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Assessment of electricity demand-supply in health facilities in resource-constrained settings: optimization and evaluation of energy systems for a case in Rwanda

Palacios, S.G.

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Assessment of electricity demand-supply in health facilities in resource-constrained settings

Optimization and evaluation of energy systems for a case in Rwanda

Silvana Gamboa Palacios
EES-2015-251

Master Programme Energy and
Environmental Sciences, University of
Groningen



**university of
groningen**

**faculty of mathematics
and natural sciences**

**energy and sustainability
research institute
groningen**

Research report of Silvana Gamboa Palacios

Cordaid (Catholic Organisation for Relief and Development Aid)

Lutherse Burgwal 10
2512 CB The Hague

Report: EES-2015-251

Supervised by:

W. (Willem) Tom, Business Developer Manager, Cordaid Health

Prof.dr. H.C. (Henk) Moll, Center for Energy and Environmental Sciences, IVEM

Prof.dr.ir. G.P.J. (Gerard) Dijkema, Center for Energy and Environmental Sciences, IVEM

Dr. R.M.J. (René) Benders, Center for Energy and Environmental Sciences, IVEM

University of Groningen

Energy and Sustainability Research Institute Groningen, ESRIG

Nijenborgh 4
9747 AG Groningen

T: 050 - 363 4760

W: www.rug.nl/fwn/research/esrig

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SUMMARY

In health facilities in resource-constrained settings, a lack of access to sustainable and reliable electricity can result on a sub-optimal delivery of healthcare services, as they do not have lighting for medical procedures and power to run essential equipment and devices to treat their patients. Currently, diesel generators are the most common solution to this issue; however they are expensive due to high fuel prices and required on-going maintenance. Also, connection to the grid in rural areas is often unreliable with frequent power outages. Renewable energies however, are cleaner solutions, but they are intermittent and capital intensive. Therefore, what would be the optimal combination to satisfy the demand of a rural health facility? Few studies have provided with empirical evidence of the linkages between electricity and the delivery of healthcare services. Health facilities require electricity for lighting, support child delivery, perform surgical procedures, emergency night-time care, refrigeration for blood and medicines, and to run other essential medical equipment. Therefore, the present research project intends to develop a protocol with the following purposes: (1) to study how to optimize energy systems in resource-constrained health facilities with renewable energies, and (2) to explore available data for assessing the impact of electricity supply on improving the delivery of healthcare services. A health facility in Rwanda called Gikomero is deeply studied as an example, focusing on solutions to improve their current electricity system, which is unreliable. In this study, the health facility is regarded as a system that requires reliable electricity supply to deliver healthcare services adequately. The main goal of optimizing the health facility's energy system is to improve the delivery of healthcare services. For a system analysis, internal and external requirements must be met involving reliability and sufficiency, and cost and sustainability. To assess electricity supply in health facilities, the local context must be studied individually and in detail. Data is collected on size of health facility, healthcare services delivered, electricity needs for equipment, current and future electricity demand-supply profiles and patterns over time, indicators of healthcare performance and diverse energy supply options that are suitable for a resource-constrained health facility. The HOMER simulation software is being used to optimize the different energy options in terms of economic, technical and environmental aspects to satisfy its current and future demand while showing various scenarios. Furthermore, to assess the impact of electricity in healthcare services delivery; data is collected on health-related indicators and electricity consumption to analyze change over time and visual relationships between these indicators.

The current demand of Gikomero health facility (HF) is dominated by the consumption of medical equipment, consuming 37% of the total electricity demand. Electricity supply options to satisfy the current and future demand of Gikomero HF are grid-connection, stand-alone diesel generators, solar PV panels, micro-wind turbines, micro-hydro power and biomass. The last two options were not feasible for this particular context. Energy storage systems such as batteries are expected to play an important role on increasing reliability, as systems relying only on renewable energy sources are vulnerable on their supply. Results show that a Business-as-usual (BAU) scenario has very high Net Present Costs (NPC) in comparison to other optimal scenarios that add new energy solutions. The BAU scenario however, shows the total costs of meeting the demand with sufficiency, meaning that blackouts are avoided through a generator running on a minimum load at all time (a perfect-functioning health facility). Also, the 'only renewables' scenario is very expensive, mainly due to capital-intensive technologies. The simulation results show that the most optimal option for the current system implies the addition of a 2kW solar system and 5 batteries, however when taking into account the future demand, the option proposed by Great Lakes Energy (GLE) of a 3kW solar system would be the most optimal, although with 5 batteries instead of 10 to avoid large expenses and oversizing. Moreover, results also show that storage is a really important aspect in resource-constrained health facilities. A 'no storage scenario' is very high on costs in the long-term, becoming un-affordable for the health facility. Here, batteries are considered as the 'game changers' and critical points for the reliability of the system. Furthermore, it was determined that the BAU system is oversized with a 12,5kW diesel generator, and that there are current energy losses in the system; this confirms the need for a storage system, even if renewable energies are not included. However, storage represents an argument for installing renewables to increase cost-effectiveness and independency. In terms of environmental emissions, the BAU scenario contrast highly with other scenarios so there is a need for an immediate response through an increase on the renewable fraction of the system.

LIST OF ABBREVIATIONS

AC	Alternating Current
AIDS	Acquired Immune Deficiency Syndrome
ANC	Ante-natal Consultation
ARVS	Antiretroviral
BAU	Business as Usual
CFL	Compact Fluorescent Lamp
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DC	Direct Current
D.o.D.	Depth of Discharge
EPA	Environmental Protection Agency
EU	European Union
Gen	Diesel Generator
GHG	Greenhouse Gasses
GLE	Great Lakes Energy
HDP	Health Development and Performance
HIO	High-Impact Opportunity
HIV	Human Immunodeficiency Virus
HF	Health Facility
HOMER	Hybrid Optimization Model for Multiple Energy Resources
IEA	International Energy Agency
IEC	Information, education and communication
KW	Kilowatt
KWh	Kilowatt-hour
LED	Light-emitting diode
MDGs	Millennium Development Goals
MinBuZa	Ministerie van Buitenlandse Zaken - The Netherlands
MINISANTE	Ministry of Health - Rwanda
MININFRA	Ministry of Infrastructure - Rwanda
NCDs	Non-communicable diseases
NGO	Non-Governmental Organisation
NO	Nitrogen Oxides
NO ₂	Nitrogen Dioxide
NPC	Net Present Costs
O ₃	Ozone
OPD	Outpatient Department
O&M	Operation & Maintenance
Pb	Lead
PBF	Performance-based Financing
PM	Particulate Matter
PMTCT	Prevention of Mother-to-Child Transmission
PNC	Post-natal Care
PV	Photovoltaic
SD	System Dynamics
SDGs	Sustainable Development Goals
SE4All	Sustainable Energy for All
SO	Sulphur Oxides
SO ₂	Sulphur Dioxide
TB	Tuberculosis

UN	United Nations
USAID	United States Agency for International Development
VCT	Voluntary Counselling and Testing
W	Watt
Wh	Watt-hour
WHO	World Health Organisation

1. INTRODUCTION

In developing countries, most rural areas often lack access to electricity or have unreliable energy supply sources. According to the International Energy Agency (IEA, 2012), the average electrification rate in sub-Saharan countries is 32% as shown in Figure 1-1. In these areas, most of health facilities do not have access to adequate energy resources to provide quality care to patients; and some of them rely on sources such as candles, flashlights and kerosene lamps. Without electricity, health facilities do not have lighting for medical procedures and power to run essential equipment and devices. In addition, they do not have hot water to create and maintain essential hygiene, and the ability to store vaccines and medicines at an appropriate temperature. These conditions may result on a sub-optimal delivery of essential healthcare services. Thus, health facilities with un-interrupted, stable and suitable electricity supply are expected to have a higher performance in delivering healthcare services. Besides of enabling a proper cold chain and improving diagnostic and curative services, the availability of reliable electricity leads to a better administration of the health facility, and supports the access to better communication channels and data management.

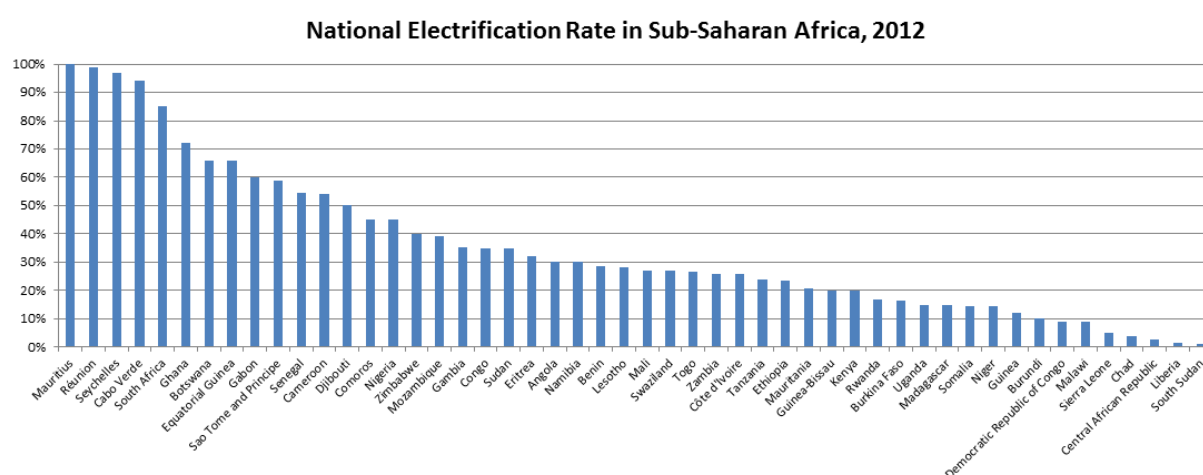


Figure 1-1 National Electrification Rate in sub-Saharan Africa (IEA, World Energy Outlook 2014)

A review led by the World Health Organisation (WHO) found that in eleven sub-Saharan African countries, an average of 26% health facilities have no electricity access; this percentage rises up to 58% in some countries (Adair-Rohani et al., 2013). In addition, fossil-based generators are expensive due to high fuel prices and the requirement of significant on-going maintenance. Here, renewable energies such as solar power are not only considered as clean solutions, but affordable and suitable for health facilities.

In 2011, the United Nations general secretary launched the Sustainable Energy for All (SE4All) initiative that aims to achieve by 2030: universal access to clean and modern energy services for households, productive uses and community applications. Additionally, the initiative aims to increase the use of renewable energy and energy efficiency (SE4All, 2015). This represents an opportunity for the community energy access agenda. Moreover, recently 'renewable energy' has been added to the Sustainable Development Goals (SDGs) in the position number seven after 'access to clean water and sanitation'; thus highlighting its significance in the current global agenda. Access to adequate, reliable, sustainable and affordable energy services is crucial for socioeconomic development; and energy access in health facilities is being considered a critical enabler of universal access to health services. In a health facility without energy, many life-saving interventions cannot be undertaken; thus creating an obstacle of the attainment of universal health coverage and the health-related Millennium Development Goals (MDGs). Several health facilities suffer from shortages of power for basic services such as lighting, communications, refrigeration, diagnostics, medical equipment and devices for safe childbirth, and the treatment of illnesses or injuries. Also, many hospitals operate

with intermittent provision or suffer from electricity outages. Additionally, the widespread use of kerosene of lighting in health facilities increases health risks due to chronic exposure to indoor air contamination, as well as safety issues (Mills, 2012). Likewise, diesel generators emit greenhouse gasses (GHG), which contribute to global warming. Clearly, there is an urgent need for closer-look to find an optimal solution to these issues.

1.1 Problem and gaps in knowledge

According to WHO (2014), reliable data on energy access in health facilities is currently very sparse and there is a need for a better understanding of the linkages between energy and quality health service delivery. The health-related MDGs have focused on access to skilled care, essential medicines and medical technologies for priority diseases and health conditions (UN, 2010). However, less attention has been given to energy's role as an enabler of healthcare delivery and the lack of energy access in many facilities in resource-constrained settings (WHO, 2014). Health facilities require electricity for lighting, support child delivery, the performance of limited surgical procedures such as suturing, emergency night-time care, refrigeration for blood and vaccines, sterilization facilities and to run other essential equipment and medical devices that are currently lying in stand-by due to lack of electricity (Cordaid, 2015). Additionally, facilities with access to electricity are more prone to attract and retain skilled health workers. Also, electricity enables the access to communication channels, and facilitates public health education and information. Yet, few studies have systematically investigated the impacts of electricity access in health facilities on health services provision (WHO, 2014). According to the WHO (2014), impacts on health outcomes are difficult to measure due to many indirect factors; these include the skills and knowledge of health staff, the availability of medicines, the proximity to treatment and time lags before measurable improvements.

The SE4All initiative and its new High-Impact Opportunity (HIO) on Energy for Women's and Children's Health has the aim to improve availability and quality of essential maternal and child healthcare through an increase on sustainable energy access in health facilities. Here, energy is being considered as a critical enabler for vital primary healthcare services, especially during maternal and childbirth emergencies. In 2010, an estimation of 287.000 women died from complications during pregnancy and childbirth; and many of these deaths could be averted with the provision of minimal lighting and medical appliances (SE4All, 2013). When energy is being introduced, healthcare staff members report fewer delays in the provision of life-saving care, more blood transfusions, and more successful child deliveries, along with an improved confidence of the patient and the healthcare provider (SE4ALL, 2013). In addition, modern energy services are critical for improved diagnosis and treatment of infectious diseases. More research is needed to establish the benefits of energy supply to improved health services delivery, and to identify the energy technologies most appropriate for different levels of health facilities (WHO, 2014). This need has motivated this study to help achieve a better understanding of the state of electricity access in health facilities in resource-constrained settings, and the optimization and impact assessment of the current energy systems. Currently, there is little measurement available of the state of electricity access in rural health facilities. Data on electricity access of health facilities have been rarely collected and have not been reported systematically on a multi-country study (Adair-Rohani et al., 2013). Moreover, the surveys used had few basic indicators that failed to capture the most important aspects of electricity supply, such as the diversity of energy sources for primary and back-up solutions, the quality of electricity supply to meet the requirements of medical devices, and other key attributes of electricity supply that involve power capacity, reliability, amongst others (WHO, 2014). Several health facilities that are grid-connected have problems such as power failures or outages during periods of peak demand, thus forcing them to rely on backup generators or to remain without power. Such electricity outages can also damage equipment and medical devices. In the case of rural settings, fossil-based generators tend to be expensive in the long-term, and the maintenance may not be locally available. Also, they produce waste heat that increases inefficiency and emissions. Solar power systems however; appear

to offer a greater reliability but are limited in capacity (WHO, 2014). Here, storage systems can play an important role. In Nigeria, solar energy is one of the in-exhaustible energy sources available for health facilities (Ani and Emetu, 2013). Thus, renewable energies appear to be a solution to energy supply issues, being also environmentally friendly.

In many countries, a lack of electricity remains a neglected barrier to the effective provision of health services. However, few studies provide empirical evidence of the linkages between energy access in health facilities and the actual health outcomes (WHO, 2014). An accumulation of empirical assessments are needed that are embedded in the local context to better understand the real impacts of modern energy services in resource-constrained health facilities and the optimal energy solutions. Studying the healthcare benefits of electricity supply would support the prioritization of energy investments towards facilities and services that are most in need. The present research project intends to develop a protocol with the following purposes: (1) to study how to optimize energy systems in resource-constrained health facilities with renewable energies, and (2) to explore available data for assessing the impact of electricity supply on improving the delivery of healthcare services. A case in Rwanda is deeply studied as an example, focusing on the provision of solar energy to improve their current electricity system. Rwanda is currently located within the lowest tier of sub-Saharan African countries with the lowest electrification rate (see Figure 1-1).

1.2 Aim of the study

Since 1914, Cordaid has worked on building flourishing communities with partners from all over the world. One of the core goals of Cordaid is to provide affordable and accessible healthcare to all, and it has achieved a long track record on this sector following the most recent development and finance methods. Currently, Cordaid has acknowledged the global need for a better understanding of the linkages between energy and healthcare services delivery. This acknowledgement has motivated the development of this study, which has the aim *to develop a protocol on how to optimize energy systems in health facilities in resource-constrained settings, and assess the impact of reliable electricity supply in the delivery of healthcare services.*

Solar energy is considered as an optimal option for electrifying rural health facilities, and with this study it will be simulated next to other supply sources to discover its role. This will be done through modelling different scenarios for a real case study of a health facility in Rwanda. Also, it is hypothesized that electricity supply will improve the healthcare performance; however there is no scientific proof of this relationship, or a method to carry out this analysis. Therefore, during the research process, a new approach will be proposed to carry out the study of linkages between electricity supply and the delivery of health services. This protocol will be useful for future larger-scale projects exploring the relationship between electricity and healthcare performance. This is the reason why this research is considered as an initial pilot study to analyze available data and test the methodological approach that represents a pre-cursor for a future larger study.

1.3 Research Questions

Main research question:

How can electricity supply be optimized and assessed in resource-constrained health facilities?

Sub-questions:

1. What are the electricity needs in health facilities in resource-constrained settings?

1.1. What are the electricity needs for healthcare services and basic medical equipment?

1.2. What is the global categorization of health facilities based on their electricity needs?

2. **What is the profile of resource-constrained electricity demand and supply in rural health facilities?**
 - 2.1. What is the current electricity demand-supply profile of the case study?
 - 2.2. What is the future electricity demand profile of the case study?
 - 2.3. What are the sources of electricity supply to satisfy the demand of resource-constrained health facilities?
 - 2.3.1. What is the role of solar energy in the rural health facility context?
3. **What are the optimal energy systems scenarios for resource-constrained health facilities?**
4. **What are the impacts of reliable electricity supply in resource-constrained health facilities?**
 - 2.1. What are the expected benefits of reliable electricity supply in resource-constrained health facilities?
 - 2.2. How does healthcare performance and electricity consumption change over time?
 - 2.3. What is the local perception of the health workers regarding the electricity supply system?

1.4 Methodology

The health facility is regarded as a system. A system that requires reliable electricity supply to deliver healthcare services adequately. This system however, is located in resource-constrained settings; therefore supply and demand are constrained and internal requirements such as sufficiency and reliability are crucial. Also, external requirements are important such as low costs and sustainability. The analysis of the health facility as a system is required to understand its components and problems, and thus be able to optimize solutions and assess impacts.

1.5 Description of the research work

The research work is divided in three phases:

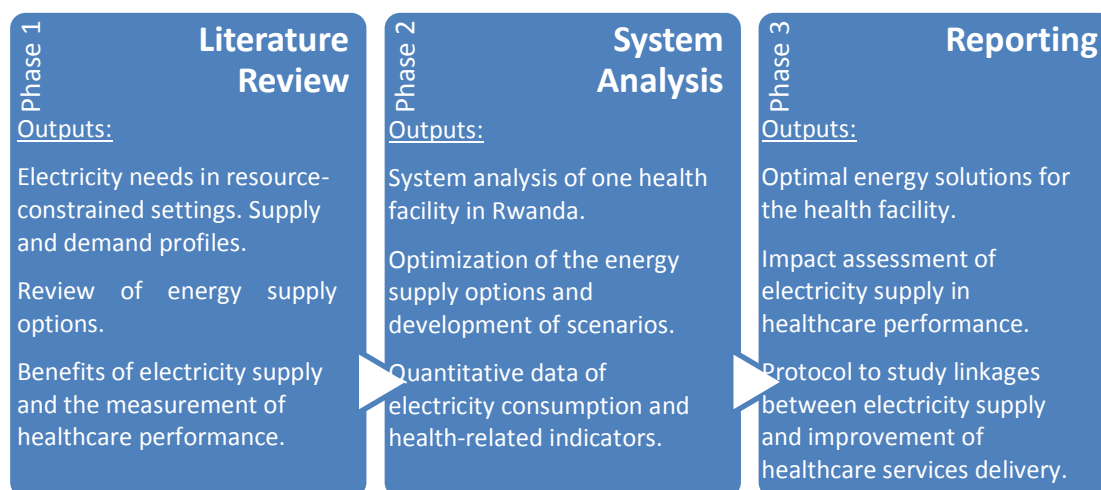


Figure 1-2. Stages of the research project.

1.5.1.1 Phase 1: Literature review (sub-questions 1 and 2)

A literature review is carried out to investigate the electricity needs for healthcare services and medical equipment in resource-constrained settings. The most prominent sources on this topic involve the World Health Organisation (WHO), the United Nations (UN), the International Energy Agency (IEA), and the United States Agency for International Development (USAID), amongst others. In addition, data will be collected from local organisations in partnership with Cordaid and supporting the development of the present study. These organisations are Great Lakes Energy (GLE) and Health Development and Performance (HDP).

Description of data collection

First, data is collected of the current electricity supply-demand profile of the health facility in study. On one side, the electricity demand profile involves a description of the energy requirements of the health facility to run medical equipment and deliver healthcare services, organised into an average load profile with its average daily distribution. A future demand profile is also estimated. On the other side, the supply profile involves the current energy supply system. Second, data on diverse energy supply options is collected with the aim to satisfy the demand of the health facility. Here, data is collected of the costs of the different energy technologies and their specifications taking into account their suitability within the context of rural health facilities in sub-Saharan Africa. Third, a review of potential benefits of reliable electricity supply will be studied from existing literature, with a focus on resource-constrained health facilities. This last part is documented in Appendix A.

1.5.1.2 Phase 2: Fieldwork (sub-questions 3 and 4)

Using the current electricity profile data of the health facility in study, a system analysis is performed. Then, an optimisation simulation model is developed to find the optimal energy solutions based on technical, economic and environmental aspects to satisfy the demand of the health facility and to discover which energy supply options are suitable for the health facility's context. Different scenarios are simulated for the case study. The methods used in this phase are described below.

HOMER simulation software

Software tools that primarily focus on stand-alone applications of renewable energies such as single building or single-project applications are the BHP screening tool, HOMER, HYDROGEMS and TRNSYS16 (Connolly et al., 2010). To optimize energy systems in health facilities, HOMER is considered as the best option available to carry out this process. The HOMER microgrid software is regarded as the global standard for optimizing the design of energy systems in any sector. It was originally developed by HOMER Energy (Hybrid Optimization Model for Multiple Energy Resources). The software provides three tools; the simulation of the operation of a microgrid over one entire year, the optimization of all possible combination of system types, and sensitivity analysis (HOMER Energy LLC, 2014-2015). HOMER was chosen because it has been applied already in health facilities and it is one of the most well-known and accessible tools in the public domain. HOMER optimizes different energy options in terms of economic costs and other aspects to show optimal architectures of the health facility's electricity system to successfully satisfy its demand. In this research, energy options are optimized based on their Net Present Costs (NPC) for different scenarios. Therefore different architectures are simulated to deliver the results with lower present costs during the project lifetime.

Impact assessment

To address question number 4, an impact assessment is carried out for which quantitative data of healthcare performance indicators will be collected. Through the health data collected at the field, it will be possible to better understand the changes in healthcare services over time. Energy data on electricity consumption will also be collected on this phase. The analysis of this data will lead to the study of how the electricity is being used within the healthcare facility. The answer to question 4 is found in Appendix A.

1.5.1.3 Phase 3: Analysis and Reporting

The last phase involves the analysis of the results of the optimization model and the different scenarios, and the analysis of change of the quantitative data collected over time (documented in Appendix A). The report could be used by Cordaid as a protocol to optimise and assess electricity supply in health facilities in resource constrained settings.

1.5.2 Scope of the research and system boundaries

The aim of this research is to study electricity supply in the healthcare sector, specifically in health facilities in resource-constrained settings. The study of electricity supply does not necessarily mean electricity access. The health facility system could have already an electricity system in place that is not reliable (due to power outages, uninterrupted flow, etc.).

Initially, more health facilities were going to be included in this study, from Rwanda and Burundi; however due to local unfavourable conditions, data collection in these health facilities will be resumed in the future for a follow-up study. The case study is a health facility called Gikomero and it is located in Rwanda. Currently, the health facility has electricity supply through the central grid and a diesel generator. In October 2015, a solar PV panel system will be installed as a back-up power source to increase reliability. Initially, this research had the aim to study change after the solar PV panels were installed back in June 2015; however due to complications and other delays; the installation of the solar PV panels was postponed to October 2015. Therefore, the study is directed to understand how the current electricity systems affect the healthcare performance. Also, an optimization simulation is carried out to learn what the optimal energy options are for this particular health facility based on the current and future electricity profile, and when using different scenarios of electricity supply. For the development of scenarios, the current supply technologies are considered and the simulation does not take into account future changes in the central grid.

Health facilities also require energy in the form of heat for cooking, water heating, space heating, sterilization and medical waste incineration, as well as for cooling in applications such as absorption refrigeration using LPG or kerosene (WHO, 2014). However, this study only focuses on energy in form of electricity.

1.5.3 Structure of the report

The report starts first with a literature review on electricity in health facilities in resource-constrained settings, involving electricity needs, categorization of health facilities and healthcare services and performance. Second, a system analysis of the case study in Rwanda is done, including a description of the health facility, its current electricity supply-demand profile and the healthcare services available, making it possible to calculate a future demand profile for the health facility. Third, a literature review is carried out regarding the energy supply options to satisfy the demand of the health facility. Fourth, follows the optimization of energy systems options for the health facility in study with the development of different scenarios. In order to carry out the optimization, specific data of diverse energy options is required and it is stated at the beginning of chapter 4. Lastly, the report finishes with a discussion, conclusions and recommendations, references and appendixes.

2. ELECTRICITY IN HEALTH FACILITIES IN RESOURCE-CONSTRAINED SETTINGS

According to the World Health Organisation (WHO, 2014), reliable data on capacity and quality of electricity supply is currently very sparse. Adair-Rohani et al. (2013) conducted a systematic review of available national data on electricity access in health facilities in sub-Saharan Africa. The authors identified 13 health facility surveys from 11 sub-Saharan African countries that met the criteria. In average, 26% of the health facilities reported no access to electricity (see Figure 2-1). Amongst 8 countries, only 28% had reliable electricity in average. There is a need to improve the geographic coverage, quality, and frequency of data collection on energy access in health facilities (Adair-Rohani et al., 2013). The results represent the significant energy insecurity at the primary level, and also the hospital level. However, it only involves around ¼ of the sub-Saharan African countries.

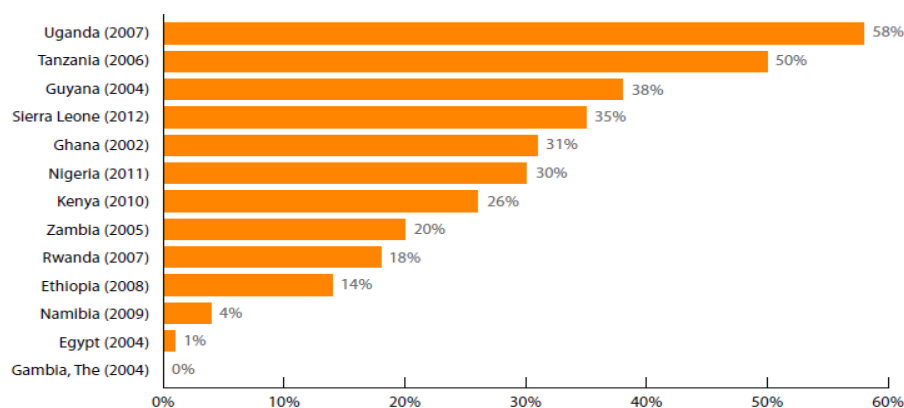


Figure 2-1 Healthcare facilities with no electricity access (Adair-Rohani et al., 2013)

This study focuses on the country Rwanda in representation of sub-Saharan African countries to gather information, analyse and develop a protocol for the assessment of electricity supply in resource-constrained health facilities. In Rwanda, there are 92 health facilities without electricity from a total of 446 health facilities (MINISANTE, 2013). Hence, around 21% of health facilities lack electricity services (see Figure 2-2).

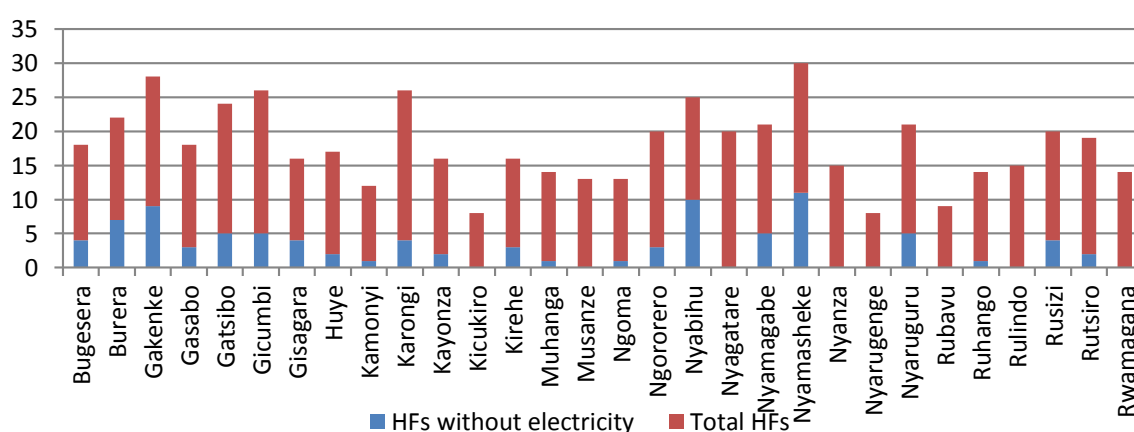


Figure 2-2 Number of health facilities per district without electricity in Rwanda (MINISANTE, 2013)

Regarding the electricity consumption in Rwandan health facilities; electricity is being used primarily for lighting, followed by the use of medical equipment, and for cooling (storing vaccines) and sterilization (MinBuZa, 2014). Also, according to the IOB Evaluation survey to local staff (MinBuZa, 2014); the use of computers and printers is important for the administration of the health facility. As seen in Figure 2-2, electricity is not new for most of the health facilities; usually they are equipped with small generators or solar energy systems. Electricity supplied from the central grid provides more power; and typically, its reliability is increased through generators. In off-grid settings, stand-

alone diesel generators are the most common solutions, backed-up by mostly kerosene lamps, candles or flashlights (WHO, 2014). For many health facilities, the grid connection implies a cost reduction and the use of more power-consuming equipment (MinBuZa, 2014). However, the energy cost in Rwanda is high (electricity tariff is around USD 23 cent/kWh), and the electricity network is old with technical losses of around 25% (MININFRA, no date). In Figure 2-3 it is shown the electricity grid infrastructure around the country and their proximity to health facilities. Currently, 74% of health facilities have access to the grid network (MININFRA, no date).

