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Article

Energy production analysis and optimization of Mini-Grid in remote areas: the case study of Habaswein, Kenya

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Abstract:

Rural electrification in remote areas of developing countries has several challenges which hinders energy access to the population. For instance the extension of the national grid to provide electricity in these areas is largely not viable. The Kenyan government has put a target to achieve universal energy access by the year 2020. In order to realize this objective, focus is being shifted to establishing off-grid power stations in rural areas.

Among rural areas to be electrified, Habaswein is a settlement in Kenya's North Eastern region without connection to the National Power Grid where Kenya Power installed a stand alone hybrid mini-grid.

Based on field observations, power generation data analysis, evaluation of the potential energy resource and simulations, this research intends to evaluate the performance of the Habaswein mini-grid and optimize the existing hybrid generation system to enhance its reliability and reduce the operation costs.

The result will be a suggestion of how Kenyan rural areas could be sustainably electrified by using renewable energy based off-grid power stations. It will contribute to bridge the research gap currently existing on that area, and it will be a vital tool to researchers, implementers and the policy makers in energy sector.

Keywords: Hybrid Mini-grid, Rural Electrification, Renewable Energy, Rural Development, Energy Access

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1. Introduction

1.1 Background of study

Reliable and affordable energy is recognized as an essential ingredient for socio-economic development and economic growth of any country in order to meet the basic human needs such as cooking, lighting and safe drinking water as well as to improve among others, education, communication and productive activities.

According to the IEA WEO 2016, an estimated 1.2 billion people – 16% of the global population – does not have access to electricity, and more than 95% of them in sub-Saharan Africa and developing Asia. Among these countries, Kenya has been faced the problem by the national grid and reaching an electrification rate of 47% in 2016 [1].

However, looking at the current energy situation, there are still a number of challenges and weaknesses that affect the energy supply sector in Kenya. The main ones are the following: (i) low access to modern energy leading to high pressure on biomass resources, (ii) high cost of energy, (iii) energy demand increase faster than the additional generation installation rate, (iv) high cost of rural electrification through grid extension due to the scattered nature of settlements, (v) frequent power outages and high system losses and (vi) high dependence on imported petroleum fuels [2].

The Kenya Government has developed the Kenya Vision 2030 as the country's new development blueprint. The vision aims at transforming Kenya into a newly industrializing, middle-income country providing a high quality of life to all its citizens by the year 2030 and it has identified provision of energy as the key to meet its goals. Aligned to this strategy document, Kenya has implemented the Energy Policy 2004, targeting to reach electricity connectivity in the rural population of 40% by 2020, has subscribed the UN Sustainable Energy for All Initiative and the manifesto of Jubilee Coalition [3].

In order to pursue the energy access for all, the challenge is focused both on energy transmission and distribution and power generation. Since the energy transmission is capital intensive and has hitherto concentrated in high population density and high economic areas, the Kenya Government has installed off-grid diesel power stations and distribution mini-grids covering some rural areas remote from the transmission grid.

The systems based on diesel generation installed by the Ministry of Energy and Petroleum to supply electricity to areas which are far from the national grid have experienced a number of challenges, such as (i) the cost of fuel increase with the remoteness of the location, (ii) on-site storage challenges, (iii) high operation and

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maintenance costs, and (iv) the gas emissions contribution to environmental pollution and global warming (CO_2).

In 2010, the Ministry of Energy and Petroleum, through the Kenya Power Company, commenced a pilot programme to hybridize these off-grid power stations by installing renewable energy power sources, particularly wind and PV-solar.

Currently, there are off-grid diesel power stations as well as pilot hybrid systems (solar, wind or solar/wind), and new installations by Rural Electrification Authority (REA) are currently ongoing. One of such operational stations is Habaswein, which consists of a 410 kW diesel generator, a 60 kW wind power plant and a 30 kWp photovoltaic (PV) solar plant.

1.2. Statement of the problem

The installations of off-grid hybrid systems in remote areas, promoted by the Ministry of Energy and Petroleum, were done without a proper study and optimization. No detailed analysis has been done to establish the performance, reliability and sustainability of the hybrid power stations in the Kenyan context. The Habaswein power station is one of the pilot off-grid hybrid stations, but the contribution of renewable energy is very low, since the energy is generated almost exclusively by the diesel generator. This study is thus geared towards covering this existing gap in relation to hybrid off grid power stations in Kenya, assess their sustainability and feasibility in meeting the rural electrification challenges, including optimization criteria and levels. Furthermore, it is prudent to investigate ways of ensuring grid stability from these variable renewable energy sources.

1.3. Justification of the study

As the Ministry of Energy and Petroleum promotes the installation of hybrid stations in remote areas, it is fundamental to conduct a in depth technical assessment of the existing hybrid plants on their system reliability, the value for the investments and their current system performance in order to advise their optimization by using renewable energy resources and ensure the technical and financial sustainability. The outcome of this study will reinforce the policy making activities of implementing the hybridization programme. Furthermore, this study aims at providing information about the use of mini-grids as a convenient solution to increase electricity access to remote areas. This information is required in order to provide impetus to upscale the installation of the mini-grids and hybrid systems. The study will also provide technical inputs on methods and ways of optimizing the hybrid- systems.

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1.4. Objectives

1.4.1. Overall Objective

The overall objective of this research is to reinforce the policy making activities of implementing the hybridization of off-grid power stations programme in Kenya and provide lessons learned on the development of mini-grids aimed at increasing access to electricity in remote areas of developing countries.

1.4.2. Specific Objective

The specific objective of the research is to evaluate the performance of the Habaswein off-grid hybrid power station based on wind, PV-solar and diesel generation, assess the potential of the renewable energy sources and optimize the existing systems to enhance its reliability, performance and sustainability.

2. Literature Review

2.1 The Relevance of hybrid systems in Off-Grid Electrification Projects

Planning for universal electricity access in countries currently with a low electrification level will entail large numbers of new grid connections. This may require the reinforcement or expansion of the transmission network and the addition of new generation, therefore demanding a complete appraisal of the power system [4], with a focus both off-grid and on-grid markets across generation, distribution, transmission and customers.

The growing consideration towards the target of universal access to energy has emphasized the role of rural electrification, and off-grid small-scale generation represents one of the most appropriate options [5].

Hybrid stand-alone electricity generating systems are often considered more reliable and less costly than systems that rely on single source of energy [6] and those based on renewable energy are economically viable especially in remote locations [7],[8]. During the recent years, the combined use of renewable energy sources, especially wind and solar, is becoming increasingly attractive and being widely used as an alternative to fossil fuel energy [9]. Governments are therefore ought to regularly evaluate the renewable power development policies in order to effectively promote the application of renewable energy sources [10], especially for off-grid power plants, since the fuel procurement can be a serious issue in rural areas, due to lack of good infrastructures, combined to long distances existing between the mini-grid and the fuel station; however, this aspect is usually disregarded in designing the mini-grid [11].

