Sveriges lantbruksuniversitet
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Institutionen för energi och teknik

Designing a sustainable and cost-efficient energy system

– A feasibility study at Rusape General Hospital in Zimbabwe

Utformning av ett hållbart och kostnadseffektivt energisystem

– En genomförbarhets studie vid Rusape General Hospital i Zimbabwe

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Abstract

Zimbabwe suffers from power outages due to reduced electricity generation from the two main energy sources coal- and hydropower. Even though the electricity supply to the hospital are highly prioritized during these blackouts, the electricity is not enough to power them all. The country has faced problems with lack of fossil fuel availability and high fuel prices. This report focuses on Rusape General Hospital in the Makoni district which is grid-connected and has diesel generators as a backup system.

The aim of this project was to perform a feasibility study and examine how a sustainable energy system at the hospital would look like to reduce the power outages. A system which would be driven by solar power and uses batteries as a backup system was investigated. It was a comparison between the current system and two potential future systems with renewable energy. One of the most critical areas is the maternity ward including an operating room, which is highly prioritized among the departments at the hospital. The project examined how the energy system would look like whether the energy production covered the entire hospital or only the maternity ward.

The information needed for the project was collected during a study visit of eight weeks at the hospital through interviews and a questionnaire formula. This was in a collaboration with Family Action for Community Empowerment in Zimbabwe and Engineers Without Borders. To analyse the different systems a software called HOMER Pro was used for the simulations. It gives the most cost-efficient energy production for a given system.

Through simulations, the most cost-efficient solution for the entire hospital was a system with photovoltaic (PV) panels, Lithium-Ion batteries and the existing diesel generators, called System 1 in this paper. It resulted in an energy production of 131 112 kWh annually from the PV panels alone and required an installed capacity of 81.1 kW. The suggested system for the maternity ward is called System 2, with PV panels and Lithium-Ion batteries. The energy production from PV panels was in this case 7 102 kWh annually and corresponded to an installed capacity of 4.43 kW.

The challenges for these two suggested systems would be the lack of installers in the country, how the global warming will affect the temperature sensitive components in the future, the high investment costs and the variations of the electric load at the hospital.

Sammanfattning

I Zimbabwe sker elavbrott till följd av otillräcklig elproduktion från de primära energikällorna kol- och vattenkraft. Trots att elförsörjning till sjukhusverksamheter prioriteras under dessa strömavbrott räcker inte den producerade elen till. Landet har haft svårigheter som följd av bristen på fossila bränslen tillsammans med höga bränslekostnader. Den här rapporten har fokuserat på Rusape General Hospital, ett sjukhus som är belägen i Makonidistriktet och ansluten till landets elnät. Den studerade byggnaden har även dieselgeneratorer som ett stödsystem.

Syftet med projektet var att utföra en genomförbarhetsstudie samt undersöka hur ett hållbart energisystem på ett sjukhus skulle kunna se ut för att reducera de återkommande elavbrotten. En jämförelse gjordes mellan det nuvarande systemet och två simulerade framtida system med förnybar energi. En av de mest kritiska områdena identifierades som förlossningsavdelningen, där finns också en operationssal innehållandes många energikrävande apparater och instrument. Projektet undersökte hur energisystemet skulle se ut beroende på om energiproduktionen täckte hela sjukhuset eller endast förlossningsavdelningen.

Informationen som behövdes för projektet samlades under studietiden på åtta veckor vid sjukhuset genom intervjuer och ett frågeställningsformulär. Det utfördes i samarbete med organisationerna Family Action for Community Empowerment in Zimbabwe and Ingenjörer utan gränser Sverige. För att analysera de olika systemen användes programmet HOMER Pro som ger användaren den mest kostnadseffektiva energiproduktionen för ett givet system.