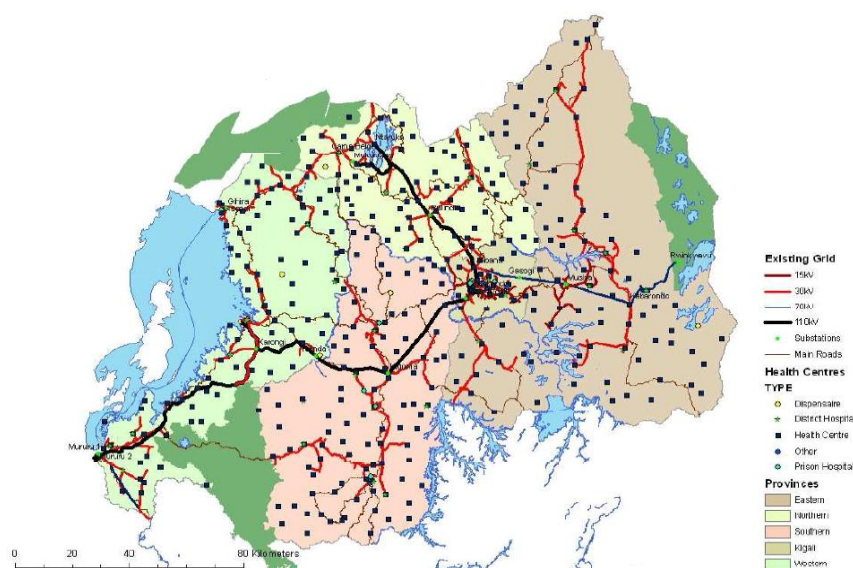


Figure 2-3. Health centers in Rwanda and the access to electricity grid networks (MININFRA, no date)

Health facilities that have no access to electricity tend to rely on energy sources such as kerosene lamps, candles or flashlights (WHO, 2014). In other cases, these sources are used as back up for unreliable primary energy sources. Back-up power sources are crucial for handling childbirths,

emergencies, surgeries, amongst others (WHO, 2014). In 2012, the Rwandan Ministry of Health launched the campaign called “Bye-bye kerosene” to phase out kerosene lamps, and solar lamps were introduced as an alternative (MinBuZa, 2014).

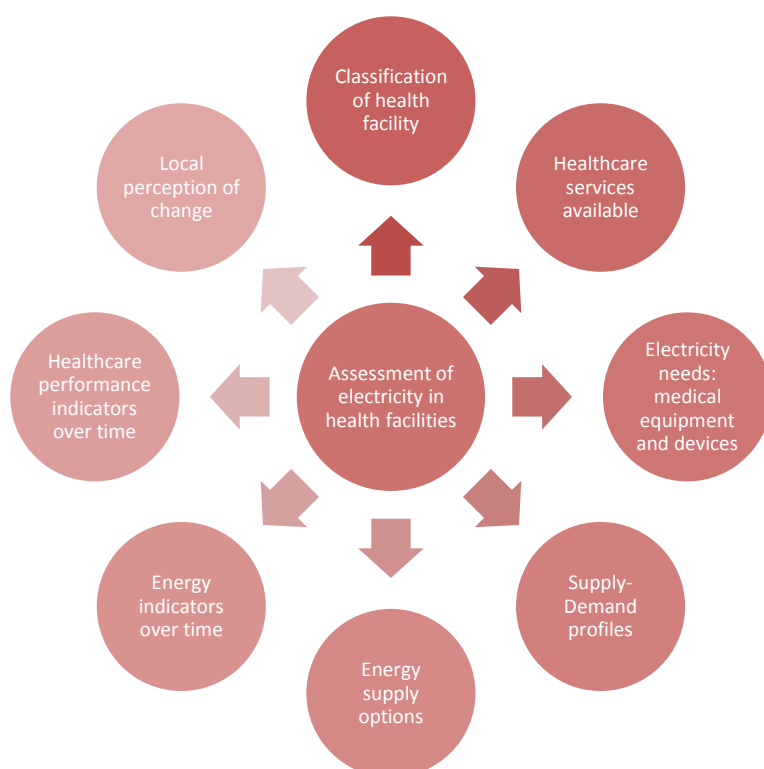


Figure 2-4 Data required for assessing and optimizing electricity in resource-constrained HF

To assess electricity supply in health facilities, the local context must be studied in detail. Information is required such as the current healthcare services delivered, the size of the health facility, its electricity needs, indicators of healthcare performance, and current energy supply sources (see Figure 2-4). Altogether, this information will facilitate the study of optimization of energy system options for the health facility, and the evaluation of impacts in healthcare performance. The following sub-sections describe the information required for the health facilities based on external references.

2.1 Healthcare services in rural health facilities

Health facilities can provide a wide range of health services such as outpatient consultation (OPD), maternal and new-born health, obstetric care, child and adolescent health, communicable and non-communicable diseases, laboratory and diagnostics, basic emergency treatment and surgical services. Each of these services may require specific equipment, trained staff and medicines. The acknowledgement of healthcare services available in a health facility supports the measurement of change in the health facility on a specific timeframe. Due to an increase on electricity reliability, more healthcare services can be introduced. However, other indirect factors that can affect healthcare services should be also taken into account such as the human factor, health workers' skills, and the availability of monetary resources, medical appliances and equipment, etc.

2.2 Electricity needs in rural health facilities

Electricity needs vary not only according to the health facility type, but also in more specific terms such as the actual services that are provided, operation hours, size of the facility, target population and available equipment. The WHO (2013) defines a medical device as “an instrument, apparatus or machine used to diagnose, treat, monitor or alleviate disease or injury. It is also used to prevent disease and compensate for injury.” Thus, any product used specifically for healthcare purposes that is not a medicine or a biological product.

See Appendix B for a list of electric equipment and its power requirements to illustrate the range and order of magnitude of electricity needs for basic health facility equipment. However, the electric equipment available varies for all levels of health facilities. According to the WHO (2014), there are no internationally validated health sector norms for the minimum amount of electricity that should be available at a health facility. The electricity requirements provide an indication of the peak demand for power in a facility when many or most devices and appliances are being used at the same time. However, some of the devices might be used intermittently, or others can remain on standby power for most of the day. Moreover, energy demands may increase due to the addition of patients extended operating hours, or new services (USAID, no date). The WHO projected that vaccine refrigeration capacity needs to expand 8 to 10 fold by 2025 to meet the needs of a growing global population (PATH and WHO, 2008). The constant emergence of new technologies also means that power requirements may vary significantly from AC to DC. AC is the traditional current for which most appliances have been originally developed. Recently, an increased number of portable and digital devices are being designed to use low-voltage DC supplied by batteries and solar PV systems (WHO, 2014). Some of these devices are vaccine refrigerators, battery-operated blood glucose monitors, LED-lit microscopes for TB diagnosis, digital pulse oximeters to measure blood oxygen levels, sphygmomanometers to measure blood pressure, low-power foetal heart monitors, ultrasounds and medical suction devices.

2.2.1 Basic medical equipment requiring electricity

Appliances that provide services in health facilities and cannot run without energy include refrigerators, sterilizers, lamps, cookers, suction machines for deliveries, incubators, microscopes, centrifuges, mixers, X-Ray viewers, etc. (EU, 2006). In a health facility, electrical equipment is needed

for lighting, to improve medical interventions (including first aid), to assist childbirth and surgeries. Also, medical equipment requiring electricity is needed for maternal and child health; for instance, to use baby warmers or incubators after the baby is born. Furthermore, immunization programmes prevent dangerous diseases from millions of children. These programmes depend upon the reliability of refrigerators to preserve the vaccine in a good environment and prevent its deterioration (IEA, 2014). Fuel supply that is interrupted in rural areas can result on spoiled vaccines. Experience shows that a dedicated PV system must be designed separately to supply energy only for vaccine refrigerators, making sure that the refrigerators have their independent power supply (IEA, 2014). A joint WHO and PATH assessment described solar refrigerators as essential to meet soaring vaccine cold chain demands (PATH and WHO, 2008). The market for solar-powered vaccine refrigerators is growing rapidly. Health-focused intergovernmental agencies are investing in this product for rural health facilities due to their significant need. Furthermore, compressor refrigerators are 3-4 times more efficient than absorption refrigerators. Also, direct-drive vaccine refrigerators connected directly to a PV array and using internal thermal storage instead of a battery are a good option (IEA, 2014).

Laboratory services also require electrical medical equipment to diagnose diseases. According to the IEA (2014), microscopes are used for diagnosis and are usually connected to AC; centrifuges are used for blood mixture, and are either connected to 12V DC or AC; spectrophotometry is being used to diagnose diseases at earlier stages; and autoclaves are used for the sterilization of medical tools and surgical equipment. For this sterilization equipment, the most economical way is to supply the energy through solar thermal collectors using PV hybrid systems (IEA, 2014). Medium and large facilities can have more sophisticated medical devices such as X-ray machine, jet sonic cleaners, compressors and water baths (IEA, 2014).

Lastly, electrical equipment is needed to increase access to communication through the availability of phone charging, the use of radio and television. Also, electrical equipment can improve data and information management through the use of desktop computers or laptops. A good data management will lead to better information accumulation that can be shared to ministries for improvements on healthcare services.

2.3 Classification of health facilities

Types of health facilities vary across countries due to their health systems, socio-economic development and policies. Also, there is a lack of comparable definitions for primary, secondary and tertiary facilities. The classification has been inconsistent and types of care at different levels were not clearly defined in terms of the facility categories used by individual countries (Adair-Rohani et al., 2013). A general classification can be comprised from three prominent sources in this working area (USAID, no date; WHO, 2010; and IEA, 2014). According to the healthcare services delivered in the health facility and its electricity needs, the health facility can be categorized within a standardized denomination. The health facilities are classified below in health posts, health centres, and hospitals. A specific classification on services available, energy consumption and number beds is shown in Table 2-1.

Health Post

The first level satisfies primary health needs of communities nearby, offering treatment for most prevalent diseases (e.g. malaria, TB, HIV/AIDS), as well as maternal and child health services and first response to emergencies (WHO, 2010). It represents the smallest health facility, and it may have a full- or part-time primary healthcare provider, but may not have a permanent doctor or nurse (USAID, no date). The energy demand is relatively low due to the availability of limited medical equipment (USAID, no date). Lights are the most significant load and consume about 35% of the total energy (IEA, 2014). And, it may be equipped with 1 or 2 vaccine refrigerators. Whereas there are

refrigerators, this is the largest consumer. Health posts are usually located in remote areas (IEA, 2014).

Health Centres

The second level or district health centres offer more health services to a larger population, having more patient beds (WHO, 2010), and it possesses more medical equipment that allows that provision of more health services including more sophisticated diagnosis (USAID, no date). It employs one or more full-time nurses, and may employ a part-time physician (USAID, no date). USAID divides health centers in three categories according to their energy requirement: Category I -> 5-10 kWh/day; Category II -> 10-20 kWh/day; Category III -> 20-30 kWh/day (see Appendix C). Contain some medical equipment and conduct emergency surgical treatments. Thus, it is equipped with diagnostic and surgical equipment. Maintains a cold chain for vaccines and blood supplies, and may have an additional refrigerator. Some advance equipment such as X-ray machine. Highest energy consumption during the day is by laboratory equipment, while lighting and fans during the night time (IEA, 2014).

Hospitals

The third level is directed to larger populations (WHO, 2010). They possess diverse medical equipment, and provide healthcare for around 10,000 people. They can include staff houses, which shows to be the larger energy consumer, about 30% of the total electricity production (IEA, 2014). Advanced equipment such as X-ray, CD4 counters, blood typing equipment (IEA, 2014). Usually, higher levels such as health centers or mainly hospitals, receive referrals of patients from lower level health facilities whenever their infrastructure do not meet specific needs such as lack of equipment, lack of electricity, lack of skilled staff, amongst others.

Table 2-1 Classification of health facilities (USAID, no date; WHO, 2010; and IEA, 2014)

Levels/Classification	Services available	Energy consumption
1. Health post	Provides limited services such as basic treatment for emergency cases and first aid (IEA, 2014). It can treat of minor illnesses and injuries, and if possible the provision of basic immunization services (USAID, no date).	Average daily consumption up to 10 kWh/day.
2. Health centre	Not only provides basic health services, but also blood tests, surgery procedures and delivery services (IEA, 2014). Advances services are obstetric procedures, injury response and diagnosis and treatment of serious infections and fevers (WHO, 2010).	Average daily energy consumption between 10-30 kWh/day
3. Hospital	Large health facilities with a wider arrange of more specialized health services (WHO, 2010).	High energy consumption that exceeds 30kWh/day

When categorizing the health facilities, it is easier to search for optimal energy solutions directed to each category and suitable to their needs and healthcare services. Also, it is possible to observe how electricity requirements relate to healthcare services.

3. SYSTEM ANALYSIS FOR RESOURCE-CONSTRAINED HEALTH FACILITIES: CASE STUDY IN RWANDA

To assess electricity supply in health facilities, a system analysis must be executed based on a health facility as a system. The introduction of new energy systems does not only lead to the addition of electricity services, it also involves a change in the whole healthcare system that has an important role in society. Here, a resource-constrained health facility system will be analysed in terms of electricity supply-demand to further assess its energy supply options and its impacts in society.

A resource-constrained health facility system is composed by resource-constrained electricity demand and supply. On one side, electricity demand depends on the level and category of the health facility as seen in Chapter 2 to be able to deliver specific healthcare services and run medical equipment. The electricity demand patterns tend to vary for each health facility according to the local context, infrastructure, economic resources and the human factor. On the other side, to satisfy the demand, electricity supply in resource-constrained settings is usually based on central grid supply, diesel generators and renewable energies (not taking into account other energy sources such as kerosene lamps and batteries). The characteristics of resource-constrained supply involve grid-connection with constant blackouts, lack of diesel availability due to remoteness or financial constraints, and intermittency of renewable energy sources. In addition, a lack of financial resources could jeopardize the availability of any of the electricity supply sources. In this chapter, one health facility in Rwanda is taken as an example to analyse resource-constrained health facilities as a system. Its demand-supply profiles are analysed in sub-section 3.1 to understand the current system, and then be able to optimise the system taking into account different energy supply sources and the future demand patterns of the health facility.

To optimise the health facility's energy system, a set of goals and requirements must be defined. Internal requirements of the energy system are sufficiency and reliability to meet the electricity demand adequately. And external requirements are economic resources and long-term sustainability. Thus, in this study the optimization of energy systems will be based on sufficiency, reliability, lower costs and sustainability aspects such as low emissions and renewability. A reliable electricity supply can be translated into many benefits for the health facility such as better treatments, more patients, more healthcare services, and motivated health workers, amongst others. The main goal of optimising the health facility's energy system is to improve the delivery of healthcare services.

3.1 Current electricity demand-supply profiles for Gikomero health facility (HF)

A real case of a health facility in sub-Saharan Africa has been chosen to assess a resource-constrained electricity system. The health facility in study is called Gikomero health facility (HF), from now on Gikomero HF, and it is described in this section (see Table 3-1).

Table 3-1 Description of Gikomero HF (HDP, July 2015)

Name	Gikomero Health Centre
Date of establishment	2008
Location	Gikomero sector, Gasabo district, Kigali
Catchment area	18,114 citizens
Distance to the closest HFs	Health post: 2km Health centre: 8km Hospital Kibagabaga: 40km
Local category of HF	Health centre
Average number of patients per month	1,476 patients

Staff members	16 (1 administrator, 7 nurses, 1 accountant, 2 laboratory technicians, 1 data manager, 1 social assistant, 1 nutritionist, 1 receptionist/cashier, 1 driver)
Number of beds	15
Ownership and management	Health Development and Performance (HDP)
Pictures of Gikomero HF	 Figure 3-1 Picture of Gikomero HF (HDP, 2012)  Figure 3-2 Picture of Gikomero HF (HDP, 2012)
Opening hours of the HF	All day (24h)
Energy sources	Diesel generator and central grid supply. Solar energy and batteries will be installed in October 2015 (see section 3.1.2.1.
Electricity functionality	Intermittent
Other	No water availability

3.1.1 Demand-side analysis

3.1.1.1 Current electricity requirements in Gikomero HF (August, 2015)

To be able to deliver the healthcare services at Gikomero HF, a diverse range of medical equipment is required. Most of the medical equipment requires electricity, and data collected in the health facilities revealed the current electricity load profile of the health facility (Table 3-2) and its average distribution during the day (Table 3-3). This information is useful to further be able to find the optimal energy solutions that are suitable and appropriate for this particular case. Also, it is useful to understand how electricity is being used in the HF from a demand-side perspective, and which equipment requires more electricity.

Table 3-2 Electricity load profile per equipment for Gikomero HF (GLE, 2015)

No.	Type	Equipment (medical and non-medical)	Quantity	Power (Watts)	Total (Watts)	Estimated Number of Daytime hours (07:00-17:59)	Number of Evening hours (18:00-21:59)	Number of Night hours (22:00-06:59)	Total hours/day	Total energy (kWh/day)
1	Security Lighting	2'Tubes(Daylight)	14	10	140		4	8	12	1,680
2	Security Lighting	4' Tubes(Daylight)	4	20	80		4	8	12	0,960
3	Lighting	CFLs	25	7	175		4		4	0,700
4	Lighting	4" Tubes	11	20	220		4		4	0,880
5	ICT	Laptop	5	40	200	4			4	0,800
6	ICT	Desktop	2	100	200	7			7	1,400
7	ICT	UPS/Backups	4	0	0	7			7	-
8	ICT	Printer	1	300	300	2			2	0,600
9	Medical Equipment	Sterilizer/Autoclave	2	600	1,200	1			1	1,200
10	Medical Equipment	Infant Radiant Warmer	1	850	850	2	2		4	3,400
11	Medical Equipment	Microscope	1	30	30	2			2	0,060
12	Medical Equipment	Agitator	1	35	35	2			2	0,070
13	Medical Equipment	Aspirator	1	50	50	2	2		4	0,200
14	Medical Equipment	Hospitex Diagnostics/Centrifuge	1	75	75	1			1	0,075
15	Medical Equipment	PH-100i/Centrifuge	1	150	150	1			1	0,150
16	Medical Equipment	Humalyzer/Centrifuge	1	80	80	1			1	0,080
17	Cooling Equipment	Fridge	2	120	240	4	1	3	8	1,920
Total energy demand (kWh/day)										14,175

Table 3-3 Distribution of daily load demand per equipment (W) for Gikomero HF (GLE, 2015)

Time	Number of Equipment from Table 3-2																	Total energy (Wh/day)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
0:00-0:59	140	80																220
1:00-1:59	140	80															240	460
2:00-2:59	140	80																220
3:00-3:59	140	80																220
4:00-4:59	140	80															240	460
5:00-5:59	140	80																220
6:00-6:59																		-
7:00-7:59									600								240	840
8:00-8:59					200	200	0											400
9:00-9:59					200	200	0											400
10:00-10:59						200	0			850			50				240	1.340
11:00-11:59						200		300			30	35		75				640
12:00-12:59													50		150			200
13:00-13:59							0										240	240
14:00-14:59					200	200	0	300			30	35				80		845
15:00-15:59					200	200	0			850								1.250
16:00-16:59						200	0										240	440
17:00-17:59																		-
18:00-18:59	140	80	175	220						850			50					1.515
19:00-19:59	140	80	175	220					600								240	1.455
20:00-20:59	140	80	175	220									50					665
21:00-21:59	140	80	175	220						850								1.465
22:00-22:59	140	80															240	460
23:00-23:59	140	80																220
Total	1.680	960	700	880	800	1.400	-	600	1.200	3.400	60	70	200	75	150	80	1.920	14.175

From the electricity load profile, it is possible to determine that the total energy demand of Gikomero HF is 14,175kWh/day. According to the distribution of daily load demand shown in Table 3-3, it is possible to draw the electric load variation below (see Figure 3-3) to easily observe which the peak hours are.

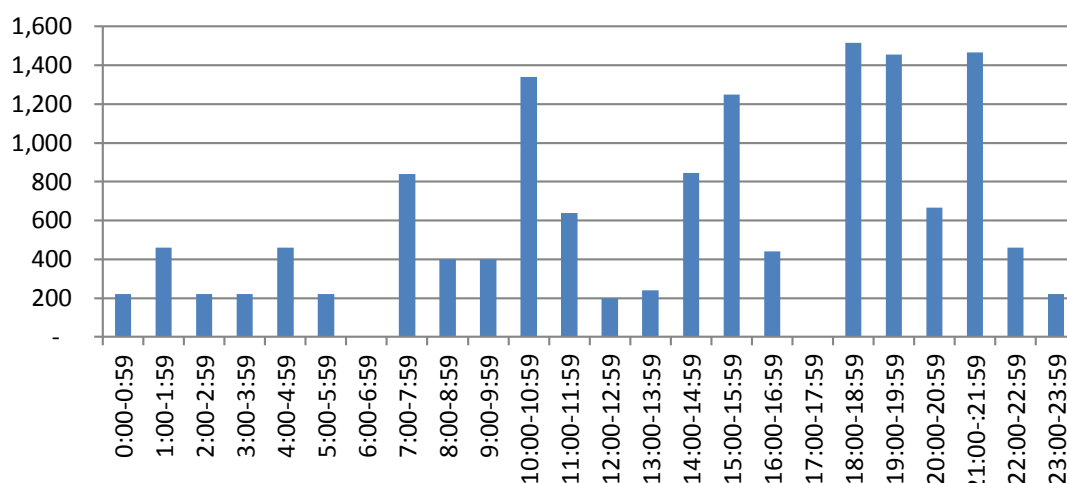


Figure 3-3 Electric load variation for Gikomero HF (kW per hour) (GLE, 2015)

The peak hours from Gikomero HF range between 18:00 and 22:00, having its maximum peak in between 18:00-19:00. Thus, the health facility has an evening peak; this can probably allocated to the use of lights after the sunset time. Around 18:00 o'clock it is considered to be the end of the working day and the HF must be busy still with attending patients; this is where light is mostly needed. The electricity load profile divided per type of equipment supports the development of a pie chart to see which equipment consumes more electricity.

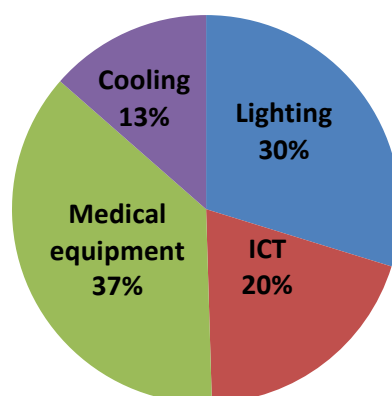


Figure 3-4 Electricity consumption per type of equipment for Gikomero HF (GLE, 2015)

The type of equipment that consumes more electricity is the medical equipment as seen in Figure 3-4, consuming 37% of the total electricity. The medical equipment with higher consumption is the Infant Radiant Warmer (Incubator) and the Sterilizer, with a consumption of 850W and 600W, respectively. Not surprisingly, this two equipment are being used during the evening peak hours according to Table 3-3, meaning that they contribute to the peak hours of the HF when also lighting is most needed. It is recommended that the peak be distributed during the rest of the day to avoid the high peaks. Thus, highly electricity-consuming equipment should be used mostly around noon and not in the evening. As seen in Figure 3-4, lighting consumes 30% of total electricity and almost the same proportion as all the medical equipment. Lighting improves medical interventions, including first aid, childbirth and surgery. Here, the use of energy saving measures should be promoted. For instance, the use of LED lights instead of CFLs. The International Energy Agency (IEA) also supports this measure. According to the IEA (2014), lights generally consume up to 40% of the energy

generated by PV panels in health facilities, and LEDs are more efficient than CFLs (IEA, 2014). For the case of Gikomero HF, changing the use of CFLs to LEDs translates into energy savings of 30W/day (taking into account the electricity requirements of CFLs and LEDs from Appendix B). Furthermore, human behaviour patterns should be influenced to save more energy with daily habits such as not leaving lights on when they are not being used, to increase the use of daylighting and natural ventilation. In the case of equipment, it is important to use them correctly and for instance, not leave the door of the refrigerator open, or even the location of the refrigerator can influence its efficiency if it is placed in a warm place that receives much sunlight.

The electricity demand profile shows how much Gikomero HF consumes on average, however in reality that could not be case due to intermittency and reliability issues. The next sub-section analyses the current power supply system in Gikomero HF and its constraints.

3.1.2 Supply-side analysis

3.1.2.1 Current power system in Gikomero HF (August, 2015)

Currently, the health facility relies on the central grid system as its primary electricity supply. This service however is highly unreliable in the local context, and the facility has to rely on a secondary power source. This secondary source is a diesel generator that is only operational 5 hours/day. This three-phase diesel generator has an installed capacity of 12,5kW and was installed in the year 1999. It is not clear how many hours a day the grid is operational, but in average the health facility has 3 blackouts/day; and in total the health facility has electricity for around 19 hours a day (HDP, 2015).

In October 2015, a solar power system with batteries will start its operation. Without this new energy system, the health facility acknowledges an issue with the electricity supply. A survey was developed in Cordaid and carried out to assess the current situation at Gikomero HF from the perception of health workers. The survey results stated that electricity is being intermittent for all healthcare services. The representative of the HF was requested for to provide the 'general satisfaction' regarding the current primary electricity system. The response was 'unsatisfied' from the following range: very satisfied, satisfied, no opinion, unsatisfied and very unsatisfied (Cordaid, 2015). The reason for this dissatisfaction was appointed to the intermittent problem, cost and maintenance of the electricity system. In the future, the new solar power system will take the position of a back-up system, and hopefully this issue will be solved. The new solar power system consists of an array of 12 PV panels supplying in total 3kW with micro-inverters, 10 batteries Deka Gel 12V|213Ah and inverter (GLE, 2015). The introduction of the new renewable energy source is expected to increase access to electricity and improve reliability of power. The electricity system is being financed by the health facility, and the maintenance is financed partially by them and NGOs.

3.1.3 Categorization of Gikomero HF

To categorize the health facility, the USAID general categorization for health facilities is used. These categories were already described in Chapter 2, section 2.3.

USAID categorizes health facilities in health posts, health clinics and hospital. In this case, Gikomero HF will be considered as a 'health center', as it employs full-time nurses and allows sophisticated diagnoses. Within the category of health clinics, the HF will fit in between category I and category II whereas the energy requirements range between 4.4-10.3 kWh/day and 10.6-21.5 kWh/day, respectively (see Appendix C). The average daily electricity requirements of Gikomero are 14.175 kWh so this fits better in category II. However, Gikomero HF has 15 beds and it is not enough to fit into this category that documents approximately 60-120 beds. On the other side, the electrical equipment available does fit into category II. As seen on Appendix C, Category II equipment considers 2 refrigerators, 1 small refrigerator, 1 centrifuge, 1 haematology mixer, lighting, 1 autoclave, 2 incubators, 1 water bath, 1 radio and 1-3 desktop computers. All these equipment are present in Gikomero, although it only has 1 incubator. The next category adds a Portable X-Ray machine, which

consumes a significant amount of energy of 3kW (USAID, no date), and it is not available at Gikomero. Thus, the health facility has a low-moderate energy requirement for a health center.

After studying the current profile of Gikomero HF, energy options can be proposed to find a solution for its intermittency problems. Also, an optimization assessment will determine which combination of options is the most optimal. However, before optimising the current system, it is important to also analyse the future demand of Gikomero HF. This way, the system will not fall into path-dependency, and strategic decisions of current options will lead to better results in the future. The future demand scenario is built in the next section.

3.2 Future electricity demand profile of Gikomero HF

By calculating the future energy requirements of the health facility, it will be possible to strategically analyse the energy systems options that will fit in accordance to future energy demands. In this section, the future energy demand is being calculated for five years from the current date following general assumptions explained below.

It is expected that the new solar energy system will increase the reliability of power supply in Gikomero HF. And, it is assumed that this will lead to the use of more electrical equipment and the acquisition of new equipment (medical and non-medical) while increasing the availability of new healthcare services. Thus, it is assumed that more reliable electricity supply will increase the demand for electricity in the upcoming five years. To calculate this new demand profile, Gikomero HF is established on a higher category. As seen in sub-Section 3.1.3, currently Gikomero fits into the category of ‘health center: category II’ with electricity requirements of 14.175 kWh. In five years from now it is expected that Gikomero HF will fit into the category of ‘health center: category III’ (see Appendix C). Hence, the health facility will be equipped with one more microscope, one more incubator (infant radiant warmer), one more desktop computer, and one portable X-Ray machine. The use of this equipment has been modified through the addition of number of hours in a day (see Table 3-4). The future total energy demand increased up to 24,785kWh/day, fitting into the category III of ‘health centres’. Moreover, according to the future distribution of daily load demand shown in Table 3-5, the future daily electric load variation of Gikomero HF is depicted in Figure 3-5 below.

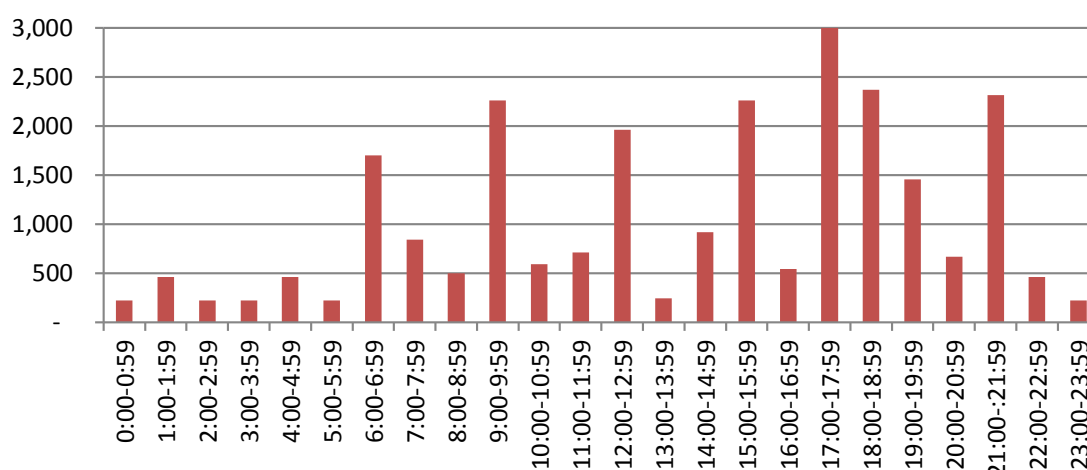


Figure 3-5 Future electric load variation for Gikomero HF (kW per hour)

In the future demand profile, the evening peak between 17:00 and 18:00 is dominated by the use of the new portable X-Ray machine, which consumes 3kW of electricity. Currently, a new technology of X-ray machines is on development, specially designed for health facilities in resource-constrained settings. This new X-ray machine consumes only 600 Watts, and is being developed by EssentialTech (GlobalDiagnostiX, 2015). Clearly, the use of this new equipment in the developing world will turn into large energy savings.