Another important aspect of evaluation of energy systems is the Project sustainability and its impact on sustainable development, in which the energy plays a crucial role.

Most of the existing off-grid solutions, whilst having a very positive impact in delivering basic energy services, are not focused on productive uses – the main

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driver of job creation and economic growth. It is therefore necessary to upscale the ambition of off-grid electrification efforts. This could be helped by the ongoing trend of cost reduction and performance improvement of the technologies for electricity supply and demand, which now allow for addressing electrification in different ways [4].

The energy availability, exploitation, development and use influences practically all fields of social, economical and political activities, environment and climate and often determines whether nations will live in peace or conflict with each other.

2.2 Alternative Methodologies for Off Grid Electrification Projects

Bhattacharyya reviewed alternative methodologies that are used for off-grid electrification projects to identify the features of each methodological approach and to present their strengths and weaknesses [12]. He focused on techno-economic feasibility studies, analytical works highlighting methodological applications and practice oriented literature. The review identified five methodological options, namely: worksheet-based tools, optimization tools, multi-criteria decision-making tools, system-based participatory tools and hybrid approaches. He recommended a hybrid approach that combines two or more options to take advantage of their strengths and weaknesses as well as to verify results from alternative approaches, but can be resource intensive and will therefore require careful consideration on a case- by- case basis.

2.3 Systems Optimization

The optimum design of a hybrid system in rural areas is challenging due to uncertain load demand, non-linear characteristics of renewable components, the high number of variables and parameters to be considered, and the fact that the optimum configuration and optimum control strategy of the system are interdependent [13].

This complexity is higher in the first system design than in the system optimization mainly due to error in short-term load forecasting that might be significant in isolated and rural context due to the high variability of the community consumption in the early stages of electrification and the difficulty to obtain data from the area and develop an estimation method [14]. However, there are software tools, such as *LoadProGen*, developed by the Polytechinc University of Milan that, given a set of input data, can simulate the corresonding load profiles which can be employed in the design process of off-grid systems for rural electrification [15].

An optimizing sizing method is necessary in order to efficiently and economically utilize the renewable energy resources. The optimizing method can help guarantee the lowest investment with full use of the technologies, so that the hybrid system can work at the optimum conditions in terms of investment and system reliability. This type of optimization requires the assessment of the system's long-term performance in order to reach the best compromise for both reliability and cost.

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In order to select an optimum combination for a hybrid system to meet the load demand, evaluation must be carried out on the basis of power reliability and system life-cycle cost [13].

The analysis should be conducted not only on the power generation side, but also taking into account the possibility of a storage component. In this regard, a case study of a wind power plant in Sao Vicente, Cape Verde, has showed that combining renewable energy forecasting and energy storage is a promising solution which enhances diesel fuel savings as well as enables the isolated grid to further increase the annual renewable energy penetration from the current 30.4% up to 38.0% while reducing grid unreliability. In general, since renewable energy forecasting ensures more accurate scheduling and energy storage can compensate the missing or exceeding scheduled production, this solution is applicable to any small size isolated power grid with large renewable energy penetration [16].

However, the design, optimization and operation control of hybrid energy systems with two or more energy sources are complex and the risk of failure is increased [17]. Researchers have studied a wide variety of methods to reduce the complexity of designing hybrid energy systems. Some useful methods include Probabilistic, Analytical, Iterative and Hybrid methods [18]. A number of studies have used these methods to design optimal hybrid systems combining two or more energy sources.

Simulation and modelling programmes are the most common tools for evaluating the performance of the hybrid systems. By using computer simulation, the optimum configuration can be found by comparing the performance and energy production cost of different system configurations.

For instance, a feasibility study of a small hydro-PV-wind hybrid system for rural electrification in Dejen District, in Ethiopia, proposed the optimal hybrid combination of wind, hydro, diesel, battery systems by using HOMER software [19].

Another example is given by the design of a microhydro-PV hybrid system by using HOMER software: thanks to the yearly simulation of the system operation, making it possible to analyse the complementary contributions of both components, the necessity of storing energy and introducing a diesel generator as back-up was revealed [20].

A further study was conducted on off-grid electrification of seven villages in the Almora district of Uttarakhand state, India, where biomass, solar, micro-hydro and wind energy sources were considered and analyzed by using LINGO and HOMER software. The scenario accounting 44.99% of energy produced by micro-hydro, 30.07% by biomass, 5.19% by biogas and 4.16% by PV, along with the additional resources of wind (1.27%) and energy plantation (12.33%) has been found to be the best among the different options considered [21].

Furthermore, Connolly [22] did a comparative study of 68 computer tools for integration of renewable resource in various energy systems. Accordingly, HOMER was evaluated as one of the most applicable for optimization, feasibility and sensitivity analysis of both off-grid and grid connected micro power systems.

Akikur [17] also pointed out that HOMER is the most used and best known of all the software tools so far developed, as it is explained below.

2.4 Resource Potential

Kenya is endowed with vast indigenous renewable energy resource potential, as confirmed by various studies. In 2001, the Ministry of Energy and Petroleum developed a Wind and Solar Resources Atlas, using synoptic weather data, which was improved in 2008 in collaboration with UNDP and other partners, with higher resolution. It showed that wind regimes can support commercial electricity generation with average speeds ranging from 8 to 14 meters per second in certain parts of Kenya, such as Marsabit, Turkana, Ngong and the Coastal region, representing a total area of 22,000 square kilometers. Buoyed by this positive outcome, the Ministry of Energy and Petroleum commenced wind data logging in specific high potential areas in December 2009. In 2013, this data was analyzed, leading to higher resolution wind maps that confirmed the huge potential for wind energy development. Incidentally, the areas with good speeds are in the remote areas on northern Kenya, which are not served by grid connected electricity.

3. Results

The study evaluates three possible solutions, with and without Battery Energy Storage Systems (BESS).

3.2.1. Hybrid diesel/PV system without BESS

The absence of a BESS implies the excess energy produced by the power plant cannot be stored and be available anytime, so the diesel generators will satisfy the demand when the PV system is not producing enough energy.

This configuration is formed by a 569 kWp PV generator, with a 193 kW inverter, and two diesel generators of 100 kW and 410 kW.

The PV total energy production would be 868,391 kWh/yr and satisfies about 40%, of load energy consumption. The excess energy produced by the PV plant is 430,993 kWh, so almost 50% of the energy produced is not consumed.

