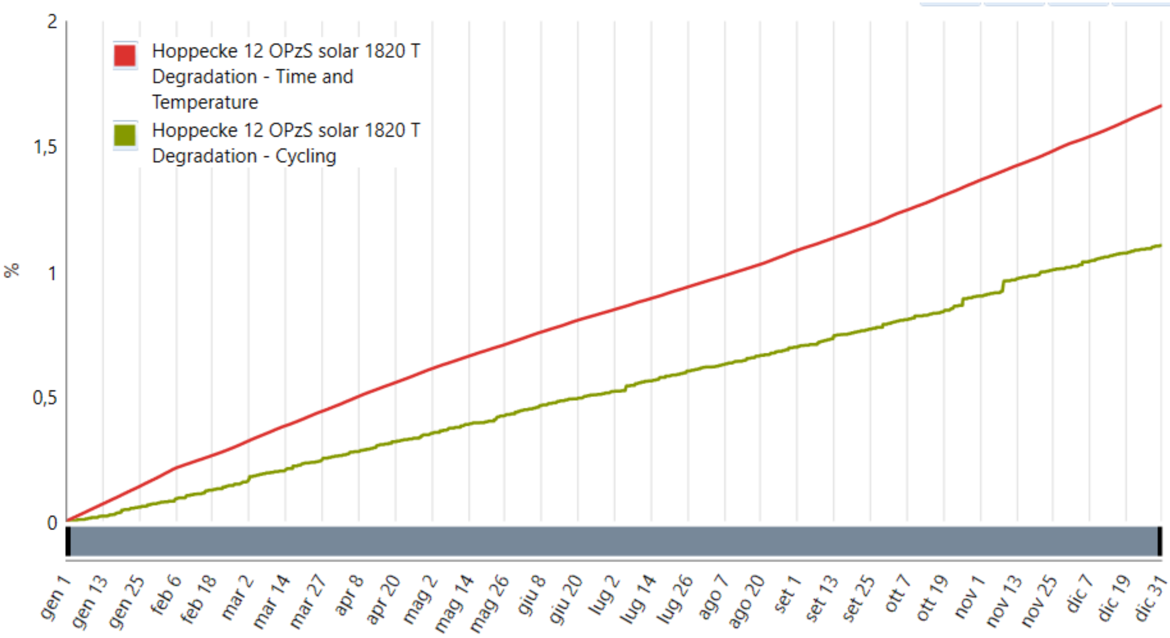


Figure 5.20 Mama Kevina - Behavioural change - battery degradation factors

Since the system design is the same as the full cooking scenario and the battery lifetime remains unchanged any variations in the HOMER cost structure are reported.
In conclusion the mini-grid, designed for full cooking scenario, can stand cooking habits variations without any penalization.

5.4 Cooking solution performance analysis

In this section, different cooking solutions including firewood, charcoal, kerosene, LPG and e-cook have been compared from the economic and environmental point of view. For the e-cook solution the full cooking scenario has been considered as a reference scenario.
Useful energy, defined as energy going into the pot and food, and calculated from the cooking preparation cycle (sub-section 3.1.3) resulted 3.6 kWh per day and 6.75 kWh per day in the low cook and high cook scenario respectively. These values represent the useful energy required for preparing two complete meal and the breakfast for Mama Kevina Hope Centre.

5.4.1 Levelized cooking cost per month

Levelized cooking cost per month is defined as the monthly expenditures for energy related to cooking activities in $/month. Method for its calculation has been presented in sub-section 3.4.1 and values of stove efficiency, fuel LHV and prices are available in Annex D.
Results of the basic analysis are depicted in Table 5.3.

BASIC ANALYSIS	Low cook	High cook
e-cook		
Electricity per day [kWh/day]	4.00	7.50
Electricity per month [kWh/month]	121.67	228.13
Cooking cost per day [$/day]	1.03	1.94
Cooking cost per month [$/month]	31.41	58.90
Firewood		
Primary Energy required [kWh/day]	25.71	48.21
Firewood per day [kg/day]	6.01	11.27
Firewood per month [kg/month]	182.74	342.64
Cooking cost per day [$/day]	0.67	1.26
Cooking cost per month [$/month]	20.47	38.38
Charcoal		
Primary Energy required [kWh/day]	13.85	25.96
Charcoal per day [kg/day]	1.75	3.29
Charcoal per month [kg/month]	53.38	100.08
Firewood per day	14.62	27.42
Firewood per month	444.82	834.03
Cooking cost per day [$/day]	0.47	0.88
Cooking cost per month [$/month]	14.20	26.62
Kerosene		
Primary Energy required [kWh/day]	9.73	18.24
Kerosene per day [l/day]	0.99	1.86
Kerosene per month [l/month]	30.19	56.61
Cooking cost per day [$/day]	1.24	2.33
Cooking cost per month [$/month]	37.83	70.93
LPG		
Primary Energy required [kWh/day]	6.79	12.74
LPG per day [kg/day]	0.54	1.01
LPG per month [kg/month]	16.35	30.65
Cooking cost per day [$/day]	1.46	2.74
Cooking cost per month [$/month]	44.46	83.36

Table 5.3 Mama Kevina - Levelized cooking cost per month

To present the results in a more effective way a box plot has been created in Excel (Figure 5.21). Lower values are representative of the low cook scenario while higher ones are representative of the high cook scenario. As for Kidegembye case study, economic convenience of firewood and charcoal solutions appears evident from this first analysis. However, the e-cook solution resulted much more convenient with respect to LPG.

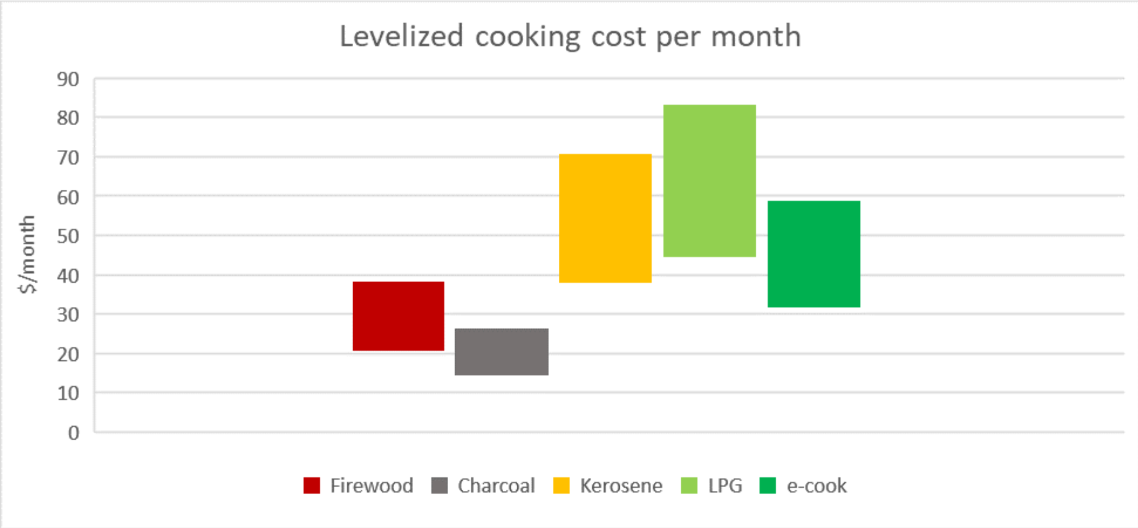


Figure 5.21 Mama Kevina - Levelized cooking cost per month

In order to avoid presenting too specific results a sensitivity analysis on stove efficiencies has been carried out (Table 5.4). A lower efficiency value and an upper one has been supposed for each technology, apart from the induction cookers for which literature agrees on the 90% value [2], [26], [70]. Efficiency values have been considered equal to Kidegembye case study.

Results are presented in a box plot (Figure 5.22) in which the lower value represent the low cook-high efficiency scenario while the upper value represents the high cook-low efficiency scenario.

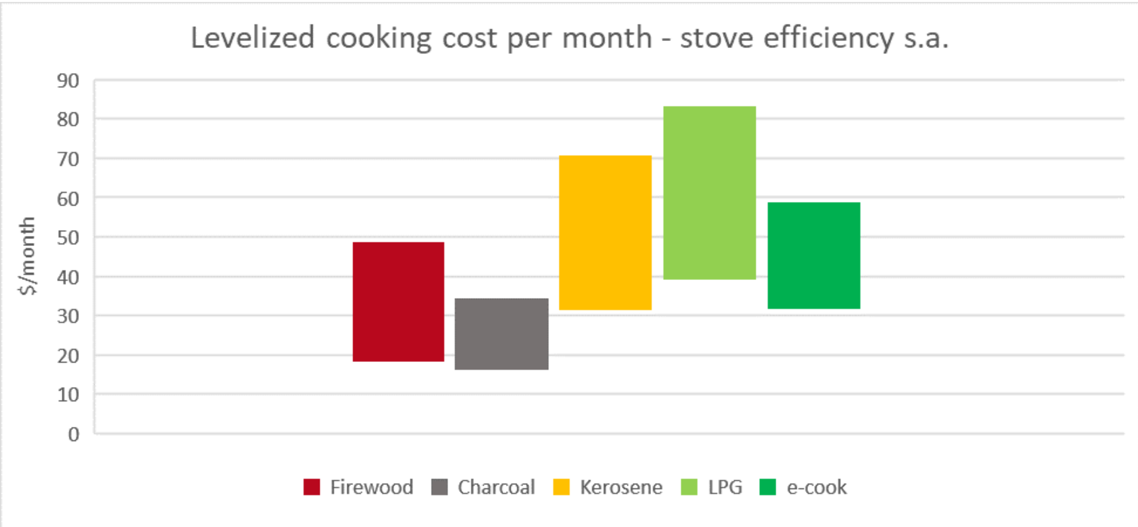


Figure 5.22 Mama Kevina - Levelized cooking cost per month - stove efficiency s.a.

SENSITIVITY ANALYSIS - STOVE EFF	Low cook		High cook	
	Low efficiency	High efficiency	Low efficiency	High efficiency
Firewood				
Primary Energy required [kWh/day]	32.73	22.93	61.36	42.99
Firewood per day [kg/day]	7.65	5.36	14.34	10.05
Firewood per month [kg/month]	232.58	162.96	436.09	305.54
Cooking cost per day [$/day]	0.86	0.60	1.61	1.13
Cooking cost per month [$/month]	26.05	18.25	48.84	34.22
Charcoal				
Primary Energy required [kWh/day]	18.00	15.52	33.75	29.09
Charcoal per day [kg/day]	2.28	1.97	4.28	3.69
Charcoal per month [kg/month]	69.39	59.82	130.11	112.16
Cooking cost per day [$/day]	0.61	0.52	1.14	0.98
Cooking cost per month [$/month]	18.46	15.91	34.61	29.84
Kerosene				
Primary Energy required [kWh/day]	9.73	8.00	18.24	15.00
Kerosene per day [l/day]	0.99	0.82	1.86	1.53
Kerosene per month [l/month]	30.19	24.82	56.61	46.54
Cooking cost per day [$/day]	1.24	1.02	2.33	1.92
Cooking cost per month [$/month]	37.83	31.10	70.93	58.32
LPG				
Primary Energy required [kWh/day]	6.79	5.96	12.74	11.18
LPG per day [kg/day]	0.54	0.47	1.01	0.88
LPG per month [kg/month]	16.35	14.34	30.65	26.89
Cooking cost per day [$/day]	1.46	1.28	2.74	2.40
Cooking cost per month [$/month]	44.46	39.01	83.36	73.15

Table 5.4 Mama Kevina - Levelized cooking cost per month - stove efficiency s.a.

As for Kidegembye case study, considering the instability of fuel prices, a sensitivity analysis on this variable, combined to the sensitivity analysis on stove efficiency, has been carried out (Table 5.5). Results are presented in a box plot (Figure 5.23) in which the lower value represents the optimistic scenario (low cook-high efficiency-low price) and the upper one represents the pessimistic scenario (high cook-low efficiency-high price). Therefore, all the plausible casuistries are expected to be included within this range.