Simularingarna visade att den mest kostnadseffektiva lösningen för hela sjukhuset var ett system med solpaneler, Litiumjonbatterier samt de befintliga dieselgeneratorerna och kallas i för System 1 i det här projektet. Det resulterade i att solpanelerna ensamma levererade en energiproduktion på 131 112 kWh årligen och att en installerad effekt på 81.1 kW krävdes. Det föreslagna systemet för förlossningsavdelningen kallas för System 2 och innehåller solpaneler samt Litiumjonbatterier. Där stod solpanelerna för en årlig energiproduktion på 7 102 kWh vilket motsvarade att en installerad effekt på 4.43 kW krävdes.

Utmaningarna med de två föreslagna systemen skulle kunna vara bristen på solelsinstallatörer i landet, hur den globala uppvärmingen i framtiden kan komma att påverka de temperaturkänsliga komponenterna, de höga investeringskostnaderna samt variationerna i den elektriska belastningen på sjukhuset.

Acknowledgements

This field study was financed by the assistance authority SIDA and was made as a collaboration with the Swedish and Zimbabwean organizations Engineers Without Borders (EWB) and Family Action for Community Empowerment in Zimbabwe (FACE Zimbabwe). The project is a part of the Renewable Energy Program (REP) established by EWB.

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Finally, we would like to thank our supervisor Mr. Ershad Ullah Khan at the Swedish University of Agricultural Sciences for great advice regarding the structure and writing of this report.

Thank you!

Abbreviations and definitions

AC - Alternating current

COE - Cost of Energy

DC - Direct current

DG - Diesel generator

Entire hospital - Main building and maternity ward

Electric energy - Energy delivered by power plants, power lines and renewable energy sources consumed in hospital appliances, such as direct-acting electric heating and lighting systems

EWB - Engineers Without Borders

FACE Zimbabwe - Family Action for Community Empowerment in Zimbabwe

I - Current [A]

LA - Lead Acid

Li-Ion - Lithium-Ion

MEPD - Ministry of Energy and Power Development

NPC - Net Present Cost

NPV - Net Present Value

NREL - National Renewable Energy Laboratory

O.R. - Operating room

P - Power [W]

PV - Photovoltaic

Q - Reactive power [VAr]

REP - Renewable Energy Program

RETs - Renewable energy technologies

S - Apparent power [VA]

SDGs - Sustainable Development Goals

SDS - Sustainable Development Scenario

UN - United Nations

UNDP - United Nations Development Programme

U - Voltage [V]

ZESA - Zimbabwe Electricity Supply Authority

ZETDC - Zimbabwe Electricity Transmission and Distribution Company

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1 Introduction

Climate change has many effects on the planet and the environment, and it has been observed for plenty of years. Scientists announce that the global temperature will proceed to rise for upcoming decades as well as the sea level (NASA Global Climate Change 2019). The predicted climate changes have started to happen, such as longer and more intense drought, heat waves and stronger hurricanes (ibid.). Zimbabwe has been facing electricity problems the last decades which have been characterized by countless of power outages on daily basis (Makonese 2016). This is one of the consequences from drought, poorly functioning hydropower and hyperinflation (Dzirutwe 2019).

The electricity and internet access are often taken for granted for residents in developed countries. In order to meet such needs a reliable grid is required. In Zimbabwe, there are 16.6 million inhabitants of which 38% have access to electricity whilst in the rural areas only 16% have access (The World Bank 2016; Nationalencyklopedin 2017). The industrial and the housing sector of Zimbabwe are both depending on a carbon intensive model and hydropower to provide electricity to the grid, where burning coal is one of the largest energy sources in Zimbabwe (Makonese 2016).

Government buildings, such as health facilities, are higher prioritized when it comes to electricity accessibility. A functional energy supply is crucial in order to obtain a safe working place, not only for the patients but also for the employees. Rusape General Hospital uses its electricity for medical equipment, medicine storage, lighting, sterilization machines and computers. It is strongly affected by power outages and at the wrong time it can cause death. The potential of solar power is strong in Zimbabwe and photovoltaic (PV) systems have a technical potential of more than 300 MW (GET.invest 2014). Thereby it is important to develop and take advantage of the electricity generation from renewable energy like solar power.