Table 1 PV plant Energy production, solution without BESS

Installed PV Power (kWp)	Average Power Output (kW)	Average Energy Output (kWh/day)	Total Energy Production (kWh/yr)	Maximum Power Output (kW)	Hours of Operation (hr/yr)
569	99,1	2,379	863,391	449	4,377

The installation of a 100 kW diesel generator allows the 410 kW diesel generator to work only at its best efficient rate, avoiding conditions of very low loads (<30% of nominal capacity): this solution improves the global efficiency of the power

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generation with fossil fuels and the diesel generators total production is 637,798 kWh/yr with a fuel consumption of 206,748 l.

Table 2 Diesel Generators Energy production, solution without BESS

Diesel Generator (kW)	Hours of Operation (hr/yr)	Numbers of Starts (starts/yr)	Operational Lifetime (yr)	Electrical Production (kWh/yr)	Minimum Output (kW)	Maximum Output (kW)	Mean Output (kW)	Fuel Consuption (l/yr)
410	3,933	602	3.81	495,937	102	292	126	163,241
100	2,720	975	5.51	141,861	25	90	52.2	43,507
Total	6,653	1,577	-	637,798	25	292	95.7	206,748

In this optimization scenario the excess electricity generated is 408,305 kWh/yr, corresponding to 27,1% of the total electricity generation which is 1,506,189 kWh/yr.

With a COE of 0.354 $/kWh and a NPC of 7,568,600.45 $, this optimization scenario, compared to the current situation, reduces (i) the diesel consumption by 184,537 l/yr, (ii) the CO_2 emissions by 484,649 kg/yr and (iii) the emissions of other pollutants by 3,612 kg/yr.

3.2.2. Hybrid diesel/PV system with limited BESS

The BESS allows the possibility to storage the excess energy produced by the power plant. In such scenario, the diesel generators will support the system to satisfy the demand when the PV system and the BESS cannot supply enough energy.

In this simulation there was evaluated a limited BESS capacity to stay within a battery capital cost of 800,000 $.

This configuration is formed by a 578 kWp PV generator, with a 206 kW inverter, a 1,328 kWh BESS capacity, and two diesel generators of 100 kW and 410 kW.

The diesel generators total production is 339,665 kWh/yr with a fuel consumption of 109,927 l/yr.

PV total energy production is 882,471 kWh/yr and satisfies the 68.4% of the load energy consumption, thanks also to the energy collected in the BESS.

Table 3 PV plant Energy production, solution with Limited BESS

Installed PV Power (kWp)	Average Power Output (kW)	Average Energy Output (kWh/day)	Total Energy Production (kWh/yr)	Maximum Power Output (kW)	Hours of Operation (hr/yr)
578	101	2,418	882,471	456	4,377

Table 4 Battery Bank operational parameters

Nominal Capacity (kWh)	Usable Nominal Capacity (kWh)	Autonomy (hr)	Energy In (kWh/yr)	Energy Out (kWh/yr)	Losses (kWh/yr)
1,328	1,062	7.57	319,224	292,867	27,409

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Table 5 Diesel Generators Energy production, solution with Limited BESS

Diesel Generator (kW)	Hours of Operation (hr/yr)	Numbers of Starts (starts/yr)	Operational Lifetime (yr)	Electrical Production (kWh/yr)	Minimum Output (kW)	Maximum Output (kW)	Mean Output (kW)	Fuel Consuption (l/yr)
410	1,919	488	7.82	224,775	102	231	117	75,030
100	2,082	840	7.20	114,890	25	90.5	55.2	34,897
Total	4,001	1,328	-	339,665	25	231	84.9	109,927

In this optimization scenario the excess electricity generated is 82,071 kWh/yr, corresponding to 6.7% of the total electricity generation which is 1,222,136 kWh/yr.

With a COE of 0.305 $/kWh and a NPC of 6,507,321.53 $, this optimization scenario, compared to the current situation, reduces (i) the diesel consumption by 281,358 l/yr, (ii) the CO_2 emissions by 738,656 kg/yr and (iii) the emissions of other pollutants by 5,681 kg/yr.

3.2.3. Hybrid diesel/PV system with optimized BESS

The BESS allows the possibility to storage the excess energy produced by the power plant. In such scenario, the diesel generators will support the system to satisfy the demand when the PV system and the BESS cannot supply enough energy.

This configuration is formed by a 808 kWp PV generator, with a 202 kW inverter, a 2,598 kWh BESS capacity andthree diesel generators of 50 kW, 100 kW and 410 kW. Three diesel generators have been chosen to reduce as much as possible the use of the 410 kW generator, which is installed as backup component. The diesel generators total production is 94,383 kWh/yr with a fuel consumption of 28,719 l/yr.

PV total energy production is 1,233,580 kWh/yr and satisfies, thanks to the energy collected in the BESS, 91.2% of load energy consumption.

Table 6 PV plant Energy production, solution with Limited BESS

Installed PV Power (kWp)	Average Power Output (kW)	Average Energy Output (kWh/day)	Total Energy Production (kWh/yr)	Maximum Power Output (kW)	Hours of Operation (hr/yr)
808	141	3,380	1,233,580	638	4,377

Table 7 Battery Bank operational parameters

Nominal Capacity (kWh)	Usable Nominal Capacity (kWh)	Autonomy (hr)	Energy In (kWh/yr)	Energy Out (kWh/yr)	Losses (kWh/yr)
2,598	2,122	15.1	555,610	510,602	46,632

Table 8 Diesel Generators Energy production, solution with Limited BESS

Diesel Generator (kW)	Hours of Operation (hr/yr)	Numbers of Starts (starts/yr)	Operational Lifetime (yr)	Electrical Production (kWh/yr)	Minimum Output (kW)	Maximum Output (kW)	Mean Output (kW)	Fuel Consuption (l/yr)
410	107	42	Over 25	17,179	117	224	161	5,329
100	816	162	18.4	65,316	25	100	80	18,810
50	809	349	18.5	11,888	12.5	41.6	14.7	4,580
Total	1732	553	-	94,383	12.5	224	54.5	28,719

In this optimization scenario the excess electricity generated, excluding energy losses, is 156,674 kWh/yr, corresponding to 11,8% of the total electricity generation which is 1,327,963 kWh/yr.

With a COE of 0.253 $/kWh and a NPC of 6,179,443.19 $, this optimization scenario, compared to the current situation, reduces (i) the diesel consumption by 362,566 l/yr, (ii) the CO_2 emissions by 951,658 kg/yr and (iii) the emissions of other pollutants by 7,310 kg/yr.

3.2.4 Environmental evaluation

For environmental evaluation of all solutions presented above, yearly Green House Gas emissions were considered (Table 9). The hybrid plants present lower emissions because fuel consumption is lower than the present plant, the installation of a BESS achieve the maximum reduction of pollutants because the battery system can supply energy when the PV plant is not working, indeed, in the configuration without BESS, the diesel generators will work every time the PV plant is not producing enough power. Genset emissions are evaluate through software emissions factors: Green House Gas emissions versus energy production ratio (kg/kWh).