SENSITIVITY ANALYSIS - STOVE EFFICIENCY & FUEL PRICE	Optimistic scenario	Pessimistic scenario
e-cook		
Electricity per day [kWh/day]	4.00	7.50
Electricity per month [kWh/month]	121.67	228.13
Cooking cost per day [$/day]	1.03	1.94
Cooking cost per month [$/month]	31.41	58.90
Firewood		
Primary Energy required [kWh/day]	22.93	61.36
Cooking cost per day [$/day]	0.00	1.61
Cooking cost per month [$/month]	0.00	48.84
Charcoal		
Primary Energy required [kWh/day]	15.52	33.75
Cooking cost per day [$/day]	0.39	1.71
Cooking cost per month [$/month]	11.89	52.04
Kerosene		
Primary Energy required [kWh/day]	8.00	18.24
Cooking cost per day [$/day]	0.73	2.33
Cooking cost per month [$/month]	22.34	70.93
LPG		
Primary Energy required [kWh/day]	5.96	12.74
Cooking cost per day [$/day]	1.04	2.74
Cooking cost per month [$/month]	31.55	83.36

Table 5.5 Mama Kevina - Levelized cooking cost per month - stove efficiency & fuel price s.a.

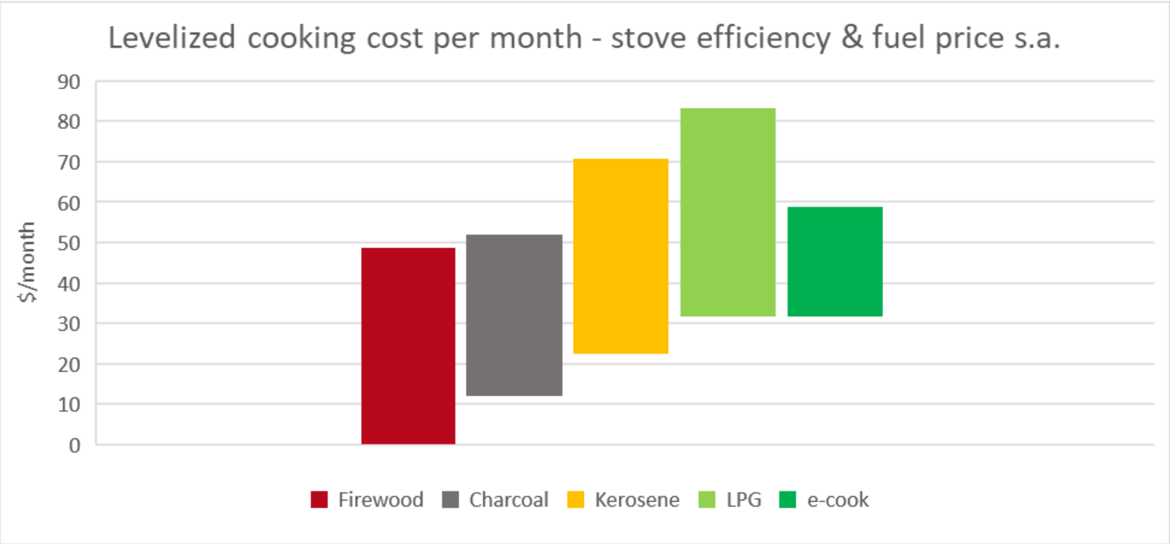


Figure 5.23 Mama Kevina - Levelized cooking cost per month stove efficiency and fuel price s.a.

Providing a range of cost, rather than an absolute value, makes possible to carry out a comprehensive comparison between all the cooking technologies. The e-cook upper value resulted comparable to firewood and charcoal solutions one, its lower value is instead embraced in all the other cooking solution ranges.

The conclusion is the same as for Kidegembye case study, the e-cook solution should not be abandoned a priori but rather constitutes a valid alternative especially compared to LPG. Moreover, this comparison has been carried out only from the economic point of view, the crucial added value of the e-cook solution is guaranteeing access to electricity and to clean cooking at the same time.

5.4.2 LCCM

In this sub-section, results about levelized cost of cooking a meal (sub-section 3.4.2) have been presented. As for levelized cooking cost per month, sensitivity analysis on stove efficiency and fuel price have been carried out.

Results about the basic analysis on LCCM are depicted in Table 5.6. Stove efficiencies and fuel prices considered are the same as the levelized cooking cost per month basic analysis. In addition, price of the different stoves has been defined.

To present the results in a more effective way a box plot has been created in Excel as for levelized cooking cost per month (Figure 5.24). Lower values are representative of the low cook scenario while higher ones are representative of the high cook scenario. Economic convenience of firewood and charcoal solutions appears evident from the box plot also for LCCM, while the e-cook solution is instead comparable to the kerosene one. LPG results the most expensive option as for levelized cooking cost per month.

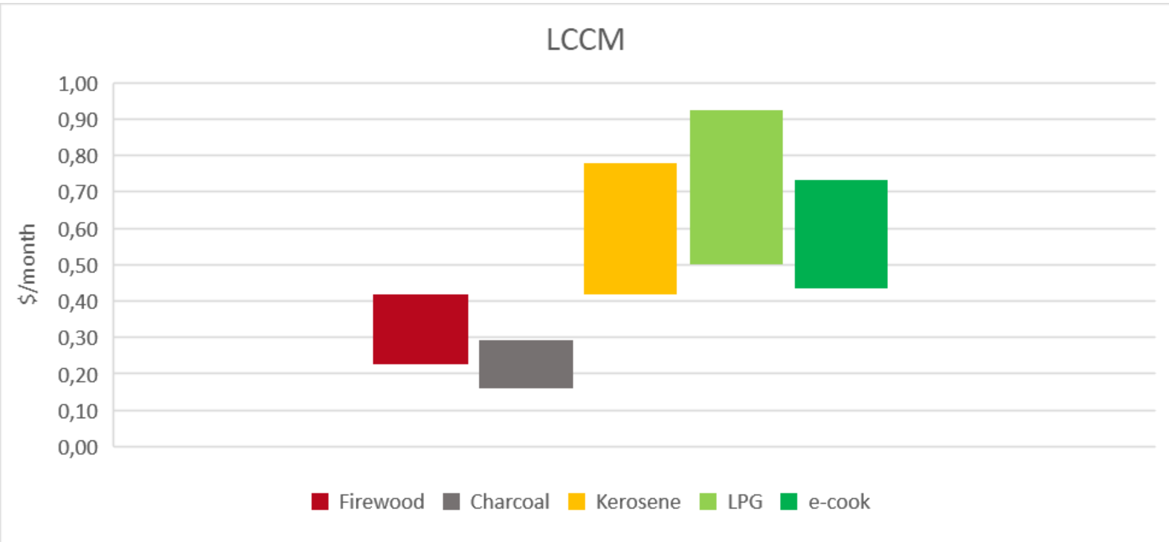


Figure 5.24 Mama Kevina - LCCM

BASIC ANALYSIS	Low cook	High cook
e-cook		
Electricity per day [kWh/day]	4.000	7.500
Electricity per meal [kWh/meal]	1.333	2.500
LCCM_fuel [$/meal]	0.344	0.646
LCCM_stove [$/meal]	0.087	0.087
LCCM [$/meal]	0.432	0.733
Firewood		
Primary Energy required [kWh/day]	25.714	48.214
Primary Energy required [kWh/meal]	8.571	16.071
LCCM_fuel [$/meal]	0.224	0.421
LCCM_stove [$/meal]	0.000	0.000
LCCM [$/meal]	0.224	0.421
Charcoal		
Primary Energy required [kWh/day]	13.846	25.962
Primary Energy required [kWh/meal]	4.615	8.654
LCCM_fuel [$/meal]	0.156	0.292
LCCM_stove [$/meal]	0.002	0.002
LCCM [$/meal]	0.158	0.294
Kerosene		
Primary Energy required [kWh/day]	9.730	18.243
Primary Energy required [kWh/meal]	3.243	6.081
LCCM_fuel	0.415	0.777
LCCM_stove	0.004	0.004
LCCM [$/meal]	0.418	0.781
LPG		
Primary Energy required [kWh/day]	6.792	12.736
Primary Energy required [kWh/meal]	2.264	4.245
LCCM_fuel	0.487	0.914
LCCM_stove	0.012	0.012
LCCM [$/meal]	0.499	0.926

Table 5.6 Mama Kevina – LCCM

Also for LCCM a sensitivity analysis on stove efficiency has been carried out. Efficiency values considered are the same used for levelized cooking cost per month. Results are presented in Table 5.7 and depicted in an excel box plot (Figure 5.25).

SENSITIVITY ANALYSIS - STOVE EFF	Low cook		High cook	
	Low efficiency	**High efficiency**	**Low efficiency**	**High efficiency**
Firewood				
Primary Energy required [kWh/day]	32.727	22.930	61.364	42.994
Primary Energy required [kWh/meal]	10.909	7.643	20.455	14.331
LCCM_fuel [$/meal]	0.285	0.200	0.535	0.375
LCCM_stove [$/meal]	0.000	0.000	0.000	0.000
LCCM [$/meal]	0.285	0.200	0.535	0.375
Charcoal				
Primary Energy required [kWh/day]	18.000	15.517	33.750	29.095
Primary Energy required [kWh/meal]	6.000	5.172	11.250	9.698
LCCM_fuel [$/meal]	0.202	0.174	0.379	0.327
LCCM_stove [$/meal]	0.002	0.002	0.002	0.002
LCCM [$/meal]	0.205	0.177	0.382	0.329
Kerosene				
Primary Energy required [kWh/day]	9.730	8.000	18.243	15.000
Primary Energy required [kWh/meal]	3.243	2.667	6.081	5.000
LCCM_fuel [$/meal]	0.415	0.341	0.777	0.639
LCCM_stove [$/meal]	0.004	0.004	0.004	0.004
LCCM [$/meal]	0.418	0.344	0.781	0.643
LPG				
Primary Energy required [kWh/day]	6.792	5.960	12.736	11.175
Primary Energy required [kWh/meal]	2.264	1.987	4.245	3.725
LCCM_fuel [$/meal]	0.487	0.428	0.914	0.802
LCCM_stove [$/meal]	0.012	0.012	0.012	0.012
LCCM [$/meal]	0.499	0.440	0.926	0.814

Table 5.7 Mama Kevina - LCCM - stove efficiency s.a.

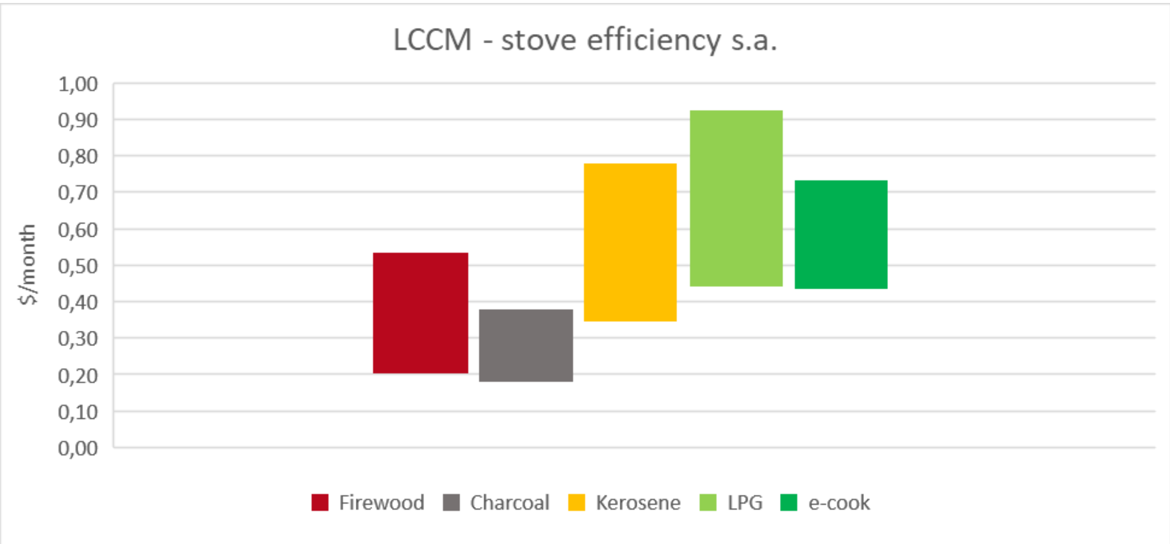


Figure 5.25 Mama Kevina - LCCM - stove efficiency s.a.

In addition, considering the instability of fuel prices, a sensitivity analysis on this variable, combined to the sensitivity analysis on stove efficiency and price, has been carried out (). Results are presented in a box plot () in which the lower value represents the optimistic scenario (low cook-high efficiency-low price) and the upper one represents the pessimistic scenario (high cook-low efficiency-high price). Therefore, all the plausible casuistries are expected to be included within this range.