Table 3-4 Future electricity load profile per equipment for Gikomero HF

No.	Type	Equipment (medical and non-medical)	Quantity	Power (Watts)	Total (Watts)	Estimated Number of Daytime hours (07:00-17:59)	Number of Evening hours (18:00-21:59)	Number of Night hours (22:00-06:59)	Total hours/day	Total energy (kWh/day)
1	Security Lighting	2'Tubes (Daylight)	14	10	140		4	8	12	1,68
2	Security Lighting	4' Tubes (Daylight)	4	20	80		4	8	12	0,96
3	Lighting	CFLs	25	7	175		4		4	0,7
4	Lighting	4" Tubes	11	20	220		4		4	0,88
5	ICT	Laptop	5	40	200	4			4	0,8
6	ICT	Desktop	3	100	300	7			7	2,1
7	ICT	UPS/Backups	4	0	0	7			7	0
8	ICT	Printer	1	300	300	2			2	0,6
9	Medical Equipment	Sterilizer/Autoclave	2	600	1200	1			1	1,2
10	Medical Equipment	Infant Radiant Warmer	2	850	1700	3	2	1	6	10,2
11	Medical Equipment	Microscope	2	30	60	3			3	0,18
12	Medical Equipment	Agitator	1	35	35	2			2	0,07
13	Medical Equipment	Aspirator	1	50	50	2	2		4	0,2
14	Medical Equipment	Hospitex Diagnostics/Centrifuge	1	75	75	1			1	0,075
15	Medical Equipment	PH-100i/Centrifuge	1	150	150	1			1	0,15
16	Medical Equipment	Humalyzer/Centrifuge	1	80	80	1			1	0,08
17	Cooling Equipment	Fridge	2	120	240	4	1	3	8	1,92
18	Medical Equipment	Portable X-Ray Machine	1	3000	3000	1			1	3
Total energy demand (kWh/day)										24,795

Table 3-5 Future distribution of daily load demand per equipment (W) for Gikomero HF

Number of Equipment from Table 3-4																			
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total energy (Wh/day)
0:00-0:59	140	80																	220
1:00-1:59	140	80															240		460
2:00-2:59	140	80																	220
3:00-3:59	140	80																	220
4:00-4:59	140	80															240		460
5:00-5:59	140	80																	220
6:00-6:59										1.700									1.700
7:00-7:59									600								240		840
8:00-8:59					200	300	-												500
9:00-9:59					200	300	-			1.700	60								2.260
10:00-10:59						300	-						50				240		590
11:00-11:59						300		300				35		75					710
12:00-12:59										1.700	60		50		150				1.960
13:00-13:59							-										240		240
14:00-14:59					200	300	-	300				35				80			915
15:00-15:59					200	300	-			1.700	60								2.260
16:00-16:59						300	-										240		540
17:00-17:59																		3.000	3.000
18:00-18:59	140	80	175	220						1.700			50						2.365
19:00-19:59	140	80	175	220					600								240		1.455
20:00-20:59	140	80	175	220									50						665
21:00-:21:59	140	80	175	220						1.700									2.315
22:00-22:59	140	80															240		460
23:00-23:59	140	80																	220
Total	1.680	960	700	880	800	2.100	-	600	1.200	10.200	180	70	200	75	150	80	1.920	3.000	24.795

3.3 Electricity supply options for resource-constrained health facilities

After analysing the current and future electricity demand profiles of Gikomero HF, energy supply options are proposed to find a solution for the intermittency problems. As mentioned before, the optimization of the health facility's electricity system has internal and external requirements. Internal requirements for the energy system options involve sufficiency and reliability, and external requirements involve costs and sustainability. In this section, the energy system options are described from literature and compared to each other focusing on the context of a resource-constrained health facility and taking into account the aforementioned requirements.

The present section emphasizes the role of solar energy and other energy technologies that are suitable in the rural context for resource-constrained health facilities. According to the WHO (2014), the traditional form of energy supply for health facilities involves grid-connection backed-up by on-site diesel generator. This is the case of Gikomero HF in Rwanda. In off-grid settings, stand-alone diesel generators have been the primary source of power. These are backed-up by a second fuel-based generator or by flashlights and kerosene lamps in small health facilities or health posts. A backup power source is crucial for handling childbirths, emergencies, surgeries, vaccine storage or laboratories. Yet, primary power sources are more critical for health facilities in developing countries, where grid supply is interrupted and unreliable (WHO, 2014). Adair-Rohani et al. (2013) stated that from the survey data mentioned before, over one-fourth health facilities received power from a diesel generator, and over one-tenth from the central grid. For hospitals, almost all of them reported the use of diesel generators for power, and over one-half the connection to the central grid (Adair-Rohani et al., 2013). A description of the main electricity sources used in resource-constrained health facilities is provided in the sub-sections below. These energy sources are considered as potential options to satisfy the demand patterns of Gikomero HF.

3.3.1 Grid-connection

In rural health facilities, a reliable electricity supply from the central grid is important for healthcare services (medical equipment, sterilisation, cooling, etc.), and makes the work in rural areas more attractive for qualified medical staff (MinBuZa, 2014). However, in many rural areas a lack of access to the central grid and low qualities of grid-connection has led to the use of fossil fuel sources as a small-scale power generation system (Dada, 2014). As seen for the case of Gikomero HF, the central grid supply tends to be often unreliable with an average of 3 blackouts a day. Hence, the health facility has allocated a diesel generator as a secondary energy source, which is not necessarily the most optimal and sustainable solution. According to Yadoo and Cruickshank (2012), frequent blackouts or 'brownouts' (large voltage drops that can damage appliances) may result from the mismanagement of the central grid, poor transmission infrastructure, or generation capacity shortages, especially for rural customers at the end of the network. Also, due to higher operational costs involved in distributing electricity in rural areas, the service may be poor or almost non-existent (Yadoo and Cruickshank, 2012). Often due to remote locations, it could be even more cost-effective to electrify health facilities with off-grid energy systems than connecting them to the central grid. In these cases, grid-connection could be unfeasible due to economic constraints, low consumption levels or geographical difficulties such as long distances and high altitudes. Also, in some cases, national or regional utility companies developed their grid-extension plan without considering the potential for certain communities to acquire off-grid energy supply systems; or even some renewable off-grid projects have been dropped at a later stage due to unanticipated grid-expansion, thus affecting the local economy and possibilities for improvements in sustainable development (Rahman et al., 2013). Extending the national grid network can have economic, technical and social advantages when the population served live close to the existing grid. Grid-based electrification can also simplify maintenance and administration duties such as billing and tariff collection whereas the centralised authorities assumed these responsibilities with accountability (Yadoo and Cruickshank, 2012).

However, in the context of rural Africa, many health facilities are remotely located; thus off-grid solutions could appear to be more suitable such as diesel generators and/or renewable off-grid energy systems because unreliability and shortage of grid power in many areas can severely hamper economic development (Yadoo and Cruickshank, 2012); and in the context of health facilities, it can negatively affect the delivery of healthcare services.

3.3.2 Stand-alone diesel generators

For many rural health facilities in developing countries, off-grid electrification solutions represent optimal means of extending electricity supply in terms of investment required, efficiency and reliability. Stand-alone diesel generators have been the most common off-grid solution for powering health facilities (WHO, 2014), with backup mostly by kerosene lamps, candles or flashlights. Diesel generators offer lower capital costs than many renewable off-grid solutions, and also it is capable of providing AC power allowing a wider range of appliances to function (Yadoo and Cruickshank, 2012). In comparison to the diesel generators, off-grid renewable energy solutions have been criticised for being more expensive and unreliable (Yadoo and Cruickshank, 2012). However, for many health facilities, diesel generators have become increasingly expensive to maintain (WHO, 2014) due to their high operating costs increasing their lifetime levelised cost. Also, fuel costs are particularly high, especially in resource-constrained settings. Yet, considering the rising price of oil-based fuels. While fuel costs have increased, the costs for renewable energy technologies have declined, making them more affordable for financial savings in health facilities. Also, small health facilities face more challenges when maintaining and fuelling generators (WHO, 2014). Due to high operating costs, electricity provision is often limited to a few hours. The study carried out by Adair-Rohani et al. (2013) reflects the unreliability of generators the power health facilities in some sub-Saharan countries; this was evident due to the high proportion of facilities reporting generators not functioning or lacking fuel. Hence, there is a growing importance of solar electricity sources in health facilities, both as a stand-alone system and in combination with other sources. A case study in Liberia from Adair-Rohani et al. (2013) found out that in 2012; more public primary health facilities were using solar power than fossil fuel generators. The data used suggested that a higher level of reliability was achieved on health facilities using solar-powered systems as a primary source than those relying on generators. In addition, 81% of solar-equipped facilities reported having electricity available during the day of the survey in comparison to 52% of facilities using generators (Adair-Rohani et al., 2013). Thus, solar power might be more reliable than generators in these resource-constrained settings. Currently, the diesel generator available at Gikomero HF is only operational for 5 hours/day with outages of 2 times/week, and the diesel price is 1.28 \$/L (GLE, 2015). Detailed economic costs and specifications for the diesel generator are stated in the next chapter, as it is considered as one of the energy technologies available for the optimization simulation of Gikomero HF.

3.3.3 The role of solar energy in resource-constrained health facilities

In comparison with conventional power sources, renewable energy systems have lower operation costs and produce fewer or no emissions. In renewable energy systems, battery maintenance, occasional cleaning, and theft prevention are the major operating costs. Furthermore, when compared to diesel generators, renewable energy technologies can protect against fluctuations in international fuel prices, improving energy security and local resilience (Yadoo and Cruickshank, 2012). In remote small health facilities with a low load (health posts), autonomous PV systems are considered the best option (IEA, 2014). The WHO and USAID have stated the increase use of solar energy in health facilities in resource-constrained settings. Adair-Rohani et al. (2013) document that solar energy is growing in popularity; and across all health facilities from a survey data from 9 sub-Saharan African countries; over one-third received at least some power from solar energy. PV systems are convenient because they can operate alone in remote areas far from other sources of

electricity. Their use is expected to increase in the coming decades, especially in developing countries and in off-grid applications (McKinney et al., 2012).

Solar systems generate electricity from sunlight collected by solar photovoltaic (PV) panels. Combined with batteries, these systems are excellent for small to moderate sized loads in remote locations. They are highly modular and easy to customize, also they produce neither noise nor emissions (USAID, no date). Additionally, solar PV panels produce DC power, and inverters are needed to convert the power into AC. The latter current is most required on medical equipment used in HFs of Level 2 or higher (USAID, no date). In many tropical countries, solar systems with battery storage can provide reliable power on most days of the year, with the advantage of low operating costs, as no fuel is required. Furthermore, solar power is healthier for the local people, patients and health workers, as it does not generate air pollution and greenhouse gasses emissions, and it reduces burning risks associated to kerosene lamps (Mills, 2012). The exposure to diesel or kerosene emissions is associated to the development of respiratory diseases (WHO, 2009). Hybrid solar-diesel systems can also capture most of the health and climate savings mentioned, and increase reliability of the system by mitigating intermittency issues.

Nevertheless, solar PV panels also face some challenges. No power can be produced in the evenings, and also high seasonal weather variations with cloudy environments can also negatively affect the power production. Hence, due to its intermittency, solar power must be combined with an alternative fuel source or an energy storage system (i.e. batteries) if a 24hour service is required. This is the case of health facilities, as they can receive patients at any time during the day and night for emergencies and child deliveries. Furthermore, other barriers to effective uptake of PV solar systems include security issues, inadequate budgets in small health facilities for replacement of solar system batteries and spare parts, and lack of technical capacity to troubleshoot and perform equipment maintenance (WHO, 2014).

3.3.3.1 Costs

The cost of PV systems is primarily capital expense. Since the mid-1970s, the manufacturing cost of these has been decreasing steadily (McKinney et al., 2012). However, it is still considered one of the most expensive options for off-grid electrification due to its high capital costs (Yadoo and Cruickshank, 2012). Installed PV systems can cost \$8-12/W (USAID, no date); and some analysts may believe that in the not-too-far future prices may drop to \$0.5/W or less (McKinney et al., 2012). The IEA (2014) indicated that the turnkey cost for a small-scale stand-alone PV system is USD 6,000 per kW. The major share of capital cost is in modules and batteries, which account for around 60% (IEA, 2014).

The lifetime costs of Solar PV panels systems are much lower when compared to diesel generators that require constant fuel inputs. However, the initial cost of purchase is likely cheaper for generators than solar systems (WHO, 2014). Such comparison is misleading though, because fossil fuels may not be available in a certain area, and it causes environmental impacts that are not internalized their cost (McKinney et al., 2012). Nevertheless, high capital costs represent an issue for rural health facilities that usually lack financial resources to purchase these systems that in the long-term would be translated into cost savings. Stand-alone PV systems with no diesel backup are cost-effective and recommended when energy requirements are less than 5kWh/day and there is a good constant sunshine (IEA, 2014).

3.3.3.2 Operation and Maintenance (O&M)

Operation and maintenance (O&M) of PV systems are low compared to the capital costs, estimated around 1% of the capital investment per year (IEA, 2014). The solar PV panels have considerably a very long lifetime, between 20-30 years (USAID, no date). And the average lifetime of batteries normally is 6 years (IEA, 2014). However, as mentioned before regular maintenance on batteries is

essential, as they should be checked every month, with the electrolyte level replenished as needed. A professional technician should also perform an annual maintenance check, examining wiring connections, mounting bolts, and inverter operation (USAID, no date).

3.3.3.3 DC power

Solar PV panels generate DC power current, and its increased use on rural health facilities has pushed more research into energy efficient DC medical appliances, as seen in Appendix B. DC medical appliances are very attractive for small health facilities, as the use of traditional AC devices with solar PV systems requires an inverter to convert DC power into AC. The addition of an inverter increases costs and maintenance liabilities (WHO, 2014). However, creating one single DC power supply platform without AC conversion remains currently a challenge. DC power from solar PV panels or batteries is typically produced at only one voltage level (e.g. 24 V), while voltage requirements for DC devices tend to vary between 3-34 V, thus requiring voltage conversion (WHO, 2014). Hybrid AC/DC building energy systems must be explored in industrialized countries to analyse their energy savings potential. These new energy systems could be a viable option for rural health facilities in resource-constrained settings whereas DC equipment can fulfil the needs to deliver basic healthcare services.

For stand-alone PV systems, DC coupling is recommended. Overall system efficiency is higher with DC coupling if the main average load occurs during night (use of battery), and with AC if the main average load occurs during the day (IEA, 2014). Usually the system voltage is set to be 12V, 24V, or 48V. If required, an inverter is used to convert the generated power from DC to 110V or 230V AC.

3.3.3.4 Local solar resource

Solar systems are rated in terms of peak power (W or kW) they can produce. This is multiplied by the peak sun hours (PSH) factor to determine the energy (kWh) produced per day. An optimal setting in Africa receives >5 PSH per day, and with a 1 kW system, it would produce 5 kWh per day (USAID, no date). According to the NASA surface meteorology and solar energy database for the location of Gikomero HF, the solar global horizontal irradiation (GHI) resource was downloaded in HOMER simulation software with an annual average of 4,88 kWh/m²/day. Appendix D depicts the seasonal variation for Solar GHI resource over a year in the location of the health facility. The values are monthly averaged over a period of 22 years (July 1983 – June 2005). HOMER facilitates the allocation of the solar resource when specifying the specific location of the project (latitude and longitude).

3.3.3.5 Solar Energy Services for Healthcare (SESH)

Great Lakes Energy (GLE) has developed the technology called SESH, which represents a remote monitoring platform tied into a modular solar energy system for ensuring constant and reliable power, and being able to report relevant data. As mentioned earlier, in Gikomero HF a new solar system will start its operation in October 2015 to test the technology SESH. The installed capacity of the solar PV system is 3kW with an initial capital cost of \$10,000 for the PV panels alone, including installation. This solar power system has a modular design, which allows easy escalation; and each solar panel or module has a micro-inverter, which enables every solar panel to perform at its maximum potential and gives the possibility to integrate any existing PV into a single system. Information about costs and specifications of the new solar system is documented in Chapter 4.

3.3.4 Other off-grid energy systems

3.3.4.1 Hybrid PV-diesel systems

A hybrid system is described as an electricity production system consisting on a combination of two or more types of energy system. According to Ani and Emetu (2013), a hybrid PV-diesel system can reduce the operational cost and quantity of air pollutants in comparison with only a diesel generator

system. For medium and large facilities (health centres and hospitals), hybrid systems are the most economic and reliable option (IEA, 2014). A PV-diesel hybrid solution is the most cost-efficient option over time, especially in regions with prolonged periods of cloudy weather and fuel availability. This optimized system allows the facility to rely on diesel generation for peak loads only, while using PV solar power directly or store energy in battery during other periods.

For small and mid-size health facilities, hybrid PV-diesel systems can achieve a lifetime fuel savings on an order of 75-80% while ensuring reliable electricity supply (WHO, 2014). Small-scale energy management systems can shift efficiently between different energy sources so clinics harness sunlight during most operating hours, but benefit from automatic generator backup in peak periods or when solar storage has been depleted. Hybrid systems can also have other configurations such as wind-diesel hybrid systems. Renewable or hybrid energy systems still require higher capital investments than conventional generators.

3.3.4.2 Micro-wind power

Modern wind turbines are relatively simple technologies that consist of blades and a rotor connected to an electrical generator, along with a control system, mounted on top of a tall tower (McKinney et al., 2012). According to van Rijn (2015), a wind turbine has a lifetime of 20 years for the rural setting, where they usually have a height of 6 meters and the initial capital is \$1.000. Same as the costs of solar PV systems, the costs of wind electricity have decreased dramatically in the last 10 years (McKinney et al., 2012). Small wind turbines are well suited to supply power in remote locations that are not grid-connected, especially in developing countries. However, they depend highly on the location due to variable wind speed. Seasonal variations in wind speed and directions can be subject to rapid and wide fluctuations that can significantly affect the volatility of production output (McKinney et al., 2012). On seasonal and daily basis, the strongest and steadiest winds may not blow during the peak demand for electricity. Also, to ensure technical sustainability, the availability of local manufacturers is crucial for the long-term supply of spare parts (Ferrer-Martí et al., 2012). Small wind turbines can be combined with a PV system to increase reliability of supply. Currently, the Rwandan government is planning to electrify rural areas with off-grid solutions such as micro-wind power, solar systems and micro-hydro power. This is why this technology is considered as one of the potential energy supply options to satisfy the demand at Gikomero HF, even if currently there are no plans to implement micro-wind systems for the health facility. Furthermore, a national wind atlas for Rwanda is currently being developed with the support of the Belgian government, so it is expected that wind power systems will become more popular in the country (MININFRA, no date).

The local wind resource was downloaded from the same database as the solar resource and for the specific location of Gikomero HF. The annual average wind speed is 3,01m/s. Appendix D depicts the seasonal variation for wind resource over a year. The values are monthly averaged over a period of 10 years (July 1983 – June 1993), and are calculated at 50m above the surface of the earth.

3.3.4.3 Micro-hydro power

Micro-hydro power appears to be a favoured option from renewable off-grid technologies due to its low levelised costs, provision of AC power required for most medical equipment, and its potential to provide a 24hour service without the need of batteries. However, the implementation of micro-hydro power systems strictly depends on the availability of hydro resources close to the facility location, and also its applicability is limited as it requires the presence of inclined slopes and steady water flows (Yadoo and Cruickshank, 2012). Also, the system depends on seasonal variations as production can significantly drop during dry seasons. At present, in Rwanda there are few micro-hydro power systems connected to isolated microgrids; the installed capacity represents 500kW (MININFRA, no date). For the case of Gikomero HF, there is no river close, therefore it is not considered as an energy supply option.

3.3.4.4 Biomass-based systems

Next to micro-hydro power systems, biomass systems are one of the lower cost renewable off-grid technologies (on a levelised cost basis) according to Yadoo and Cruickshank (2012). If there is fuel stock available, a 24hour service is possible. However, the availability of fuel fluctuates depending on the harvest cycle. Also, the cultivation of fuel stock could take place on land that could be used to grow vital food crops. In the rural areas of Rwanda, biogas is commonly used for lighting and cooking in raw gas form, however there are currently no perceptions for using biogas for electricity (GLE, 2015). This is the reason why biomass-based systems are not considered as an energy supply option for Gikomero HF.

3.3.5 Energy storage systems

Off-grid energy systems that only rely on one renewable energy source face a greater threat of supply vulnerability. Therefore, it should be ensured that a diverse supply mix is integrated into the off-grid energy system or that an energy storage system is available (Yadoo and Cruickshank, 2012). However, a storage system is an additional equipment, therefore it will increase the system's capital costs. Nevertheless, by adding energy storage systems, long-term issues of stand-alone energy systems can be solved such as supply shortages and intermittency. Energy storage systems could be batteries, flywheels and fuel cells. Batteries are often used in connection with solar PV systems and require replacing every certain time depending on usage. Besides of the relatively low-maintenance requirements for solar power systems, battery management and replacement are critical to ensure long-term sustainability. Local access to materials is not always available in rural areas, and the health facility can face economic constraints to replace the system. Under tropical, equatorial or arid conditions, lead acid batteries can have a lifespan of only 2-5 years depending on usage, and then they must be safely disposed. It is important to state that exposure to lead of improperly disposed batteries can cause severe poisoning. Alternatively, lithium batteries could pose fire risks (USAID, no date).

In resource-constrained settings, and especially in remote areas, energy storage systems such as batteries are considered as one of the most important aspects for ensuring reliability. Batteries can solve intermittency and unreliability issues, mainly in health facilities whereas the internal system requirements are sufficiency and reliability; here storage plays an important role and can be considered as a 'game changer'. In the next chapter, the energy supply systems described above will be assessed to find the optimal configurations (system architecture) to satisfy the demand of Gikomero HF. Different scenarios will be simulated, and it will be possible to determine the role of each technology and how important storage systems are in resource-constrained health facilities.

4. OPTIMIZATION OF ENERGY SYSTEMS IN RESOURCE-CONSTRAINED HEALTH FACILITIES

After describing the current and future electricity profiles of Gikomero HF, and the possible energy options suitable for a resource-constrained context, an optimization model can be built to discover and analyse the optimal combination of energy technologies for this particular case involving different scenarios. Also, it is possible to determine the role of solar energy. As explained before, Gikomero HF will have solar PV panels implemented soon; however with this study it can be stated how optimal is this solution from a technical, environmental and economic point of view. Furthermore, this optimization assessment can be included as part of the protocol to electrify health facilities in the future with the most suitable technologies according to the health facility size and category, and its electricity needs.

4.1 Methods

4.1.1 HOMER simulation software

The HOMER microgrid software is considered the global standard for optimizing the design of energy systems in any sector. It was originally developed at the National Renewable Energy Laboratory, and modified and distributed by HOMER Energy (Hybrid Optimization Model for Multiple Energy Resources). The software provides three tools; these are simulation of the operation of a microgrid for one entire year, optimization of all possible combination of system types, and sensitivity analysis (HOMER Energy LLC, 2014-2015). The objective of the optimisation simulation is to evaluate the economic and technical feasibility for different technology options, while considering variations in technology costs and energy resource availability (Connolly et al., 2010).

HOMER has experience on microgrids and distributed energy systems that can include a combination of renewable energy technologies, storage systems, and fossil-based sources (either through stand-alone systems or grid-connected). The software simulates and optimises stand-alone and grid-connected power systems with any combination of wind turbines, solar PV panels, micro-hydro power, biomass power, generators, fuel cells, batteries and hydrogen storage; while serving electric and thermal loads (by individual or district-heating systems). It simulates all costs except fuel handling costs. The simulation considers a one-year time-period using a minimum timestep of 1 minute. It also performs a sensitivity analysis that helps to investigate the effects of uncertainty in input variables. Overall, the HOMER model simplifies the task of designing microgrids; and its optimization and sensitivity analysis algorithms allow the evaluation of economic and technical feasibility of different energy options, and to account for variations in costs, electricity load, and the availability of energy resources. Furthermore, the software is relatively simple and easy to use, and adaptable to a wide variety of projects. It provides a chronological simulation that is essential for modelling variable resources such as solar and wind power. Also, the sensitivity analysis helps to determine potential impacts of uncertain factors such as fuel prices.

In this study, HOMER is useful to simulate energy options in rural health facilities, as it models both conventional and renewable energy technologies, either isolated or grid-connected. And, it is adjusted to the electric load profile of the health facility, allowing variability to make it more realistic. Additionally, it allows the simulation of natural resources such as solar and wind in accordance to the pre-defined location of the health facility. The results of simulating health facilities can provide information about optimal energy technologies customized to the local context and settings, and will visualize costs of technologies, determining the most cost-effective options to meet the electrical load and needs. Health facilities in resource-constrained settings have few monetary resources, and these resources should be spent cautiously. Through the implementation of optimal energy options, monetary and energy savings can be achieved. Moreover, the difference between HOMER and other

simulation software is that it focuses primarily on stand-alone power applications of renewable energies such as for a single building, a local community or for single-projects (Connolly et al., 2010). Rural health facilities are single buildings that are usually remotely located, and many of them lack connection to the grid; therefore, stand-alone energy systems are good options for their power supply.

4.1.2 Model building and assumptions

The model is first built based on the data collected from Gikomero HF, the case study in Rwanda (see Chapter 3). Data about technology options and costs have been obtained from others sources with the contribution of GLE, HDP and van Rijn (2015). Also, data of HOMER Energy is being used whereas references are not being explicitly specified in the model building.

When starting the model in HOMER, the location of the health facility is set in the Gikomero area in Rwanda (see Figure 4-1).



Figure 4-1 Location of Gikomero HF (Model HOMER Gikomero HF, 2015)

To start building the model, first the electric load must be specified based on the current daily electricity load profile for the health facility. The current detailed electricity load profile for Gikomero HF can be found in section 3.1. Afterwards, another model will be built based on the future electricity load profile specified in section 3.2. Second, the energy supply technologies or ‘components’ that represent an option to satisfy the electric demand of the health facility are added with

their respective costs and specifications. The energy supply options are described in section 3.3. Third, the respective resources to fuel renewable-based components are set for the specific location. In the case of Gikomero HF, the resources are wind and solar. The detailed steps to build the model are described within the next sub-sections.

4.1.2.1 Load Profile

The electric load is the source that consumes power; in this case the health facility. The electric load profile of the health facility was specified in section 3.1. The daily load profile is divided per hour within one average day, as seen in the left side graph of Figure 4-2 as ‘daily profile’. This profile is repeated over a year, as shown in the right side graph of Figure 4-2 as ‘seasonal profile’.

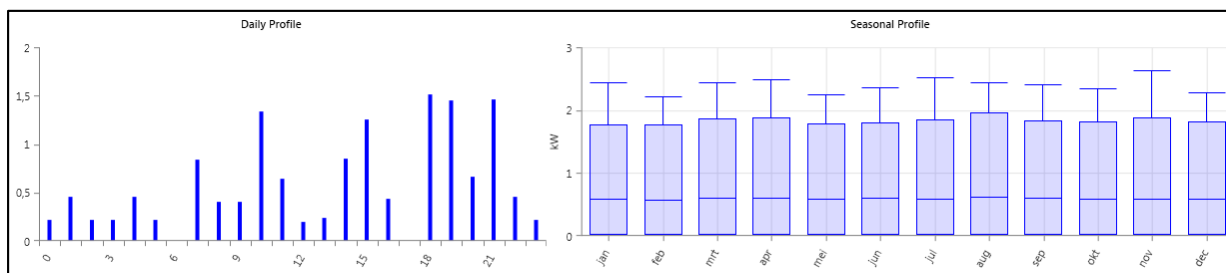


Figure 4-2 Electric load profile of Gikomero HF

After allocating the daily profile, the seasonal profile of the electric load in Gikomero HF tends to be uniform, as HOMER automatically sets it equal for every month of the year. This is due to the fact that the electric load is provided for an average daily basis with no variability over time. It is assumed

that there is no cyclic annual variation or ‘peak month’. However, to make the load profile more realistic, random variability can be added. According to the user help manual of HOMER (2014), measured load data is seldom available; therefore users usually synthesize load data by specifying typical daily load profiles and then adding a percentage of randomness. Random variability is defined with two values, ‘day-to-day’ and ‘timestep’. Adding day-to-day variability causes HOMER to perturb each day’s load profile by a random amount, so that the load retains the same shape for each day, but is scaled upwards or downwards. On the other side, timestep variability disturbs the shape of the load profile without affecting its size. When combining both values, a more realistic data can be created (HOMER Energy, 2014). The mechanism to add random variability is that HOMER first assembles the year-long array data from the daily electric load specified; then it steps through that time series and in each timestep, it multiplies the value in that timestep by a perturbation factor α where:

$$\alpha = 1 + \delta_d + \delta_{ts}$$

δ_d = Daily perturbation value

δ_{ts} = Timestep perturbation value

HOMER randomly draws the daily perturbation value once per day from a normal distribution with a mean of zero and standard deviation equal to the ‘daily variability’ value. Same, it randomly draws timestep perturbation value every timestep from a normal distribution with a mean of zero and standard deviation equal to the ‘timestep variability’ value.

The WHO (2014) made a hypothetical case simulation for a health facility in Kenya, and provided realistic results with day-to-day 10% variability and timestep 15% variability. To be consistent, in this model of Gikomero HF, random variability was added to the model, through a day-to-day value of 10% and a timestep value of 15% (see Figure 4-3).

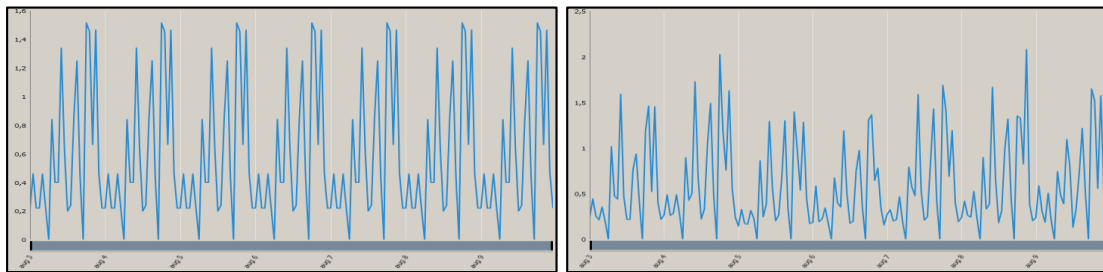


Figure 4-3 Plot of first week of August for Gikomero HF without and with random variability

In Figure 4-3, two plots of the electric load profile during the first week of August are depicted. The one at the left was before adding random variability and the one at the right after adding the values stated above.

It is assumed that there is no peak shifting for the current load profile. As depicted in the daily profile, the peak is in the late afternoon (from 18:00) when users turn on lights and other energy high demanding medical equipment such as autoclave and incubator. If the peak would be spread around the day or around noon by shifting high-consuming equipment to be used during those times, solar energy could power this type of equipment, and other energy sources could be used during nights when there is no sun. In HOMER, there is no peak shifting options or the introduction of energy saving measures to spread the peak to other times of the days. The next sub-section describes the energy options that could satisfy the demand profile of Gikomero HF. The description is based on the parameters required to allocate the energy technologies in the model such as economic costs and technical specifications.