Table 9 Green House Gas Emission comparison

	Diesel Consumption (l/yr)	CO2 emissions (kg/yr)	Other pollutants (kg/yr)	Reduction of diesel consumption (l/yr)	Reduction of CO2 emissions (kg/yr)	Reduction of other pollutants (kg/yr)
Present	391,285	1,026,828[1]	8,170	-	-	-
No BESS	206,748	542,179	4,558	184,537	484,649	3,612
Limited BESS	109,927	288,172	2488.84	281,358	738,656	5,681
Optimized BESS	28,719	75,170	860.31	362,566	951,658	7,310

1 The CO_2 emissions were calculated by simulating the present system, with the present consumption, in HOMER PRO

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3.2.5 Economic evaluation

For economic evaluation of all solutions presented above, please refer to the following table (Table 10).

Table 10 Comparison of economics.Plant

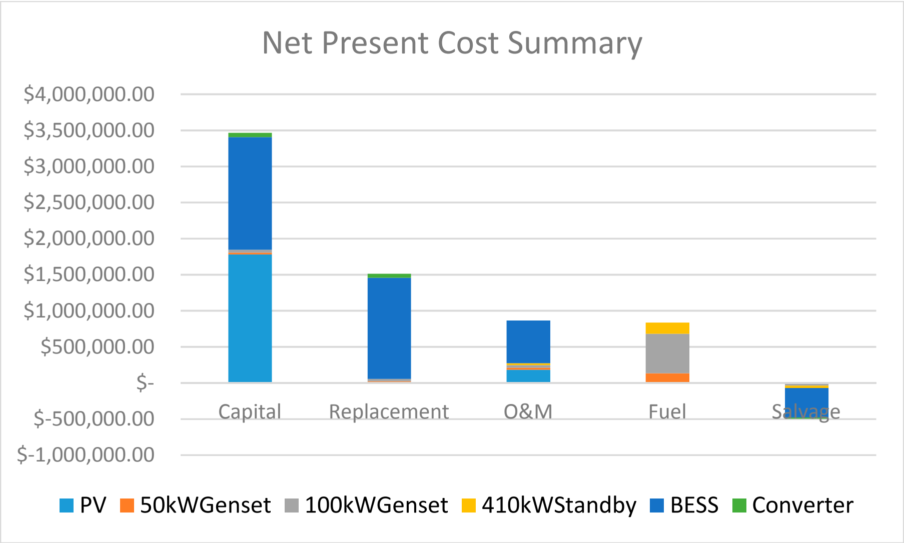
	Diesel Gen (kW)	Capex ($)	PV (kWp)	BESS (kWh)	Wind farm (kW)	Fuel Consumption (l/yr)	Diesel and O&M ($/yr)	COE ($/kWh)	NPC ($)
Present	410	0	30	-	60	391,285	578,681	0.46	10,600,000
No BESS	410 100	1.35 M	569	-	60	206,748	285,561	0.354	7,568,600
Limited BESS	410 100	2.15 M	578	1,328	60	109,927	169,556	0.305	6,507,321
Optim. BESS	410 100 50	3.46 M	808	2,598	60	28,719	74,740	0.253	6,179,443

NPC of present configuration is higher than hybrid configurations: costs of fuel, O&M and replacement are larger for genset. In the hybrid configurations, the O&M costs are lower that current one thanks to a reduction in fuel consumption. This difference influences the COE of the four configurations: COE of hybrid plants is lower than genset plant: 0.354 $/kWh, 0.305 $/kWh and 0.253 versus 0.46 $/kWh.

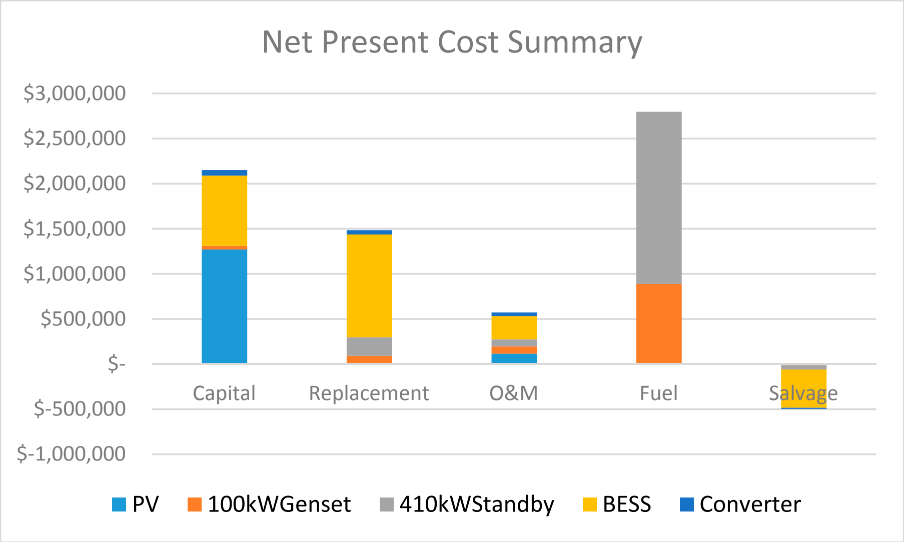
The three proposed solutions can guarantee a relevant cost reduction but there are differences between the solution with and without BESS.

The following graphs show the Net Present Costs Summary of the three solutions.

The solution without BESS has a lower Capex but high fuel costs due to the larger use of the diesel generators,whereas the solutions with BESS have lower fuel costs, which are the most variable, but the O&M costs are higher due to the BESS replacement cost, which grows with the storage capacity.



366
367 **Figure 1** Net Present Cost Summary, configuration Optimized BESS
368



369
370 **Figure 2** Net Present Cost Summary configuration limited BESS
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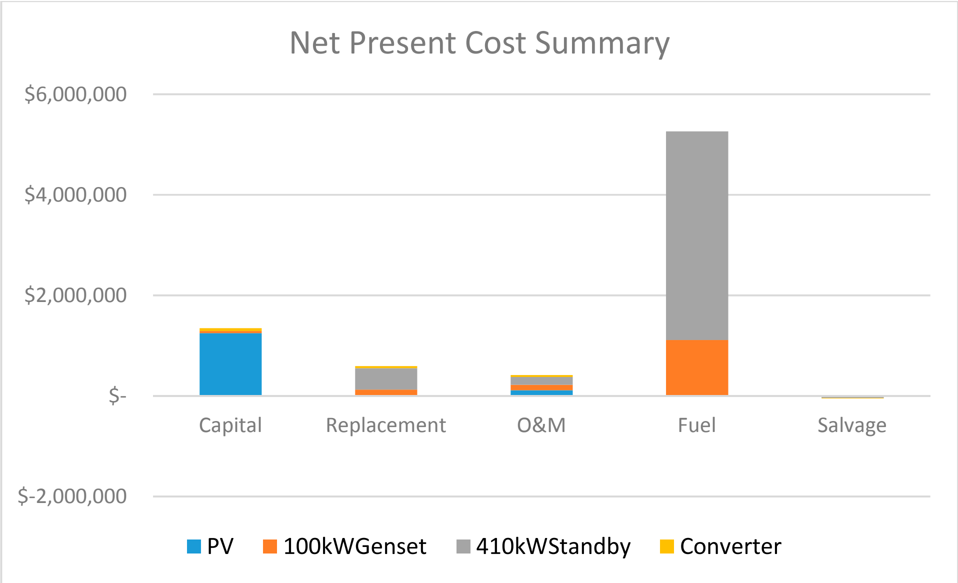

Figure 3 Net Present Cost Summary configuration without BESS

Without a sufficient initial financial means, the solution without BESS is the best solution, it reduces the COE but it is still highly dependent from the fuel price variability.