SENSITIVITY ANALYSIS - STOVE EFF AND FUEL&STOVE PRICE	Optimistic scenario	Pessimistic scenario
e-cook		
Electricity per day [kWh/day]	4.000	7.500
Electricity per meal [kWh/meal]	1.333	2.500
LCCM_fuel [$/meal]	0.344	0.646
LCCM_stove [$/meal]	0.087	0.087
LCCM [$/meal]	0.432	0.733
Firewood		
Primary Energy required [kWh/meal]	7.643	20.455
LCCM_fuel [$/meal]	0.000	0.535
LCCM_stove [$/meal]	0.000	0.000
LCCM [$/meal]	0.000	0.535
Charcoal		
Primary Energy required [kWh/meal]	5.172	11.250
LCCM_fuel [$/meal]	0.130	0.570
LCCM_stove [$/meal]	0.001	0.002
LCCM [$/meal]	0.131	0.573
Kerosene		
Primary Energy required [kWh/meal]	2.667	6.081
LCCM_fuel [$/meal]	0.245	0.777
LCCM_stove [$/meal]	0.001	0.004
LCCM [$/meal]	0.246	0.781
LPG		
Primary Energy required [kWh/meal]	1.987	4.245
LCCM_fuel [$/meal]	0.346	0.914
LCCM_stove [$/meal]	0.022	0.022
LCCM [$/meal]	0.368	0.935

Table 5.8 Mama Kevina - LCCM - stove efficiency and fuel&stove price s.a.

As for levelized cooking cost per month, the e-cook solution is very interesting also for LCCM indicator, thus taking into account stove related costs. Its range is slightly higher than the charcoal solution and is embraced by the kerosene one. LPG represents the most expensive alternative also for LCCM analysis as for levelized cooking cost per month.

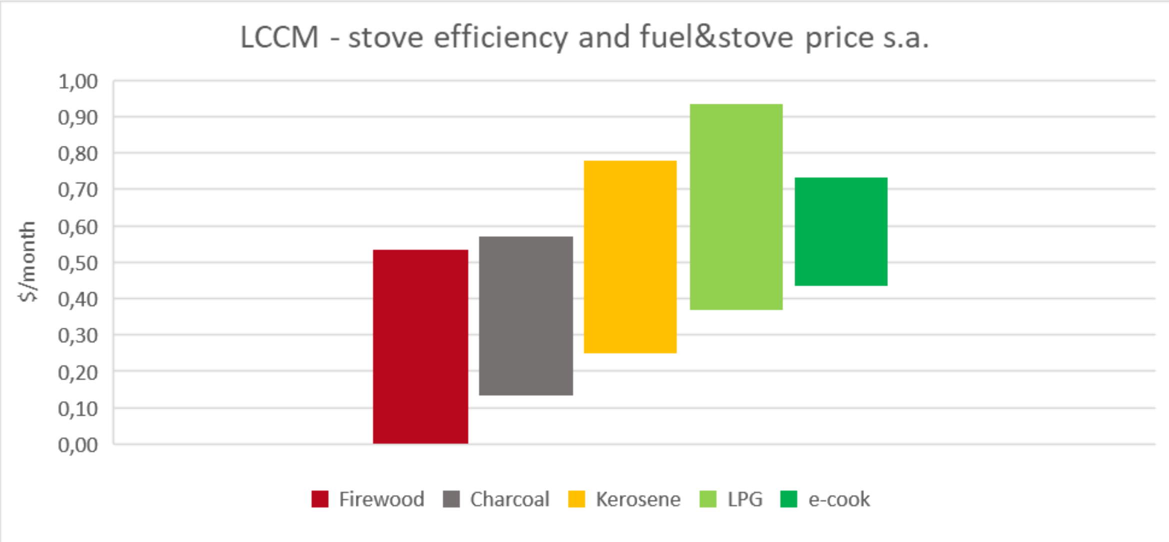


Figure 5.26 Mama Kevina - LCCM - stove efficiency and fuel & stove price s.a.

5.4.3 Comparison between two modern technology: electricity versus LPG

The two main alternatives for access to clean cooking are globally represented by electricity and LPG. Results from levelized cooking cost per month and LCCM analysis showed that the e-cook solution is cost-effective with respect to the LPG one also for the institutional case study. The aim of this sub-section is to quantify, through economic indicators such as payback time (PBT) and internal rate of return (IRR) the e-cook convenience.

Data for the e-cook solution are related to the full cooking scenario. According with HOMER simulation, for the full cooking scenario, initial investment for the mini-grid construction is equal to 25291 $ while O&M costs are around 147 $/year. Replacement of inverter occurs during the 15th year of operation, battery replacement instead occurs in the 13th year. In addition, 10 years life time has been considered for induction stoves, hence replacement of these components take part in the 10th year of operation.

Data for the LPG solution are instead related to the base load scenario to meet electricity demand and to calculated LPG consumption for cooking needs. According with HOMER simulation, for the base load scenario, initial investment for the mini-grid construction is equal to 21550 $ while O&M costs are around 127 $/year. Replacement of inverter occurs during the 15th year of operation, battery replacement instead occurs in the 13th year. In addition, as for the induction stove, the life time of the LPG stove has been considered equal to 10 years. Moreover, for LPG stoves, regulators must be changed every four years for safety reasons [6].

As for Kidegembye case study three different scenarios for LPG pricing have been considered.

NPC profile within the project lifetime have been plotted, for each scenario (Figure 5.27, Figure 5.28 and Figure 5.29). In the e-cook NPC profiles, decreasing value in the last year of the project is due to salvage.

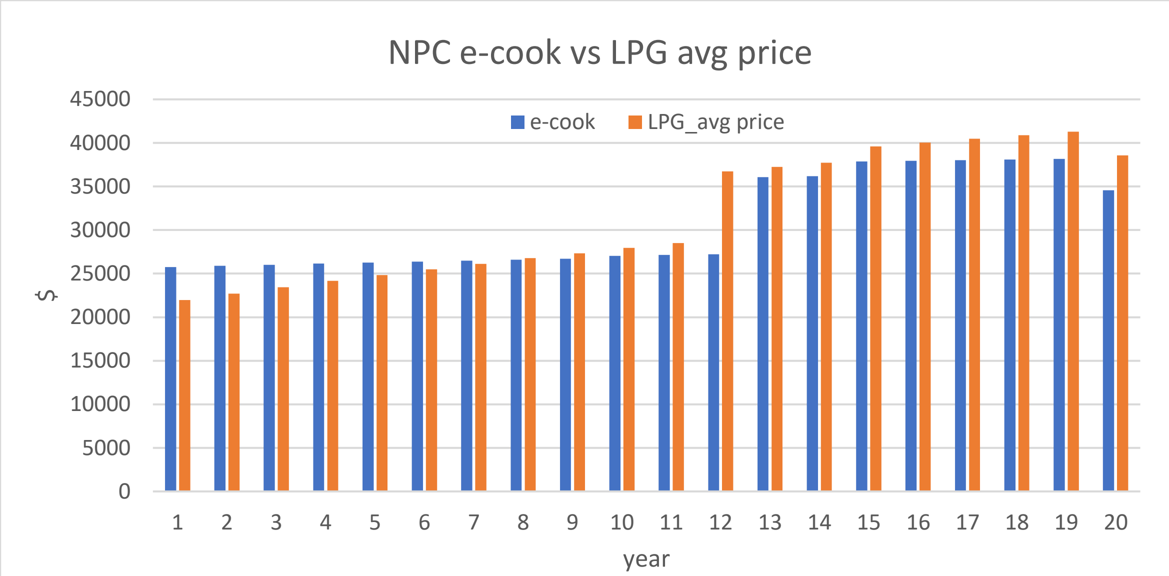


Figure 5.27 Mama Kevina – NPC of e-cook vs LPG average price

PBT	**7,70**	**years**
IRR	**18,07%**	

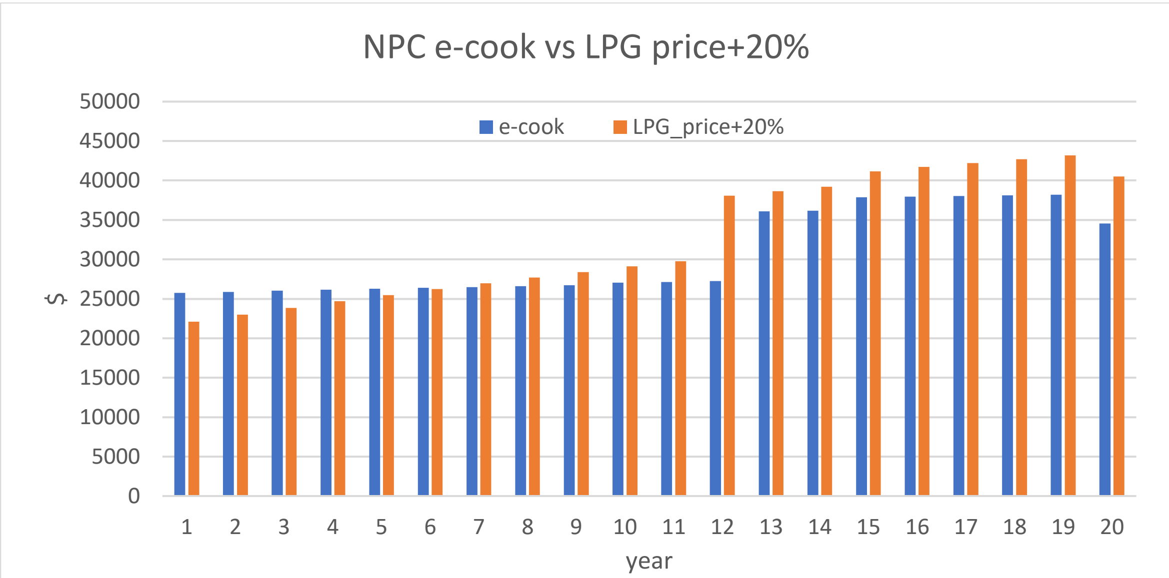


Figure 5.28 Mama Kevina - NPC of e-cook vs LPG with price increased by 20%

PBT	**6,22**	**years**
IRR	**21,52%**	

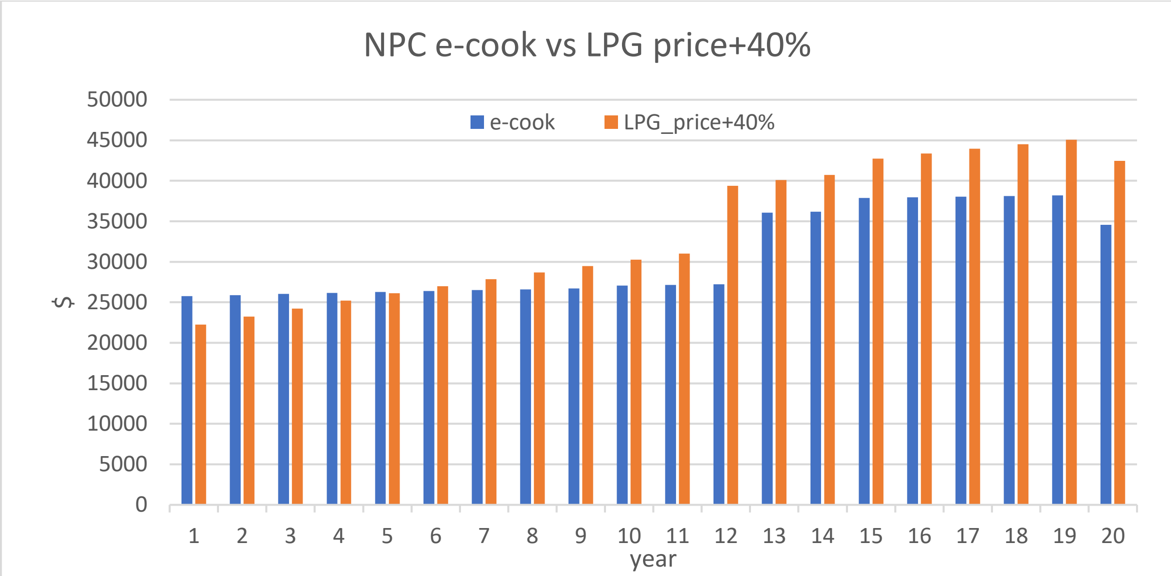


Figure 5.29 Mama Kevina - NPC of e-cook vs LPG with price increased by 40%

PBT	**5,20**	**years**
IRR	**24,87%**	

5.4.4 Savings of e-cook

The real added value of the e-cook solution is that energy for cooking is produced for Mama Kevina Hope Center by the solar powered mini-grid. Energy is therefore produced in a clean, renewable and reliable way without any impact on health or environment and neither in socio-economic development.