4.1.2.2 Components

The components are energy technologies that are part of the power system. Here, it is possible to add generators, solar PV panels, wind turbines, batteries, converters, hydropower systems, biomass, central grid and flywheel components. The components that require resource information such as solar and wind, require the seasonal data from the corresponding resource. This was already described in sub-section 3.3.

The added components are stated below. On each component technical specifications are required next to the costs for purchase, installation, replacement, operation and maintenance. The capital cost is the initial purchase price (including installation), the replacement cost is the cost of replacing the component at the end of its lifetime, and the O&M cost is the annual cost of operating and maintaining the component. Additionally, the model allows a sensitivity analysis on certain variables.

a) Diesel generator '12kW Genset'

Currently, Gikomero HF has a diesel generator of 12.5kW as seen in the supply-side analysis (See section 3.1.2). This generator was added to the model. The respective costs for the diesel generator are shown in Table 4-1. Technical specifications for the diesel generator are found in Appendix E.

Table 4-1 Costs for diesel generator

Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/hour)
1	0	350	0.350

As seen in Table 4-1, the initial capital costs were set to zero as the generator is already in place and the model should not simulate the costs of buying it again. Replacement costs are 350 \$/kW (Appropriate Technology Africa, 2011), and O&M was set to 0,350 €/hour (van Rijn, 2015). The lifetime in hours was set for a range of 15.000, 20.000 and 25.000 hours (van Rijn, 2015) with a sensitivity analysis of these three values, as it was difficult to obtain the real value. Moreover, diesel fuel price range for sensitivity analysis is 1; 1,28 and 1,5 \$/L. The current diesel fuel price for Gikomero HF is 1.28 \$/L (HDP, 2015), however prices are subject to change, that is why a sensitivity analysis was added (HDP, 2015).

b) PV panels 'Generic flat plate PV'

In Gikomero HF, the new solar power system has an installed capacity of 3kW as specified in sub-section 3.1.2. However, more kilowatts were added to the size to increase possibility and options for the future. Also, a dedicated inverter is added to the system. See Appendix E for the specifications added to the model. When specifying the capital and replacement costs, all costs associated with the PV system are taken into account, these include: (a) PV panels, (b) mounting hardware, (c) tracking system, (d) control system (maximum power point tracker), (e) wiring, and (f) installation.

Table 4-2 Costs for the solar PV panels and the dedicated inverter

	Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
Solar PV panels	3	10,000 (GLE, 2015)	7,500	0
Dedicated inverter	2,58	2,500	2,500	0

Table 4-2 shows the costs for the solar PV panels and the dedicated inverter. The O&M cost is assumed to be zero as it only involves cleaning once in a while, which is considered a negligible cost. According to GLE (2015), the total PV micro-inverter power is 2.58kW and the total capital cost is \$2,500; the maintenance is minimal or negligible. Furthermore, the dedicated inverter lifetime is 15 years according to HOMER Energy (2015). The size was set for the range of (kW): 1; 2,58; 3; 4 and 6.

c) Wind turbine 'Generic 3kW'

Although there are currently no plans to implement a wind turbine in Gikomero HF, this technology was considered as one of the options due to their growing implementation in rural settings. When specifying the capital and replacement costs, all costs associated with the wind energy system are taking into account, these include: (a) turbine rotor and tower, (b) control system (c) wiring and (d) installation (see Table 4-3). The quantity of wind turbines was set from 0 to 5 to keep possibilities open. See Appendix E for more specifications.

Table 4-3 Costs for the wind turbine (van Rijn, 2015)

Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
1	1,000	500	500

d) Battery 'Deka Gel 12V 213Ah'

The batteries that will be implemented in Gikomero HF are model Deka Gel 12V 213Ah. This model was introduced to the library of HOMER, as it was not found in the database. According to GLE (2015), the total battery bank of 10 batteries is 25.56kWh, and the total initial cost is about \$9,520 (see Table 4-4 below). The replacement would be equal to the initial cost because the whole bank would be replaced; and this would happen after 4-8 years depending on the usage and charge. Also, these are maintenance free Gel batteries (GLE, 2015).

Table 4-4 Costs for the battery

Quantity (number of batteries)	Capital (\$)	Replacement (\$)	O&M (\$/year)
10	9,520	9,520	0

The minimum state of charge of the batteries was set to 60%, as the design normally allows 30-40% Depth of Discharge (D.o.D.) (van Rijn, 2015). The life throughput was set to 3,550kWh (van Rijn, 2015). In total, there will be implemented 10 batteries each 213Ah/12V with 2 parallel strings of 5 batteries in series (24V) (GLE, 2015). See Appendix E for the specifications of the battery.

e) Converter 'System converter'

The load peak of Gikomero HF is 2.63kW. The converter size initial option has been set to 2.63kW to meet the peak, and also other options of 3; 4; 4.5; 5; 6 and 7. The inverter is actually rated 5kVA with 4.5kW continuous power (GLE, 2015). According to van Rijn (2015), 5 converters cost €2,200/kW, with an assumed replacement cost of €2,200/kW and a lifetime of 12 years (See table 4-5 below).

Table 4-5 Costs for the converter

Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
5	2,200	2,200	0

The diesel generator runs on a separate line, but has a connection to the inverter to charge the batteries when there is no both solar energy and central grid supply (GLE, 2015). Thus, the inverter is selected parallel to the AC generator. See Appendix E for other variables of the system converter.

f) Grid

Currently, Gikomero HF relies on power from the central grid. The current grid power price is 0,22 \$/kWh (HDP, 2015), and a sensitivity analysis was added of 0,10 and 0,30 \$/kWh due to possible

power price fluctuations. HDP (2015) stated that “it is not clear how many hours a day the central grid is operational, but in total the HF has electricity for around 19 hours a day. And, they have in average 3 blackouts a day”. Therefore, a grid outage was scheduled to make the simulation more realistic. It was assumed that the grid power goes off 3 hours/day from 18:00 until 21:00 every day. As seen before, this is where the peak load is; therefore this would be considered the worst-case scenario, putting pressure in the system at most critical hours. It is expected that HOMER simulates the system to use other optimal power sources within those critical times of the day. Regarding grid reliability, the mean failure frequency was set as 2,160 times/year, which entail 3 blackouts/day. It is assumed that the mean repair time is 1 hour in rural settings, and that there is no repair time variability. Moreover, the grid is not prohibited for charging the battery; but it is prohibited to carry out grid sales. See Table 4-6 for the specification of grid variables.

Table 4-6 Grid variables

Annual purchase capacity	Generic 3kW
Grid power price (\$/kWh)	0.10; 0.22; 0.30 [sensitivity analysis]
Prohibit any battery charging (Yes/No)	No
Prohibit any grid sales (Yes/No)	Yes
Grid outages (hours/day)	3 (18:00 – 21:00 every day)
Reliability	
– Mean failure frequency (1/year)	2,160
– Repair time mean (h)	1
– Repair time variability (%)	0
Emissions	
– Carbon dioxide (g/kWh)	632
– Carbon monoxide (g/kWh)	0
– Unburned hydrocarbons (g/kWh)	0
– Particulate matter (g/kWh)	0
– Sulphur dioxide (g/kWh)	2.74
– Nitrogen Oxides (g/kWh)	1.34

4.1.2.3 Resources

In HOMER, a ‘resource’ is anything that comes from outside the system, and is used by a component to generate energy (HOMER Energy, 2014). The Solar GHI resource and the Wind resource were added to the model of Gikomero HF. The annual seasonal variations for these resources are shown in Appendix D. The annual average for the solar GHI resource is 4.88 kWh/m²/day, and annual average wind speed is 3,01 m/s.

After adding the electric load, the components and resources, the model built for Gikomero HF is complete, and the scheme is shown in Figure 4-4.

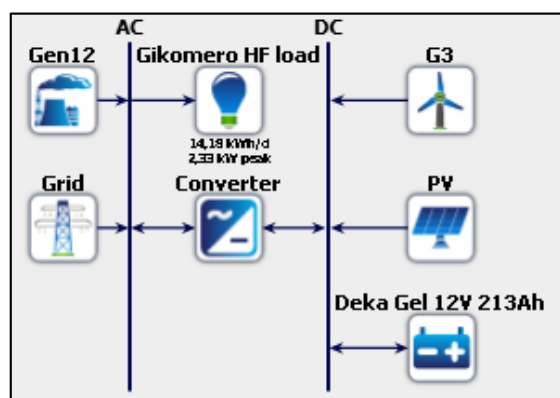


Figure 4-4 Microgrid scheme of Gikomero HF (Model HOMER Gikomero HF, 2015)

4.2 Results

The model described above is called the ‘current system scenario’. After running the simulation, HOMER shows the top-ranked system configurations according to the Net Present Costs (NPC). Thus, showing the optimized architecture of energy options to satisfy the demand of Gikomero HF based on costs. In resource-constrained health facilities, economic savings are very important due to the lack of financial resources. This is why the optimization is based on systems with lower costs that meet the internal requirements of sufficiency and reliability. To meet these internal requirements, the maximum annual capacity shortage is left as zero because the load is crucial for healthcare services. If the value is zero, then the power system must meet 100% of the electric load specified, plus the required operating reserve (HOMER Energy, 2014). Other external requirements such as sustainability and environmental aspects are considered as secondary. However, the environment must not be underestimated. Therefore, various scenarios were modelled for Gikomero HF next to the ‘current system scenario’ or BAU. Other scenarios are the ‘new system scenario’ to be implemented in Oct-15, ‘no grid scenario’, ‘no generator scenario’, ‘no storage scenario’, ‘only renewables scenario’ and ‘future system scenario’. These other scenarios will give a better picture of the energy options when increasing renewability of the system (i.e. renewable fraction) and lowering emissions. Also, more scenarios will reduce the obstacles of implementing certain technologies and having to deal with a lack of local supply chains. And lastly, adding a ‘future system scenario’ is helpful to avoid falling into path-dependency, and to be able to make strategic choices at the present date that are also optimal to meet the future demand of the health facility. Results for scenarios are in Table 4-7, showing the system architecture for each scenario to meet the demand and their respective costs. Sustainability aspects for each scenario are shown in Table 4-8. The parameters shown are pre-selected for this particular study; nevertheless HOMER gives more parameters that could be used for different analyses.

4.2.1 Net Present Costs (NPC) results

HOMER uses the NPC to represent the life-cycle cost of a system. The total NPC condenses all costs and revenues that occur within the lifetime of the project into a total sum in year-zero dollars, with future cash flows discounted back to year zero. In the model, costs include capital costs, replacement costs, operating and maintenance costs, fuel costs if applicable, the cost of buying electricity from the grid if available, and miscellaneous costs such as emissions penalties (not applicable in this particular case). Revenues include the income from selling power to the grid if possible, and any salvage that occurs at the end of the project lifetime. With the NPC, costs are positive and revenues are negative; thus being the opposite of the Net Present Value (NPV) and differing only in sign. In the model, the project lifetime is 25 years and the discount rate is 8%. The formula to calculate the NPV is the following;

$$NPV(i, N) = \sum_{t=0}^N \frac{R_t}{(1+i)^t}$$

Where:

$$\begin{aligned} N &= \text{Total number of periods} \\ i &= \text{Discount rate} \\ R &= \text{Net cash flow} \\ t &= \text{time of the cash flow} \end{aligned}$$

Table 4-7 Optimization results based on costs for Gikomero HF

Optimizations		Architecture						Costs (\$)			
		Solar PV panels (kW)	Dedicated converter (kW)	Wind turbine (kW)	Diesel generator (kW)	Batteries	Grid connection	Converter (kW)	NPC	Initial capital	Operating Cost
BAU		-	-	-	12,5	-	Yes	-	175.647,90	0	13.587,14
Current system scenario	Opt. 1	2	1	-	12,5	5	Yes	3	29.406,72	13.715,66	1.213,77
	Opt. 2	-	-	-	12,5	5	Yes	3	29.885,01	6.080,00	1.841,42
	Opt. 3	2	1	1	12,5	5	Yes	3	36.518,29	14.715,66	1.686,53
	Opt. 4	-	-	1	12,5	5	Yes	3	36.951,30	7.080,00	2.310,68
	Opt. 5	7	3	-	12,5	-	Yes	3	138.694,80	27.560,31	8.596,74
	Opt. 6	6	3	1	12,5	-	Yes	3	145.914,70	25.226,98	9.335,72
	Opt. 7	-	-	-	12,5	-	Yes	-	175.649,80	0	13.587,28
	Opt. 8	-	-	1	12,5	-	Yes	3	184.906,50	2.320,00	14.123,87
New system (Oct-15)		3	2,58	-	12,5	10	Yes	5	42.471,68	24.000,00	1.428,87
No grid scenario		7	2,58	-	12,5	15	No	7	68.746,10	43.193,34	1.976,62
No generator scenario		No feasible solution									
No storage scenario		7	3	-	12,5	-	Yes	3	138.694,80	27.560,31	8.596,74
Only renewables scenario	Opt. 1	12	2,58	-	-	20	No	5	85.697,07	63.740,00	1.698,48
	Opt. 2	12	2,58	1	-	20	No	5	93.230,40	63.740,00	2.203,86
	Opt. 3	15	5	4	-	15	No	5	118.523,30	75.324,96	3.341,58
Future system scenario (5 years)	Opt. 1	3	2,58	-	12,5	5	Yes	4	50.081,80	19.020,00	2.402,77
	Opt. 2 (no grid)	11	4	-	12,5	20	No	9	108.052,30	63.542,64	3.442,01
	Opt. 3 (no gen)	4	3	-	-	10	Yes	4	55.180,52	27.520,31	2.139,64

Table 4-8 Sustainability aspects of optimization results for Gikomero HF

Optimizations		Sustainability									
		Renewable fraction (%)	Diesel generator operating hours	Fuel consumption (L)	Grid electricity purchase (kWh)	Emissions (kg/year)					
						Carbon dioxide	Carbon monoxide	Unburned hydrocarbons	Particulate matter	Sulfur dioxide	Nitrogen oxides
BAU		-	1.984	2.963,56	3.904,40	10.270,00	19,26	2,13	1,45	26,36	177,11
Current system scenario	Opt. 1	31,78	10	18,73	3.485,27	2.252,00	0,12	0,01	0,01	9,65	5,76
	Opt. 2	-	32	58,71	5.692,58	3.752,30	0,38	0,04	0,03	15,91	11,03
	Opt. 3	33,61	8	15,05	3.399,07	2.187,80	0,10	0,01	0,01	9,39	5,43
	Opt. 4	-	31	56,30	5.562,75	3.663,90	0,37	0,04	0,03	15,54	10,72
	Opt. 5	-	1.261	1.883,64	2.221,52	6.362,40	12,24	1,36	0,92	16,04	112,22
	Opt. 6	-	1.297	1.937,42	2.222,15	6.504,40	12,59	1,39	0,95	16,33	115,34
	Opt. 7	-	1.984	2.963,56	3.904,40	10.270,00	19,26	2,13	1,45	26,36	177,11
	Opt. 8	-	1.983	2.962,07	3.826,25	10.216,00	19,25	2,13	1,45	26,14	176,92
New system (Oct-15)		46,21	-	-	2.782,98	1.758,80	-	-	-	7,63	3,73
No grid scenario		88,32	95	229,84	-	605,25	1,49	0,17	0,11	1,22	13,33
No generator scenario		<i>No feasible solution</i>									
No storage scenario		-	1.261	1.883,64	2.221,52	6.362,40	12,24	1,36	0,92	16,04	112,22
Only renewables scenario	Opt. 1	100,00	-	-	-	-	-	-	-	-	-
	Opt. 2	100,00	-	-	-	-	-	-	-	-	-
	Opt. 3	100,00	-	-	-	-	-	-	-	-	-
Future system scenario (5 years)	Opt. 1	27,68	94	176,55	6.124,58	4.335,70	1,15	0,13	0,09	17,72	18,45
	Opt. 2 (no grid)	80,67	210,00	626,23	-	1.649,10	4,07	0,45	0,31	3,31	36,32
	Opt. 3 (no gen)	37,20	-	-	5.681,53	3.590,70	-	-	-	15,57	7,61

4.2.2 Sensitivity analysis results

After running the simulation, HOMER displays a sensitivity cases table listing the optimal systems for each sensitivity case. Thus, every sensitivity case has optimization results of best feasible systems for that specific sensitivity case. A sensitivity analysis can result in a huge amount of output data, involving hundreds of sensitivity cases. For Gikomero HF, the variables subject to uncertainty are the lifetime of the diesel generator, the diesel fuel price, and the grid power price. The 'current system scenario' was simulated with a range of values for these particular variables. However, the sensitivity case chosen for optimization results was the average case. Hence, the lifetime of the diesel generator is 20.000 hours, the diesel fuel price is 1,28 \$/L, the power price is 0,22 \$/kWh. The optimization results for this sensitivity case are the ones shown in Table 4-7 and Table 4-8. Still, it is important to do a sensitivity analysis because it is uncertain as into what exact value of some variable should be. When specifying a range of variables, it is possible to determine how important the variable is, and how the results can change depending on its value (HOMER Energy, 2014).

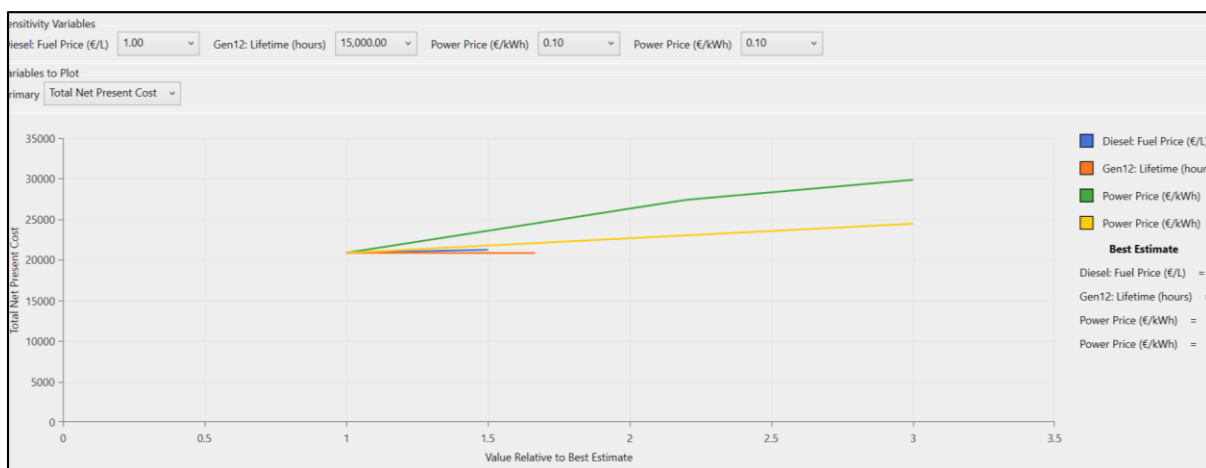


Figure 4-5 Spider graph for sensitivity analysis

Figure 4-5 shows a spider graph of the values subject to a sensitivity analysis. These values are the diesel price, the lifetime of the diesel generator and the grid power price. The nominal scenario is pre-selected and each sensitivity variable corresponds to one line of the value relative to the best estimate (i.e. nominal scenario).

4.2.3 Optimization results

4.2.3.1 Business-as-usual (BAU) scenario

The 'BAU scenario' is a baseline point of comparison. This scenario has the current electric architecture of the health facility with a 12,5 kW diesel generator and grid-connection. And the results in Table 4-7 show what will happen if nothing is done to improve the electricity system, meaning that no new electric supply systems are added to satisfy the demand. It is known however, that this system is unreliable due to frequent power outages. Therefore, the results reflect a perfect-functioning system when the demand is satisfied with reliability and sufficiency to avoid power outages. This is one of the reasons why the NPC for BAU are very high reaching \$175.648. Figure 4-6 depicts the comparison between the different scenarios, showing how high the NPC for BAU are when compared to other optimal solutions. The other scenarios are described within the next sub-sections.

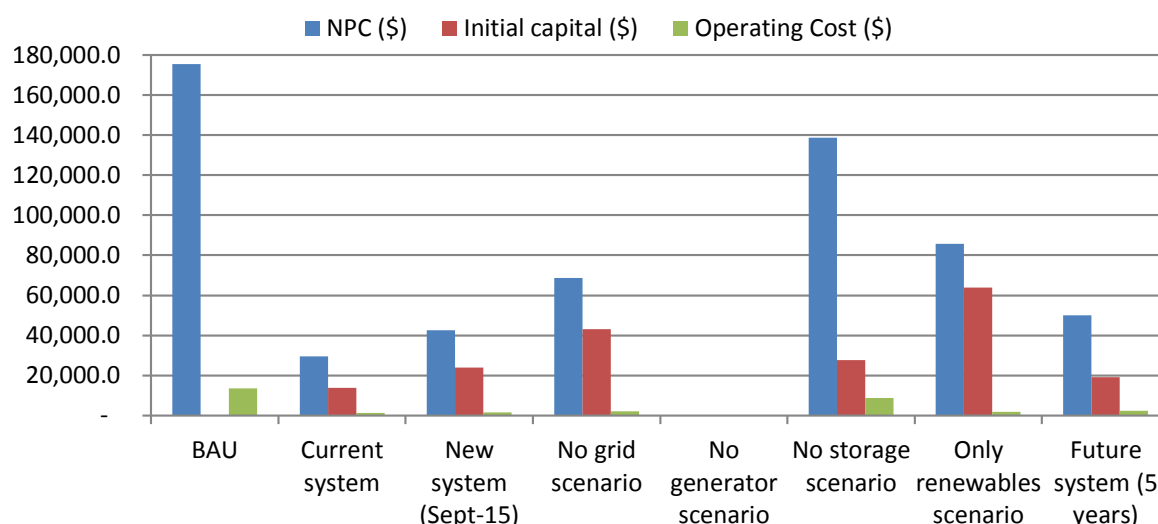


Figure 4-6 Comparison of costs for the different scenarios (using the first-ranked optimal option for each scenario)

4.2.3.2 Current system scenario

The 'current system scenario' represents the optimization of the current system when adding other energy supply components seen in section 3.3 such as solar PV panels, wind turbines and batteries. Therefore, results show the optimal options to satisfy the demand of Gikomero HF with different architectures. As seen in Table 4-7, the first-ranked option for the 'current system scenario' has an architecture of 2kW solar PV panels, 1kW dedicated converter, 12,5kW diesel generator, 5 (1 string), 2,63kW system converter and grid-connection. The second-ranked option considers 5 batteries, the 12,5kW diesel generator, a 3kW system converter and a central grid supply. The third-ranked option considers the same architecture as the first option plus adding one wind turbine of 3kW. These were the top 3 options for electrifying Gikomero HF currently with NPC of around \$30,000. The second option however, has a lower initial capital because solar panels and wind turbines are not recommended. Figure 4-7 shows the 8-optimization options for the 'current system scenario', the top 3 ranked options are visualized from left to right. It can be observed that option 7 is the BAU scenario, and that its NPC exceed \$150,000.

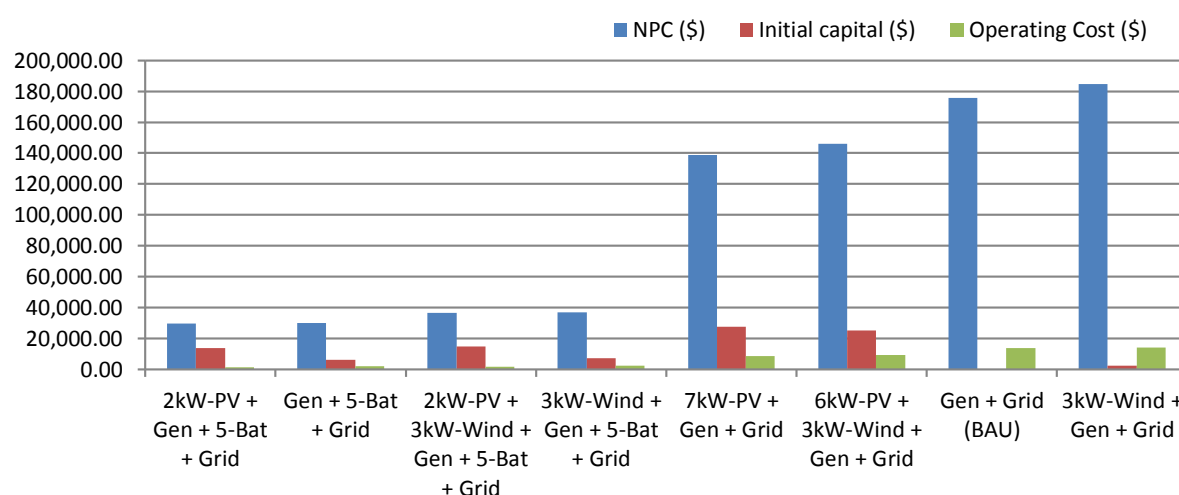


Figure 4-7 Costs for the 8-optimization options of the 'current system scenario'.

In this scenario, it is assumed that there is a diesel generator already available and that the health facility is connected to the grid, as this is actually the current system architecture. Nevertheless, it is

important to also simulate other scenarios just in case these energy supply options are not available anymore for Gikomero HF, and also to explore more sustainable solutions.

4.2.3.3 New system scenario

The optimization options from the ‘current system scenario’ can be compared to the option that Gikomero HF is implementing in October 2015 called the ‘new system scenario’. This new system has access to the grid, 10 batteries (2 strings of 5 batteries per string), a 12,5 kW diesel generator, a system converter of 4,5 kW, and 3kW solar PV panels with 2,58 kW dedicated converter. No sensitivity analysis was simulated for this option, and the possibility of adding wind turbines was included, however there are no plans to implement this technology in Gikomero HF at present. The first-ranked option did not brought up the addition of a wind turbine; therefore it is not recommended for this particular system in terms of NPC. The NPC for this new system is \$42.472, being higher than the top 3 optimization options from the ‘current system scenario’. This is because the new system has 1 kW more solar PV panels installed and 1 more string of batteries. Also, the converters have a larger size.

4.2.3.4 No grid scenario

What would happen if the health facility had no grid-connection? What if Gikomero HF is in the middle of nowhere in a highly remote place? This scenario was developed to see what the optimal options for the health facility are to satisfy its demand in such a case. In this scenario, an upgrade to 7 kW of solar PV panels would be required with 3 strings of batteries. The NPC increases significantly to \$68,746. Thus, being more than double in comparison to the ‘current system scenario’ optimization options.

4.2.3.5 No generator scenario

It is interesting to simulate a case with no diesel generator. The generator is from the year 1999 and it could breakdown anytime in the following years. Then, how can Gikomero HF satisfy its demand without a diesel generator? This scenario was modelled in HOMER, however no feasible solutions were found due to capacity shortage constraints and by also having too high net grid purchases that are highly unreliable (from frequent power outages). Thus, HOMER tried to find the most optimal solutions based in costs, but this system would be too expensive for the health facility, as it would mostly rely on the grid to satisfy its demand, which is not a reliable source.

4.2.3.6 No storage scenario

Energy storage is a critical aspect for increasing reliability, especially when the system relies on renewable energies such as solar and wind power that are characterized with intermittency. In this scenario, an option without batteries is simulated, and then it can be seen in Table 4-7 that the system will require 7 kW of solar PV panels. This option is the most expensive first-ranked solution from all the scenarios in exception of BAU, as it has a NPC of \$138.695. This is most likely due to high operating costs of purchasing power from the grid and to fuel the generator when avoiding frequent power outages. This means that the system in this scenario is oversized and that there are energy losses. Here, storage systems can be the game-changers, as they increase reliability and avoid these energy losses, even when renewable energies are not added to the system.

4.2.3.7 Only renewables scenario

The system’s external requirements do not only involve costs, they also involve environmental aspects for reducing externalities that are translated into negative impacts to the environment. Variables such as renewable fraction and emissions show how environmentally friendly the optimization option is. However, in terms of costs, it is interesting to include a scenario with

renewable energies only to analyse how expensive it could be and which architecture would be appropriate. Three optimal options for the ‘only renewables scenario’ are shown in Table 4-7. The simulation gave two optimal solutions; the first-ranked option has only solar PV panels and batteries, however the second-ranked option includes wind turbines with a higher NPC. A third option was simulated separately while adding a restriction of 15 batteries (3 strings) as a maximum. It can be seen that that prices increase significantly with this last option (See Figure 4-8). In general, the NPC for this scenario is high in comparison with the other scenarios, as they do not fall below \$80,000.

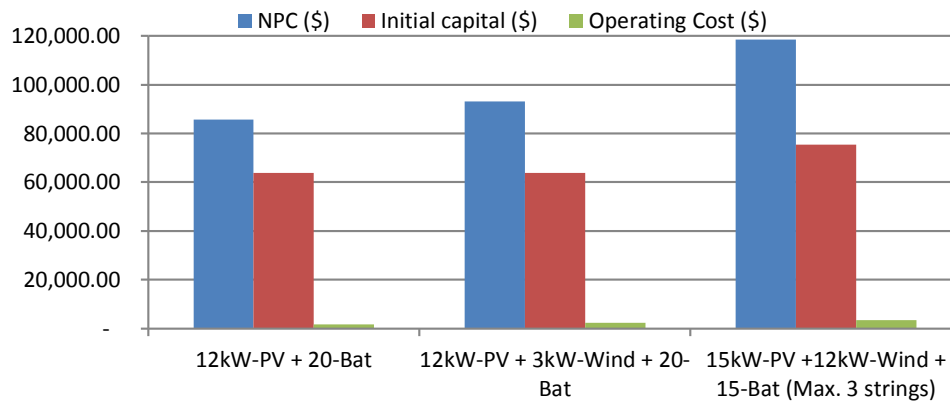


Figure 4-8 Costs for 3 optimal options of the ‘only renewables scenario’.

4.2.3.8 Future system scenario

As mentioned before, it is important to include a future system scenario whereas energy options are optimized to meet the future demand profile estimated in section 3.2. It was estimated that in 5 years the future total energy demand of Gikomero HF would increase up to 24,785kW/day. A simulation model in HOMER was built with the same energy options to meet this future demand, following the assumption that the central grid and the diesel generator remain the same for the next 5 years. The optimization results show that the first-ranked option has an architecture of 3 kW solar panels with 2.58 kW dedicated converter, the 12,5kW diesel generator, 5 batteries (1 string) and 4 kW system converter. This architecture is similar to the ‘new system scenario’; however it only has one string of batteries instead of two. This scenario was also simulated with no grid-connection and with no diesel generator just in case these options are not available anymore or due to unreliability issues. Figure 4-9 shows the three options for the future system. The optimal solution would be to add 3kW solar panels and 5 batteries. Also, it is interesting to observe that the model does give feasible results for a ‘future no generator’ scenario.