The solutions with BESS have a lower dependence from the fuel price but a higher Capital cost.

4. Discussion

This paper studied some technical, environmental and economic aspects of solutions that can be applied in rural areas without access to electricity in developing countries. We have considered the case study of the community of Habaswein, Kenya, where a off-grid diesel generator supplies energy with a partial contribution of a PV plant and a wind farm.

The present plant performances were studied and the main characteristics and problems of the plant highlighted:

- there is a growing energy demand recorded: the number of connections is almost tripled from the start up of the minigrid and there is a constant growth of energy production;
- the energy production supplied by the diesel generator is dominant with large emissions of GHG and other pollutants;
- the energy production cost is high and it is subjected to many variations due to operation condition of the plant.

The HOMER PRO software was used to carry out the study of the optimization of the present plant, through which various adoptable solutions have been studied, by applying fully renewable or hybrid configurations. Technical and operational values have been evaluated for each solution, and subsequently, the most cost-effective solutions have been chosen and compared with the present plant.

As result of this study, three different solutions to compare were selected: one with limited storage, one with storage optimized by Homer Pro and one without storage. The criteria applied to drive technical solutions were the following:

- Capital cost: the solution without storage has a lower initial cost;
- Operational cost: the solution with storage needs less fuel so the yearly cost of the plant will be lower and will be less subjected to the fuel price variations;
- Dependency on the fuel price: the fuel price is the expense which drives the cost of the plant during his life, it is variable and it is difficult to make prevision on its variation during the years;
- Polluting emissions: the solution with storage needs less fuel which is the origin of the pollutants.

This study's results show that all the selected optimization solutions are able to improve the current plant. The main common aspects can be summarized as follows:

1. Considering 25 years plant lifetime, hybrid configurations are more convenient in comparison with non-renewable configurations as the base case is. In fact, the hybrid solutions have a lower NPC then the base case and that influences the COE of every configurations: the solutions with BESS vary their COE from 0.253 to 0.305 $/kWh, about 43% less than base case COE.
2. Hybrid solutions are more competitive at the economic level, compared to non-renewable solutions, also in developing countries, with weak economies and where factors like inflation and real interest rate are unpredictable. This kind of solutions bring to save money, as reported in the economic evaluation, that could be used differently, for instance investments in local enterprises and social goods;
3. Hybrid solutions brings to save fuel and so to reduce Greenhouse Gases emissions, with savings of tens to hundreds of tons of CO_2 every year, compared with alternative solutions based on fossil fuels. Thus, with an overall point of view, the use and diffusion of renewable energy in developing country, instead of traditional energy systems, represents a strong contribution to reach the objectives of greenhouse emission reduction, set by the international community in the COP21 of Paris.

5. Materials and Methods

5.1 Study location

The study has been undertaken at Habaswein hybrid off grid power station situated in Kenya, its geographical coordinates are 1° 0' 33'' North, 39° 29' 17'' East, Habaswein is a settlement in Kenya's North Eastern region, which is almost exclusively inhabited by ethnic Somalis. The name Habaswein literally means a lot of dust. The town falls under Wajir south constituency in Wajir County whose population was 138,000 in the 2009 census.

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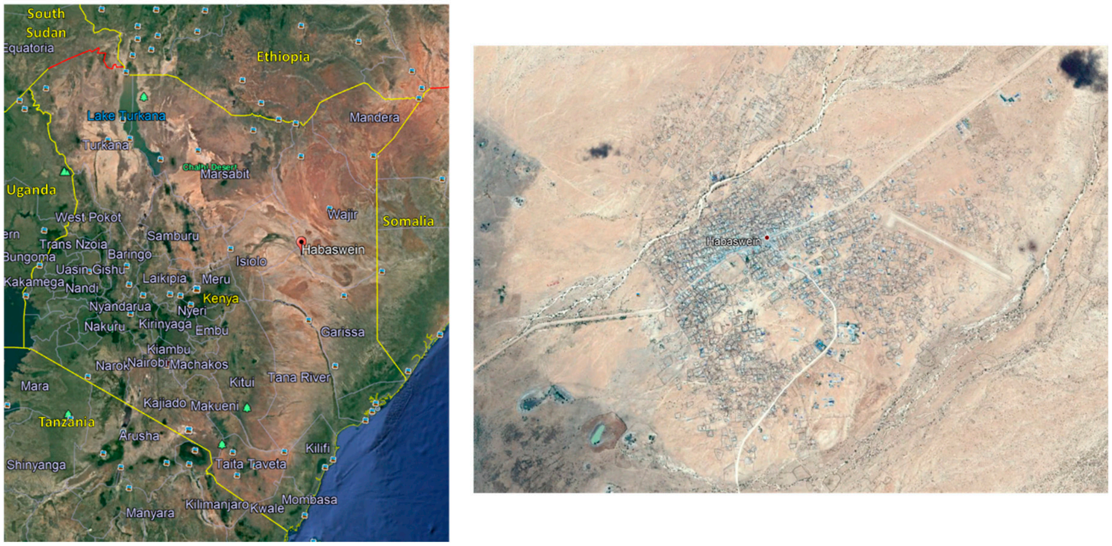

Figure 4 Habaswein location

5.2 Data Collection

Raw primary data of the hybrid station performance for five years have been obtained from the Kenya Power and Lighting Company (KPLC) in regards to the energy generated by the diesel, wind and solar components, the fuel consumption, and the power loads.

5.3 Minigrid technical specification

The existing electricity generation is a diesel-based system. The system consists of one diesel generator with total capacity of 410 kW, a 30 kWp photovoltaic plant and a wind farm of 3 wind turbines of 20 kW each, all synchronized in the same bus bar. The system supplies electricity demand for nearly 365 days a year. A diesel generator was installed in 2010 and, due to serious problems, it was substituted in 2012 by a similar generator with the same power.

In detail, the mini grid consists of the components as in Tab. 11.