In this sub-section savings of the e-cook solution are presented. Savings have been calculated for the optimistic and pessimistic scenarios and within this range all plausible casuistries are likely to be embraced.

SAVINGS e-COOK	**Optimistic**	**Pessimistic**
Saved firewood [kg/month]	162,96	436,09
Saved firewood [ton/year]	1,96	5,23
Saved charcoal [kg/month]	59,82	130,11
Saved charcoal [ton/year]	0,72	1,56
Saved firewood per charcoal [ton/year]	5,98	13,01
Saved kerosene [l/month]	24,82	56,61
Saved kerosene [l/year]	297,88	679,28
Saved LPG [kg/month]	14,34	30,65
Saved LPG [kg/year]	172,11	367,77
Saved LPG tank 15kg [#/year]	11,5	24,5

6. Conclusions

The aim of this thesis work was to investigate the techno-economic feasibility of the e-cook concept implemented in a solar powered mini-grid, and to explore its actual potential in developing countries, also given the scarce presence of similar studies in the literature. The analysis was conducted for the village of Kidegembye and for Mama Kevina Hope Center in Tanzania, representative of a residential and institutional case study respectively. Load profiles for mini-grid design have been modelled with a new method based on cooking cycles defined on local cooking habits. Through this new method, starting from simple field data, it's possible to consider load deriving from cooking activities within the load modelling process. Given the fact that cooking-related energy represents over 90% of total primary energy demand of a household in developing countries, this new method can represent a starting point for a comprehensive solution for access to energy in such countries. Moreover, it can be implemented in LoadProGen guaranteeing a new development of the software in the direction of access to clean cooking through the e-cook concept.

Results showed that the impact on load profiles of induction stoves is very significant. For the residential case study, the peak power of the mean load curve passed from around 6 kW for the base load scenario to around 30 kW for the full cooking scenario. Consequently, the optimal size of the mini-grid passed from 11.55 kW to 37.40 kW and the initial investment cost increased from around 31000 $ to around 113000 $.

Regarding the institutional case study, induction kitchen had less impact on load profiles since highly energy consuming appliances, such as washing machine, iron or fridge, were already present in the centre. In addition, a sort of economy of scale was provided since one appliance is used to cook for a bigger group of people. The peak power of the mean load curve passed from around 2 kW for the base load scenario, to around 3.5 kW for the full cooking scenario. Accordingly, the size of the mini-grid passed from 7.7 kW to around 9.625 kW and the initial investment cost increased from around 21000 $ to around 25000 $. The potential of e-cook solution for the "institutional" case study, representing a wide number of similar structure all around Africa, is therefore evident.

Effects of cultural barriers, leading to phenomena as fuel stacking, on the e-cook mini-grid was analysed for the residential case study. The reduction in daily energy demand increased the effective autonomy of battery in the system, expected battery lifetime consequently grew from 16.1 years to 18.8 years. As the mini-grid components were the same of the full cooking scenario the purchase costs remained unchanged. However, the increased lifetime of the battery pack allowed to postpone its replacement and therefore to gain a higher salvage. For this reason, the NPC reduced from around 137000 $ to 127000 $ while the LCOE instead grew from 0.2369 $/kWh to 0.2741 $/kWh because reduction in energy request is more significant than NPC reduction.

Furthermore, providing induction stoves makes plausible a shift in the meals preparation windows that will likely take part just before meal time. While a similar shift in a village is unlikely to happen, in an institutional structure like Mama Kevina where a restricted group of people is responsible of cooking is more plausible. Effects of these possible behavioural changes on the e-cook mini-grid were investigated. Estimated daily energy demand remained almost unchanged respect to full cooking scenario as expected. However, the different load profile with less energy request during early morning and with a peak window during the PV array most productive period, change the battery state of charge throughout the year. Despite a slight reduction in number of equivalent cycle per year, the battery expected lifetime remained 12 years. This is related to the crucial effect of temperature on battery lifetime, the variable which triggers battery replacement was indeed time and temperature degradation factor. Since the system design was the same as the full cooking scenario and the battery lifetime remained unchanged any variations in cost were reported. For these reasons the e-cook mini-grid, designed for full cooking scenario, can stand cooking habits variations without any penalization.

Implementing demand side management technology in an already built mini-grid had instead slight effects visible from HOMER outputs. Indeed, all simulation results remained almost unchanged apart from a slight increase in battery lifetime that passed from 16.1 to 16.5 years. In addition, a small reduction in unmet electric load resulted. Real benefits of demand side management technology are fully exploited only if a specific mini-grid is properly designed for the relative scenario. However, it’s unsafe to size a mini-grid relying on an imaginary proper users’ behaviour. Indeed, mini-grid users might not follow the expected behaviour and in such a scenario, the mini-grid would result undersized. Demand side management technology remains an interesting technology for peak shifting and brownouts reduction, however they must be accompanied by an intensive education program.

In order to pursue the thesis’ aim, a performance analysis on different fuels for cooking was carried out. Results were presented in a range between a *pessimistic scenario* and an *optimistic scenario*. Providing a range of cost, rather than an absolute value, gave the possibility to carry out a comprehensive confront between all the cooking technologies. The first performance indicator computed was the levelized cooking cost per month which represents monthly expenditure for fuel. Regarding the residential case study, levelized cooking cost per month, for a household of five inhabitants, accounted for 0 to 19.21

$/month for firewood (0-25.9% of income), 5.05 to 20.47 $/month for charcoal (6.8-27.6% on income) and 9.49 to 27.90 $/month for kerosene (12.8-37.7% of income). For the two modern fuels it accounted for 12.25 to 21.26 $/month for e-cook (16.5-28.7% of income) and from 13.41 to 32.79 $/month for LPG (18.1-44.3% on income). Regarding instead the institutional case study, monthly expenditure for fuel, accounted for 0-48.84 $/month for firewood, 11.89 to 52.04 $/month for charcoal and 22.34 to 70.93 $/month for kerosene. For the two modern fuels it accounted for 31.41 to 58.90 $/month for e-cook solution and for 31.55 to 83.36 $/month for LPG solution.
Economic convenience of firewood and charcoal appeared evident in both case studies. However, the e-cook solution represented a valid alternative since its costs were comparable with the kerosene solution and even lower than the LPG one.
Moreover, Levelized Cost of Cooking a Meal, introduced by Fuso Nerini in 2016, was computed to provide a second proof of the e-cook solution cost-effectiveness. Regarding the residential case study, it resulted 0 to 0.253 $/meal for firewood, 0.067 to 0.272 $/meal for charcoal and 0.127 to 0.372 $/meal for kerosene. For the two modern fuels it accounted for 0.181 to 0.300 $/meal for the e-cook solution and 0.191 to 0.446 $/meal for the LPG one. Since Fuso Nerini's values were computed for a household of five people in Kenya, a country bordering Tanzania, with similar cooking habits, was possible to carry out a comparison. For each fuel/technology combination, Fuso Nerini's values were within the LCCM calculated range, apart from the e-cook solution. This difference was mainly due to the fact that Fuso Nerini referred the e-cook scenario to an electric stove with an efficiency equal to 70% rather than an induction stove with 90% efficiency. Moreover, Fuso Nerini provided a single value for each fuel/technology combination. Within this thesis work instead, a range of results were presented, rather than a single value, to provide a more comprehensive evaluation and to provide results that are likely to embrace all the possible casuistries.
Regarding instead the institutional case study, LCCM resulted 0 to 0.535 $/meal for firewood, 0.131 to 0.573 $/meal for charcoal and 0.246 to 0.781 $/meal for kerosene. For the two modern fuels it accounted for 0.432 to 0.733 $/meal for the e-cook solution and 0.368 to 0.935 $/meal for LPG one.
The trend highlighted for levelized cooking cost per month was confirmed also for LCCM. Firewood and charcoal represented the cheapest solutions; however, the optimistic scenario of the e-cook solution is embraced between the range of these two traditional solution. Furthermore, the e-cook solution was confirmed as a valid alternative since its costs were comparable with the kerosene solution and even lower than the LPG one.

A thorough comparison was carried out between the two main alternative for access to clean cooking, represented by electricity and LPG. Results of levelized cooking cost per month and LCCM analysis showed that the e-cook solution is cost-effective with respect to the LPG one. Accordingly, to quantify this economic convenience Pay Back Time (PBT) and Internal Rate of Return (IRR) of the e-cook solution were calculated. For the residential case study, it resulted 7.63 to 11.23 years of PBT with a IRR of 8.58 to 14.35%. For the institutional case study instead, it resulted 5.20 to 7.70 years of PBT with a IRR of 18.07 to 24.87%. This specific economic analysis confirmed the cost-effectiveness of the e-cook solution with respect to the LPG one. PBT and IRR reported values for the institutional case are highly interesting and provide a reference for possible future development of the e-cook concept in similar contexts.

In addition, the e-cook solution compared to all other ones presented savings in terms of non-renewable fuel consumption. For the residential case study 27.43 to 67.93 tons of firewood per year, 10.07 to 20.27 tons of charcoal, 4178 to 8817 liters of kerosene and 161 to 318 15 kg LPG tank could be saved. For the institutional case study instead 1.96 to 5.23 tons of firewood per year, 0.72 to 1.56 tons of charcoal per year, 298 to 679 liters of kerosene and 12 to 25 15 kg tank of LPG could be saved.

Achieving sustainable cooking is one of the greatest challenges of our time and connects many Sustainable Development Goals (SDGs). The e-cook concept, as an option for access to clean cooking, is often abandoned a priori because, according with IEA: «*it requires a large amount of power, which means that is not suitable for off-grid power supply and is relatively expensive».* Within this thesis work, through a techno-economic analysis of the e-cook concept, its cost-effectiveness was instead proved. Accordingly, the e-cook solution should not be abandoned a priori but rather constitutes a valid alternative especially compared to LPG. Moreover, the crucial added value of the e-cook solution is guaranteeing access to electricity and to clean cooking at the same time and in a clean and renewable way.

Future developments

The new method for load curve modelling taking into account also loads deriving from cooking activities could be implemented in LoadProGen. In this way the process would be automated exploiting the calculation power of the software. LoadProGen will therefore acquire a comprehensive vision on access to energy issue giving the right importance to access to clean cooking. Consequently, many simulations regarding e-cook concept implementation in renewable powered mini-grid could be carried out starting from load profiles modelled through LoadProGen.

Moreover, this thesis work can be expanded considering *Multicookers* as the electric cooking appliance of the e-cook concept. Despite a lower versatility respect to induction stoves, these kind of appliances is characterized by a lower power rate that is around 700-1000W depending on the capacity.

Finally, according with the results of this thesis, it is worth to deeply investigate the e-cook concept implementation in “institutional” structures. This kind of structures is representative of schools, small hospitals, residential centre, convents or similar buildings widely present all around sub-Saharan Africa. Furthermore, given the nature of this institutional structure, usually linked to some occidental association, is easier to find donors and investors.

Annex A: Components datasheet

Solar Panel: QCELLS275W

Il nuovo modulo ad alte prestazioni Q.PLUS BFR-G4.1 è la soluzione ideale per tutte le applicazioni, grazie all'innovativa tecnologia delle celle Q.ANTUM. Il design di queste celle, che ha fatto segnare record mondiali, è stato sviluppato per raggiungere migliori prestazioni in condizioni reali di funzionamento – tanto in caso di minima intensità dei raggi solari, quanto nelle calde giornate estive.

TECNOLOGIA DELLE CELLE Q.ANTUM: BASSI COSTI DI PRODUZIONE ENERGETICA
Maggior rendimento in rapporto alla superficie e costi BOS inferiori grazie a classi di potenza maggiori e ad un'efficienza fino al 17,1 %.

TECNOLOGIA INNOVATIVA PER OGNI CONDIZIONE ATMOSFERICA
Ottimi rendimenti in qualsiasi condizione atmosferica grazie al particolare comportamento in condizioni di scarso irradiamento e alta temperatura.

LIVELLI DI EFFICIENZA COSTANTI
Sicurezza di rendimento a lungo termine grazie alla tecnologia anti PID[1], Hot-Spot Protect e Traceable Quality Tra.Q™.

TELAI LEGGERI E DI QUALITÀ
Telaio in lega di alluminio high-tech, certificati come altamente resistenti a neve (5400 Pa) e vento (4000 Pa).

RIDUZIONE MASSIMA DEI COSTI
Fino al 10 % di risparmio sui costi di logistica grazie ad un maggiore numero di moduli per cartone.