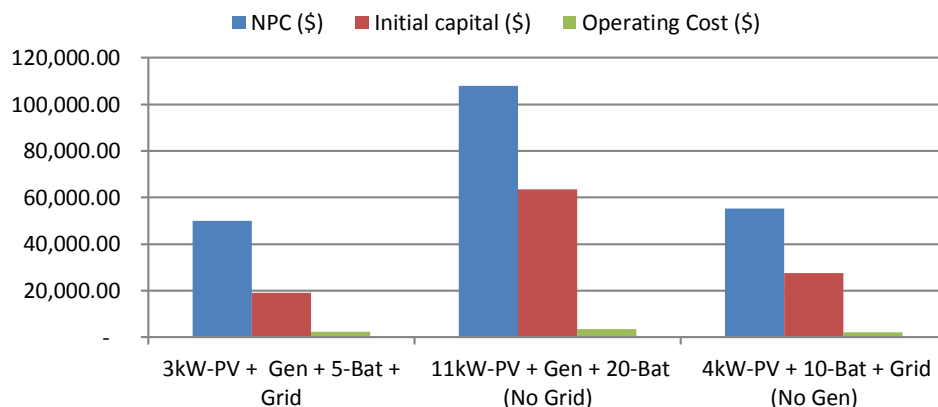


Figure 4-9 Costs for the optimal options of the ‘future system scenario’.

4.2.4 Environmental results

External requirements for the system also involve sustainability aspects. For each scenario, pre-selected sustainability variables are specified in Table 4-8. Thus, it is possible to observe which scenarios have more renewable energies, consume less fuel and purchases less energy from the grid. Also, the calculation of emissions is interesting to draw conclusions about which scenario emit less pollutants to the environment. The cleanest scenario is the 'only renewable scenario', followed by the 'no grid scenario' and the second-ranked option for the 'future system scenario' and the 'new system scenario' based on total emissions per year and renewable fraction (see sub-sections below).

4.2.4.1 Carbon dioxide emissions

Carbon dioxide or CO₂ is the most well-known greenhouse gas (GHG), and its excess causes the Earth's surface to warm abnormally contributing to climate change. The major sources of CO₂ are the burning of fossil fuels and deforestation; which contribute around 50% of global warming (McKinney et al., 2012). Figure 4-10 shows the emissions of CO₂ in kg/year for each scenario and in some cases the optimal options for the specific scenarios.

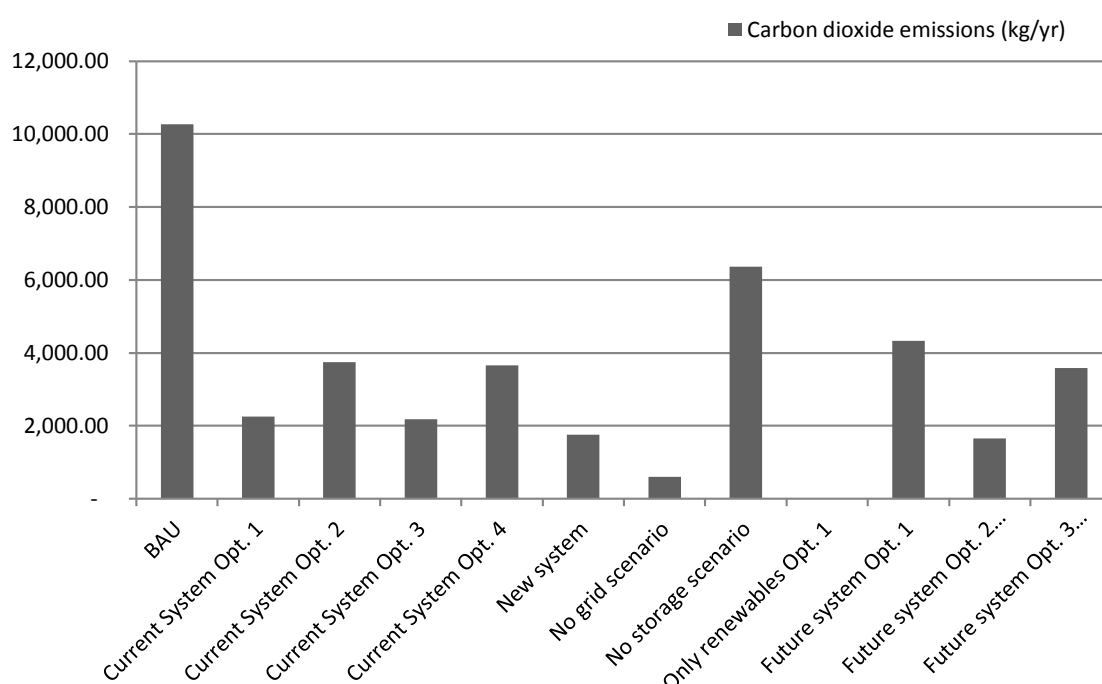


Figure 4-10 Carbon dioxide emissions in kg/year for each scenario

4.2.4.2 Air pollutants

Currently, the Environmental Protection Agency (EPA, 2015) recognizes six basic criteria pollutants. These are particulate matter (PM), sulphur dioxide (SO₂), nitrogen dioxide (NO₂), ozone (O₃), lead (Pb), and carbon monoxide (CO). The sources of these pollutants are (1) the combustion of fossil fuels by motor vehicles or stationary sources such as power plants, and (2) other industrial processes (McKinney et al., 2012). Nevertheless, fossil fuel burning is the main cause of air pollution problems we face. This is the reason why environmentalists advocate the switch to alternative fuels such as solar and wind. Main air pollutants are described below.

Carbon monoxides (CO)

Carbon monoxide can be a deadly gas in high concentrations, as it can interfere with the ability of blood cells to carry oxygen to the organs in human beings. Concentrations such as 50 ppm can cause headaches and other effects in few hours (McKinney et al., 2012). Incomplete combustion when fossil fuels are burned under less than ideal conditions produce CO. For instance, an engine with poor air supply or low burning temperature produces more CO than another engine with better conditions. Hydrocarbons are also released through combustion, and are considered cancer-causing chemicals (McKinney et al., 2012).

Particulate matter (PM)

Particulate matters are any particles of dispersed matter, solid or liquid, which are larger than individual molecules (McKinney et al., 2012). These small particles can penetrate deep into small canals of the respiratory system, where they cannot be easily coughed up or removed. According to McKinney et al. (2012), the accumulation of sufficient amounts of these fine particles causes impaired breathing from blockage and irritation, resulting in long-term illnesses. Statistical studies show that increases in particulate concentration in the atmosphere are correlated with increased visits to hospitals for respiratory problems and illnesses associated with breathing (McKinney et al., 2012).

Sulphur oxides (SO)

Sulphur oxides are produced when fossil fuels that contain sulphur are burned. In terms of negative impacts, SOX may be considered as the most serious local and regional air pollutant. Sulphur dioxide or SO₂ is a gas that is toxic to living things. Plants are very sensitive, and the effects on people range from irritations in the eyes and respiratory and heart failures (McKinney et al., 2012). Death can occur in just 30 seconds at concentrations as low as 3 parts per million (mg/kg). Additionally, sulphur dioxide is also the main cause of acid rain (McKinney et al., 2012).

Nitrogen oxides (NO)

Nitrogen oxides are one of the major causes of smog and other photochemical pollutants in urban areas. A photochemical pollutant is a secondary pollutant that is produced when sunlight initiates chemical reactions between NOX, VOCs, and other air components (McKinney et al., 2012). Direct effects on people and animals from these chemicals include irritation of eyes, lungs and other mucous membranes (McKinney et al., 2012). In addition to their role in smog, nitrogen oxides also contribute highly to acid rain. NOX are mainly produced through the burning of fossil fuels in transportation and power generation. In particular, diesel combustion produces high temperatures that create high levels of NOX pollutants; also diesel fuels have high sulphur content, which can be 5,000 ppm or more (McKinney et al., 2012).

Figure 4-11 depicts the emissions in kg/year of the above mentioned air pollutants for each of the scenarios for Gikomero HF. It is observed that the highest emissions are emitted by the BAU scenario due to its reliance on the diesel generator and the grid.

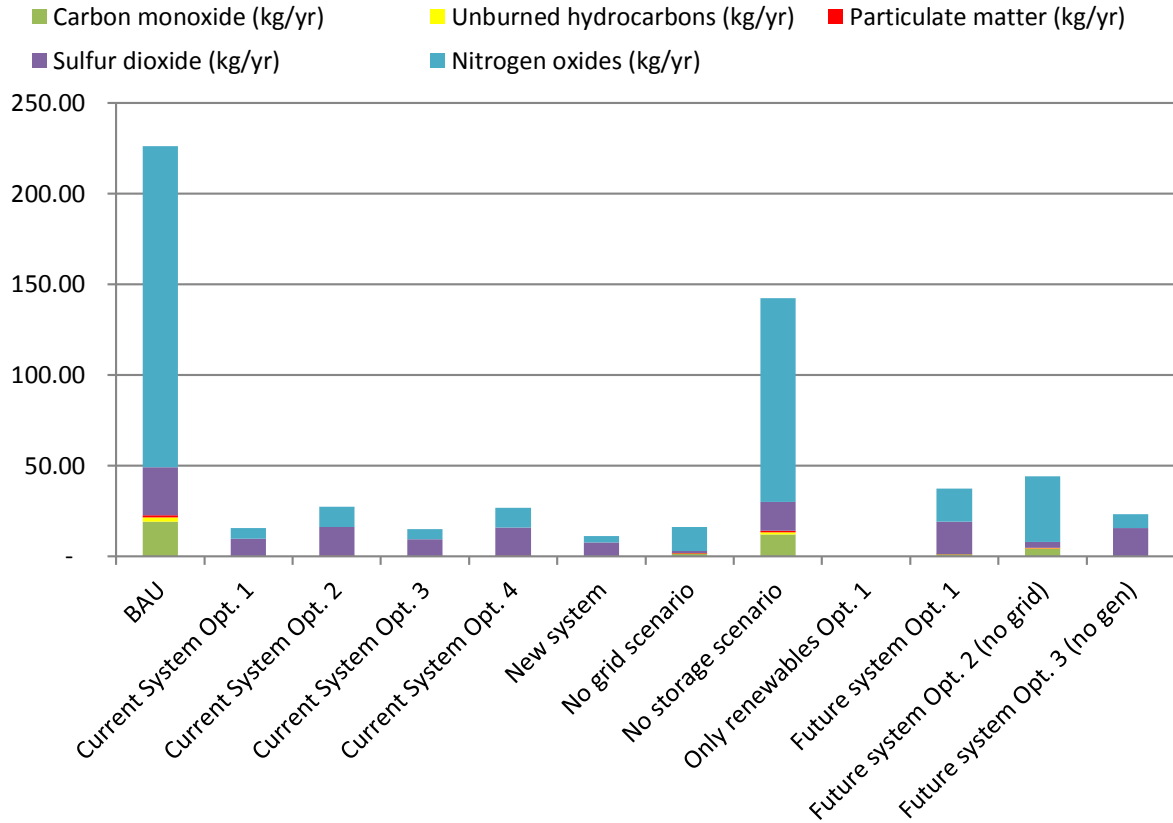


Figure 4-11 Air pollutants emissions in kg/year for each scenario

To calculate the emissions of CO₂ and SO₂, HOMER uses the emission factors from the other four air pollutants specified before, next to the carbon and sulphur content of the fuel; with the following assumptions: (1) any carbon in fuel no emitted as CO or unburned hydrocarbons gets emitted as CO₂, (2) the carbon fraction of the unburned hydrocarbons is the same as of the fuel, and (3) any sulphur in the burned fuel that is not emitted as PM is emitted as SO₂ (HOMER Energy, 2014).

4.2.4.3 Renewable fraction

Renewable fraction is the fraction on the energy delivered to the load that originated from renewable power sources (See Figure 4-12). To calculate the renewable fraction, the formula used is the following:

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{served}}$$

Where:

$$E_{nonren} = \text{Non-renewable electrical production (kWh)}$$

$$E_{served} = \text{Total electrical load serviced } \left(\frac{\text{kWh}}{\text{year}} \right)$$

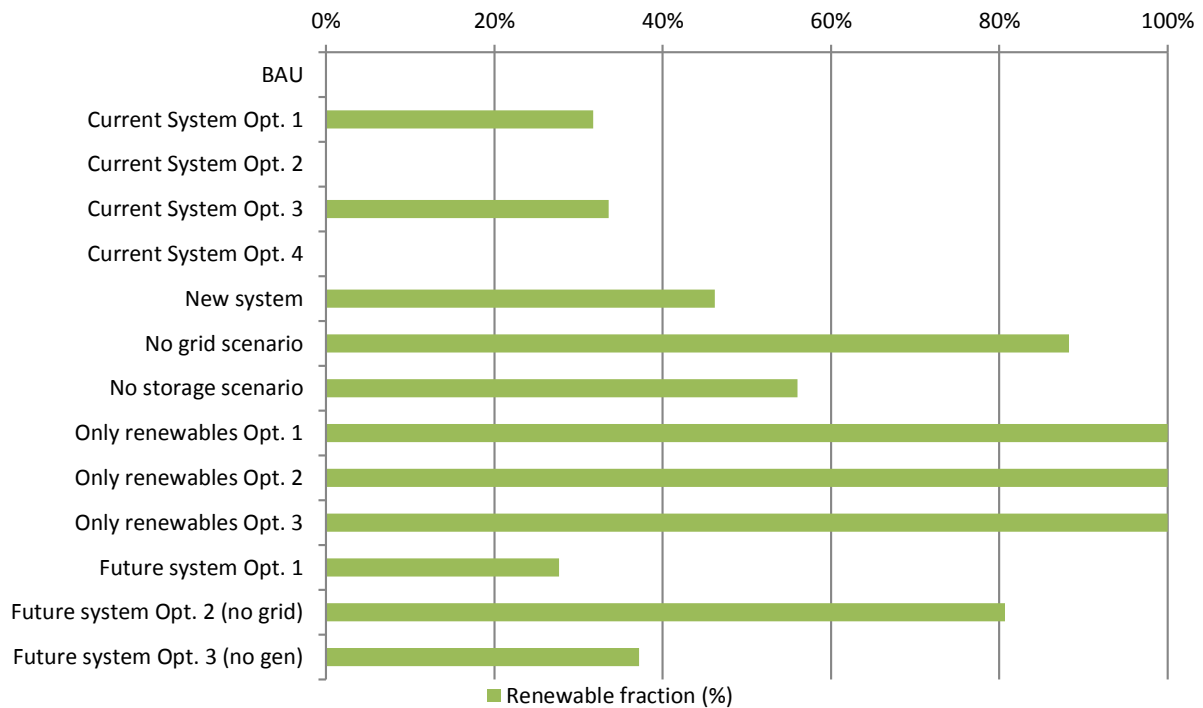


Figure 4-12 Renewable fractions for each scenario

Surprisingly, in the results from HOMER, the ‘no storage scenario’ had a renewable fraction of zero, and this scenario relies on 7 kW of solar PV panels. The reason why this happened is because this scenario had a lot of excess production to overcome unreliable power outages. Thus, although there is a significant electricity production from solar energy, the total annual diesel generator production and grid purchases exceed the total load (kWh) for the year. Of course this is not the only way to calculate renewable fraction, but this is how it is done by HOMER Energy. This brings up the question if the software tends to prioritize the electricity production from non-renewable energy sources and grid purchase. In Figure 4-12, the ‘no storage scenario’ was calculated differently by dividing the total renewable electrical production (kWh) over the total electricity production (kWh), resulting on 56%.

5. DISCUSSION

5.1 About the case study: Gikomero HF

The case chosen in this study is a good example for developing the protocol of assessing HFs in resource-constrained settings. Besides of being a mid-size health facility, Gikomero HF has energy supply problems such as unreliability and frequent blackouts that could have been leading to a sub-optimal delivery of healthcare services, and causing the dissatisfaction of the health workers. It was interesting to use this case to optimise its energy supply options in order to improve its current situation by increasing reliability and by satisfying its demand daily patterns. One characteristic of this particular case is that currently the HF is connected to the central grid, and still many problems arise. Several empirical studies have focused on the assessment of HFs that are remotely located and have no access to the grid, or other HFs that have no access to electricity at all. However, it is also interesting to study health facilities such as Gikomero HF that suffer from unreliability even though they are grid-connected. This case study however, cannot be generalized because each health facility differs from each other. On one side, energy demand patterns tend to vary for all health facilities, as they depend on the size of the health facility, the medical equipment available and their frequency of use, the health services available, open hours of the health facility, and even user behaviour patterns. Some health workers can have certain bad habits such as leaving the refrigerator door open for long periods while stocking or withdrawing medicines and vaccines, or others tend to leave lights on when not needed and when there is no one in the room. On the other side, the energy supply sources vary between HFs, some of them rely on the central grid and others could be so remotely located that grid-connection becomes unfeasible. Also, in relation to the renewable resources available, some HFs can rely on solar energy, others on wind power or hydro-power if there is a river with adequate water flow close by. All these differences can cause significant variations on the assessment performed in this study, as the optimisation results would be performed for a different demand-supply profile and context. Thus, the results of this study should not be used to represent other HFs.

The demand profile of Gikomero HF shows that medical equipment is the highest electricity consuming type of equipment of the HF, however this may not be the case for other HFs where they use other medical equipment and devices. Moreover, the electric load variation from Table 3-3 is based on an average day of the HF, and it can be expected that this load varies daily so one single profile cannot be set to represent every day, although it gives an insight of the HF's demand profile. Yet, it is possible to observe in the load profile (Figure 3-3) that some hours have no demand and this is because when the data is collected, users tend to round up or down the times they use the equipment to one specific hour of the day to facilitate the data collection; however during the usual daily use, the equipment is not used at that one specific hour, as the time of use differs according to the needs of the day. When building the model of Gikomero HF, random variability was added to the load profile to create a more realistic profile (see section 4.1.2.1). Furthermore, it is observed that the daily peak load of Gikomero HF is between 18:00-19:00 hours and this does not necessarily mean that other HFs have their peak load at the same hours, specially when other health facilities are closed during the evening. Ani and Emetu (2013) studied a health facility in Nigeria with a daily load of 19kWh, and its annual peak load was observed between 12:00-13:00 hours, mainly due to the sterilizer with a power consumption of 1.564 W. The second high consuming equipment in their case study is the Water Bath with a power consumption of 1.000 W (Ani and Emetu, 2013). When comparing this Nigerian case to Gikomero HF, it is possible to see how different health facilities can be from each other. Both health facilities are classified as health centres within the category II, but they use different equipment and have different demand-supply profiles. For instance, on the supply side, the Nigeria case is not grid-connected and has a 2,5kW diesel generator, 48 Surrrette 6CS25P Battery Cycle Charging, and a 19kW converter (Ani and Emetu, 2013); whereas Gikomero HF relies on a 12,5kW diesel generator and grid-connection to satisfy its daily load of 14.175kW.

5.2 About HOMER simulation software

Besides of being user-friendly, HOMER is a well-developed software that can be useful for any sector. The software facilitates the allocation of different energy supply technologies to satisfy a load, either both electric and/or thermal. When modelling the case of Gikomero HF, it was possible to add stand-alone energy systems and also access to the grid, giving the possibility to introduce unreliability issues of scheduled power outages from the grid supply. Thus, creating a more realistic profile that emphasizes and tries to solve the major problem currently affecting the health facility.

The development of different scenarios to satisfy the current-future electricity demand of Gikomero HF gives the opportunity to assess different paths to take for the future. It is crucial to ensure that the solution chosen is in accordance to the needs and requirements of the health facility, not only for the present but also for the future. However, some assumptions for the future were made that can have implications on the modelling of scenarios and the results. On the supply side, it is assumed that the central grid will stay the same over the next 5 years with an unreliable supply of frequent power outages and no changes in the energy mix. Also, it is assumed that the HF will still use the existing 12,5kW diesel generator, which in reality can have effects on the future supply due to unexpected break-downs or need for replacement. On the demand side, the future profile of the health facility is modelled in HOMER by estimating an increase in one category of the HF and adding more equipment. This scenario however, does not include other factors that can affect the demand in the future, and HOMER does not facilitate an estimation of a future demand increase or decrease. Furthermore, the development of many simulation models were required in order to assess different scenarios, as one model was not sufficient because some components needed to be removed or added and there is no possibility to switch them on/off for the simulation.

Energy saving measures can be added in HOMER, for instance by considering the use of fluorescent lights that are more efficient than incandescent lights. This measure however, tends to be more expensive but it would contribute on reducing the electrical demand of the HF by 30W/day. Nevertheless, this measure was not included in the simulation model to solve the supply issues of Gikomero HF, as it is assumed that the change would be insignificant. Although for some health facilities, energy efficient lights could represent a significant impact. According to the IEA, lighting equipment consumes up to 40% of the energy produced by PV panels in HFs. Moreover, it would be interesting that HOMER allows 'peak shifting' options such as modifying the electric load profile so the peak is distributed more uniformly during the day by using high-energy demand equipment at other times of the day when renewables energies are at their production peak.

5.3 About optimization results

Optimization results in terms of lower costs for different scenarios are very useful for a health facility in resource-constrained settings. One of their main requirements is to keep costs down as much as possible while having a reliable system that meets the demand with sufficiency. It was observed in the results that energy storage is crucial to increase reliability and reduce costs in the long-term. Although batteries represent a high initial capital cost of \$9.520 for 10 batteries, in the long run they are the game-changers. It was documented on diverse literature that all electricity supply options have constraints for the rural context, either problems of reliability, intermittency, maintenance, fuel availability, local supply of parts and replacement, amongst others; however, storage energy systems have the crucial role to keep the system working reliably and avoiding energy losses. That is why optimization assessments are required to analyse the best options taking into account the costs of the project lifetime.

From the optimization results, it was observed that the 'Business-as-Usual' (BAU) scenario has very high NPC in comparison with the other scenarios, being the highest one. This is explained because the scenario is built to meet the full demand avoiding outages; therefore the systems runs at

minimum load at all time, having excess production that increases its operational costs. Thus, the health facility is currently relying on a system that is highly sub-optimal. Here, the costs of not having electricity all time are being internalized and the continuance with the BAU system will make the HF pay more for electricity than when modifying its system if they aim for reliability and sufficiency. In reality, the situation differs from the BAU scenario because the HF has no economic resources to pay for a generator running at a minimum load all time to increase reliability and sufficiency. Thus, the HF has no choice to keep on with its unreliable system. A comparison between the BAU scenario and the electricity consumption data collected from Gikomero HF is elaborated in sub-section 5.3.1 to see how much the scenario differs from reality.

The difference between the NPC of the 'BAU scenario' and the 'new system scenario' (to be implemented in October 2015) is \$133.176. Hence, the health facility that currently has a 12,5kW diesel generator and connection to the central grid will save around \$130.000 (including internalized costs of not having electricity) by implementing a solar energy system consisting of 3kW solar PV panels and a bank of 10 batteries that increases the system's reliability. In Gikomero HF, paying \$24.000 as initial capital to implement a solar energy system will translate into an NPC of \$42.472, when continuing with the BAU scenario and paying no initial capital will translate into an NPC of \$175.648. Moreover, when comparing the 'new system scenario' with the optimization results of the 'current system scenario' it is shown that to satisfy the current demand, the health facility does not necessarily need a 3kW solar energy system with 2 strings of 5 batteries each. Actually, a 2kW solar system with 1 string of 5 batteries would be enough (see 'current system scenario' first-ranked optimization option), saving up to \$13.605 on the project lifetime in comparison with the 'new system' scenario. However, when taking into account the future demand of the health facility, a 3kW solar energy system is required (see 'future system scenario'), emphasizing it is better to implement an over-sized system at present to reduce costs in the future of adapting the system to the new demand. For a health facility that requires reliability and sufficiency more than any other institution, having more backup sources and available energy storage systems is helpful. It is not ideal that a health facility gives unreliable treatment to patients and that medical equipment remains in a storage room because it cannot be used due to lack of electricity supply (GLE, 2015). Also, some equipment is damaged due to power outages and frequent blackouts, so having storage systems will prevent this from happening.

It is also observed that wind turbines are not present within any first-ranked optimization result for the scenarios performed. This could mean that solar systems represent a better energy supply source on resource-constrained settings. It was specified on literature that rural communities and remote health facilities are increasing their use of solar energy systems (Ani and Emetu, 2013; Adair-Rohani et al., 2013; McKinney et al., 2012). Furthermore, it was simulated the scenarios of not having any access to the grid or a diesel generator available, and also not having energy storage and the scenario of relying only in renewable energy sources. From these scenarios, the one with lower costs is the 'no grid scenario' replacing the grid power with a higher installed capacity of solar power (7kW) and 3 strings of batteries. This shows the high importance of energy storage systems, and it is also reflected in the 'only renewables scenario' whereas 4 strings of batteries are required in the first-ranked optimization option. In the scenario of renewables, 12kW of solar PV panels are needed to replace the 12,5kW diesel generator and the batteries take care of intermittency issues. It can be observed that whenever there is no storage system the NPC increases up to \$138.695 due to significant energy losses of an oversized system that functions perfectly; this represents a difference of \$109.288 from the lowest NPC optimization result from the 'current system scenario'. Furthermore, the 'no generator scenario' brought up no feasible results. This could be because this scenario will not meet the demand with reliability and sufficiency because too much energy would have been purchased by the grid, which is highly unreliable with frequent outages, and renewable energies cannot meet the minimum load to avoid outages at all times due to intermittency; thus being this scenario extremely expensive for the health facility to pay for and representing an unfeasible option because unreliability issues would not be solved. However, a future scenario was simulated with no generator

and feasible results were available. Thus, questioning the modelling of the ‘no generator’ scenario that considers the current demand.

In terms of environmental and sustainability results, it is clear that the ‘only renewables scenario’ is the cleanest option based on highest renewable fraction, no fossil fuels and no air pollutants and CO₂ emissions. However, these emissions results do not take into account the emissions during the total life-cycle of the technology (including extraction and manufacturing emissions). Solar PV systems on average generate less than 250 gr. CO₂/kWh of power produced, including life-cycle emissions (Edenhofer et al., 2011) and they do not generate local emissions. Also, it has been estimated, that the production and deployment of solar cells arrays (and wind turbines) can use about 3% of the fossil fuel that would instead be burned in a coal power plant to generate an approximate amount of electricity (McKinney et al., 2012). Therefore, when looking at the results from CO₂ emissions in kg/year for each scenario, the inclusion of total life-cycle emissions would not have significant implications on the results. In relation to emissions, it is good to see that the new system to be implemented has zero diesel generator operating hours and no fuel consumption, meaning that it practically does not rely on the generator anymore to satisfy the health facility’s demand; however, this also means that the system would be oversized, and by reducing the number of batteries from 10 to 5 batteries costs would be reduced and the future demand would be satisfied. Nevertheless, it is safer to implement a system that is over-dimensioned than under-dimensioned.

5.3.1 Comparison between optimization results and electricity consumption data

Data was collected for Gikomero HF regarding its expenses on electricity from January 2014 until June 2015. With this data, it was possible to roughly calculate an estimation of the electricity consumption over time in the health facility from the diesel generator and the central grid. The data however, is not considered very reliable due to imprecise indicators and assumptions to make the calculation. The data is found in Appendix F and Appendix G.

When comparing the estimated actual electricity consumption data with the results from HOMER for the BAU scenario, it is observed that there is a big difference between them. On one side, BAU scenario purchases 3.904kWh from the grid per year, which results on 325kWh/month; and it consumes 2.964L of diesel per year, which results on 247L/month. On the other side, the electricity indicators show that the grid consumption has an average of 376,19kWh (see Figure 5-1), which is comparable to BAU scenario; however in relation to the fuel consumption, the indicators show that it is always less than 247L/month (see Figure 5-2).

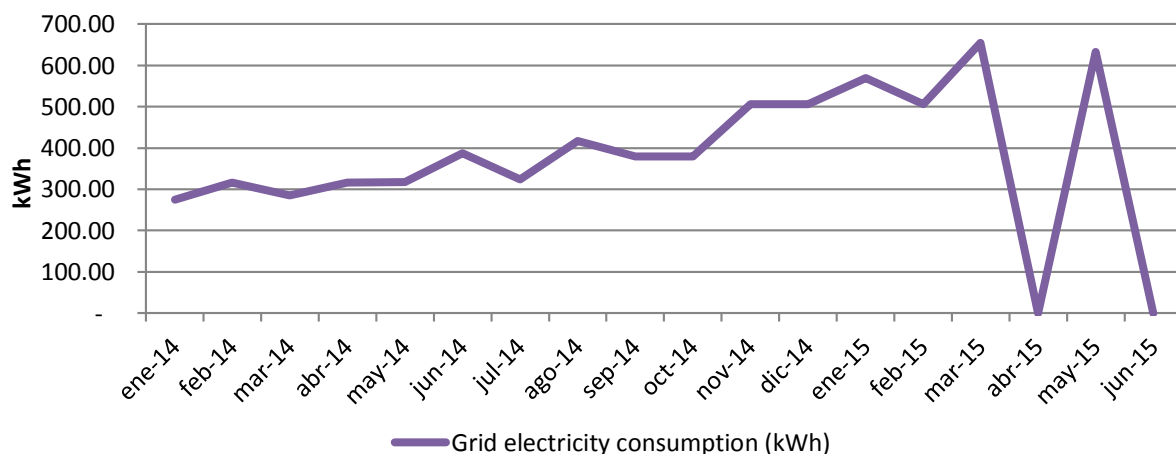


Figure 5-1 Grid electricity consumption over time of Gikomero HF (Adapted from Cordaid, 2015)

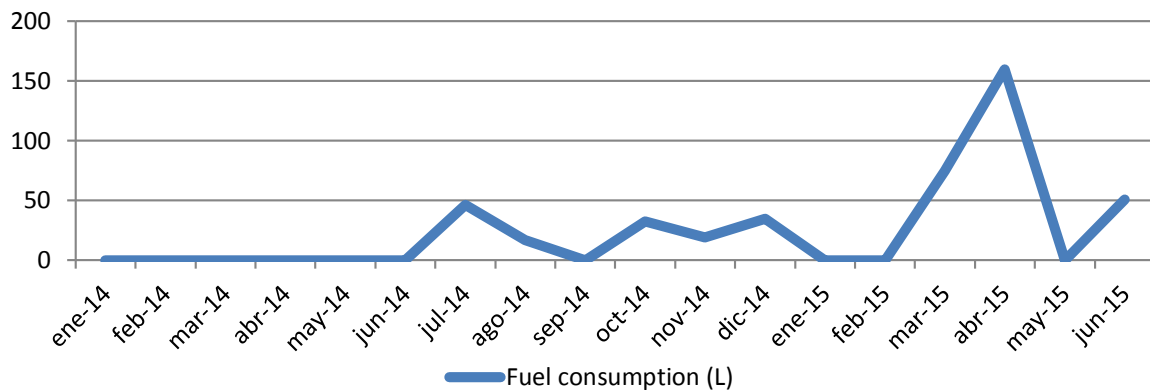


Figure 5-2 Fuel consumption over time of Gikomero HF (Adapted from Cordaid, 2015)

The comparison between data shows that the diesel generator from BAU scenario is consuming more fuel and thus producing more electricity than what is needed. In practice, the generator should produce the amount of electricity that is not produced by the grid to satisfy the demand; this amount would be 1.270kWh/year (given 5.174kWh of electric load minus 3.904kWh grid purchases). When looking at the HOMER report for BAU scenario (see Appendix H); the electrical production of the generator is 6.200 kWh; thus having an excess production of 4.930 kWh/year. This means that in the model, the generator operates on full capacity all year losing high amounts of energy. Hence, the BAU system is very inefficient as it is currently oversized, resulting in 79,5% energy losses per year. This is also reflected in the operating costs of BAU scenario that are \$13.587/year, and the electricity expenses indicators show costs of \$1.376/year (see Figure 5-3). This explains why BAU scenario is so expensive. However, the main reason for this is because the BAU scenario represents a perfect-functioning system that avoids power outages by operating with a minimum load of 3kW at all times.