1.1 Background

1.1.1 Pilot project

The organisation Engineers Without Borders (EWB) has started a pilot project at the hospital in Rusape as a part of the Renewable Energy Program (REP) where they will install 8 quantities of 325W and 24V PV panels for the maternity ward together with four batteries with 12V each. For more details see Appendix, Table A.8. REP's goals are to cut diesel reliance, strengthen self-sufficiency and improve healthcare. Such a system, that could provide the buildings with renewable energy, will help to improve hospital care standards. For example, children under five years of mortality amount to about 7% (UNICEF 2016). The PV panels, from SunTech, offers an efficiency up to 17.5% (Solar Market 2019). This will result in 2.6 kW installed solar energy on the roof. By using the economical assessment from their quotation, a price per installed kW can be calculated for a potential installation of PV panels for the entire hospital. The planned energy system will consist of PV panels from SunTech, batteries from Deka 210Ah and a converter from Growat. More technical specifications can be found in Table A.8. Table 1 shows the total cost, including VAT (value-added tax). These can be used to get an approximation of what a future system will cost for the entire hospital. See calculations in Appendix, Table A.9.

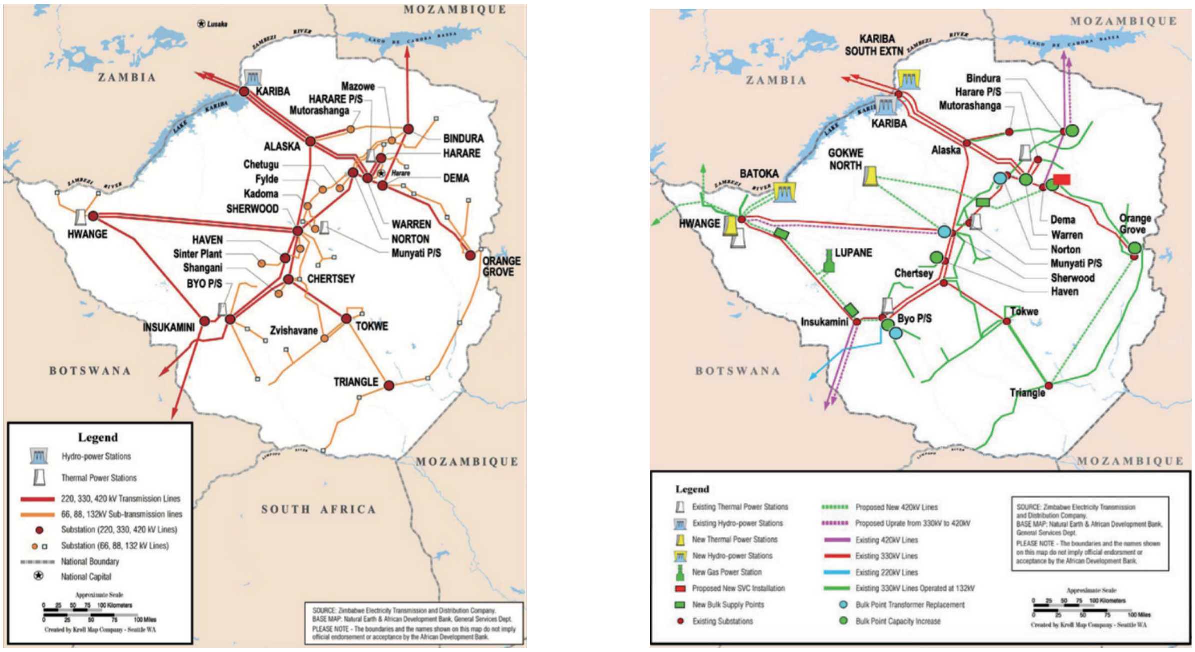
Table 1: Quotation per installed capacity

PV panel system	Battery system
1.334 $/W	0.498 $/Wh

1.1.2 Electricity

The country's electricity sector is dominated by the state owned company Zimbabwe Electricity Supply Authority (ZESA) Holdings (Makonese 2016). The state-owned enterprise ZESA Holdings owns and operates the entire national transmission system but due to increasing energy consumption, the company have faced challenges to produce enough electricity to meet that demand (ibid.). It is believed that the shortages were caused due to growing urbanisation and lack of investments (ibid.). The electricity demand expects to increase within the next few years since the country have started to renew all the economy sectors (ibid.). Statics showed that the country consumed more energy than they produced (U.S. Energy Information Administration 2016).