Table 11 Habaswein Hybrid Minigrid Components

Typology	Installed Capacity (KW)	Year of Installation	Type of fuel used
Diesel Generator	410	2012	Diesel
Photovoltaic	30	2012	-
Wind	60	2012	-

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5.4 Data Analysis

5.4.1. Market growth and energy production

Fig. 5 shows the trend of the number of minigrid customers over the years.

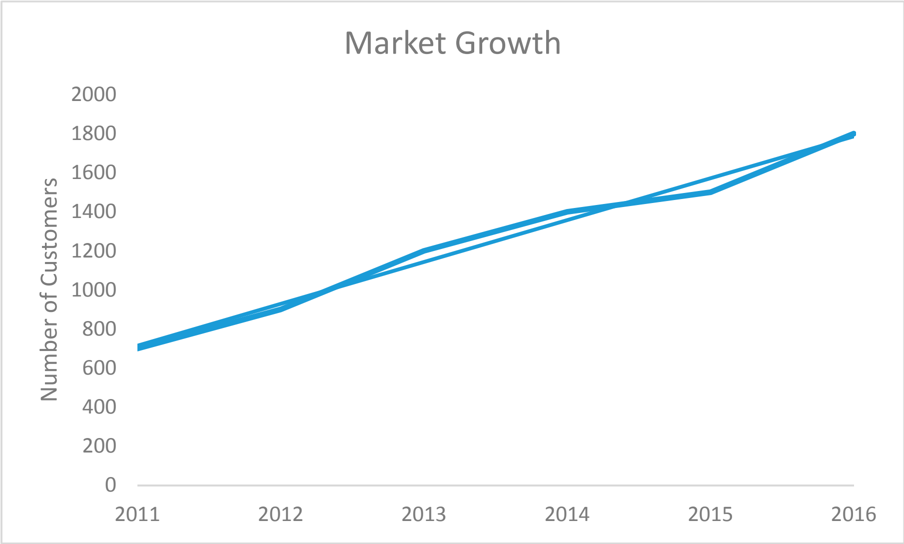

Figure 5 Market Growth

The chart shows that, in 5 years, the number of customers has almost tripled; in parallel with the number of customers, there is a growth of the energy production. The Fig. 6 shows the trend of electricity production from 2011 to 2015, divided by type of energy source.

The energy production growth rate is less than the customers growth probably because the new customers are domestic users, while the first customers were both domestic and productive users.

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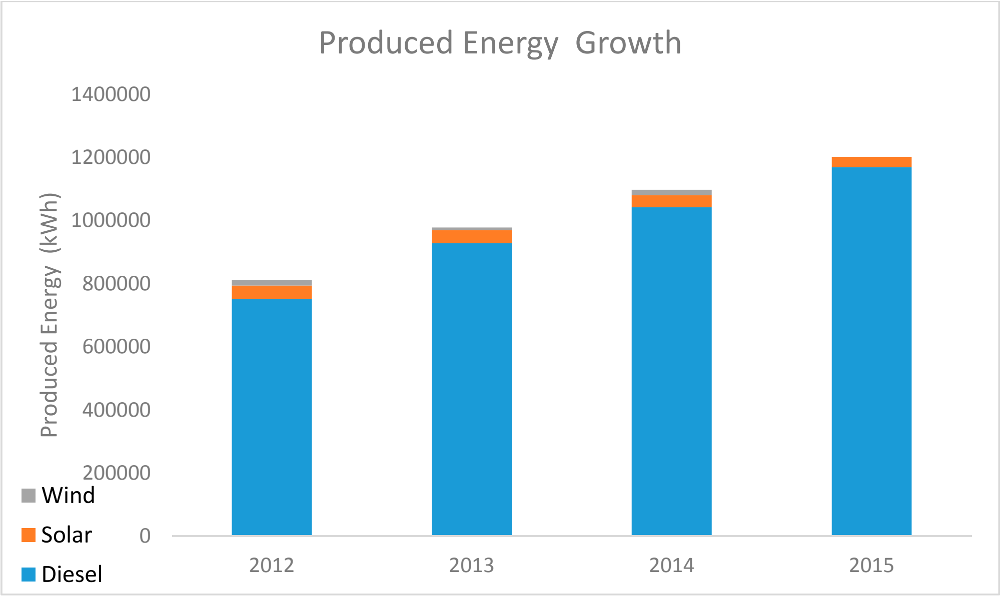

Figure 6 Produced Energy Growth

The increase of energy production is about 50% in 4 years. It can also be noticed that this production increment was realized exclusively through the diesel generator; Energy production through renewable sources remains marginal.

5.4.2. 2014 – Yearly analysis

The behavior of the Habaswein Hybrid minigrid is presented in more detail by choosing a reference year, in particular 2014 and by carrying out a global annual, monthly and daily analysis.

The 2014 was chosen because there were less interruptions of the minigrid operation.

The Fig. 7 shows the energy mix through which energy production was carried out.

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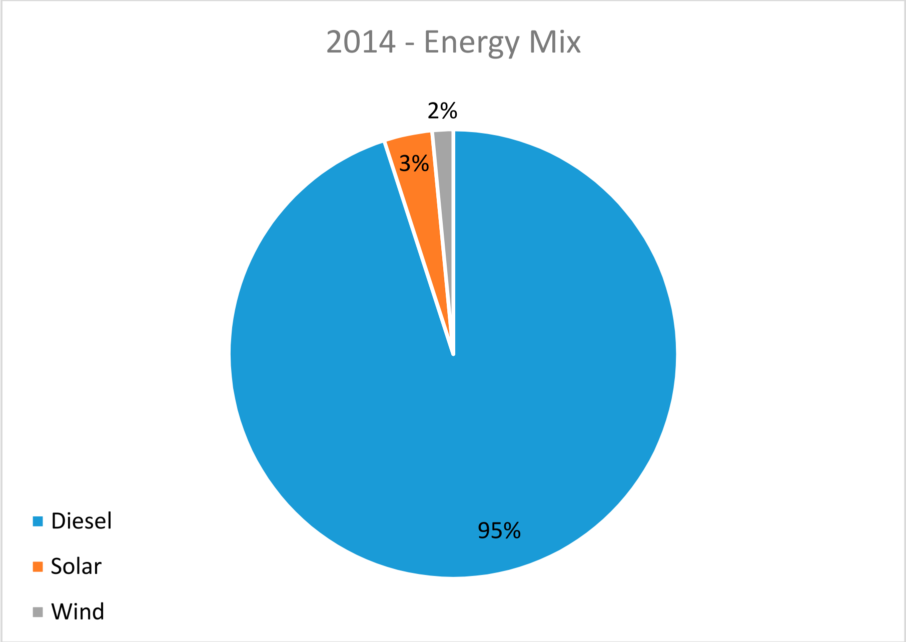

Figure 7 Energy mix, year 2014

As can be seen from the chart, energy production has been realized almost entirely using Diesel generators. Only 5% of the electricity generation was produced using renewable energy sources.