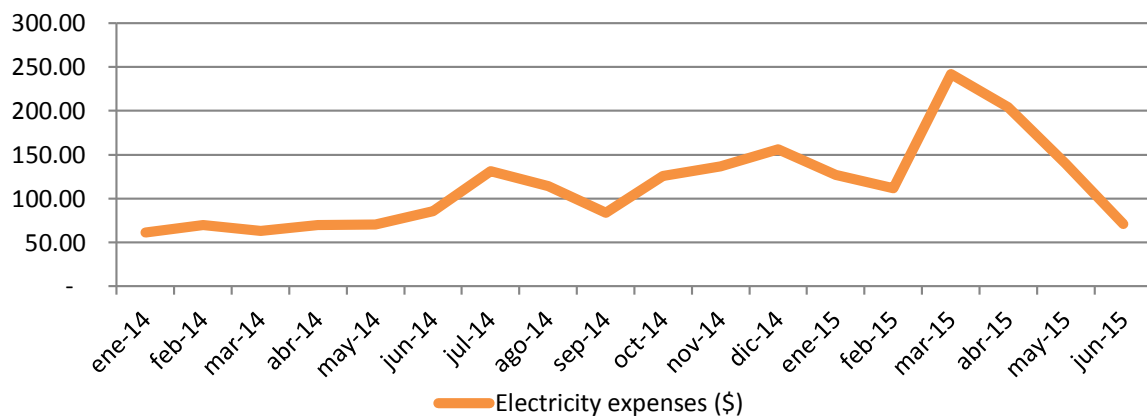


Figure 5-3 Electricity expenses over time for fuel consumption and grid purchases of Gikomero HF (Adapted from Cordaid, 2015)

By having a reliable and sufficient BAU system, it is ensured that the health facility will have electricity with no interruptions, which is crucial to deliver healthcare services. Nevertheless, this insurance is reflected in the high operational costs and emissions. This is why it can be specified upfront that the results from the BAU system internalize the costs of not having electricity. And when implementing storage systems, the system becomes more efficient. This shows how important storage systems are to avoid system losses even for the BAU case whereas renewable energies are not included. Furthermore, the reason why the diesel generator was not allocated in HOMER with a lower size is because this generator is already present at Gikomero HF and it is assumed that the current supply system will not be changed nor removed. However, by reducing the installed capacity of the diesel generator, the system would not be oversized anymore and energy losses would be avoided.

6. CONCLUSIONS

Currently, health facilities in resource-constrained settings are suffering from unreliable and unsustainable access to electricity supply. Electric services in these settings must be optimized and assessed for each individual case to find the most suitable energy systems to satisfy the current and future demand of the health facilities. Through the report, it has been stated the importance of reliable energy for the delivery of healthcare services and medical treatments. And next to the most recent literature and case studies in the subject, it has been tested that the protocol to assess the supply-demand and optimize energy systems on each individual case as a 'holistic system' involves the following guidelines: (1) the evaluation of electricity needs and classification of the health facility, (2) the analysis of supply-demand profiles, (3) the optimization of electricity supply sources to satisfy the demand, and (4) the impact assessment of electricity supply on healthcare services delivery.

The global classification of health facilities is subdivided in health posts, health centres (categories I, II and III), and hospitals. The health facility in study, namely Gikomero HF, fits into a health centre of category II with a total electricity demand of 14,175kWh/day. On the demand side, peak hours range in the evening between 18:00 and 22:00, most likely due to use of lighting after sunset. The medical equipment has the highest electricity consumption amongst other equipment when consuming 37% from the total electricity demand, being the infant radiant warmer and the sterilizer the highest-consuming medical equipment. On the supply side, the health facility has connection to the grid and a diesel generator of 12,5kW. According to a local survey (Cordaid, 2015), the representative from the health facility is 'unsatisfied' with the primary electricity system due to its intermittent supply (with frequent blackouts), high costs and maintenance liabilities. A solution to this problem and to satisfy the current/future demand sustainably is to include renewable energy systems in the electricity network. An optimal combination of energy supply technologies can significantly improve the economic situation of the health facility and the quality of delivering healthcare services. Energy supply technologies involve: grid-connection, stand-alone diesel generators, solar energy systems, micro-wind power, micro-hydro power, biomass and hybrid systems. Not forgetting the addition of storage systems to increase reliability. The system requirements of the supply side are sufficiency and reliability, and it has been studied and concluded that all the electricity supply technologies that fit in this context are constrained for different reasons: the grid supply is unreliable due to frequent outages; the diesel generator depends on the availability of fuel and it is operationally expensive with high-maintenance requirements; and renewable energy sources are intermittent and depend on resource availability. The use of storage systems however, is capital intensive but increases reliability, as off-grid systems relying only on renewables offer a greater threat of vulnerable supply. Also the availability of a local supply infrastructure is needed for replacements of parts. On past studies, it has been documented that solar energy systems are highly attractive in resource-constrained settings. By optimizing different supply sources to satisfy the demand of Gikomero HF, it is possible to determine optimal solutions for the health facility taking into account future demand and proving the role of renewable energies.

Worldwide, HOMER is the most recent updated software for microgrid architecture optimization that can be used for any sector. Derived from the results, the optimal option in terms of lifetime costs for sufficiency and reliability involves a 2kW solar system with 5 batteries, next to the current 12,5kW diesel generator and grid-connection. However, to consider the future demand, the same architecture is optimal with a 3kW solar panel system, as the present demand is always limited by the future demand. This means that the solution provided by Great Lakes Energy (GLE) is an optimal option in terms of costs; however optimization results show that the system could be oversized with 10 batteries instead of 5 batteries. Nevertheless, it is safer to install an over-dimensioned system than an under-dimensioned system that cannot satisfy the future full demand. This is the reason why optimization assessments are important at an early stage.

The simulation of different scenarios help to analyse other architecture possibilities specially to meet the systems' external requirements such as environmental aspects or to simulate a health facility that is remotely located with no access to grid-connection or no energy storage systems. The Business-as-Usual (BAU) scenario has the highest emissions of all pollutants during the project lifetime, so a health facility with the architecture of Gikomero HF as it is now can significantly affect the environment negatively, and also it would make the health facility spend more economic resources for electricity in the long-term than when changing to other supply sources. Nevertheless, it was observed in the optimization results how high is the contrast between the BAU scenario and the other scenarios in terms of costs and emissions. This is explained as the BAU case is simulated as a perfect-functioning reliable health facility, whereas frequent outages are avoided because the diesel generator is operating at the minimum load (3kW) all times, and this is the reason why there is an excess production in this scenario and the system is oversized increasing energy losses, emissions and high operational costs. Therefore, when comparing the BAU results with the real situation (electricity consumption indicators), the operation costs are lower in reality. Hence, the reliable BAU scenario internalizes the costs of not having electricity due to 3 blackouts a day, and this is highly important because electricity is crucial for the delivery of healthcare services and the maximum annual capacity shortage should be zero. The energy losses in this case show how important storage systems are; this is also observed in the 'no storage scenario' whereas there is over-production to keep the system functioning perfectly, and is reflected on the high operational costs and emissions. Thus, energy storage systems play an important role to keep a reliable perfect-functioning system that is also cost-effective in the long-term. Moreover, it is concluded from the scenario analysis that an 'only renewables scenario' is too expensive for resource-constrained health facilities, and that overall, storage systems are the 'game-changers' in these settings because they help to avoid system energy losses and damage of equipment due to frequent power outages. All electricity supply options are constrained but when adding batteries to the system reliability issues are solved, allowing the effective use of solar energy. Therefore, it is not mainly the role of solar energy; it is the role of storage. Without storage, costs are multiplied by five over the project lifetime in comparison with the 'current system' scenario optimal solution in order to satisfy the demand reliably. In the case of Gikomero HF, an addition of only batteries and no solar energy is also considered as optimal, but as storage by itself is expensive, it does provide an argument for solar energy. In the future, the health facility with solar energy and storage will become more cost-effective operationally and will increase its energy independency, as the reduction of payments for grid electricity will compensate the investment in solar energy.

These were the reasons why optimization assessments are required to be able to evaluate and compare different system configurations by defining goals and system requirements. Thus, it is possible to answer questions such as renewable energies produce more electricity but does it increase reliability? Here is where storage plays the most important role for energy security. The frequent review of energy technologies will determine the energy requirements for healthcare services delivery and provide a demand-driven approach to energy access.

7. RECOMMENDATIONS

To assess electricity supply-demand in resource-constrained health facilities, each case must be studied individually, not using centralized data or standardized case studies. The protocol provided here shows how in detail the health facility should be assessed to draw conclusions on optimal energy solutions. The data collected for the health facility involved the description of the health facility, the demand-supply profiles, the medical equipment and healthcare services available, and the energy supply options the fit in the local context. There is currently no procedure to collect this data, and this process would not have been possible without the support of local organisations. Hence, it is crucial to develop standardised methods to collect data of different health facilities in order to carry out the assessment shown in this study. Also, the information for each case varies significantly on health facility size, electrical equipment, supply-demand profiles, location, resources available, etc. The case study of Gikomero HF cannot be generalized for other health facilities. For instance, peak-shifting recommendations are individual for the health facility in accordance to their peak hours and equipment used. The peak hours could be shifted during the day so most equipment is used during sun peak hours, thus better distributing the daily load and charging batteries during the day to be used at night hours. However some equipment can be used at other times and some not, and this should be studied on further research and real cases. By performing the assessment shown within this study in at least 50 health facilities, it will be possible to understand better the local context and determine better solutions to energy-related constraints. Additionally, it would allow a better planning of future infrastructure projects, strategic decision-making and the development of new policies. Also, more studies are needed to explore the energy savings potential of DC medical equipment, especially developed for resource-constrained settings. For instance, large savings could be achieved through a switch to portable equipment such as the new X-Ray machine from EssentialTech.

It is recommended that categorization methods be updated taking into account different frameworks of most prominent sources and to develop a worldwide standard to classify health facilities in terms of size, healthcare services available and energy requirements. Without this classification, it is difficult to proceed to optimizations and assessments due to varying contexts.

7.1 Using the HOMER simulation software for resource-constrained health facilities

Below are found some recommendations for improvement of the modelling software used in accordance to the experience for this study:

- The load profile could be more detailed (to add specific load sources such as equipment, lighting, etc.). Then, the software could add the possibility of peak shifting to better distribute the load during the day by changing the time of use of certain equipment when possible; this measure however would reduce the storage needs. In addition, human behaviour energy saving measures might be interesting to explore on further research.
- The availability of hydro resource could be derived in accordance to the specified location. Thus, obtaining the availability of a river close and its average stream flow.
- The renewable fraction calculation should take into account the case of an excess production over a year; and in this case, it should not prioritize the electrical production from non-renewable energy sources for the results.
- There could be an option for switching on/off components for each simulation and make it easier to draw comparisons of results for different scenarios.

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APPENDIX A

HEALTHCARE IMPACT ASSESSMENT OF ELECTRICITY SUPPLY IN RESOURCE-CONSTRAINED HEALTH FACILITIES

SUMMARY

To assess the impact of electricity consumption in healthcare performance indicators, health data was collected from the health facility over a period of time and a list of health-related indicators is provided in this section. Both health- and electricity- indicators are analysed over time to find visual 'related' patterns. However, due to the short time period, small sample size and unprecise indicators' values, the results cannot be stated as reliable, and there is not real relationship established in this study. The present analysis is on a test phase to later on scale-up the study by increasing the sample size, extending the time period and increasing the reliability of indicators in order to draw better results and linkages between energy and health. In addition, the influence of indirect factors must be taken into account for the assessment in the next phase; indicators such as the human factor and skills, the availability of medical equipment and devices, financial resources, water availability, infrastructure and access to thermal energy. Further studies are required to proof the linkages between electricity and the delivery of healthcare services.

INTRODUCTION

1.1. Impact assessment

To assess the impact of electricity supply on the delivery of healthcare services, indicators measuring electricity supply-demand in the health facility are needed, next to indicators measuring healthcare performance. These indicators must be collected and measured for the same time period in order to analyse electricity production and consumption patterns over time, and how they can affect healthcare performance indicators through observing variations. However, other indirect factors can affect the variations. Thus, a Systems Dynamics (SD) model can facilitate a holistic overview inputs, outputs and flows within the health facility over time. This involves electricity supply as one of the main inputs and healthcare performance (healthcare services delivery) as the output. Other variables involved are monetary resources, human resources, water availability and health infrastructure (medical equipment and devices). A model can be built to understand system change through calculations. A general conceptual framework or logic model based on Theory of Change (KU, 2014) is depicted in Figure A-1 containing variables of inputs, activities, outputs and impact; these are: solar PV panels, electricity production and consumption or energy usage, and healthcare performance; leading to improved healthcare delivery services. The variables involved show a general picture of aspects that lead to the outcome focusing only on electricity supply.

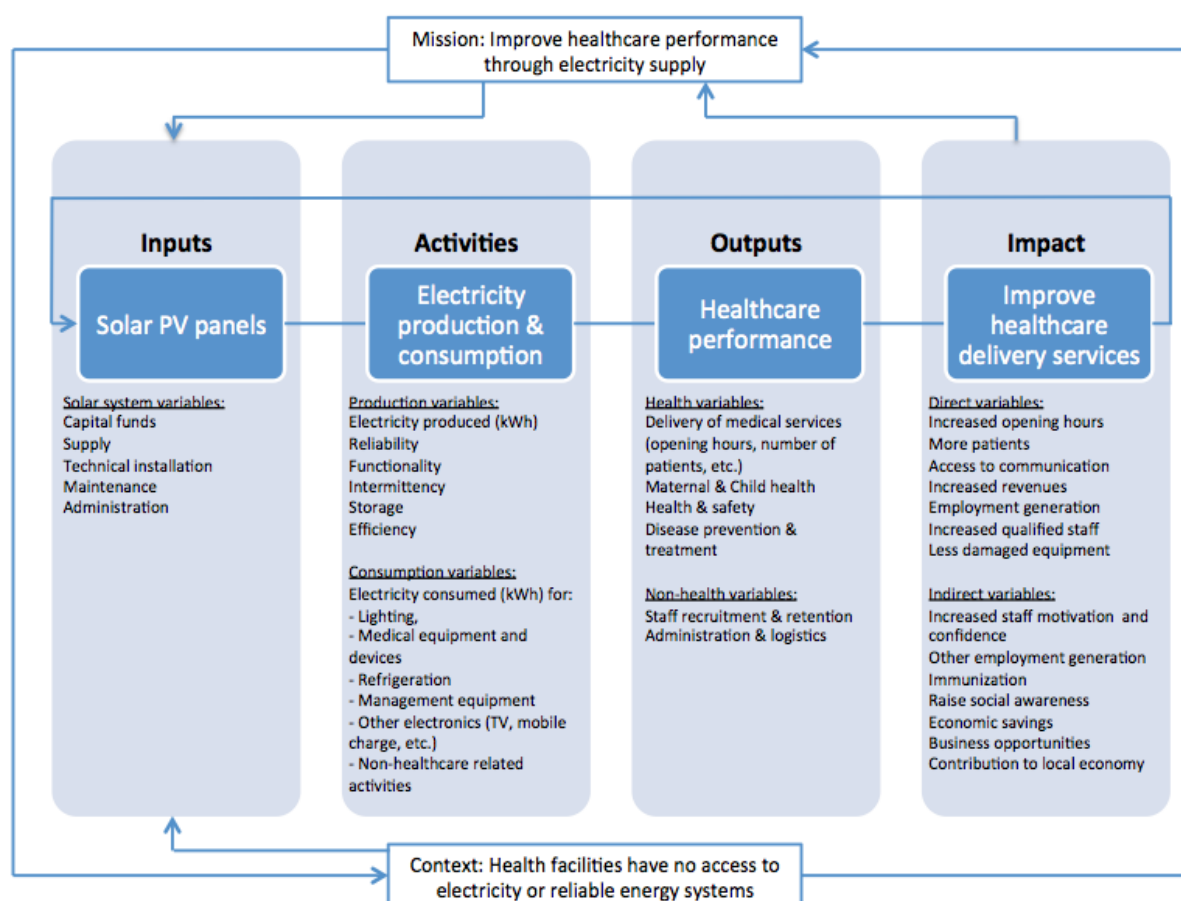


Figure A-1. Logic model (Theory of change) for the impact of solar PV electrification activities in health facilities (developed by S. Gamboa at Cordaid, 2015).

Cordaid has a long track record on innovative approaches to provide accessible healthcare for health facilities in fragile areas. Currently, Cordaid holds Performance-based Financing (PBF) indicators that are used to measure healthcare performance over time. Available PBF indicators will support the pre-selection of potential indicators to measure healthcare performance for this study, and data from electricity production and consumption will be used to measure inputs on electricity. The present study represents an initial pilot study to develop a protocol on how to perform the impact assessment. And a mathematical model will not be developed until all the necessary data is available, which would be in the next phase. Here, it will be shown which data is available on electricity supply and healthcare performance indicators, and an analysis of change will be performed to observe variations over a certain period of time. However, this will only be carried out for one health facility, hence results cannot be generalized.

1.2. Data collection

The methods for gathering qualitative and quantitative data to carry out the impact assessment are based on one case study in Rwanda. To measure healthcare performance, PBF indicators are available since January 2014 until June 2015. These indicators lead to a pre-selection of potential indicators that can be subject to variation due to changes on electricity supply patterns. Data on electricity production and consumption will be gathered from data loggers if possible, and/or complemented with information of the health facility in relation to expenses on electricity on the same period of time.

HEALTHCARE IMPACT ASSESSMENT

A baseline assessment of the current impact of electricity supply is carried out in this section. After this assessment, it will be possible to evaluate changes and improvements on healthcare services when renewable energy is introduced. The assessment is made over the impact of electricity consumption in the available health-related indicators over time. This assessment could bring insight on which data is currently available, how to organise it and how can it be related to electricity supply.

The following assessment can represent part of a protocol to evaluate how electricity supply can improve the delivery of healthcare services through healthcare performance indicators. Also, the assessment can support the further development of standard methods and the acknowledgement of available data.

2.1. Expected benefits of electricity supply

Energy is crucial for the provision of health services (EU, 2006). There are certain medical appliances that cannot be operated without energy, and mainly electricity. According to Adair-Rohani et al. (2013), ensuring universal access to modern energy services is essential for improving health and well-being. Currently, several rural health facilities in Eastern Africa are limited on their ability to deliver quality health services, partially due to lack of adequate, affordable and accessible energy services (EU, 2006). Table A-1 shows the potential impacts of a stable energy provision on the performance of health services.

Table A-1 Potential impacts of stable energy provision on health services performance (European Commission, 2006) Adapted from WHO (2014)

Medical services	• Prolonged opening hours with general lighting and security lights provided • Wider range of services implemented, because more qualified staff are attracted to stay • Improved emergency surgical services • Better obstetric emergency care (many maternal deaths are due to birthing complications) • Improved management of childhood illnesses • Better management of chronic conditions • Improved referral system (radio communication system between peripheral and referral units) • Better sterilization procedures leading to fewer complications • Improved planning and quality assurance
Health and safety	• General cleanliness improves with adequate lighting and water available • Inpatients feel more comfortable and secure • Staff feel more secure • Security lights provided during evening open hours
Disease prevention and treatment	• Improved cold chain and vaccine storage conditions will yield lower immunization failure rates and better • Immunization coverage • Improved testing for HIV and TB • Evening awareness sessions are possible with general lighting and TV/VCR
Staff recruitment and retention	• Better job satisfaction for staff because of better living and working conditions • Staff will want to stay longer in a place where there are better living and working conditions • Electricity in staff houses means continued medical education is possible • Easier recruitment of staff to locations with electricity and water • Easier to train staff because of improved lighting, equipment and TV/VCR
Administration and logistics	• Better administration, since it can be done in the evening • Better communication between health facilities and better planning of transport logistics

In relation to the capacity to provide health services and outside the physical structure is found the ability to attract and retain health workers and social workers to live in the rural area. Professionals are more reluctant to live in rural areas where there is no access to electricity (EU, 2006). Modern energy services combined with energy efficiency measures can effectively impact the jobs of health workers in remote areas; as reliable energy supply bring lighting in patient's homes, night time diagnosis and care, charge of cell phones for communication and data gathering, as well as the worker's safety at night (SE4ALL, 2015). Furthermore, if the cold chain is not functional when supplies arrive; then vaccines, blood and other medicines may go to waste. Also, if a clinic has no lighting, patients arriving at night must wait until morning to receive care (USAID, no date). Moreover, energy is also needed to expand services for preventing and treating rising levels of non-communicable diseases (NCDs). These include the diagnosis and treatment of breast cancer, cervical cancer, and other NCDs, whereas women particularly have a heavy burden (SE4ALL, 2015). Here, essential devices required are electrocardiograms and mammograms (WHO, 2012). According to EU (2006), the lack of access to electricity at the level of institution or physical structure results in problems such as (see Figure A-2):

- Poor storage for vaccines and medicines
- Poor facilities for sterilisation of medical tools
- Poor lighting conditions for performing operations
- Inability to provide clinical services after sunset
- Difficulty in allocating health workers in remote rural areas
- Inability to run laboratory equipment to diagnose diseases
- Poor ability to communicate with medical specialists or to make a call for transport for referrals to higher level
- Limitation to traditional cooking facilities which are inefficient, air pollutant and inadequate food intake for patients

Modern forms of energy involve the use of cleaner technologies that replace polluting materials such as firewood and kerosene. Direct impacts to health include cooking with firewood that represents a source of air pollution, and also the use of kerosene is highly dangerous to health (MinBuZa, 2014). Besides of the risk of fire or skin burns or children playing with them, kerosene lamps emit black carbon that can cause respiratory diseases by exposure. Sitting next to a kerosene lamp is considered equivalent to smoking 170 cigarettes per year (Solar Aid, 2013). Moreover, an indirect impact to health is the social/environmental awareness from better access to communication channels in health facilities through radio and television or mobile phones (MinBuZa, 2014).

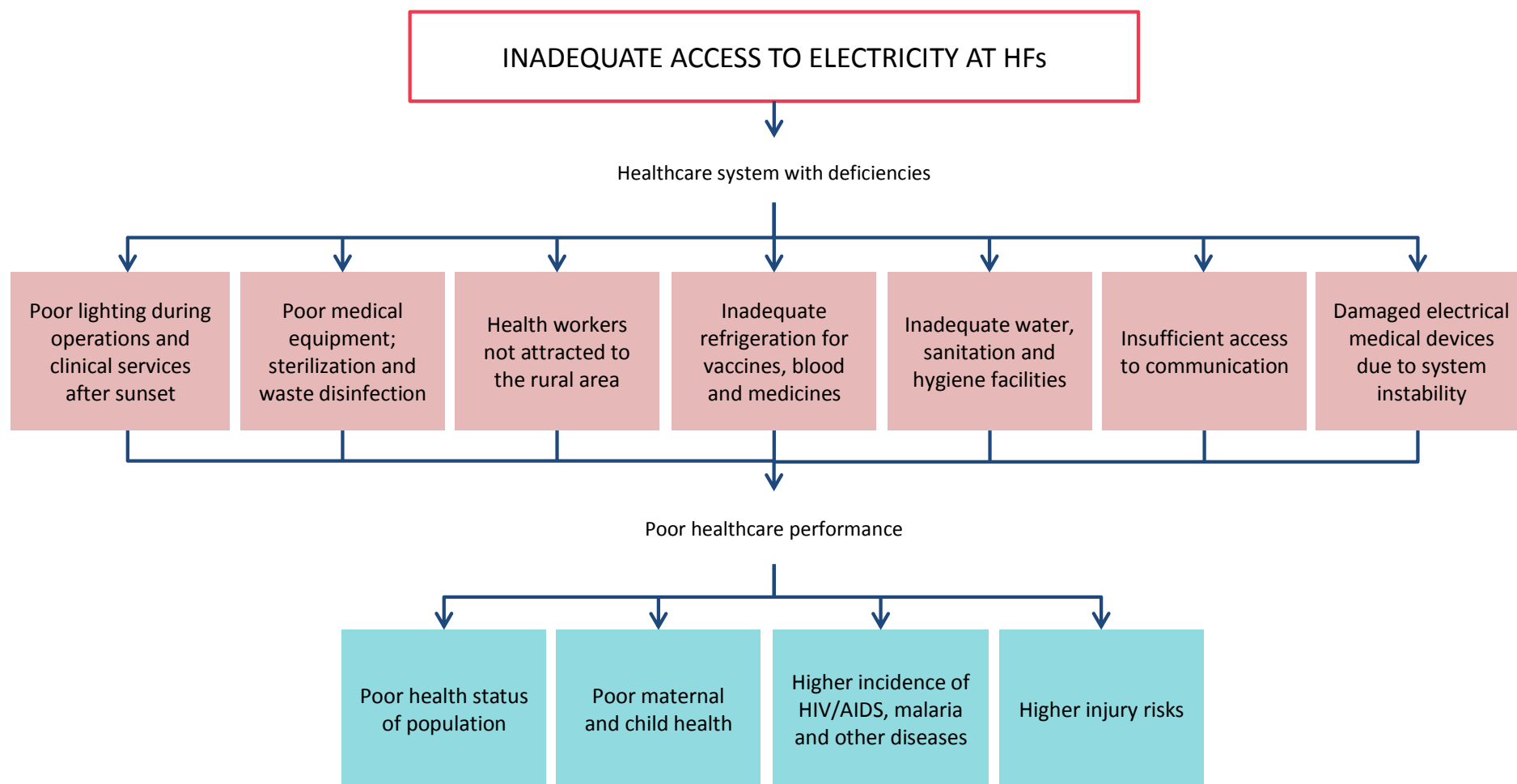


Figure A-2 Linkages between access to electricity and public health in relation to the healthcare performance of health facilities (Updated from WHO, 2014)

2.2. Impact on healthcare performance indicators

2.2.1. Measuring healthcare performance

Meeting electricity needs can have an impact on increasing and/or improving the delivery of healthcare services. However, it is important to set a way of measuring the delivery of healthcare services over time. This study proposes the use of healthcare performance indicators to measure improvements or changes in the delivery of healthcare services for a health facility. Hence, when electricity needs are met and/or new energy systems are introduced into a health facility; it is possible to visualize changes in the health-related indicators. These changes can also be influenced by other indirect aspects such as the human factor, health workers' skills, the availability of monetary resources and/or medical devices, and the infrastructure, amongst others. Below are explained the healthcare performance indicators.

Many years ago, Cordaid introduced Performance-based Financing (PBF) as an innovative approach to measure results in performance through a set of health-related indicators. Meessen et al. (2011) define performance-based financing as a “mechanism by which health providers are, at least partially, funded on the basis on their performance”. Through this mechanism, multinational donors can donate money to the health facilities and see the effect in the indicators for measuring their healthcare performance over time. The main goals of introducing PBF are to improve on the availability, accessibility and quality of key services in the health facilities (Cordaid, 2015). Performance-based financing is currently available in many countries worldwide, especially sub-Saharan African countries, which are amongst the poorest. PBF has been established in health facilities to strengthen the healthcare system, and Rwanda was one of the pioneers implementing this approach (Rusa et al., 2009). The measurement of these health-related indicators over time can be very useful for studying changes on healthcare services delivery. One of these major changes could be the access to electricity or an improvement on electricity supply services (e.g. increase of reliability and energy security). In this study, a selection of potential PBF indicators will be provided in relation to their connection with electricity supply. If electricity is being supplied, some indicators could be positively affected from it and others not.

To be able to show this possible ‘linkages’ between the electricity supply and PBF indicators, data of PBF indicators is collected next to data on electricity supply for the case in Rwanda called Gikomero health facility (HF). As the timeframe is not sufficient for carrying out an analysis of the relationship between these two factors, a protocol is provided and the case is considered as an example. The assessment of this example case in this report will show the actual health-related indicators that are currently available and the possibility of a pre-selection of significant indicators for the analysis of change. Nevertheless, health-related data varies for each health facility, therefore this report will show which data is currently available, how can it be organised and analysed; and possible stated as a standard for collection health-related indicators on health facilities in the future. There is almost no literature on a standard defined for this particular subject.

2.2.3. Methods

2.2.3.1. Data collection of healthcare performance indicators

Rwanda was the first country to set up Performance-based Financing (PBF) around 12 years ago, and it was adopted on the national policy for healthcare (Cordaid, 2015). The approach was very successful, leading to its adoption in other ten African countries. Health facilities that follow the PBF approach must report monthly on the values of health-related indicators. Audits are performed periodically to ensure that the data is accurate. In the case of Gikomero HF, data was collected of PBF indicators from January 2014 until June 2015. Data from earlier periods was not available. The data collection was performed in collaboration with HDP.

The PBF reports include hundreds of health-related indicators and information from the health facility. They are filled in from a representative of the HF on a daily basis. The reports contain very

detailed information such as the number of outpatient consultations, number of hospitalizations, deliveries at the health facilities, referrals to higher levels, finances, amongst others. However, there are many health indicators that are not relevant for this study. Here, it is important to analyse health data that could vary positively or negatively with changes in the electricity supply system. For instance, it is assumed that if there is an increase on reliability or new energy sources available, then there will be fewer complications on childbirths or less patient referrals to hospitals. The reports include other information such as the number of diagnosis of infections, specific diseases and medical conditions; these indicators are not useful for the analysis in this study. Therefore, after collecting the data, some indicators were selected as the most significant to represent change within the health facility when new forms of electricity supply are being introduced. The pre-selected health-related indicators are denominated in this study as health performance indicators, and they are shown in Table A-2. Their respective values for the timeframe Jan-14 until Jun-15 are shown in Appendix F.