SICUREZZA DI INVESTIMENTO
12 anni di garanzia sul prodotto, inclusa una garanzia lineare di 25 anni sulle prestazioni[2].

EUPD RESEARCH TOP BRAND PV MODULES EUROPE 2015

Q CELLS RENDIMENTI SICURI — ANTI PID TECHNOLOGY (APT) — HOT-SPOT PROTECT (HSP) — TRACEABLE QUALITY (TRA.Q™)

VDE Quality Tested — ID. 40032587

Photon — Q CELLS il migliore modulo solare policristallino del 2013

[1] Condizioni di test: celle a -1500V con messa a terra e superficie del modulo coperta da fogli conduttivi mettallici, 25 °C 168h

[2] Per ulteriori informazioni consultare il retro di questa scheda tecnica.

LA SOLUZIONE IDEALE PER:

Impianti sul tetto di strutture private

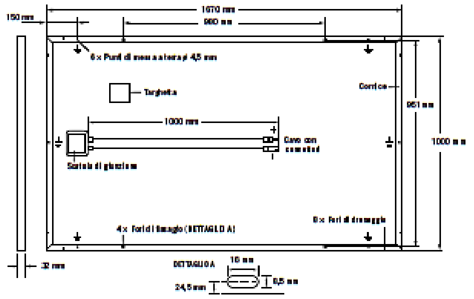
Impianti solari fotovoltaici commerciali e industriali

Engineered in **Germany**

Q CELLS

SPECIFICHE MECCANICHE

Dimensioni	1670mm × 1000mm × 32mm (cornice inclusa)
Peso	18,8kg
Lato frontale	3,2mm millimetri di vetro temprato con tecnologia anti-riflesso
Lato posteriore	Pellicola composita
Cornice	Lega di alluminio anodizzato
Cella	6 × 10 cella Q.ANTUM
Scatola di giunzione	77mm × 90mm × 15.8mm Protezione IP67, con 3 diodi di bypass
Cavo	Cavo solare 4 mm²; (+) 1000mm, (-) 1000mm
Connettore	MC4, IP68

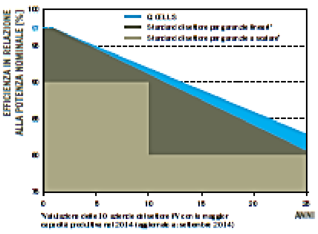


SPECIFICHE ELETTRICHE

CLASSI DI PRESTAZIONE				270	275	280
PRESTAZIONE MINIMA IN CONDIZIONI DI PROVA STANDARD, STC[1] (CAPACITÀ DI TOLLERANZA +5W / -0W)						
Minimo	Prestazioni a MPP[2]	P_{MPP}	[W]	270	275	280
	Corrente di cortocircuito*	I_{SC}	[A]	9,29	9,35	9,41
	Tensione a vuoto*	V_{OC}	[V]	38,46	38,72	38,97
	Corrente nel MPP*	I_{MPP}	[A]	8,70	8,77	8,84
	Tensione nel MPP*	V_{MPP}	[V]	31,04	31,36	31,67
	Efficienza[2]	η	[%]	≥16,2	≥16,5	≥16,8
PRESTAZIONE MINIMA IN CONDIZIONI DI NORMALE FUNZIONAMENTO, NOC[3]						
Minimo	Prestazioni a MPP[2]	P_{MPP}	[W]	199,6	203,3	207,0
	Corrente di cortocircuito*	I_{SC}	[A]	7,49	7,54	7,58
	Tensione a vuoto*	V_{OC}	[V]	35,89	36,13	36,37
	Corrente nel MPP*	I_{MPP}	[A]	6,81	6,87	6,93
	Tensione nel MPP*	V_{MPP}	[V]	29,30	29,59	29,87

[1]1000 W/m², 25°C, spettro AM 1.5G [2]Tolleranza di misura STC ±3%; NOC ±5% [3]800 W/m², NOCT, spettro AM 1.5G * Valori tipici, i valori effettivi potrebbero essere differenti

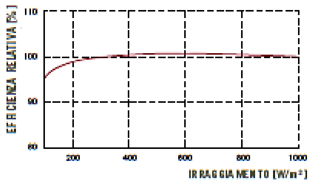
Q CELLS GARANZIA SULLA POTENZA



Potenza nominale pari ad almeno 97% nel corso del primo anno. Degrado annuo non superiore a 0,6%. Potenza nominale pari ad almeno 92% dopo 10 anni. Potenza nominale pari ad almeno 83% dopo 25 anni.

Le garanzie sul prodotto e sulla potenza possono variare secondo il paese di installazione. Garanzie integrali conformi ai termini approvati dall'organizzazione commerciale Q CELLS dei rispettivi Paesi.

PRESTAZIONI IN CASO DI BASSA IRRAGGIAMENTO



Tipica prestazione dei moduli a condizioni di irradiamento basse rispetto alle condizioni STC (25°C, 1000W/m²).

COEFFICIENTI DI TEMPERATURA IN CONDIZIONI STANDARD

Coefficienti di temperatura di I_{SC}	α	[%/K]	+0,04	Coefficienti di temperatura di V_{OC}	β	[%/K]	−0,29
Coefficienti di temperatura di P_{MPP}	γ	[%/K]	−0,40	Normal Operating Cell Temperature	NOCT	[°C]	45

SPECIFICHE PER L'INTEGRAZIONE DEL SISTEMA

Tensione massima di sistema	V_{SYS}	[V]	1000	Classe di protezione	II
Massima corrente inversa	I_R	[A]	20	Resistenza Ignifuga	C
Carico vento/neve (Test de charge conformément à la norme IEC 61215)		[Pa]	4000/ 5400	Temperatura dei moduli consentita in regime di funzionamento continuo	−40°C – +85°C

RICONOSCIMENTI E CERTIFICATI

VDE Quality Tested; IEC 61215 (Ed.2); IEC 61730 (Ed.1), Classe di applicazione A.
Questa scheda tecnica è conforme alla normativa DIN EN 50380.

PARTNER

AVVISO: È necessario attenersi rigorosamente alle istruzioni riportate nel manuale di installazione. Per ulteriori informazioni sulle possibilità di utilizzo del prodotto, consultare le Istruzioni per l'installazione e per l'uso.

Hanwha Q CELLS GmbH
Sonnenallee 17-21, 06766 Bitterfeld-Wolfen, Germany | TEL +49 (0)3494 66 99-23444 | FAX +49 (0)3494 66 99-23000 | EMAIL sales@q-cells.com | WEB www.q-cells.com

Engineered in **Germany**

Q CELLS

Battery: Hoppecke OPzS solar.power

OPzS solar.power

Vented lead-acid battery for cyclic applications

Motive Power Systems
Reserve Power Systems
Special Power Systems
Service

Your benefits with HOPPECKE OPzS solar.power

- **Highest cycle stability during PSoC[1] operation** - due to tubular plate design with efficient charge current acceptance
- **Maximum efficiency with reduced charging factor** - ready for use of optional elelctrolyte recirculation
- **Maximum compatibility** - dimensions according to DIN 40736-1
- **Higher short-circuit safety even during the installation** - based on HOPPECKE system connectors
- **Extremely extended water refill intervals up to maintenance-free** - optional use of AquaGen® recombination system minimizes emission of gas and aerosols[2]

Typical applications of HOPPECKE OPzS solar.power

- **Solar-/Off-grid applications**
  Power supply for remote off-grid applications and isolated power networks, drinking water supply systems, healthcare facilities
- **Telecommunications**
  Mobile phone stations
  BTS-stations
  Off-grid/on-grid solutions
- **Traffic systems**
  Signalling systems
  Lighting

HOPPECKE
POWER FROM INNOVATION

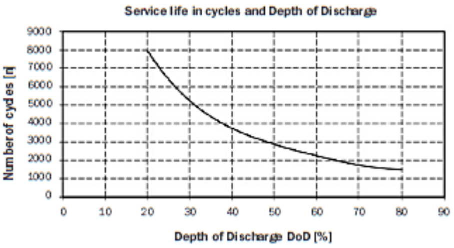
HOPPECKE
POWER FROM INNOVATION

OPzS solar.power

Type overview

Capacities, dimensions and weights

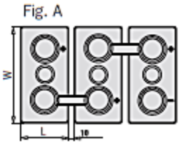
Type	C_{100}/1.85 V Ah	C_{50}/1.85 V Ah	C_{24}/1.83 V Ah	C_{10}/1.80 V Ah	C_5/1.77 V Ah	max. Weight kg	Weight electrolyte kg (1.24 kg/l)	max.* Length L mm	max.* Width W mm	max.* Height H mm	Fig.
4 OPzS solar.power 280	280	265	245	213	182	17.1	4.5	105	208	420	A
5 OPzS solar.power 350	350	330	307	266	227	20.7	5.6	126	208	420	A
6 OPzS solar.power 420	420	395	370	320	273	24.6	6.7	147	208	420	A
5 OPzS solar.power 520	520	490	454	390	345	29.1	8.5	126	208	535	A
6 OPzS solar.power 620	620	585	542	468	414	34.1	10.1	147	208	535	A
7 OPzS solar.power 730	730	685	634	546	483	39.2	11.7	168	208	535	A
6 OPzS solar.power 910	910	860	797	686	590	46.1	13.3	147	208	710	A
7 OPzS solar.power 1070	1070	1002	930	801	691	59.1	16.7	215	193	710	B
8 OPzS solar.power 1220	1220	1145	1063	915	790	63.1	17.3	215	193	710	B
9 OPzS solar.power 1370	1370	1283	1192	1026	887	72.4	20.5	215	235	710	B
10 OPzS solar.power 1520	1520	1425	1325	1140	985	76.4	21.1	215	235	710	B
11 OPzS solar.power 1670	1670	1572	1459	1256	1086	86.6	25.2	215	277	710	B
12 OPzS solar.power 1820	1820	1715	1591	1370	1185	90.6	25.8	215	277	710	B
12 OPzS solar.power 2170	2170	2010	1843	1610	1400	110.4	32.7	215	277	855	B
14 OPzS solar.power 2540	2540	2349	2163	1881	1632	142.3	46.2	215	400	815	C
16 OPzS solar.power 2900	2900	2685	2472	2150	1865	150.9	45.9	215	400	815	C
18 OPzS solar.power 3250	3250	3015	2765	2412	2097	179.1	56.4	215	490	815	D
20 OPzS solar.power 3610	3610	3350	3072	2680	2330	187.3	55.7	215	490	815	D
22 OPzS solar.power 3980	3980	3685	3388	2952	2562	212.5	67.0	215	580	815	D
24 OPzS solar.power 4340	4340	4020	3696	3220	2795	221.2	66.4	215	580	815	D
26 OPzS solar.power 4700	4700	4355	4004	3488	3028	229.6	65.4	215	580	815	D



C_{100}, C_{50}, C_{24}, C_{10} and C_5 =
Capacity at 100 h, 50 h, 24 h, 10 h and 5 h discharge

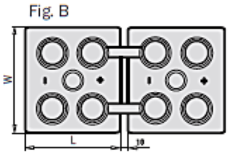
* according to DIN 40736-1 data to be understood as maximum values

Fig. A



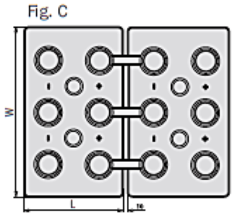
4 OPzS solar.power 280 - 6 OPzS solar.power 910

Fig. B



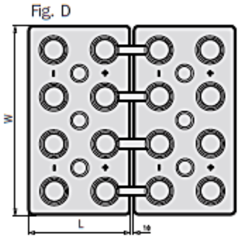
7 OPzS solar.power 1070 - 12 OPzS solar.power 2170

Fig. C

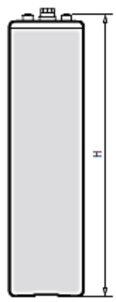


14 OPzS solar.power 2540 - 16 OPzS solar.power 2900

Fig. D



18 OPzS solar.power 3250 - 26 OPzS solar.power 4700



Optimal environmental compatibility - closed loop for recovery of materials in an accredited recycling system

IEC 60896-11
IEC 61427

[1] Partial State of Charge (Teilentladebetrieb)
[2] Similar to sealed lead-acid batteries

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POWER FROM INNOVATION

HOPPECKE Batterien GmbH & Co. KG
P.O. Box 1140 · D-59914 Brilon · Germany
Bontkirchener Straße 1 · D-59929 Brilon-Hoppecke
Phone +49(0)2963 61-374
Fax +49(0)2963 61-270
Email info@hoppecke.com
www.hoppecke.com

MPPT Solar charge controller: Magnum PT-100

PT-100 CHARGE CONTROLLER

Maximize Energy Harvest and Improve Battery Life

Model Numbers

- PT-100

Available For

- Renewable Energy Systems
  - Off-grid Power
  - Back-up Power

Works With

- MS Series
- MS-PAE Series
- MMP Panel System
- MP Panel System

Introductory Pricing

- $899 MSRP

The PT-100 is a Maximum Power Point Tracker (MPPT) charge controller designed to harvest the maximum available energy from the PV array and deliver it to the batteries. The PT-100's MPPT algorithm finds the maximum power point of the array and operates at this point while regulating the output current and battery voltage to fully charge the battery.