Monthly energy production is shown in Fig. 8. As can be seen, this presents a limited variability over the year with an average energy value of 91,417 ± 7,671 kWh with a total yearly production of 1,097,413 kWh. Referring to the mean value, the maximum and minimum of the energy production deviates by 10%.

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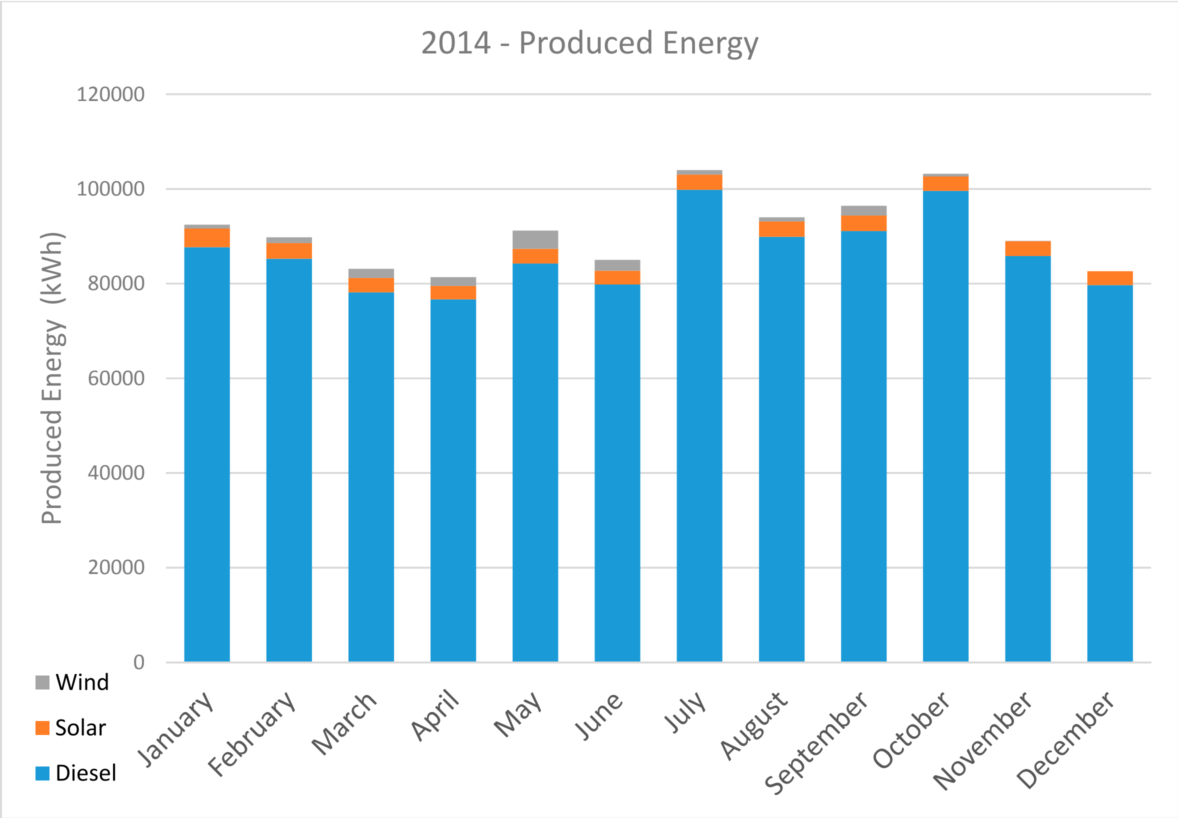

Figure 8 Monthly energy production, year 2014

In Fig. 9 is represented the typical behavior of the energy production during a day.

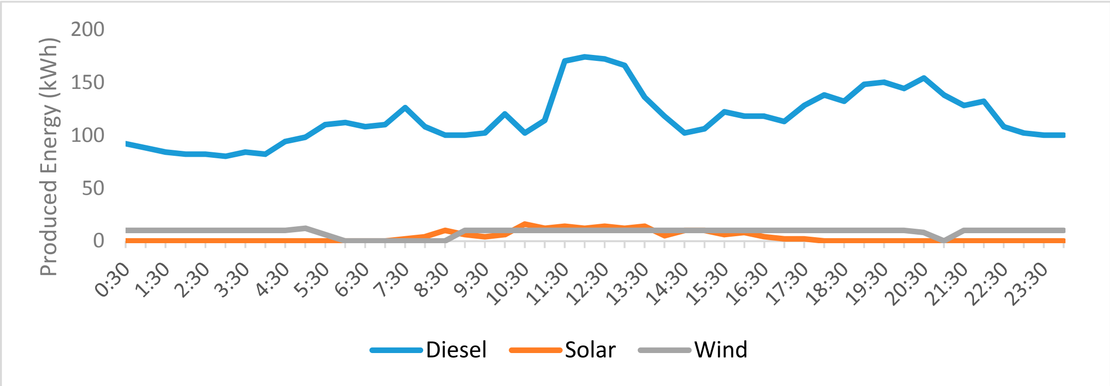

Figure 9 Typical daily energy production, year 2014

As it can be observed from the chart, there are two peaks in the production one towards the middle of the day and one evening.

5.4.3. Operational Costs

In 2014 the total amount of the operational cost was 578.681,82 $, including diesel supply, ordinary and extraordinary maintenance.

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Table 12 Monthly operational data, year 2014

	jan	feb	mar	apr	may	jun	jul	aug	sept	oct	nov	dec
Consumption [litre]	35,742	31,359	35,044	29,888	28,796	32,879	33,678	35,758	33,507	36,047	30,437	28,150
Cost [$]	46,360	41,318	46,292	39,481	38,069	44,155	45,216	47,809	37,834	47,705	37,672	31,292
Energy Production [kWh]	92,868	89,808	83,127	81,364	95,920	85,016	103,992	94,028	96,433	103,216	89,040	82,604
Energy cost [$/kWh]	0.50	0.46	0.56	0.49	0.40	0.52	0.43	0.51	0.39	0.46	0.42	0.38
Energy production Rate [kWh/litre]	2.60	2.86	2.37	2.72	3.33	2.59	3.09	2.63	2.88	2.86	2.93	2.93

The average energy cost is 0.46 $/kWh but there is a strong variation during the year with a maximum variation of 0.10 $/kWh, corresponding to 22% of the energy price.

This important variation is due to the diesel price variability and to operation condition of the plant, the following graph compares the Energy production rate with the diesel generator efficiency, it is evident that the two curves have opposite trend, when the Energy production rate increases the energy cost decreases and vice-versa.

This shows how strong is the influence of the diesel generator on the variation of the operational cost of the mini-grid of Habaswein and how uncertainty there is around the energy cost variation.