Table A-2 Pre-selected health performance indicators (Cordaid, 2015)

Healthcare performance indicators	Sub-indicators
Outpatient morbidity	A1 new cases <5 years (M) A2 new cases <5 years (F) A3 new cases >=5 - 19 (M) A4 new cases >=5 - 19 (F) A5 new cases >= 20 (M) A6 new cases >= 20 (F) A7 Total new cases A8 Old cases (M) A9 Old cases (F) A10 Total new + old cases (A7+A8+A9)
Referrals	B1 Referred to hospital B2 Counter referrals received
Integrated Management of Childhood Illnesses (IMCI) for children <5	C1 Number of children treated in IMCI services
Hospitalizations	D1 Present at the beginning of month D2 Admissions during the month D3 Discharges during the month D3.1 Cured D3.2 Died D3.3 Abandoned D3.4 Referred to hospital D4 Present at the end of the month (C1+C2-C3) D5 Number of beds D6 Potential number of hospitalization days (Beds*Days in Month) D7 Total hospitalization days (Hospitalization effective) D8 Number of hospital days of discharged patients D9 Total hospitalized (not maternity) D9.1 <5 years (M) D9.2 <5 years (F) D9.3 >=5 - 19 (M) D9.4 >=5 - 19 (F) D9.5 >= 20 (M) D9.6 >= 20 (F) D10 Total maternity admissions D10.1 >=5 - 19 (F) D10.2 >= 20 (F) D11 Deaths all

Antenatal Consultations	E1	ANC new registrations
Obstetrical Complications	F1	Number of cases OPD
	F1.1	Number of cases OPD NC
	F1.2	Number of cases hospitalized
	F1.3	Number of deaths
	F1.4	Ante-partum or Post-partum haemorrhage (APH-PPH) cases
	F1.5	Sepsis / Postpartum infection
	F1.6	Prolonged or Obstructed labour
	F1.7	Other complications
Emergency Obstetric Care Interventions (Basic)	FA1	Number of emergency obstetric care interventions (basic)
	FA2	Women placed under observation for >=72 hours
	FA3	Women referred for emergency care to higher levels
Deliveries	G1	Total deliveries
	G2	Multiple pregnancies (twins, triplets, etc.)
	G3	Deliveries referred to higher level
	G4	Maternal deaths during delivery
	G5	Births, live
	G6	Birth weight <2.5 kg (alive, not premature)
	G7	Premature birth weight <2.5 kg (alive, 22-37 weeks)
	G8	Stillbirths
	G9	Death at birth of live born babies (born at the HF) within 30min
	G10	New-borns resuscitated
	G11	New-borns referred to higher level
Postnatal care (PNC)	H1	PNC new registrations (Mother + Baby)
	H1.1	Mother
	H1.2	Baby
	H2	PNC complication referred (mother or baby)
Neonatal care	I1	Admitted for hospitalization
	I2	Deaths
Vaccinations¹	J1	Total vaccinations
Laboratory	K1	Blood smears ²
(Total number of samples analysed)	K2	Rapid Diagnostic Tests for Malaria
	K3	Stools ³
	K4	Urine ⁴
	K5	Sputum ⁵
	K6	Blood ⁶
	K7	Other lab tests
Drugs	L1	Quantity received
	L2	Quantity dispensed
	L3	Stock at the end of the month
	L4	Quantity Expired/Damaged/Lost
Finances	M1	Total revenues (including other revenues)
	M1.1	Preventive care
	M1.2	Curative care (including hospitalization)
	M1.3	Deliveries
	M1.4	Laboratory
	M1.5	Sale of medicines/supplies
	M1.6	Minor surgery
	M1.7	PBF
	M1.8	Other state subsidies
	M1.9	Contribution from other donors
	M1.10	Others
	M2	Total expenses

M2.1	Purchase of medicines, medical materials
M2.2	Salaries, social security, taxes, personnel payments, bonuses
M2.3	Transport expenses (travel, maintenance, fuel, purchases)
M2.4	Fuel and motor oil
M2.5	Office supplies
M2.6	Maintenance of infrastructure and cleaning
M2.7	Maintenance of medical equipment
M2.8	Maintenance of non-medical equipment
M2.9	Water and Electricity
M2.10	Communication (Internet, Telephone...)
M2.11	Training
M2.12	Purchase medical equipment
M2.13	Purchase non-medical equipment
M2.14	Other expenses

M3 Balance of revenues and expenses (J1-J2)

¹Vaccinations include the following vaccine antigen item: BCG, Polio-Zero (P0), Polio-1 (OPV1), Polio-2 (OPV2), Polio-3 (OPV3), DTP-HepB-Hib1, DTP-HepB-Hib2, DTP-HepB-Hib3, Pneumococcus 1, Pneumococcus 2, Pneumococcus 3, Rotavirus 1, Rotavirus 2, Rotavirus 3, Measles&Rubella (MR), Insecticide impregnated bed nets distributed, Measles vaccination, HPV 1, HPV 2, HPV 3

²Laboratory exams for Blood Smears include: Plasmodium, Micro-filaria, Borellia, Trypanosoma

³Laboratory exams for Stools include: Entamoebahistolytica, Entamoeba coli, Giardia, Acariasis, Ankylostomiasis (hookworms), Schistosoma, Trichuris, Taenia, Other parasites

⁴Urine exams include: Sugar, Albumin, Pregnancy test

⁵Sputum exams include: Diagnosis of TB by microscopy and Control of TB positive patients

⁶Blood exams include: RPR, HIV, Hemoglobin, Hemoglobin, ESR/VS, Full Blood Count (FBC/NFS), ALAT (GPT), Creatinine, Blood glucose (glycémie), Amylase, CD4

The collection of the above data of health-related indicators was not easy, as this data is very sensitive and also due long distances and indirect collection (through HDP); it takes more time to obtain the reports. In addition, data before January 2014 was not available; thus generating obstacles for the analysis. When the size of the data is larger, the results are more accurate. Furthermore, organising the data requires the allocation of each value to a template table (shown in Appendix F). This task is also time-consuming and would be better if the template is given in excel to the health facilities so they can allocate the precise values themselves. While organising the data, some small mistakes could be observed. Thus, the audits for the report must be reinforced.

Using the above healthcare performance indicators can be very useful to observe the changes and variations on its values across the time; and that will help to figure out the impact of big changes such as modifications in electricity supply. To test this, data was also collected on indicators of electricity production and consumption. This is elaborated in the next sub-section.

2.2.3.1. Data collection of electricity production and consumption

Currently, it is very difficult to collect data about electricity production and consumption on a selected timeframe. Data is usually collected from health workers, and they have little knowledge on electricity supply, energy technologies and aspects related. There is no documented information about the production and consumption of electricity for the past years. Also, the monthly reports on health-related indicators contain very few data on electricity. As seen in Table A-2, the indicator of 'Finances' contains sub-indicators M2.4 and M2.9 of monthly expenses on 'Fuel and motor oil' and 'Water and electricity', respectively. The first one includes the expenses on diesel to fuel the generator; however it may also involve data on fuel for transport. And the second one may also include some expenses on water. However, as mentioned earlier, Gikomero HF has no water availability according to local sources, hence expenses on 'water and electricity' regarded to electricity alone. Also, it was assumed that expenses on 'fuel and motor oil' are only related to the purchase of diesel to fuel the generator. Table A-3 shows the electricity-related indicators, and the

respective values for Gikomero HF during the timeframe Jan-14 until Jun-15 can be found in Appendix G.

Table A-3 Electricity-related indicators (Cordaid, 2015)

Electricity-related indicators		Sub-indicators	
Finances	M2	Total expenses	
		M2.4	Fuel and motor oil
		M2.4.1	Fuel price 1.28 \$/L ¹
		M2.4.2	Energy content of diesel 10 kWh/L
		M2.4.3	Efficiency 50%
		M2.4.4	Generator electricity consumption ² (kWh)
Electricity from the grid³	N1	Electricity expenses ³	
	N2	Unit cost/kWh	0.22 \$/kWh ⁴
	N3	Electricity consumption from the grid (kWh)	
Electricity consumption	O1	Generator + Grid electricity consumption ⁵ (kWh)	

¹The local price of diesel (L) is subject of variation. The stated value is provided by HDP (2015)

²This indicator can be obtained using the following equation: (M2.4/M2.4.1) x M2.4.2 x M2.4.3

³The electricity expenses from the grid are related to indicator on water and electricity

⁴The local cost per kWh is subject of variation. The stated value is provided by GLE (2015)

⁵This indicator can be obtained using the following equation: M2.4.4 + N3

Because real data on electricity production and consumption was not available, the indicators of Table A-3 were used to calculate electricity consumption patterns since January 2014 until June 2015. It should be stated that the values are not precise and the data follows many assumptions. It is recommended to implement data loggers in the health facilities to make it easier to collect data on electricity; especially to carry out an impact assessment because it is interesting to compare before-after scenarios to analyse and observe what the main changes are.

2.2.3. Results

2.2.3.1. Data analysis and results

After collecting the data on healthcare performance indicators and electricity consumption for the timeframe January 2014 until June 2015, it is possible to observe the patterns of changes over time and place the two types of indicators (health and electricity) together to see if there is any visible 'related' pattern between them. Nevertheless, as it was mentioned before, these indicators are not very accurate, especially the electricity-related indicators. Thus, real results cannot be drawn from this analysis. Although, this procedure can be considered as a protocol or guideline to further pursue this analysis in case more accurate data is obtained for larger time periods. Additionally, this assessment shows which data is currently available and what can be done with it on further studies.

The figure below shows the electricity consumption patterns from the grid and the diesel generator for the period of Jan-14 until Jun-15 in Gikomero HF.

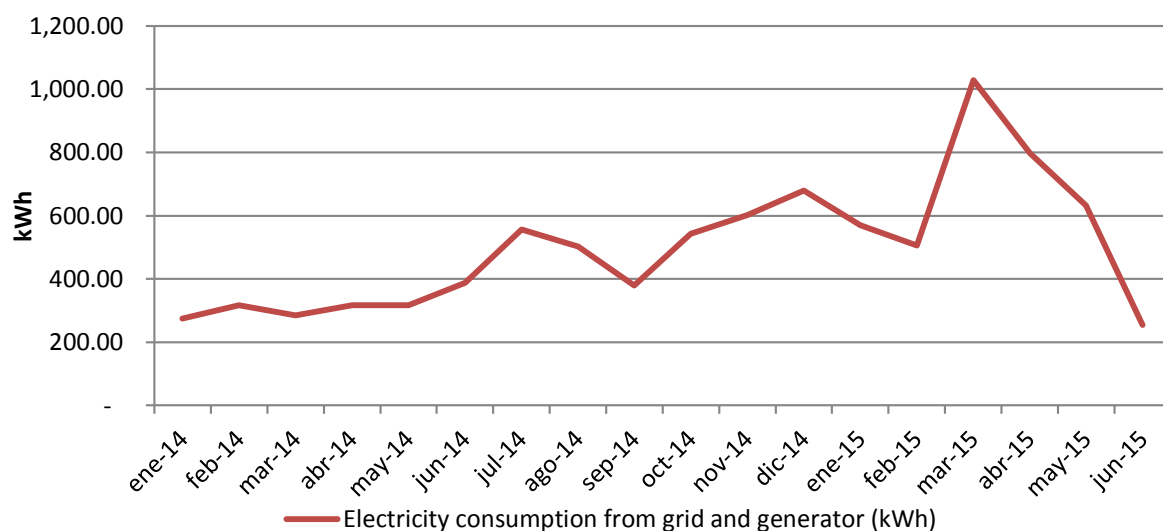


Figure A-3 Total electricity consumption at Gikomero HF (Adapted from Cordaid, 2015)

Figure A-3 show that electricity consumption has been increasing over the past months, with an abnormal peak on Mar-15 and an abnormal drop-down in Jun-15. These abnormalities could be regarded to a bad allocation of data or due to major events at the health facility. As seen in Appendix G, grid expenses are very high for Mar-15 and also fuel expenses are relatively high during the same month. On Jun-15 however, there are no grid electricity expenses and the fuel expenses are not so high. Furthermore, data on fuel expenses in Appendix G shows that diesel consumption is zero for the months between Jan-14 and Jun-14. This could be due to damages on the diesel generator equipment.

The figures below depict a group of health performance indicators that may receive an impact through changes one electricity supply. These indicators are shown in the same figure with the above electricity consumption patterns (in red colour) to visually compare the patterns over time.

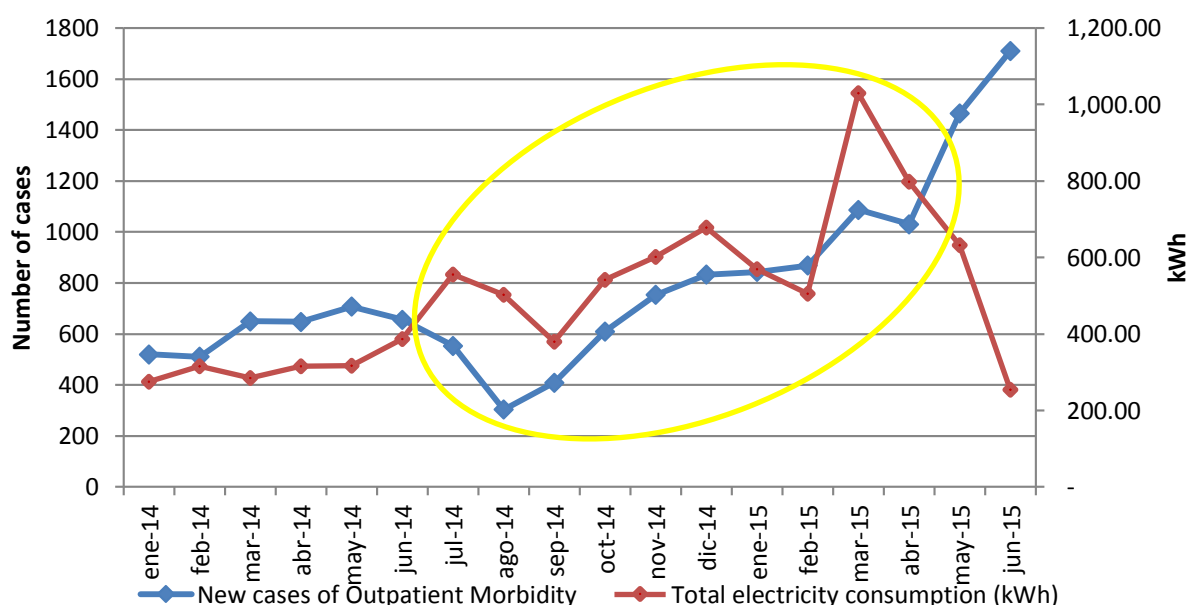


Figure A-4 New cases of Outpatient Morbidity and total electricity consumption (Adapted from Cordaid, 2015)

In Figure A-4, it can be observed that there is a similar pattern on the months between Jul-14 and Apr-15. This period is captured on a yellow circle within the figure. An increase of new cases of outpatient morbidity could increase electricity consumption because patients require the use of

electricity to be treated (e.g. using certain medical equipment, during after-sunset treatments, etc.). Alike, less patients attended could lower the electricity usage in the health facility. However, due to a short period of analysis, the influence of indirect factors and the inaccuracy of indicators, a clear relationship cannot be established.

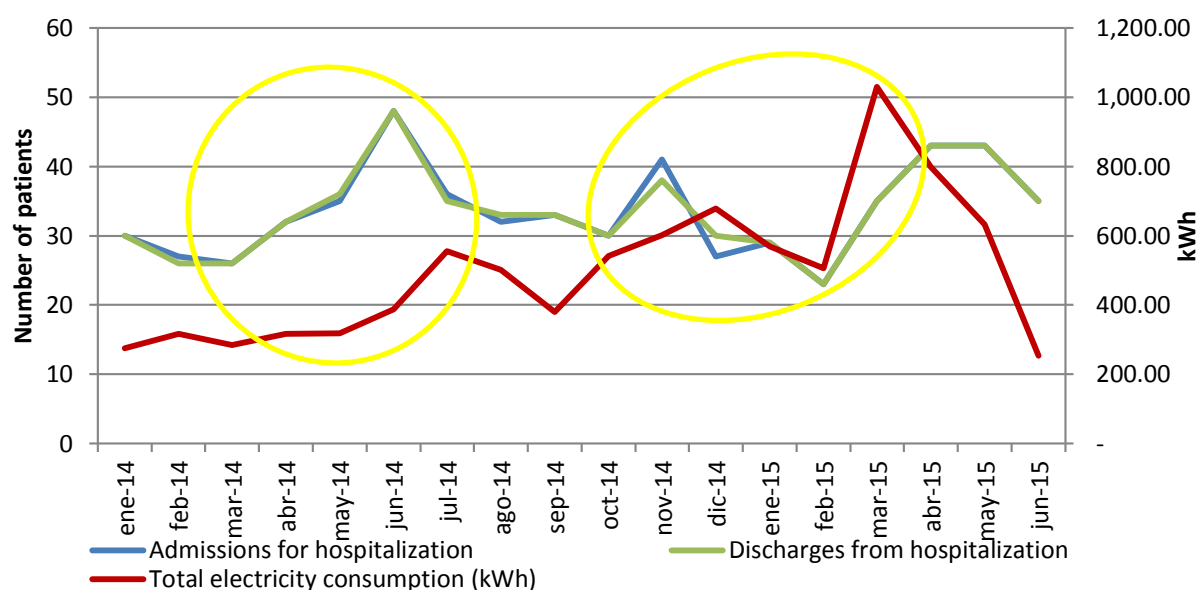


Figure A-5 Hospitalizations: admissions and discharges per month and total electricity consumption (Adapted from Cordaid, 2015)

It is assumed that more hospitalizations in the health facility require more use of electricity for lighting in the evenings, run medical equipment all time, etc. In Figure A-5, these patterns can be observed between months Mar-14 and Jul-14 and between Oct-14 and Mar-15 in exception of Dec-14. These patterns could be partially supported with the fact that hospitalized patients consume electricity, especially during the evening.

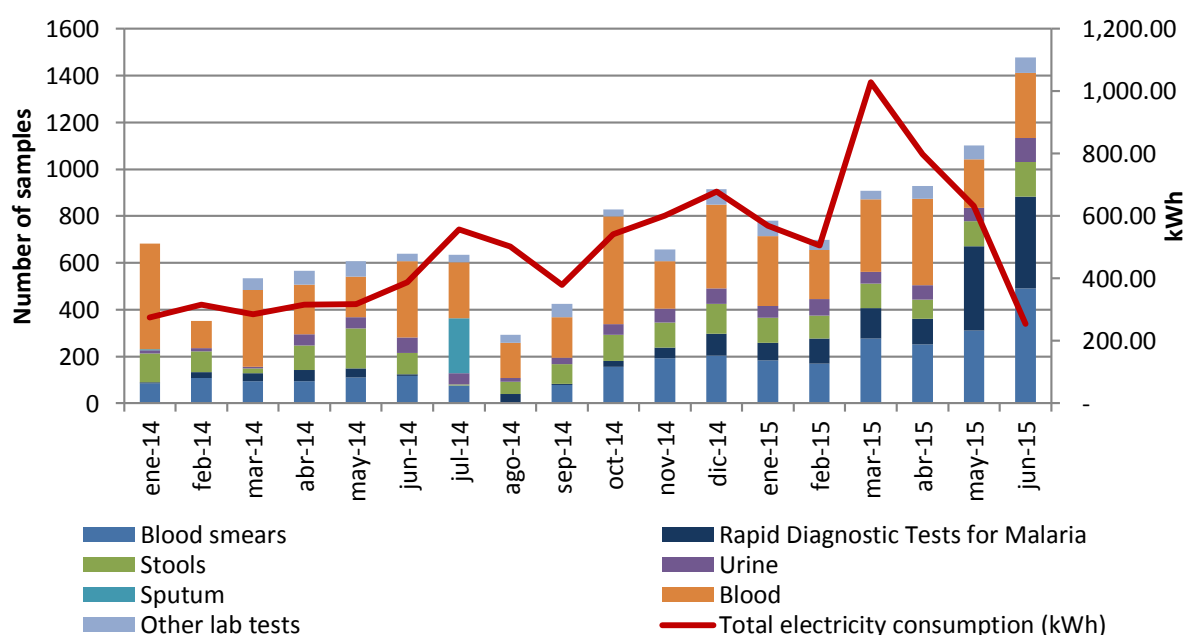


Figure A-6 Number of laboratory samples analyzed and total electricity consumption (Adapted from Cordaid, 2015)

Laboratory services require the use of electricity for running microscopes, centrifuges, refrigeration of vaccines and medicines, etc. Therefore, it is assumed that the analysis of more samples in the laboratory will increase the usage of electricity. In Figure A-6 it is possible to observe overall an increase of laboratory samples analyzed over time and also an increase on the consumption of electricity (in exception of the last two months of the period). Yet, the period of time is too short to draw reliable conclusions. Below, the total revenues per service are visualized over time next to the total electricity consumption.

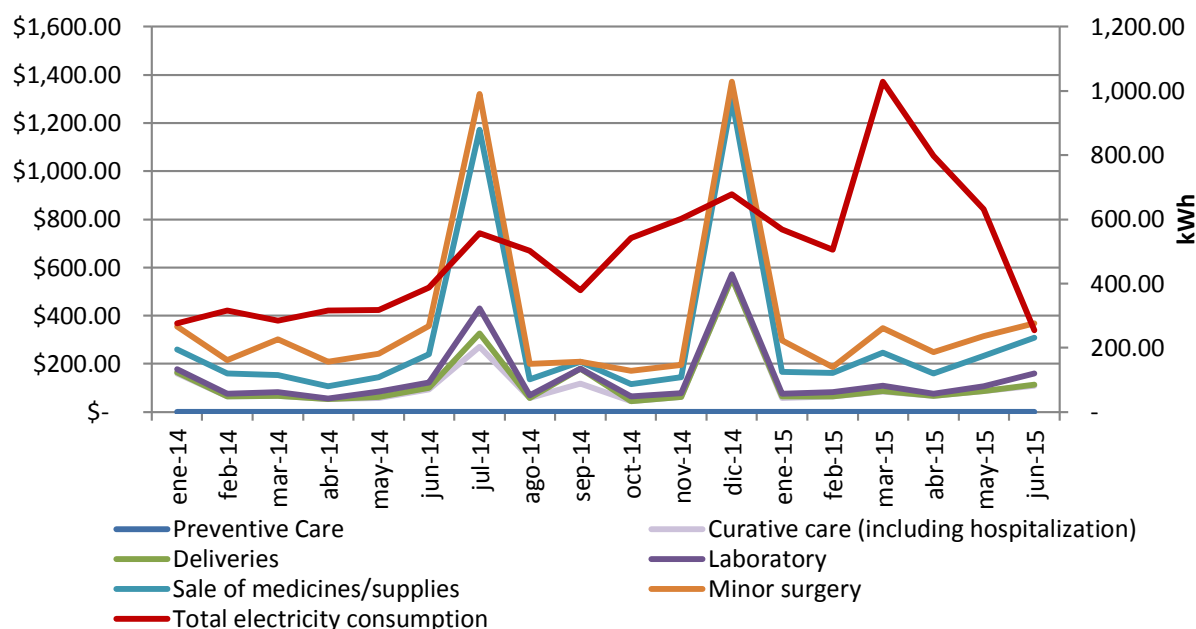


Figure A-7 Revenues per service and total electricity consumption (Adapted from Cordaid, 2015)

In Figure A-7 there are two major peaks of revenues in Jul-14 and Dec-14, especially for minor surgeries and the sale of medicines/supplies. These revenue peaks match with the peaks for electricity consumption during the same months. This could be due to an increased delivery of services which require the use of electricity to run medical equipment, for lighting during medical treatments and surgical procedures, for the storage of medicines, etc.

The same graphs were developed for other potential health-indicators for the analysis (see Table A-2); however no outstanding relation was found. The graphs do not provide a clear 'relationship' or similar pattern between health indicators and electricity consumption. However, the number of new cases of outpatient morbidity, the number of hospitalizations and the number of laboratory samples did show an interesting partial 'related' pattern. Nevertheless, as explained earlier, it is not possible to draw significant conclusions for such a short period of time and without considering other factors that could influence the indicators. Also, one sample size is not enough and the indicators must very reliable. This assessment however, provides a protocol of a method to visualize change in health facilities over time in relation to electricity consumption. Further studies needs to be done in this subject.

2.2.4. Discussion about the impact assessment

One of the biggest limitations of this analysis performed in this section is the influence of indirect factors such as the human factor, the availability of medical equipment and devices, financial resources, water availability, infrastructure, access to thermal energy, amongst others. Hence, the development of a mathematical model and statistical analysis could be interesting when taking into account all variables involved within the health facility system. Nevertheless, when analysing the data available for Gikomero HF it was possible to observe a partial 'related' pattern between very few indicators. However, these observations cannot be considered as reliable results due to a short

time period, small sample size and a lack of data collection procedures. Even though there are frequent audits carried out to evaluate the information collected, the data is not very accurate due to common mistakes on data collection and management. In the current study, there are visual abnormalities on the energy data collected, and the implementation of data loggers in the short-term will improve the energy data collection to avoid these issues. However, this means that the results of this analysis are not very reliable and should only be used as an example of methods to study linkages between electricity consumption and the delivery of healthcare services. Furthermore, the data on indicators is available for a short period of time since Jan-14 until the present date; and to perform an analysis of indicators and relationships, data for longer periods of time is required, at least for three years to be able to establish better linkages.

2.2.4. Conclusions and recommendations about the impact assessment

To assess the impact of electricity consumption variations on the delivery of healthcare services, indicators for measuring healthcare performance were pre-selected. These indicators are tentative for analysing patterns and changes over time in relation to electricity. After the analysis made over a short period of time, it is concluded that there could be a linkage between the use of electricity and certain health indicators such as number of new cases of outpatient morbidity, the number of hospitalizations, the number of laboratory samples and the revenues per services. However, a larger period of time is needed to determine reliable linkages, and also the analysis should be performed for a larger sample size and taking into account indirect factors that can influence the health indicators.

The Performance-based Financing (PBF) indicators could be improved to provide more precise indicators on measuring electricity & health –related variations. As an example, currently there is no distinction between expenses on water and electricity, as they are considered within the same expense line; this represents an obstacle for assessing water availability or electricity consumption independently. The same situation is for the indicator of ‘fuel and transport expenses’ that causes confusions on assigning the value to transport or to purchase diesel for the generator. Moreover, a pre-selection of indicators was done and specified in this study, and it is recommended that these indicators become more electricity-oriented instead of being much health-related, for instance interesting indicators could be the number of babies using an infant warmer or the number of vaccines and medicines that are damaged due to bad refrigeration. Furthermore, to improve the delivery of healthcare services, access to electricity is one of the components, but other elements such as access to water and sanitation, access to economic resources, access to medical equipment and devices, and the access to skilled health workers are also part of the health system. Additionally, access to thermal energy is also an important element.

To perform the impact assessment, it is recommended to study at least 50 health facilities following the protocol of this study including indirect factors, and collecting data for a time period of more than three years to be able to understand better the local context, determine better solutions to energy-related constraints, and to derive reliable results of relationships between electricity and the delivery of healthcare services.