Features

- **MPPT:** Maximum Power Point Tracking technology for increased PV power output efficiency.
- **Multi-state Charging:** Maximizes system performance and improves battery life.
- **Optimal Battery Charging:** Automatic battery temperature compensation using an included external temperature sensor for optimum battery charging, even during extreme temperature changes.
- **Voltage Options:** Compatible with 12, 24, or 48V battery systems with automatic detection of system voltage.
- **GFDI:** Integrated PV Ground-Fault Detection and Interruption/ Indication, with pre-fault leakage/ diagnostic metering.
- **Extensive Electronic Protection:** Over-temperature protection, power derating when temperature is high, PV short circuit and high PV input shutdown, output overcurrent protection and night-time back-feed (reverse current) protection.
- **Support a Large PV Array:** A single controller supports a large PV array up to 6600W.
- **High Efficiency:** The PT-100 provides higher than 99% conversion efficiency and uses less than two watts of power in nighttime mode.
- **LED Indicators and Screen:** Multiple LED indicators and large digital LED screen on front panel for easy-to-read system information.
- **AFCI:** An integrated PV Arc-Fault Circuit Interrupter detects, indicates, and extinguishes series arcs. The AFCI is designed to meet the new National Electric Code (NEC) Article 690.11 requirements.
- **Convenient Installation:** Run all of the wiring to the unique, remain-in-place wiring box with ease prior to installing the full PT-100 unit.
- **On-site Updates:** The PT-100's software can be updated on site.
- **Easy MP and MMP integration:** The PT-100 is designed to work with a Magnum Panel (MP) or Mini-Magnum Panel (MMP). It provides room and access to PV and battery disconnect breakers.

Even More Functionality with the Optional Remote

- Built-in programmable auxiliary relay for device control.
- Internal data logging functionality keeps energy harvest information and battery Ahr/Whr data up to 255 days. Use the optional remote to display this information.

PT-100 CHARGE CONTROLLER SPECIFICATIONS

	PT-100
ELECTRICAL SPECIFICATIONS	
Maximum PV input voltage (any condition)	200 VDC + battery voltage or 240 VDC - whichever is lower
Maximum PV operating voltage	187 VDC
Maximum PV array short circuit current	100 ADC
Nominal battery voltage range	12, 24, or 48 VDC
Battery charger output voltage range	10 to 66 VDC
Continuous charger output current	100 ADC (from -20 °C to +40 °C) with proportional power reduction up to 60 °C ambient
Maximum output power	6600 watts
Peak (and full power) efficiency	>99% (98% typical)
Tare loss / nighttime power consumption	<2 watts (fan off, display/LEDs off)
Charger regulation method	Automatic three-stage (bulk, absorption, float) charge with manual equalization
GENERAL FEATURES AND CAPABILITIES	
Battery temperature compensation	With Battery Temperature Sensor (BTS) connected (battery temperature -20 °C to +55 °C)
Internal cooling	Using dual ball-bearing fans for long life
Overcurrent protection	With two overlapping circuits
Over-temperature protection	On transformer and MOSFETS
Listings	ETL Listed to UL/cUL 1741, CSA C22.2 #107.1-01
Warranty	Five years parts and labor
ENVIRONMENTAL SPECIFICATIONS	
Operating temperature	-20° C to +60° C (-4° F to 140° F)
Nonoperating temperature	-40° C to +70° C (-40° F to 158° F)
Operating humidity	0 to 95% RH non condensing
PHYSICAL SPECIFICATIONS	
Enclosure type	Indoor, ventilated, with removable powder-coated conduit box
Unit dimensions (w x h x d)	8.5" x 15.5" x 4.0" (21.6 cm x 39.4 cm x 10.2 cm)
Shipping dimensions (w x h x d)	11.5" x 19.5" x 8.125" (29.2 cm x 49.5 cm x 20.6 cm)
Mounting	Mounted on a vertical surface (wall) or installed on MP or MMP enclosure
Weight	12.5 lb (5.7 kg)
Shipping weight	15 lb (6.8 kg)
Max operating altitude	15,000' (4570 m)

Sensata Technologies

The World Depends on Sensors and Controls

MAGNUM-DIMENSIONS
2211 West Casino Road
Everett, Washington 98204 USA
425-353-8833

4467 White Bear Pkwy
St. Paul, MN 55110 USA
800-553-6418

www.magnumenergy.com

Testing for specifications at 25° C.
Specifications subject to change without notice.

March 2015 Rev B Part #64-0660

System inverter: Schneider Conext SW 4048

Life Is On | Schneider Electric

Proven value for off-grid, backup power and self-consumption

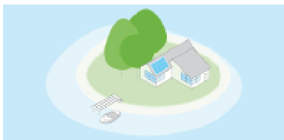
Conext™ SW inverter/charger

The Conext SW is a pure sine wave inverter that provides reliable power after a simple installation. The unique features of the Conext SW adds value for both installers and system owners globally.

Solution at a glance

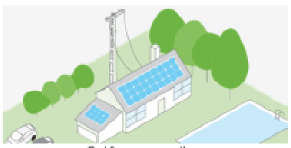
Delivering proven value at a competitive price, the Conext SW inverter/charger provides the best value for off-grid solar, self-consumption and long-term backup for homes, small business and small remote communities.

- **High reliability** design proven through extreme testing under the harhsest conditions.
- Leading performance in **surge capability** and charging efficiency.
- Most advanced **energy optimization** configurable features with the ability to cover a wide variety of applications.
- Complete balance of system and comprehensive commissioning tools for **easy-installation**.
- **Plug and play** monitoring and control based on Xanbus network.
- **Scalable** to 8kW with the addition of a second unit.
- **Simple** to install, maintain and operate.



Off-grid solar

Backup power



Self-consumption

Conext SW Inverter/charger

Technical Specifications - North America

Device short name	SW 2524 120/240	SW 4024 120/240	SW 4048 120/240
Electrical specifications - inverter			
Output power (continuous) at 25°C	3000 W	3400 W	3800 W
Output power (30 min) at 25°C	3300 W	4000 W	4400 W
Output power (5 sec) at 25°C	5000 W	7000 W	7000 W
Peak current	24.3 A	41 A	41 A
Output frequency	50 / 60 Hz selectable	50 / 60 Hz selectable	50 / 60 Hz selectable
Output voltage	120 / 240 Vac	120 / 240 Vac	120 / 240 Vac
Output wave form	True sine wave	True sine wave	True sine wave
Optimal efficiency	91.5%	92%	94%
Idle consumption search mode	<11 W	<11 W	<11 W
Input DC voltage range	20 - 34 Vdc	20 - 34 Vdc	40 - 68 Vdc
AC connections	Single / Split phase	Single / Split phase	Single / Split phase
Electrical specifications - charger			
Output current	65 A	90 A	45 A
Nominal output voltage	24 Vdc	24 Vdc	48 Vdc
Output voltage range	12 - 32 Vdc	12 - 32 Vdc	24 - 64 Vdc
Charge control	2 or 3 stage	2 or 3 stage	2 or 3 stage
Charge temperature compensation	Yes - BTS included	Yes - BTS included	Yes - BTS included
Optimal efficiency	90%	90%	92%
AC input power factor	> 0.98	> 0.98	> 0.98
Input current	9 A	13 A	12 A
Input AC voltage	120 / 240 Vac split phase	120 / 240 Vac split phase	120 / 240 Vac split phase
Input AC voltage range line to neutral	95 - 135 Vac single phase 170 - 270 Vac	95 - 135 Vac single phase 170 - 270 Vac	95 - 135 Vac single phase 170 - 270 Vac
Dead battery charge	Yes	Yes	Yes
General specifications			
Tare loss	**24 W**	**29 W**	**27 W**
Compatible battery types	FLA, Gel, AGM, Custom	FLA, Gel, AGM, Custom	FLA, Gel, AGM, Custom
Transfer relay rating	30 A	30 A	30 A
Transfer time (AC to inverter and inverter to AC)	<1 cycle (16.7 ms)	<1 cycle (16.7ms)	<1 cycle (16.7 ms)
Optimal operating temperature range	-20°C to 60°C (-4°F to 140°F)	-20°C to 60°C (-4°F to 140°F)	-20°C to 60°C (-4°F to 140°F)
Storage ambient temperature range	-40°C to 85°C (-40°F to 185°F)	-40°C to 85°C (-40°F to 185°F)	-40°C to 85°C (-40°F to 185°F)
Humidity Operation / storage	≤ 95% RH, non condensing	≤ 95% RH, non condensing	≤ 95% RH, non condensing
Ingress protection rating	Indoor only, IP20	Indoor only, IP20	Indoor only, IP20
Altitute (operating)	2000 m (6562 ft)	2000 m (6562 ft)	2000 m (6562 ft)
Product weight	22.3 kg (49.0 lb)	28.1 kg (62.0 lb)	28.1 kg (62.0 lb)
Shipping weight	27.2 kg (60.0 lb)	35.0 kg (77.1 lb)	35.0 kg (77.1 lb)
Product dimensions (H x W x D)	41.8 x 34.1 x 19.7 cm (16.5 x 13.4 x 7.6 in)	41.8 x 34.1 x 19.7 cm (16.5 x 13.4 x 7.6 in)	41.8 x 34.1 x 19.7 cm (16.5 x 13.4 x 7.6 in)
Shipping dimensions (H x W x D)	56.0 x 44.0 x 32.0 cm (22.0 x 17.3 x 12.6 in)	56.0 x 44.0 x 32.0 cm (22.0 x 17.3 x 12.6 in)	56.0 x 44.0 x 32.0 cm (22.0 x 17.3 x 12.6 in)
System network and remote monitoring	Available	Available	Available
Warranty (Depending on the country of installation)	2 or 5 years	2 or 5 years	2 or 5 years
Part number	865-2524	865-4024	865-4048
Regulatory approvals			
Safety	c(CSA) us mark CSA C22.2, No. 107.1-01 UL1741 Ed2		
EMC	FCC Part 15 Class B		
Compatible products			
Universal DC distribution panel	865-1016		
AC distribution panel (120/240 V)	865-1017		
Conext System Control Panel	865-1050-01		
Conext Automatic Generator Start	865-1060-01		
Conext ComBox	865-1058		
Conext MPPT 80 600 or 60 150 solar charge controller	865-1032 or 865-1030-1		
Conext SW On/Off Remote Switch	865-1052		
Conext Battery Monitor	865-1080-01		
Conext SW Stacking Kit	865-1019 for 120 / 240 Vac		
Conext Configuration Tool	865-1155-01		

Specifications are subject to change without notice.

DS20160624_ConextSW

Life Is On | Schneider Electric

System inverter: Schneider Conext XW 6848NA

NEW Conext XW+ NA inverter/charger

One solution for global power needs

Conext™ XW+ is an adaptable single-phase and three-phase inverter/charger system with grid-tie functionality and dual AC power inputs. Available solar charge controllers, monitoring, and automated generator control modules enable further adaptability. From a single Conext XW+ unit to clusters up to 102 kW, the Conext XW+ is a scalable system that allows for the integration of solar capacity as required. Adaptable and scalable, the Schneider Electric™ Conext XW+ system is the one solution for grid-interactive and off-grid, residential and commercial, solar and backup power applications.

Why choose Conext XW+ NA?