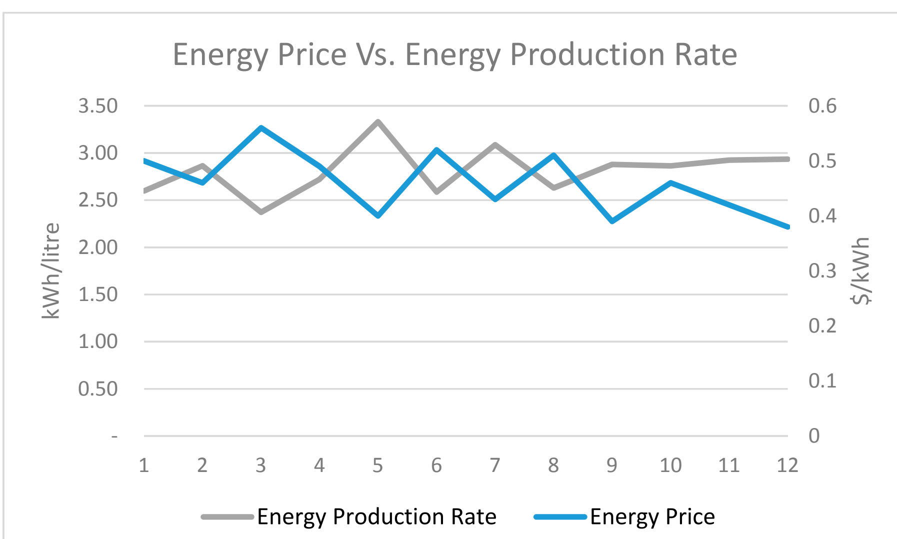

Figure 10 Energy Price Vs. Energy Production Rate

5.5 Simulation and Optmization with HOMER PRO

HOMER software will be used to simulate and model different mix scenarios with the aim of establishing the optimal penetration levels of renewable energy. HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. It has been developed by United States National Renewable Energy Laboratory since 1993. It is developed specifically to meet the needs of renewable energy industry's system analysis and optimization. There are three main tasks that can be performed by HOMER: simulation, optimization and sensitivity analysis. In the simulation process, HOMER models a system and determines its technical feasibility and life cycle. In the optimization process, HOMER performs simulation on different system configurations to come out with the optimal selection. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of inputs to account for uncertainty in the model inputs. Detailed description on HOMER software can be found in [23], [24].

HOMER Pro Microgrid Analysis Tool 3.9.2 [25] is the simulation tool adopted for the optimization of the plant. This simulation tool assists in the planning and design of renewable energy based micro-grid. The physical behavior of each power plant configuration, their life-cycle cost and the energetic and economic comparison were made through the three main operation of the software: Simulation, Optimization and Sensitivity Analysis.

In the Simulation area, HOMER Pro determines technical behavior, feasibility and life-cycle cost of a system for every hour of the year. The assessment is made not only for the entire system: the operation of each component is simulated to examine how the components works in relationship with the entire system.

In the Optimization section HOMER displays each feasible system and its configuration in a search space sorted by the minimum cost depending on the total net present cost. In this way, we can find the optimal configuration which satisfies the constraints imposed in the model. The description of economic output is set out in the following paragraph.

In the section of Sensitivity Analysis, the user can analyse the effects of parameter variations in time and the behaviour of the sensitivity variables. The sensitivity variables are those parameters entered by the user and having different values.

Before the construction of the model, the first step needed is the evaluation of the load which could be electric, thermal or both, although in this study we focus on the electric load. In the present paper the yearly electric load profile adopted was the measured load of 2014 with 30 minutes step.

5.5.1. Renewable Resources assessment

There have been considered two main renewable resources, solar irradiation and wind.

The solar irradiation and surface annual solar radiation data have been obtained from an average of 20 years of NASA data (freely available also at [26]). The scaled average annual of daily solar radiation in this region is 5.90 kWh/m2. The average clearness index for the mini grid is 0.59 (Table 13, Figure 11).

Table 13 Solar Irradiation and Clearness index

Month	Clearness Index	Daily Radiation (kWh/m2/day)
January	0.63	6.269
February	0.639	6.589
March	0.577	6.054
April	0.547	5.602
May	0.594	5.785
June	0.58	5.463
July	0.571	5.442
August	0.594	5.931
September	0.631	6.52
October	0.579	5.967
November	0.544	5.433
December	0.593	5.804

Figure 11 Solar Irradiation and Clearness index

5.5.1.1. Wind

Implementation of the wind solution were discarded because the data analysis revealed a low energy production of the existing turbines. Indeed, the wind NASA data and on site wind measurement doesn't justify the measured low energy production, it should be investigated the reason of the misworking.

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The biomass were not considered due to their scarcity.

5.5.2. Components and cost

5.5.2.1. PV Panels

The PV array size is calculated using the *Homer OptimizerTM* algorithm. The considered PV system and replacement cost is 2,200 $/kWp. The O&M cost is set to 10 $/kWp/year.

The solar module type is a polycrystalline PV panel with efficiency 15%. The system includes PV modules costs, installation cost, transportation cost, cables and security system cost and balance of system cost.

5.5.2.2. Inverter

The Inverter size is calculated using the *Homer OptimizerTM* algorithm. The cost is 300 $/kW. The efficiency of the inverter is 95%.

5.5.2.3. BESS

For the BESS we consider a Li-Ion battery, with round trip losses of 8% [28], an estimated costof 600 $/kWh, an O&M cost of 10 $/kWh/year, and a connection on the DC bus. For the limited BESS solution, the size of the BESS is varied from 500 kWh to 1300 kWh with a step of 50 kWh.

5.5.2.4. Diesel Generators

The Diesel Generator is considered as a backup system, the present micro-grid has a 410 kW generator but, for the most of the time, it is oversized compared to the load curve. It has been evaluated the installation of additional generators.

For the 410 kW diesel generator it has not considered a capital cost because it is actually working, the replacement cost is 90,000 $, the O&M cost is 2 $/h. The 100 kW generator cost and its replacement are set to 40,000 $ and the O&M cost is 2 $/h. The 50 kW generator cost and its replacement are set to 25,000 $ and the O&M cost is 1 $/h.

The diesel cost is set to 1.28 $/l which is the average cost of the diesel in Habaswein in 2014.

5.5.3. Economic parameters

The lifetime of the plant for the economic evaluation is 25 years. The main factors to evaluate the economic optimal solution for the optimization of the Habaswein power plant are Net Present Cost (NPC) and the cost of electricity (COE). The

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esteemed lifetime of the PV panels is 25 years, the inverter 15 years, the BESS 10 years, the diesel generators 15,000 hours.

The discount rate of this study is 10% [27] and inflation rate is 8% (The World Bank).

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