APPENDIX B

Table B-1 Electricity requirements of electrical equipment for health services (WHO, 2014)

Health services		Electrical devices	Indicative power rating (W) operation mode	AC power supply	DC power supply or battery port
Infrastructure	Basic amenities	Basic lighting requirements for health clinics are estimated at: ~162 lumens/m², provided through:			
		- Incandescent (~7~18 lm/W)	~10.8 W/m ²	110/220 V AC	-
		- Halogen (~15 lm/W)	~ 1.8 W/m ²	110/220 V AC	12 V DC
		- CFL (~45–70 lm/W)	~ 2.16 W/m ²	110/220 V AC	-
		- LED (~50- 100 lm/W)	~1.8–2.14 W/m ²	110/220 V AC	10–30 V DC
		Security lighting, outdoors	40–160 W CFL/LED 200–600 incandescent	110/220 V AC	10–30 V DC
		Mobile phone battery (charging)	5–20 W	110/220 V AC	5–16.5 V DC
		Desktop computer	156–200 W	110/220 V AC	8–20 V DC
		Laptop computer	20–60 W	110/220 V AC	12–20 V DC
		Internet (V-Sat connection)	85 W-500	110/220 V AC	15–24 V DC
		Printer, ink jet	6513–100 W	110/220 V AC	12–20 V DC
		Printer, laser	150–1100 W	110/220 V AC	-
		VHF radio receiver:			
		- Stand-by	2 W	110/220 V AC	12 V DC
		- Transmitting	30 W		
		Ceiling fan (AC)	50–100 W	110/220 V AC	-
		Ceiling fan (DC)	28 W	-	12 V DC
		Refrigerator, 165 L (for food & water):			
		- AC	150–200 W	110/220 V AC	-
		- DC	40–80 W	-	12V DC
		Portable electric space heater	1392–150025 W	110/220 V AC	48 V DC
		Portable air conditioner (AC & DC variants)	1000–1500 W	110/220 V AC	48 V DC

Specific Services	Processing of equipment for reuse	Countertop autoclave (steam sterilizer) (19–45 L)	1200–2850 W	110/220 V AC	-
		Dry heat sterilizer	500 W–1.56 kW	110/220 V AC	-
	Healthcare waste management	Small waste autoclave (35–178 L)	2–6 kW	220 V AC	-
		Autoclave grinder	1400 W	-	-
		Small water pump – clinic	50–200 W	-	15–30 V DC
		Water pump – district health centre	400–1000 W	110/220 V AC	-
		UV water purifier	10–40 W	-	12 V DC
		Reverse osmosis/other water purifier	264 W–570 W	110/220 V AC	-
	General outpatient services	Micro-nebulizer	2.5– 36 W	100–240 V AC	9–12 V DC
		Nebulizer	80–90 W–	110/220 V AC	-
		Oxygen concentrator	270–310 W 70 W	110/220 V AC -	- 12–18 V DC
		Pulse oximeter	50 W	110/220 V AC	-
		Pulse oximeter (AA battery-operated)	2–3 W	-	1.5–3 V DC
	Antenatal, child and adolescent health	Vaccine refrigerator (polio, measles, DPT-Hib+HepB, BCG & tetanus toxoid) designed to perform at 43°C:			
		- Vestfrost VLS200 AC (electric mains) 100 litres (WHO/PQS: E003/031)	115 W stable running (710 Wh/day)	110/220 V AC	N/A
		- Dometic TCW 3000 DC (solar-charged, battery-driven) vaccine refrigerator, 110 litres (WHO/PQS-E003/008)	250 W solar array	N/A	12/24 V DC
	Obstetric and new-born	- Sure Chill BLF100 DC (solar direct-drive) vaccine refrigerator, 99 litres (WHO/PQS: E003/019)	370 W +/- solar array	N/A	12/24 V DC
		LED light for phototherapy treatment of neo-natal jaundice	440 W	110/220 V AC	-
		Suction apparatus	90–200 W 33 W	110/220 V AC -	- ± 12 V DC
		Vacuum aspirator or D&C kit	36–96 W	110/220 V AC	± 3–6 V DC
		Neo-natal incubator	800–1035 W	110/220 V AC	-
		Neo-natal infant warmer	125/550 W	110/230 V AC	-

		Fetal heart monitor (Doppler)	1.5–3 W (AA battery)	-	1.5–3 V DC
		Ultrasound	800–1000 W	110/220 V AC	-
		Portable ultrasound	6 W (idle) – 22–28 W (active-charging)	100–240 V AC	11–15 V DC
	General diagnostics, blood analysis and laboratory equipment	Laboratory refrigerator	60–160 W 40–80 W (165 L)	110/220 V AC -	- 12/24 V DC
		Centrifuge	250 – 400 W (low-medium speeds)	110/220 V AC	-
		Mini-centrifuge	25 W	-	12 V DC
		Haematology analyser	230–400 W	-	-
		Blood chemistry analyser	45–88 W	-	-
		Blood chemistry analyser (hand-held)	-	-	18 V DC battery
		CD4 counter	200 W	110/220 V AC	12 V DC
		Brightfield white light microscope (with LED light)	20–30 W	110/220 V AC	3–6 V DC
		LED microscope (for fluorescence smear microscopy (halogen or LED light))	70 W	110/220 V AC	12 V DC
		Mercury/xenon fluorescence microscope	75–200 W	220–240 V AC	-
		X-ray machine	15–20 KW 30–40 KW 50–80 KW	120 V AC 1Φ/108–230 V AC 3Φ/400–480 V AC	- - -
		Portable X-ray machine	3–4 KW	90–264 V AC	
		Laboratory incubator	200 W	110/220 V AC	12 V DC
		Vortex mixer	18 W 70–90W	90/220 V AC 120/230 V AC	6 V DC -
	TB diagnosis	Sputum-smear microscopy (LED microscope w/fluorescent smear)	30 W (+ 6 W LED bulb) 20–30 W91, (+6 W LED bulbs)	110/230 V AC -	- 6V DC
		GeneXpert MTB/RIF diagnostic	190 W	110/220 V AC	12/24 V DC
	HIV diagnosis	ELISA test reader	500–650 W	110/220 V AC	48 V DC
	Cardiovascular	Portable electrocardiograph (ECG)	1.2 W–45/70W	100/240 V AC	3–12 V DC

	diagnosis/treatment	Defibrillator with ECG	130–200 W 100–130 W	110/220 V AC -	14–15 V DC 11.1 V DC
	Diabetes	Blood glucose monitor	<1 W	-	3.3–5 V DC

Basic surgical services	Suction apparatus (AC)	90–200 W	110/220 V AC	
	Suction apparatus (DC)	33 W		± 12 V DC
	Anaesthesia machine	1440 W	110/220 V AC	
	Low-energy anaesthesia machine with DC monitor backup	480 W – oxygen concentrator 20 W – monitor	220V	12 V DC backup (for monitor)

APPENDIX C

Table C-1 Category I Health Clinic: Power and Energy Consumption (USAID, no date)

		A	B	C = AxB	D	E = CxD	F = E/1000
Category I Health Clinic Power and Energy Consumption		Quantity	Power (Watts)	Total Watts	On-Time (watt hours/day)	Wattage (hours/ day)	kWh/day
Description of Devices	Vaccine Refrigerator/Freezer	1	60	60	6.0 - 12.0	360 - 720	0.36 - 0.72
	Small Refrigerator (non-medical use)	1	300	300	5.0	1,500	1.5
	Centrifuge	1	575	575	1.0 - 1.5	575 - 862.5	0.575 - 0.8625
	Hematology Mixer	1	28	28	1.0 - 1.5	28 - 42	0.028 - 0.042
	Microscope	1 - 2	15	15 - 30	3.0 - 4.0	45 - 120	0.045 - 0.12
	Lighting	2	10	20	2 - 10	40 - 200	0.040 - 0.2
	Incubator	1	400	400	2.0 - 12.0	800 - 4,800	0.8 - 4.8
	Water Bath	1	1,000	1,000	1.0 - 2.0	1,000 - 2,000	1 - 2
	Communication via VHF Radio	1					
	Stand-by		2	2	12.0	24	0.024
	Transmitting		30	30	1.0 - 2.0	30 - 60	0.030 - 0.060
Total				2,430 - 2445		4,402 - 10,328.5	4.4 - 10.3

Table C-2 Category II Health Clinic: Power and Energy Consumption (USAID, no date)

	A	B	C = AxB	D	E = CxD	F = E/1000	
Category II Health Clinic Power and Energy Consumption	Quantity	Power (Watts)	Total Watts	On-Time (watt hours/day)	Wattage (hours/ day)	kWh/day	
Description of Devices	Vaccine Refrigerator/Freezer	2	60	120	6.0 - 12.0	720 - 1,440	0.72 - 1.44
	Small Refrigerator (non-medical use)	1	300	300	5.0	1,500	1.5
	Centrifuge	1	575	575	2.0	1,150	1.15
	Hematology Mixer	1	28	28	2.0	56	0.056
	Microscope	2	15	30	5.0	150	0.15
	Lighting	2 - 3	15	30 - 45	10.0	300 - 450	0.3 - 0.45
	Sterilizer Oven (Laboratory Autoclave)	1	1,564	1,564	1.0	1,564	1.564
	Incubator	2	400	800	2.0 - 12.0	1,600 - 9,600	1.6 - 9.6
	Water Bath	1	1,000	1,000	2.0	2,000	2.0
	Communication via VHF Radio	1					
	Stand-by		2	2	12.0	24	0.024
	Transmitting		30	30	2.0 - 3.0	60 - 90	0.060 - 0.09
	Desktop Computer	1 - 3					
	Power Save Mode		50	50 - 150	7.0	350 - 1,050	0.35 - 1.05
	In Use		150	150 - 450	5.0	750 - 2,250	0.750 - 2.25
	Printer	1	65	65	3.0	195	0.195
	Total			4,744 - 5,159		10,569 - 21,519	10.6 - 21.5

Table C-3 Category III Health Clinic: Power and Energy Consumption (USAID, no date)

		A	B	C = AxB	D	E = CxD	F = E/1000
Category III Health Clinic Power and Energy Consumption		Quantity	Power (Watts)	Total Watts	On-Time (watt hours/day)	Wattage (hours/ day)	kWh/ day
Description of Devices	Vaccine Refrigerator/Freezer	3	60	180	6.0 - 12.0	1,080 - 2,160	1.08 - 2.16
	Small Refrigerator (non-medical use)	1	300	300	5.0	1,500	1.5
	Centrifuge	1	575	575	3.0	1,725	1.725
	Hematology Mixer	1	28	28	3.0	84	0.084
	Microscope	3	15	45	6.0	270	0.27
	Lighting	3 - 4	15	45 - 60	10.0	450 - 600	0.45 - 0.6
	Incubator	3	400	1,200	2.0 - 12.0	2,400 - 14,400	2.4 - 14.4
	Water Bath	1	1,000	1,000	2.0	2,000	2.0
	Communication via VHF Radio	1					
	Stand-by		2	2	12.0	24	0.024
	Transmitting		30	30	3.0 - 4.0	90 - 120	0.090 - 0.120
	Desktop Computer	3 - 6					
	Power Save Mode		50	150 - 300	7.0	1,050 - 2,100	1.05 - 2.1
	In Use		150	450 - 900	5.0	2,250 - 4,500	2.25 - 4.5
	Printer	1	65	65	4.0	260	0.26
	Portable X-Ray Machine	1	3,000	3,000	1.0	3,000	3.0
	Total			8,634 - 9,249		17,597 - 34,157	17.6 - 34.2

APPENDIX D

Figure D-1 Annual seasonal variations for Solar GHI resource (NASA surface meteorology and solar energy database, 2015)

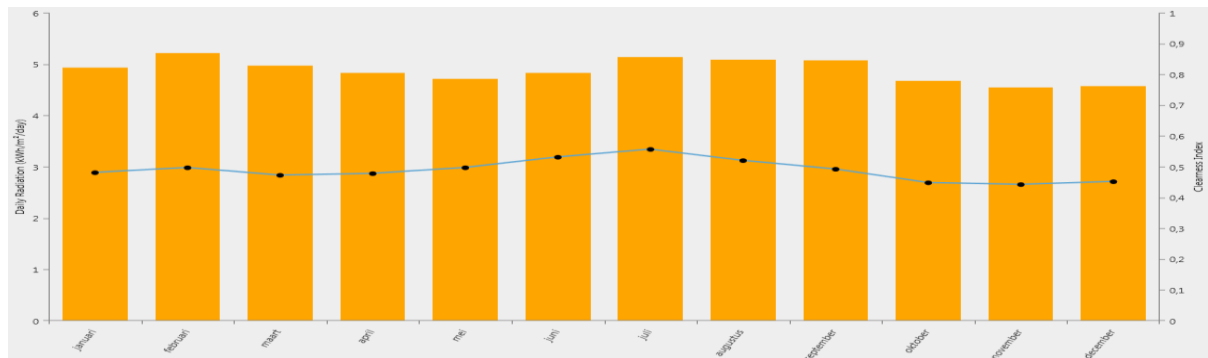
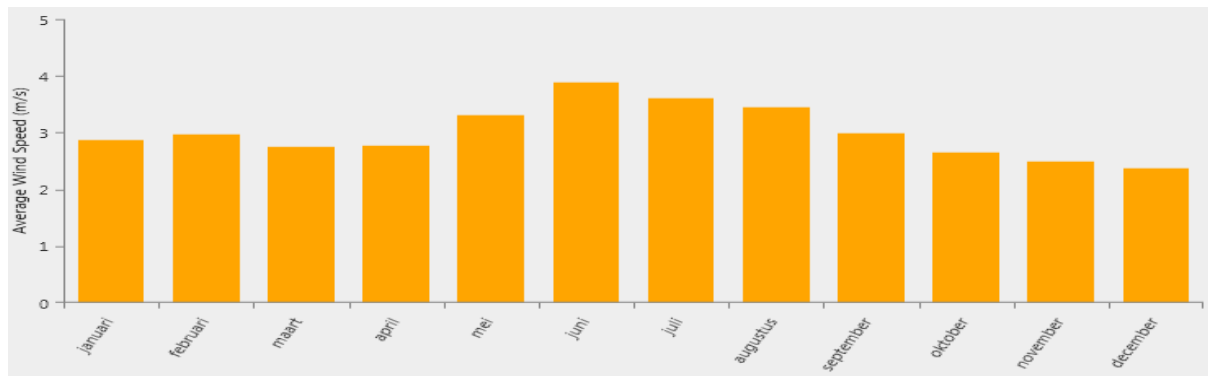


Figure D-2 Annual seasonal variations for Wind resource (NASA surface meteorology and solar energy database, 2015)



APPENDIX E

Table E-1 Diesel generator variables

Name	12.5kW Genset
Size	12.5kW
Minimum load ratio	25%
Heat recovery ratio	0%
Lifetime (Hours)	15,000; 20,000; 25,000 [sensitivity analysis]
Minimum runtime (Minutes)	0

Table E-2 Fuel properties

Type of fuel	Diesel
Fuel price (\$/L)	1.00; 1.28; 1.5 [sensitivity analysis]
Lower heating value (MJ/kg)	43.2 (12kWh/kg)
Density (kg/m3)	820
Carbon content (%)	88
Sulphur content (%)	0,33
Emissions	
– Carbon monoxide (g/L)	6.50
– Unburned hydrocarbons (g/L)	0.72
– Particulate matter (g/L)	0.49
– Proportion of fuel sulphur converted to PM (g/L)	2.20
– Nitrogen Oxides (g/L)	58

Table E-3 Solar PV panels' variables

Name	Generic flat plate PV
Size (kW)	0; 1; 2; 3; 4; 5; 6; 7; 8
Electrical bus (AC/DC)	DC
Lifetime	25 years
Derating factor	80%
Dedicated converter (Yes/No)	Yes (see Table 3-10 below)

Table E-4 Wind turbine variables

Name	Generic 3kW
Quantity of wind turbines	0; 1; 2; 3; 4; 5
Electrical bus (AC/DC)	DC
Lifetime	20 years
Hub height (m)	6.00

Table E-5 Battery variables

Name	Deka Gel 12V 213Ah
Number of strings	0; 1; 2; 3
Batteries per string	5
Initial state of charge	100%
Minimum state of charge	60%
Lifetime throughput (kWh)	3,550.00
Minimum battery life	-
Round trip efficiency	85%
Float life	8 years

Maximum capacity (Ah)	244.971
Capacity ratio	0.329
Rate constant	0.597
Max charge rate (A/Ah)	1
Max charge current (A)	57
Max discharge current (A)	133.903
Website	

Table E-6 System converter variables

Name	System converter
Size	0; 3; 4; 4.5; 5; 6
Inverter input:	
– Lifetime	12 years
– Efficiency	90%
– Relative capacity	100%
– Parallel with AC generator (Yes/No)	Yes
Rectifier input:	
– Relative capacity	100%
– Efficiency	85%

APPENDIX F

Table F-1 Performance-based Financing health-related indicators for Gikomero health facility (Cordaid, 2015)

PBF Health Indicators			jan-14	feb-14	mrt-14	apr-14	mei-14	jun-14	jul-14	aug-14	sep-14	okt-14	nov-14	dec-14	jan-15	feb-15	mrt-15	apr-15	mei-15	jun-15
A	Outpatient morbidity	A1 new cases <5 years (M)	4	27	18	17	25	12	23	11	17	14	18	16	9	10	28	39	23	23
		A2 new cases <5 years (F)	8	39	10	26	15	17	11	20	10	29	20	13	13	12	26	28	17	19
		A3 new cases >=5 - 19 (M)	91	80	107	101	69	114	99	20	56	86	147	175	136	193	184	178	296	390
		A4 new cases >=5 - 19 (F)	125	120	151	120	120	148	125	29	52	85	116	182	150	205	216	241	315	428
		A5 new cases >= 20 (M)	113	95	169	190	220	134	146	93	106	159	157	200	189	181	197	237	402	431
		A6 new cases >= 20 (F)	179	150	195	194	258	231	150	131	168	237	296	247	346	268	436	308	413	420
		A7 Total new cases	520	511	650	648	707	656	554	304	409	610	754	833	843	869	1087	1031	1466	1711
		A8 Old cases (M)	8	11	3	10	3	1	8	2	7	14	10	4	8	3	10	10	6	12
		A9 Old cases (F)	6	5	1	5	4	16	4	1	1	4	6	6	4	5	12	10	8	6
		A10 Total new + old cases (A7+A8+A9)	534	527	654	663	714	673	566	307	417	628	770	843	855	877	1109	1051	1480	1729
B	Referrals	B1 Referred to hospital	17	26	15	18	13	19	8	7	12	23	13	15	18	20	25	14	20	24
		B2 Counter referrals received	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
C	Integrated Management of Childhood Illnesses (IMCI) for children <5	C1 Number of children treated in IMCI services	12	66	28	43	40	29	34	31	28	37	38	30	21	22	54	68	40	52
D	Hospitalizations	D1 Present at the beginning of month	0	0	1	1	1	0	0	1	0	0	0	3	0	0	0	0	0	0
		D2 Admissions during the month	30	27	26	32	35	48	36	32	33	30	41	27	29	23	35	43	43	35
		D3 Discharges during the month	30	26	26	32	36	48	35	33	33	30	38	30	29	23	35	43	43	35
		D3.1 Cured	28	26	25	32	36	48	35	33	33	30	36	29	28	23	35	43	43	33
		D3.2 Died	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2
		D3.3 Abandoned	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
		D3.4 Referred to hospital	2	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0
		D4 Present at the end of the month (C1+C2-C3)	0	1	1	1	0	0	1	0	0	0	3	0	0	0	0	0	0	0
		D5 Number of beds	13	13	13	13	13	13	13	7	7	7	8	8	7	13	13	13	13	13
		D6 Potential number of hospitalization days (Beds*Days in Month)	390	390	390	390	390	390	390	210	210	210	210	240	210	196	390	390	390	390
		D7 Total hospitalization days (Hospitalization effective)	90	84	78	96	98	144	105	8	8	15	89	56	71	57	78	92	94	88

		D8	Number of hospital days of discharged patients	3	3	3	96	98	144	106	8	8	515	89	56	71	57	78	92	94	88
		D9	Total hospitalized (not maternity)	5	5	6	7	4	6	3	5	5	16	21	4	5	23	35	43	43	35
		D9.1	<5 years (M)	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0
		D9.2	<5 years (F)	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
		D9.3	>=5 - 19 (M)	0	1	0	0	0	0	0	1	1	0	4	1	1	0	1	1	0	1
		D9.4	>=5 - 19 (F)	0	1	1	2	1	0	0	2	2	0	3	0	0	2	0	6	2	5
		D9.5	>= 20 (M)	1	1	1	1	2	1	2	0	0	15	5	2	2	0	2	3	0	0
		D9.6	>= 20 (F)	4	2	3	4	1	5	1	1	1	0	9	0	2	21	32	33	40	29
		D10	Total maternity admissions	25	22	20	24	32	42	33	27	27	0	20	22	24	-	-	-	-	-
		D10.1	>=5 - 19 (F)	3	2	5	1	2	2	5	2	2	0	2	2	3	-	-	-	-	-
		D10.2	>= 20 (F)	22	20	15	23	30	40	28	25	25	0	18	20	21	-	-	-	-	-
		D11	Deaths all	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2
E	Antenatal Consultations	E1	ANC new registrations	58	48	69	51	52	48	44	28	39	8	32	62	52	52	61	43	41	61
F	Obstetrical Complications	F1	Number of cases OPD	0	1	1	2	2	0	0	0	0	0	5	0	0	0	2	0	0	0
		F1.1	Number of cases OPD NC	0	0	0	0	0	0	0	0	0	0	5	0	0	0	2	0	0	0
		F1.2	Number of cases hospitalized	0	1	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0
		F1.3	Number of deaths	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		F1.4	Ante-partum or Post-partum haemorrhage (APH-PPH) cases	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		F1.5	Sepsis / Postpartum infection	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0
		F1.6	Prolonged or Obstructed labour	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		F1.7	Other complications	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FA	Emergency Obstetric Care Interventions (Basic)	FA1	Number of emergency obstetric care interventions (basic)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		FA2	Women placed under observation for >=72 hours	25	23	19	24	32	40	32	27	25	22	17	23	24	19	26	30	34	28
		FA3	Women referred for emergency care to higher levels	0	1	1	0	0	2	1	0	2	0	0	0	0	0	0	0	34	0
G	Deliveries	G1	Total deliveries	25	23	20	24	32	42	33	27	27	22	17	23	24	19	26	30	34	28
		G2	Multiple pregnancies (twins, triplets, etc.)	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
		G3	Deliveries referred to higher level	8	0	0	9	11	9	10	6	12	8	10	16	9	9	14	8	11	8
		G4	Maternal deaths during delivery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		G5	Births, live	24	24	20	24	32	43	33	27	27	24	17	23	24	19	25	30	33	28
		G6	Birth weight <2.5 kg (alive, not premature)	1	0	0	1	1	0	0	0	0	3	1	0	0	0	0	3	0	2

	G7	Premature birth weight <2.5 kg (alive, 22-37 weeks)	0	2	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0		
	G8	Stillbirths	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	G9	Death at birth of live born babies (born at the HF) within 30min	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0		
	G10	Newborns resuscitated	0	0	1	0	2	1	0	0	2	0	1	1	1	1	1	0	1	1		
	G11	Newborns referred to higher level	0	2	1	0	0	2	0	0	2	2	0	1	0	0	0	0	0	0		
H	Postnatal care	H1	PNC new registrations (Mother + Baby)	49	44	40	48	64	85	66	54	54	46	34	46	48	38	52	60	67	56	
		H1.1	Mother	25	22	20	24	32	42	33	27	27	22	17	23	24	19	26	30	34	28	
		H1.2	Baby	24	22	20	24	32	43	33	27	27	24	17	23	24	19	26	30	33	28	
		H2	PNC complication referred (mother or baby)	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	
I	Neonatal	I1	Admitted for hospitalization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
		I2	Deaths	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
J	Vaccinations ¹	J1	Total vaccinations	766	669	683	704	1145	749	974	979	1468	911	894	916	865	671	1058	796	782	897	
K	Laboratory	K1	Blood smears ²	86	109	95	95	111	117	77	6	78	155	192	204	184	170	277	252	311	492	
		(Total number of samples analysed)	K2	Rapid Diagnostic Tests for Malaria	5	24	34	47	39	7	0	33	5	25	45	93	75	106	130	108	361	390
		K3	Stool ³	122	90	20	105	170	92	4	53	85	112	109	128	106	98	105	82	107	148	
		K4	Urine ⁴	13	12	7	48	47	66	47	17	27	47	58	65	50	71	50	63	56	103	
		K5	Sputum ⁵	6	0	0	0	0	0	236	0	0	0	0	0	0	0	0	0	0	0	0
		K6	Blood ⁶	451	118	329	211	175	326	239	149	173	459	203	359	300	209	309	368	208	278	
		K7	Other lab tests	0	0	50	60	65	31	31	34	56	30	50	66	65	44	37	56	58	67	
L	Drugs	L1	Quantity received	-	-	-	-	-	-	-	-	-	-	-	-	-	355	21270	480	16010	11620	
		L2	Quantity dispensed	5930	4875	6439	4055	1749	2879	4029	2850	4358	4966	6377	5467	6400	5534	14889	11901	10188	17926	
		L3	Stock at the end of the month	10809	26040	19161	15394	18818	19606	29275	26904	44311	25125	32176	26293	21012	16702	20341	12643	16024	19675	
		L4	Quantity Expired/Damaged/Lost	0	0	0	0	0	0	6	0	0	0	500	0	0	2000	0	0	0	0	200

¹Vaccinations include the following vaccine antigen item: BCG, Polio-Zero (P0), Polio-1 (OPV1), Polio-2 (OPV2), Polio-3 (OPV3), DTP-HepB-Hib1, DTP-HepB-Hib2, DTP-HepB-Hib3, Pneumococcus 1, Pneumococcus 2, Pneumococcus 3, Rotavirus 1, Rotavirus 2, Rotavirus 3, Measles&Rubella (MR), Insecticide impregnated bed nets distributed, Measles vaccination, HPV 1, HPV 2, HPV 3

²Laboratory exams for Blood Smears include: Plasmodium, Micro-filaria, Borellia, Trypanosoma

³Laboratory exams for Stools include: Entamoebahistolitica, Entamoeba coli, Giardia, Acariasis, Ankylostomiasis (hooworms), Schistosoma, Trichuris, Taenia, Other parasites

⁴Urine exams include: Sugar, Albumin, Pregnancy test

⁵Sputum exams include: Diagnosis of TB by microscopy and Control of TB positive patients

⁶Blood exams include: RPR, HIV, Hemoglobin, Hemoglobin, ESR/VS, Full Blood Count (FBC/NFS), ALAT (GPT), Creatinine, Blood glucose (glycémie), Amylase, CD4

Table F-2 Performance-based Financing economic indicators for Gikomero health facility (Cordaid, 2015)

			jan-14	feb-14	mrt-14	apr-14	mei-14	jun-14	jul-14	aug-14	sep-14	okt-14	nov-14	dec-14	jan-15	feb-15	mrt-15	apr-15	mei-15	jun-15		
M	Finances	M1	Total revenues (including other revenues)	10955,05	1562,80	9386,49	2084,20	12153,07	1905,58	9129,93	7694,24	2993,52	5300,44	7442,33	2520,36	2264,39	7672,92	8732,14	3559,65	11085,52	1461,90	
			M1.1	Preventive care	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			M1.2	Curative care (including hospitalization)	161,04	64,90	67,03	54,43	57,95	92,48	271,66	57,71	118,91	45,87	62,24	555,61	59,09	65,66	83,92	66,39	86,44	109,37
			M1.3	Deliveries	3,78	0	0	0	5,04	7,56	54,10	0	61,24	0	0	0	6,36	0	3,78	0	0	3,78
			M1.4	Laboratory	12,78	11,73	16,03	2,27	22,51	22,72	104,72	12,49	0	18,25	14,77	16,69	9,51	17,26	20,94	9,93	21,13	46,59
			M1.5	Sale of medicines/supplies	81,16	82,67	70,48	50,56	58,01	117,45	741,98	65,07	27,94	51,67	66,58	727,50	91,99	79,31	137,64	82,85	125,61	148,24
			M1.6	Minor surgery	95,52	56,30	148,09	100,38	99,25	117,49	148,82	65,24	0	54,95	50,76	70,91	131,43	23,69	101,30	88,97	81,13	60,02
			M1.7	PBF	771,57	0	0	0	0	0	0	0	0	0	0	0	0	0	3172,79	1374,84	0	723,71
			M1.8	Other state subsidies	6962	679,45	1571,40	698,52	8374,51	0	2134,86	6961,99	0	698,52	6961,99	273	0	6961,99	0	1716,32	6961,99	0
			M1.9	Contribution from other donors	0	378	2794,10	126	592,78	938,45	3439,19	0	0	370,65	238,77	822,71	199,68	397,97	0	0	428,21	126
			M1.10	Others	2867,20	289,76	4719,37	1052,03	2943,03	609,43	2234,62	531,75	2785,43	4060,52	47,22	53,94	1766,33	127,04	5211,76	220,36	3381,01	244,19
		M2	Total expenses	4015,70	4269,72	11125,46	3176,48	2517,98	10106,68	4943,95	5688,38	3156,42	4551,78	7501,24	6573,86	4244,05	5867,72	6942,45	2453,85	8124,86	11793,50	
			M2.1	Purchase of medicines, medical materials	0	0	0	0	0	0	0	0	0	3552,45	0	0	0	2655,28	0	1400	3314,17	
			M2.2	Salaries, social security, taxes, personnel payments, bonuses	2881,53	2597,82	2071,17	2419,82	2060,05	5963,85	3995,08	2305,05	2814,54	2851,98	2337,33	2087,52	3325,13	2160,45	2399,37	1194,12	4183,47	3734,46
			M2.3	Transport expenses (travel, maintenance, fuel, purchases)	218,4	38,5	431,44	62,16	98,56	494,31	793,8	42,7	142,81	229,32	199,00	778,96	503,39	100,8	166,	331,66	929,48	279,3
			M2.4	Fuel and motor oil	0	0	0	0	0	0	59,5	21,7	0	41,72	24,5	44,24	0	0	95,9	204,4	0	65,1
			M2.5	Office supplies	19,6	0	420,84	21	0	3,08	0	3,78	3,08	0	1,55	563,64	0	0	0,84	382,69	0	28,98
			M2.6	Maintenance of infrastructure and cleaning	420	420	450,8	63	257,04	261,42	1,54	4,76	99,19	248,5	338,87	12,6	281,82	42,49	264,6	3,15	491,61	555,52
			M2.7	Maintenance of medical equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			M2.8	Maintenance of non-medical equipment	0	0	0	0	0	0	0	0	0	0	0	427,84	0	0	0	21	0	14
			M2.9	Water and Electricity	60,97	70	63	70	70,35	85,75	71,68	92,4	84	84	112	112	126,7	112	146,02	0	140	5,6
			M2.10	Communication (Internet, Telephone...)	4,06	0,7	91,7	14,7	12,6	12,6	21,56	101,22	3,36	43,4	43,4	938	7	87,92	48,3	43,4	72,8	72,8

	M2.11	Training	358,4	490	3026,1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M2.12	Purchase medical equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M2.13	Purchase non-medical equipment	0	0	0	0	0	0	0	0	67,2	0	0	0	0	355,74	0	0	33,6
	M2.14	Other expenses	52,73	652,71	4570,4092	525,81	19,38	3285,68	0,79	3116,76	9,44	985,66	892,13	1609,05	0	3364,06	810,39	273,43	907,51
M3		Balance of revenues and expenses (J1-J2)	6939,35	-2706,93	-1738,9708	-1092,29	9635,09	-8201,10	4185,97	2005,87	-162,90	748,66	-58,91	-4053,50	-1979,67	1805,20	1789,69	1105,80	2960,66

APPENDIX G

Table G-1 Electricity consumption indicators for Gikomero health facility (Cordaid, 2015)

			jan-14	feb-14	mrt-14	apr-14	mei-14	jun-14	jul-14	aug-14	sep-14	okt-14	nov-14	dec-14	jan-15	feb-15	mrt-15	apr-15	mei-15	jun-15
Electricity N from the grid	M2.4	Fuel and motor oil (\$)	-	-	-	-	-	-	59,50	21,70	-	41,72	24,50	44,24	-	-	95,90	204,40	-	65,10
	M2.4.1	Local fuel price ¹ (\$/L)	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
	M2.4.2	Energy content (kWh/L)	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
	M2.4.3	Efficiency (%)	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
	M2.4.4	Generator electricity consumption ² (kWh)	0,00	0,00	0,00	0,00	0,00	0,00	232,42	84,77	0,00	162,97	95,70	172,81	0,00	0,00	374,61	798,44	0,00	254,30
	N1	Electricity expenses ³ (\$)	60,97	70,00	63,00	70,00	70,35	85,75	71,68	92,40	84,00	84,00	112,00	112,00	126,70	112,00	146,02	-	140,00	5,60
	N2	Unit cost/kWh ⁴	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22
	N3	kWh	275,41	316,20	284,58	316,20	317,78	387,34	323,79	417,38	379,44	379,44	505,92	505,92	569,16	505,92	654,53	-	632,40	-
Total O electricity consumption	O1	Generator + Grid ⁵ (kWh)	275,41	316,20	284,58	316,20	317,78	387,34	556,21	502,15	379,44	542,41	601,62	678,73	569,16	505,92	1.029,14	798,44	632,40	254,30

¹The local price of diesel (L) is subject to variation. The stated value is provided by HDP (2015)

²This indicator can be obtained using the following equation: (M2.4/M2.4.1) x M2.4.2 x M2.4.3

³The electricity expenses from the grid are related to indicator on water and electricity

⁴The local cost per kWh is subject of variation. The stated value is provided by GLE (2015)

⁵This indicator can be obtained using the following equation: M2.4.4 + N3

APPENDIX H

Figure H-1 Electrical summary for BAU scenario (Model HOMER for Gikomero HF, 2015)

Quantity	Value	Units
Excess electricity	4928	kWh/yr
Unmet load	0	kWh/yr
Capacity shortage	0	kWh/yr
Renewable fraction	0	

Component	Production(kWh/yr)	Fraction (%)
Generator	6,200	61
Grid Purchases	3,904	39
Total	10,104	100

Load	Consumption(kWh/yr)	Fraction (%)
AC primary load	5,174	100
DC primary load	0	0
Grid Sales	3	0
Total	5,177	100