True bankability

- Warranty from a trusted partner with over 177 years of experience
- World leader in industrial power drives, UPS and electrical distribution
- Strong service infrastructure worldwide to support your global needs

Higher return on investment

- Excellent load starting with high 30-minute and 5-second power
- Performs in hot environments up to 70°C
- Intelligent functionality enables solar prioritization, load shifting, peak shaving, and assists small generators with heavy loads
- Backup power with grid-tie functionality converts external DC power to AC power for export to the utility grid

Flexible

- Single or three phase systems from 7.0 kW to 102 kW
- Supports DC coupled and AC coupled off-grid and grid-tie architectures
- Supports charging of Lithium Ion battery packs

Easy to service

- Field serviceable with replacement boards and spare parts
- Monitor, troubleshoot or upgrade firmware with Conext ComBox

Designed for reliability

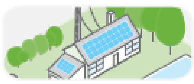
- Extensive quality and reliability testing
- Highly Accelerated Life Testing (HALT)
- Globally proven and recognized field performance

Easy to install

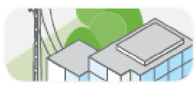
- System configures quickly into compact wall-mounted system
- Integrates both grid and generator power with dual AC inputs
- Balance of system components integrates battery bank, solar charge controllers and generators
- Commission the entire system with PC software tool and Conext ComBox

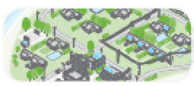
Product applications


Residential grid-tie solar with backup power


Self-consumption


off-grid solar


Backup power


Community electrification

www.SEsolar.com

NEW Conext XW+ series (120/240V)

Device short name	XW+ 5548 NA	XW+ 6848 NA
Inverter AC output		
Output power (continuous) at 25°C	5500 W	6800 W
Overload 30 min / 60 sec at 25°C	7000 W / 9500 W	8500 W / 12000 W
Output power (continuous) at 40°C	4500 W	6000 W
Maximum output current 60 seconds (rms)	82 A (120 V); 41 A (240 V)	102 A (120 V); 52 A (240 V)
Output frequency (selectable)	50 / 60 Hz	50 / 60 Hz
Output voltage	L-N: 120 V +/- 3%; L-L: 240 V +/- 3%	L-N: 120 V +/- 3%; L-L: 240 V +/- 3%
Total harmonic distortion (THD) at rated power	< 5%	< 5%
Idle consumption search mode	< 8 W	< 8 W
Input DC voltage range	42 to 60 V (48 V Nominal)	42 to 60 V (48 V Nominal)
Maximum input DC current	150 A	180 A
Charger DC output		
Maximum output charge current	110 A	140 A
Output voltage range	40 - 64 V (48 V Nominal)	40 - 64 V (48 V Nominal)
Charge control	Three stage, two stage, boost, custom	Three stage, two stage, boost, custom
Charge temperature compensation	Battery temperature sensor included	Battery temperature sensor included
Power factor corrected charging	0.98	0.98
Compatible battery types	Flooded (default), Gel, AGM, LiON, custom*	Flooded (default), Gel, AGM,LiON, custom*
Batter bank range (scaled to PV array size)	440 - 10000 Ah	440 - 10000 Ah
AC input		
AC 1 (grid) input current (selectable limit)	3 - 60 A (60 A default)	3 - 60 A (60 A default)
AC 2 (generator) input current (selectable limit)	3 - 60 A (60 A default)	3 - 60 A (60 A default)
Automatic transfer relay rating / typical transfer time	60 A / 8 ms	60 A / 8 ms
AC input voltage limits (bypass/charge mode)	L-N: 78 - 140 V (120 V nominal) L-L: 160 - 270 V (240 V nominal)	L-N: 78 - 140 V (120 V nominal) L-L: 160 - 270 V (240 V nominal)
AC input frequency range (bypass/charge mode)	55 - 65 Hz (default); 52 - 68 Hz (allowable)	55 - 65 Hz (default); 52 - 68 Hz (allowable)
AC grid-tie output		
Grid sell current range on AC1(selectable limit)	0 to 40 A (120 V) / 0 to 20 A (240 V)	0 to 48 A (120 V) / 0 to 27 A (240 V)
Grid sell voltage range on AC1 (auto adjusts entering sell mode)	L-N:105.5 to 132 +/- 1.5 V L-L: 211 to 264 +/- 3.0 V	L-N:105.5 to 132 +/- 1.5 V L-L: 211 to 264 +/- 3.0 V
Grid sell frequency range on AC1 (auto adjust entering sell mode)	59.4 to 60.4 +/- 0.05 Hz	59.4 to 60.4 +/- 0.05 Hz
Efficiency		
Peak	95.7%	95.7%
CEC weighted efficiency	93.0%	92.5%
General specifications		
Part number	865-5548-01	865-6848-01
Product / shipping weight	53.5 kg (118.0 lb) / 75.0 kg (165.0 lb)	55.2 kg (121.7 lb) / 76.7 kg (169.0 lb)
Product dimensions (H x W x D)	58 x 41 x 23 cm (23 x 16 x 9 in)	58 x 41 x 23 cm (23 x 16 x 9 in)
Shipping dimensions (H x W x D)	71.1 x 57.2 x 39.4 cm (28.0 x 22.5 x 15.5 in)	71.1 x 57.2 x 39.4 cm (28.0 x 22.5 x 15.5 in)
IP degree of protection	NEMA Type 1 Indoor	
Operating air temperature range	-25°C to 70°C (-13°F to 158°F) (power derated above 25°C (77°F)	
Warranty (Depending on the country of installation)	2 or 5 years	2 or 5 years
Features		
System monitoring and network communications	Available	
Intelligent features	Grid sell, peak load shave, generator support, prioritized consumption of battery or external DC energy	
Auxiliary port	0 to 12 V, maximum 250 mA DC output, selectable triggers	
Off-grid AC coupling	Frequency control	
Multi-unit operation	Single and split phase: up to four units in parallel, three phase: up to 12 units in multi-cluster configuration with external AC contactor	
Regulatory approval		
Safety	UL1741, CSA 107.1	
EMC directive	FCC and Industry Canada Class B	
Interconnect	IEEE 1547 and CSA 107.1	

Specifications are subject to change without notice.

Conext XW+ works with the following Schneider Electric products

XW+ Power Distribution Panel
Product no. 865-1015-01

Conext System Control Panel
Product no. 865-1050-1

Conext Automatic Generator Start
Product no. 865-1060-01

MPPT 60 150 solar charge controller
Product no. 865-1030-1

MPPT 80 600 solar charge controller
Product no. 865-1032

Conext Combox communication device
Product no. 865-1058

Conext Battery Monitor
Product no. 865-1080-01

XW Configuration Tool
Product no. 865-1155

 DS20140725_ConextXW+NA

Annex B: Results of questionnaire on electric appliances

Kidegembye village (conducted by Berti):

Specific user class *(j)*	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle [min]	functioning time [min]	Starting time Win 1 [min] *[1-1440]*	Ending time Win 1 [min] *[1-1440]*	Starting time Win 2 [min] *[1-1440]*	Ending time Win 2 [min] *[1-1440]*
HH_01	Charger	5	4	30	240	1020	1320	0	0
	Ind_ligths	18	5	30	660	1	360	1080	1440
	Out_lights	18	2	60	660	1	360	1080	1440
	Radio	10	1	30	150	1080	1260	0	0
	TV	80	1	30	150	1080	1260	0	0
HH_02	Charger	5	2	30	120	1080	1260	0	0
	Ind_ligths	18	6	30	150	1080	1260	0	0
	Iron	1	1	5	15	360	540	0	0
	Out_lights	18	2	60	300	1080	1440	0	0
	Radio	10	1	30	300	360	540	1080	1260
	TV	80	1	30	150	1080	1260	0	0
HH_03	Charger	5	2	30	120	1080	1260	0	0
	Ind_ligths	18	5	30	660	1	360	1080	1440
	Out_lights	18	1	60	660	1	360	1080	1440
	Radio	10	1	30	150	1080	1260	0	0
HH_04	Charger	5	2	30	120	1080	1260	0	0

	Ind_ligths	18	3	30	660	1	360	1080	1440
	Out_lights	18	2	60	660	1	360	1080	1440
HH_05	Charger	5	2	30	120	1200	1440	0	0
	Ind_ligths	18	3	30	210	1080	1320	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
	TV	80	1	30	210	1200	1440	0	0
HH_06	Charger	5	2	30	120	1080	1260	0	0
	Ind_ligths	18	7	30	150	1080	1260	0	0
	Out_lights	18	2	60	360	1	360	1080	1140
	Radio	10	1	30	300	720	1080	0	0
	TV	80	1	30	150	1080	1260	0	0
HH_07	Charger	5	4	30	240	1080	1440	0	0
	Ind_ligths	18	10	30	300	1080	1440	0	0
	Out_lights	18	1	60	660	1	360	1080	1440
	Radio	10	3	30	300	1080	1440	0	0
	TV	80	3	30	300	1080	1440	0	0
HH_08	Charger	5	3	30	240	1	360	1080	1440
	Ind_ligths	18	4	30	480	1	360	1080	1260
	Iron	1	1	10	30	360	540	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
	Radio	10	1	10	150	1080	1260	0	0
	TV	80	1	30	300	360	540	1080	1260
HH_09	Charger	5	3	30	240	1	360	1080	1440

	Ind_ligths	18	4	30	480	1	360	1080	1260
	Iron	1	1	10	30	360	540	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
	Radio	10	1	30	300	1080	1440	0	0
	TV	80	1	30	300	360	540	1080	1260
HH_10	Charger	5	2	30	120	1080	1440	0	0
	Ind_ligths	18	7	30	660	1	360	1080	1440
HH_11	Charger	5	2	30	90	360	540	0	0
	Ind_ligths	18	4	30	300	1080	1440	0	0
	Out_lights	18	1	60	660	1	360	1080	1440
	Radio	10	1	30	660	1	360	1080	1440
	TV	80	1	30	150	1080	1260	0	0
HH_12	Charger	5	2	30	360	1	360	1260	1440
	Ind_ligths	18	7	30	150	1080	1260	0	0
	Out_lights	18	3	60	660	1	360	1080	1440
	Radio	10	1	30	300	1080	1440	0	0
	TV	80	1	30	300	1080	1440	0	0
HH_13	Ind_ligths	18	3	30	210	1080	1320	0	0
	Out_lights	18	1	60	660	1	360	1080	1440
HH_14	Charger	5	6	30	120	1260	1440	0	0
	Ind_ligths	18	8	30	600	1	300	1080	1440
	Iron	1	1	10	30	360	420	0	0
	Out_lights	18	5	60	660	1	360	1080	1440

	Radio	10	1	30	90	1140	1260	0	0
	TV	80	1	30	210	1140	1380	0	0
HH_15	Charger	5	2	30	120	1140	1320	0	0
	Ind_ligths	18	6	30	150	1140	1320	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
	Radio	10	1	30	150	1140	1320	0	0
	TV	80	1	30	150	1140	1320	0	0
HH_16	Charger	5	2	30	180	1	300	1260	1440
	Ind_ligths	18	15	30	150	1080	1260	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
	Radio	10	1	30	210	1080	1320	0	0
	TV	80	1	30	210	1080	1320	0	0
HH_17	Charger	5	3	30	180	1200	1440	0	0
	Ind_ligths	18	4	30	210	1080	1320	0	0
	Iron	1	1	10	30	1140	1200	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
	Radio	10	1	30	150	1140	1320	0	0
	TV	80	1	30	150	1140	1320	0	0
HH_18	Charger	5	2	30	60	1140	1260	0	0
	Ind_ligths	18	4	30	150	1140	1320	0	0
	Radio	10	1	30	210	360	420	1140	1320
HH_19	Charger	5	1	30	180	1	300	1260	1440
	Ind_ligths	18	4	30	90	1140	1260	0	0

	Out_lights	18	1	60	600	1	360	1140	1440
	Radio	10	1	30	210	300	420	1140	1260
	TV	80	1	30	60	1140	1260	0	0
HH_20	Charger	5	2	30	240	1	360	960	1440
	Ind_ligths	18	6	30	150	1140	1320	0	0
	Iron	1	1	10	30	300	360	0	0
	Out_lights	18	1	60	540	1	300	1140	1440
	Radio	10	1	30	60	1200	1320	0	0
	TV	80	1	30	90	1200	1320	0	0
HH_21	Charger	5	3	30	120	960	1140	0	0
	Ind_ligths	18	3	30	210	1080	1320	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
	Radio	10	1	30	210	1080	1320	0	0
HH_22	Charger	5	2	30	180	480	600	1140	1260
	Ind_ligths	18	6	30	60	1080	1200	0	0
	Out_lights	18	3	60	600	1	360	1140	1440
	Radio	10	1	30	300	300	420	1020	1260
HH_23	Ind_ligths	18	3	30	660	1	360	1080	1440
	Out_lights	18	4	60	480	1	300	1200	1440
HH_24	Charger	5	3	30	120	1080	1260	0	0
	Ind_ligths	18	7	30	90	1140	1260	0	0
	Out_lights	18	3	60	660	1	360	1080	1440
	Radio	10	1	30	240	300	480	1140	1260