Zimbabwe Electricity Transmission and Distribution Company (ZETDC) is a subsidiary of ZESA Holdings, and answer for the development, operation and maintenance of both the transmission and distribution network. ZETDC plans to upgrade the existing transmission and sub-transmission networks during a ten-year period, starting from 2010. The existing transmission power grid is shown in Figure 1a). The upgrade will strengthen and extend the existing transmission lines of Zimbabwe which can be seen in Figure 1b). Furthermore, the transmission system consists of 420kV, 330kV, 220kV, 132kV, 88kV and 66kV lines and substations with a total length of a little more than 7 000 km. (African Development Bank Group 2011; ZESA Holding 2013)



a) Existing power grid (African Development Bank Group 2011)

b) Existing and suggested extension of power grid (African Development Bank Group 2011)

Figure 1: Overview of the existing power grid a) and the existing and potential extension of the power grid b) in Zimbabwe

1.1.3 Power generation from PV panels

In 2018 the total power generation from PV panels was more than 570 TWh worldwide. It increased by 31% compared to the previous year which makes the solar PV stands for 2% of the global electricity generation. The power generation level in 2030, set by the Sustainable Development Scenario (SDS), will be reached if the annual growth of solar PV generation is 16%. Figure 2 shows the development of power generation from solar PV and how it will exponentially increase in the future, according to SDS. (International Energy Agency 2019)

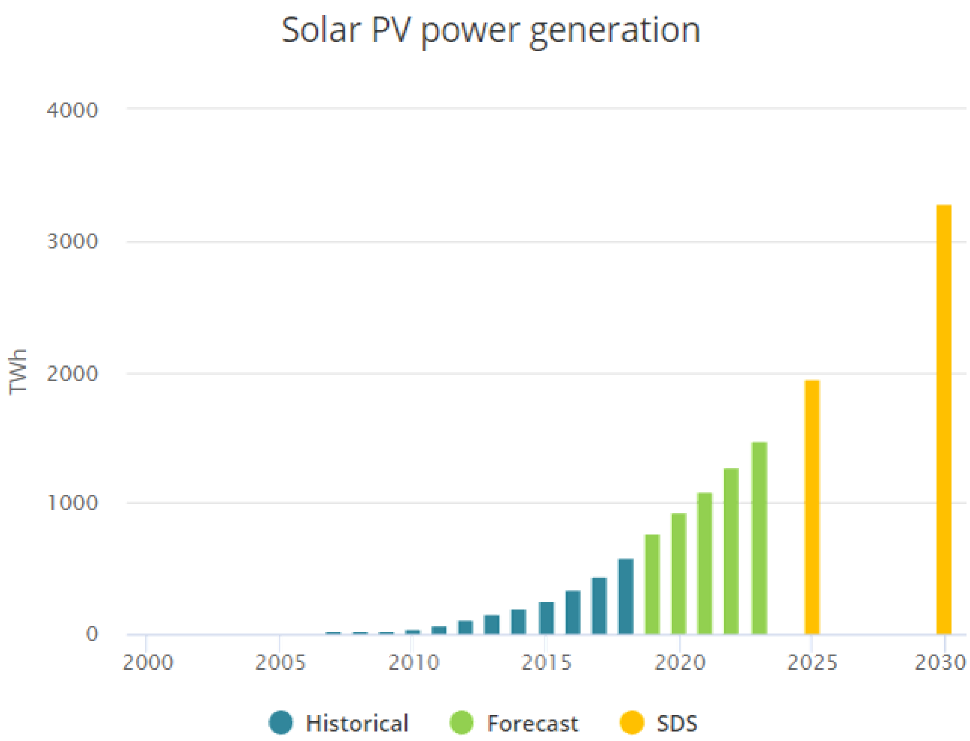


Figure 2: Solar PV power generation, historical and potential

1.1.4 Energy sources

In the southern Africa, Zimbabwe have one of the greatest potential to utilize renewable energy in forms if hydro, solar, geothermal, wind and biomass (Makonese 2016). Approximately 43% of the electricity supply in Zimbabwe is based on coal power whilst about 57% of the supply is generated by hydropower (ibid.). The country have potential to generate electricity production from hydro, solar and biomass power as resources (GET.invest 2014). Only a small part of Zimbabwe's hydropower potential have been utilized and the solar and biomass resources are so far relatively untapped (ibid.). Energy provided from wind power is believed to have a low potential compared to neighboring countries since the wind speed is considered too low (ibid.).

Hydropower The electric power, utilized from hydropower, is produced from the Kariba dam located in the Zambezi river basin. The southern Kariba hydropower station generates electricity to Zimbabwe and has a theoretical capacity of 750 MW. The reliance on the availability of water was a drawback. Due to the dependency of such systems, the grid becomes vulnerable if the hydro station would face challenges such as drought. To retain the water in the dam the Zimbabwe Power Company (ZPC) must decrease the capacity of the hydropower plant. (Makonese 2016)

A consequence of poorly rainfall and drought, the water level have decreased which causes less electricity production and thus the energy production have to be scaled down. Hence the Kariba dam has an annual effect of 542 MW. To minimize the risk of running out of electricity a daily power cut of 10-hour has been implemented in Zimbabwe. The lack of power forces Zimbabweans to pay high cost living since they must use other alternatives in order to access power. (Thompson 2019)

Coal power There is a big amount of coal resources in the Hwange district, where the Hwange power station can is located. Due to economic restraints the state-owned company, Hwange colliery company, has failed to increase the coal production. Despite that the power station have an installed capacity that reaches around 900 MW it only produces less than 250 MW. The power generation of Zimbabwe is about half of the country's peak demand which forces industries to rely on diesel generators to meet their energy needs. In the end of 2015, China agreed to provide Zimbabwe with a 1.2 billion loan in order to add more power of generating capacity to the station in Hwange. To meet the increasing demand, the government decided to ban any use of electric geysers in residential and commercial sectors. (Makonese 2016)

Since May this year, the country suffered from 18-hour daily power outages as a result of drought and aging coal power stations. According to the finance minister these were the consequences from the shrinking economy in Zimbabwe. The lack of electricity generation from coal and hydropower forces the nation to import more electricity and rely on foreign power companies. The electricity often got imported from power companies in South Africa and they can also struggle to meet South Africa's energy demand. Furthermore, Zimbabwe already has debts to these companies and foreign currency is required which already is in short supply. (Dzirutwe and Fenton 2019)

1.1.5 Solar home systems in Zimbabwe

In rural areas and parts of the new suburbs there were almost no access to electricity. Regions within the range of accessing electricity supply were constantly affected by the failing grid. Enterprises and individuals who can afford uses fuelled generators or other power supplies in order to avoid blackouts. There were a few who have started using solar PV systems as a backup or as primary energy source. (Chahuruvaa and Dei 2017)

The Ministry of Energy and Power Development (MEPD) is committed to develop renewable energy technologies (RETs) in Zimbabwe. In a collaboration with universities and technical colleges they research RETs and efficiencies within the energy sector to be in line with the government's vision for 2030. It is about providing all citizens and households, wherever they were located, with sustainable energy solutions. However, RETs have high initial capital costs. Usually, rural households do not invest in expensive technologies especially when cheaper alternatives for cooking were available as firewood and can be collected in a nearby forest. (Makonese 2016)

1.2 Purpose and constraints

The purpose of the study was to examine the electricity needs and demands of the maternity ward, which is a department of Rusape General Hospital whilst analysing the challenges and benefits of such a solution. Furthermore, a feasibility study was made in order to investigate if installing a PV system would be economical- and energy efficient. Simulations of the entire hospital was also performed in order to see what the requirements would be if such a system was driven by solar power and had batteries as a backup system. The idea is to contribute to the transitional development conversation regarding the energy sector in Zimbabwe, to see how solar energy can help lower financial strain for healthcare facilities and in turn improve the quality of health care and a working satisfactory in Zimbabwe. In order to complete the installation of solar cells it must be financially sustainable and that is why there will be a financial aspect to the study. It will be a simple cost and benefit analysis of the system, outlining the 'financial break-even point' following on from the system capital investment.