HH_25	Charger	5	3	30	180	1080	1380	0	0
	Ind_ligths	18	4	30	270	1080	1380	0	0
	Iron	1200	1	10	30	420	540	0	0
	Out_lights	18	2	60	720	1	420	1080	1440
	Radio	10	1	30	210	1140	1380	0	0
	TV	80	1	30	210	1140	1380	0	0
HH_26	Charger	5	1	30	120	960	1140	0	0
	Ind_ligths	18	2	30	150	1140	1320	0	0
	Iron	1	1	10	60	1080	1440	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
HH_27	Charger	5	1	30	120	1080	1260	0	0
	Dvd	20	1	10	150	1140	1320	0	0
	Ind_ligths	18	2	30	150	1140	1320	0	0
	Radio	10	1	30	150	1140	1320	0	0
	TV	80	1	30	150	1140	1320	0	0
HH_28	Charger	5	4	30	120	780	1140	0	0
	Ind_ligths	18	8	30	150	1140	1320	0	0
	Out_lights	18	1	60	660	1	360	1080	1440
	Radio	10	1	30	300	960	1320	0	0
	TV	80	1	30	300	960	1320	0	0
HH_29	Charger	5	1	30	120	1140	1320	0	0
	Decoder	20	1	10	150	1140	1320	0	0
	Dvd	20	1	10	150	1140	1320	0	0

	Ind_ligths	18	6	30	210	1080	1320	0	0
	Out_lights	18	2	60	660	1	360	1080	1440
	TV	80	1	30	150	1140	1320	0	0
HH_30	Charger	5	2	30	360	1	360	1320	1440
	Ind_ligths	18	6	30	270	1080	1380	0	0
	Iron	1200	1	10	30	300	360	0	0
	Out_lights	18	3	60	660	360	1080	0	0
	Radio	10	1	30	300	360	540	1140	1320
	TV	80	1	30	300	360	540	1140	1320
HH_31	Charger	5	2	30	180	1080	1320	0	0
	Decoder	20	1	10	780	480	1320	0	0
	Ind_ligths	18	3	30	660	1	360	1080	1440
	Out_lights	18	2	60	660	1	360	1080	1440
	Radio	10	1	30	60	1140	1260	0	0
	TV	80	1	30	780	480	1320	0	0
HH_32	Charger	5	5	30	120	1080	1260	0	0
	Decoder	20	1	10	300	960	1320	0	0
	Ind_ligths	18	11	30	600	1	360	1140	1440
	Iron	1200	1	10	30	960	1020	0	0
	Out_lights	18	4	60	600	1	360	1140	1440
	Radio	10	1	30	300	960	1320	0	0
	TV	80	1	30	300	960	1320	0	0
HH_33	Charger	5	5	30	180	1080	1320	0	0
	Decoder	18	8	30	270	1080	1380	0	0

	Ind_ligths	18	2	60	180	1140	1380	0	0
	Iron	10	1	30	660	1	360	1080	1440
	Out_lights	80	2	30	210	1080	1320	0	0

Mama Kevina Hope Center:

Specific user class	Type of electrical appliance	Nominal appliance power rate [W]	Number of appliances in class	functioning cycle [min]	functioning time [min]	Starting time Win 1 [min] *[1-1440]*	Ending time Win 1 [min] *[1-1440]*	Starting time Win 2 [min] *[1-1440]*	Ending time Win 2 [min] *[1-1440]*
Guardian room	Charger	5	1	30	180	1200	1440	0	0
	Ind_ligths	10	1	30	120	1	360	1080	1440
	Out_lights	10	2	60	660	1	360	1080	1440
Craftman room	Ind_ligths	10	2	30	45	1080	1200	0	0
	Out_lights	10	2	60	660	1	360	1080	1440
Toilet	Ind_ligths	10	3	15	30	1	360	1080	1440
	Out_lights	18	1	60	660	1	360	1080	1440
Millstone room	Ind_ligths	10	3	30	60	420	540	1020	1140
	Out_lights	10	2	60	660	1	360	1080	1440
Living room + studio	Charger	5	7	30	180	1	1440		
	Ind_ligths_1	46	3	1	150	1140	1440		
	Ind_ligths_2	10	11	30	150	1140	1440		
	Bathroom_lights	10	14	30	60	1	1440		

	Studio_lights	15	2	30	150	1080	1200	1320	1440
	PC	65	2	30	120	1080	1200	1320	1440
	Iron	1000	0	15	30	540	960		
	Washing machine	2000	0	90	150	480	780	960	1140
	Out_lights	10	10	60	660	1	360	1080	1440
Sleeping room sisters	Charger	5	5	30	180	1	1440	0	0
+ kitchen	Ind_ligths	10	5	30	180	1140	1380	0	0
	Out_lights	10	4	60	660	1	360	1080	1440
	Radio	10	1	30	60	1140	1380	0	0
	TV	80	1	60	180	1140	1380	0	0
	Fridge	30	1	1440	1440	1	1440		
Garage	Ind_ligths	20	2	15	30	1140	1380	0	0
	Out_lights	10	2	60	660	1	360	1080	1440
Head office sister	Charger	5	4	30	180	1	1440		
	Ind_ligths_1	10	7	30	120	1140	1320		
	Ind_ligths_2	10	5	30	60	360	420		
	PC	65	1	60	180	480	1440		
	Fan	48	0	30	120	600	1020		
	TV	80	1	60	180	960	1260		
	Out_lights	10	10	60	660	1	360	1080	1440
Kitchen	Charger	5	1	30	120	360	1020		
	Ind_ligths	10	1	60	120	1020	1140		
	Out_lights	10	2	60	660	1	360	1080	1440

Therapeutic room	Charger	5	2	30	120	1	1440		
	Ind_ligths1	10	4	30	60	1140	1320		
	Ind_ligths2	10	2	15	30	480	570		
	Out_lights	10	2	60	660	1	360	1080	1440
Toilet	Ind_ligths	10	7	30	60	1140	1440	0	0
	Out_lights	10	2	60	660	1	360	1080	1440
Dining hall	Ind_ligths	15	5	30	120	1140	1320		
	Out_lights	10	3	60	660	1	360	1080	1440
	Fridge	30	1	1440	1440	1	1440		
Servitude room	Ind_ligths	10	8	30	120	300	420	1260	1380
+ kitchen	Out_lights	10	2	60	660	1	360	1080	1440
	Charger	5	3	30	180	300	420	1260	1380
	Fan	48	3	60	300	1	300	1200	1440
	Fridge	30	1	1440	1440	1	1440		
Siters rooms	Ind_ligths	10	2	30	150	300	480	1200	1440
+ host rooms	Out_lights	5	1	60	660	1	360	1080	1440
	Charger	5	1	30	180	1	1440		
	Fan	48	1	30	360	1	420	1320	1440
Mensa + kitchen	Ind_ligths_mensa	40	2	30	120	1080	1260		
+ Sister room	Fan1	48	1	30	60	720	840	1080	1260
	Fridge	30	1	1440	1440	1	1440		
	Toaster	500	1	5	25	420	540	720	840
	Ind_lights_sister	15	2	30	120	1080	1320		

	Fan2	48	1	30	120	840	1320	0	0
	TV	80	1	30	120	840	1320	0	0
	Charger	5	2	30	120	840	960	1260	1320
	Out_lights	10	5	60	660	1	360	1080	1440
	Ind_ligths_kitchen	15	2	30	120	300	420	1080	1320

Annex C: MATLAB scripts

Breakfast random cycle:

Editor - C:\Users\Marco\Desktop\Tesi\LoadProGen 2.0\code\B_random_cycle.m

B_random_cycle.m

```
HP=2000; MP=1500;

RND=randi([80,120],1,1)/100;
length_boil=round(5*RND);
boil=zeros(1,length_boil);
boil(1:length_boil)=HP;

RND=randi([80,120],1,1)/100;
length_cook=round(5*RND);
cook=zeros(1,length_cook);
cook(1:length_cook)=MP;

B=[boil cook]; %breakfast%
```

Lunch/dinner random cycle:

Editor - C:\Users\Marco\Desktop\Tesi\LoadProGen 2.0\code\LD_random_cycle.m*

B_random_cycle.m LD_random_cycle.m*

```
HP=2000; MP=1500; LP=500;

RND=randi([70,130],1,1)/100;
length_boil_veg=round(6*RND);
boil_veg=zeros(1,length_boil_veg);
boil_veg(1:length_boil_veg)=HP;

RND=randi([80,120],1,1)/100;
length_boil_rice=round(12.5*RND);
boil_rice=zeros(1,length_boil_rice);
boil_rice(1:length_boil_rice)=HP;

RND=randi([80,120],1,1)/100;
length_cook_veg=round(5*RND);
cook_veg=zeros(1,length_cook_veg);
cook_veg(1:length_cook_veg)=MP;

RND=randi([70,130],1,1)/100;
length_cook_rice=round(30*RND);
cook_rice=zeros(1,length_cook_rice);
cook_rice(1:length_cook_rice)=LP;

length_tot=length_boil_rice+length_boil_veg+length_cook_rice+length_cook_veg;
LD=[boil_veg cook_veg boil_rice cook_rice]; %lunch dinner%
```

Full preparation random cycle:

Editor - C:\Users\Marco\Desktop\Tesi\LoadProGen 2.0\code\FP_random_cycle.m

B_random_cycle.m | LD_random_cycle.m | FP_random_cycle.m

```
HP=2000; MP=1500; LP=500;

RND=randi([80,120],1,1)/100;
length_boil=round(5*RND);
boil=zeros(1,length_boil);
boil(1:length_boil)=HP;

RND=randi([80,120],1,1)/100;
length_cook=round(5*RND);
cook=zeros(1,length_cook);
cook(1:length_cook)=MP;

B=[boil cook]; %breakfast%

RND=randi([80,120],1,1)/100;
length_boil_veg=round(6*RND);
boil_veg=zeros(1,length_boil_veg);
boil_veg(1:length_boil_veg)=HP;

RND=randi([80,120],1,1)/100;
length_boil_rice=round(12.5*RND);
boil_rice=zeros(1,length_boil_rice);
boil_rice(1:length_boil_rice)=HP;

RND=randi([80,120],1,1)/100;
length_cook_veg=round(5*RND);
cook_veg=zeros(1,length_cook_veg);
cook_veg(1:length_cook_veg)=MP;

RND=randi([70,130],1,1)/100;
length_cook_rice=round(30*RND);
cook_rice=zeros(1,length_cook_rice);
cook_rice(1:length_cook_rice)=LP;

LD=[boil_veg cook_veg boil_rice cook_rice]; %lunch dinner%

length_lag=round(randi([1,15],1,1));
lag=ones(1,length_lag);

FP=[B lag LD]; %Full preparation%
length_FP=length(FP);
stairs(FP)
```

Annex D: Reference values

Stove efficiency:

Stove	Ref. [8]	Ref. [71]	Ref. [73]	Ref. [72]	Ref. [2], [26], [70]
Three-stone fire	0.14	0.157	-	0.11	-
Charcoal_traditional	0.26	0.232	-	0.2	-
Kerosene	0.37	0.404	0.377	0.45	-
LPG	0.53	0.604	0.531	0.55	-
Induction	-	-	-	-	0.9

LHV fuels [kWh/kg]:

Fuel	Eng_toolbox	Ref. [71]	Ref. [73]
Firewood	4.28	4.58	-
Charcoal	7.89	7.92	8.14
Kerosene	11.94	12.36	11.97
LPG	12.64	12.75	12.50

Fuel prices:

Fuel	Ref. [6]	Ref. [8]	Ref. [68]	Ref. [69]	Same (Jan-2018)
Firewood [$/kg]	-	0.092	-	-	0.112
Charcoal [$/kg]	0.4	0.199	0.31	-	0.266
Kerosene [$/l]	1	1.161	-	0.9	1.253
LPG [$/kg]	2.2	2.321	-	-	2.72

Stove prices [$]:

Stove	Ref. [6]	Ref. [8]	Jumia e-commerce	Mediaworld e-commerce
Charcoal_traditional	10	3	-	-
Kerosene	-	6	13.32-17.54	-
LPG	51.6	53	-	-
LPG regulator	6.6	-	-	-
Induction	-	-	61.53	-
Induction pot&pan	-	-	10	-
Induction kitchen	-	-	-	341.32
Induction kitchen pots	-	-	31.04	-
LPG kitchen	-	-	92.93	-

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