This paper will also contribute as a guideline to future energy systems of similar kind as well as minimize the risk of power outages during surgeries and to spread knowledge about solar energy and its many advantages. Hopefully, in the long run, renewable energy will be better exploit in the country and the dependence of imported electricity from other countries will decrease. This can also lead to lower debts and stronger economy.

1.2.1 Problem formulation

- What type of electric energy system is the most cost-efficient solution?
- How much installed capacity is needed from PV panels and batteries to have a sustainable electricity supply at the hospital?
- How much electricity can be generated from PV panels alone?
- What would the challenges be?
- Does the optimized electric energy system differ when examine the maternity ward versus the entire hospital?

1.2.2 Guidelines for the Sustainable Development Goals

The United Nations (UN) has developed a cooperation between 170 countries around the world called United Nations Development Programme (UNDP), where Sweden is included. The guidelines for the Sustainable Development Goals (SDGs) of UN exist in order to fulfil four important achievements by 2030. The achievements are to extinct extreme poverty, reduce inequality and to promote sustainable and peaceful communities. To achieve these, there are 17 sustainable goals with many subcategories. (UN 2015)

This project cannot contribute to all of the goals but nevertheless it aims to further the following goals:

3. Good health and well-being
- Ensure healthy lives and promote well-being for all at all ages.
- More reliable electricity through PV panels and batteries leads to fewer power outages and better healthcare conditions.

7. Affordable and clean energy
- Ensure access to affordable, reliable, sustainable and modern energy for all.
- Reduced dependence on fossil fuels and more renewable energy leads to sustainable energy.

12. Responsible consumption and production
- Ensure sustainable consumption and production patterns.
- Due to PV panels the production will be sustainable.

13. Climate action
- Take urgent action to combat climate change and its impacts.
- Climate action is taken by increasing the use of renewable energy while reducing fossil dependence.

17. Partnerships for the goals
- Strengthens the means of implementation and revitalize the global partnership for sustainable development.
- Through the partnership between Family Action for Community Empowerment in Zimbabwe (FACE Zimbabwe) and EWB, the relationship between the countries can be improved and increase the possibility of future collaborations.

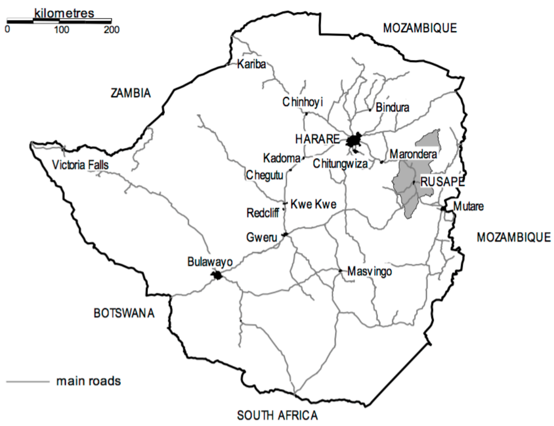
(UN 2018)

1.2.3 Constraints

In order to determine the electric energy consumption of the hospital, only the most critical areas where examined by evaluating the electronics of each room and department. To constrain this thesis only the electric energy is considered. For example, energy for hot water is excluded. Thereby when talking about the energy system in this report, it covers both the grid and all the instruments, machines and lamps which consume electricity within the critical areas at the hospital. It follows from that there is no access to instruments that could measure the actual current and voltage for each device. The critical areas correspond to departments such as maternity ward, children's ward, operating room (O.R.), X-ray room and kitchen where the access to electricity is crucial. These are also the departments which are prioritized when the diesel generator operates during a power outage.

1.3 Rusape General Hospital

The feasibility study was performed at Rusape General Hospital which is located in the Makoni district, Manicaland Province. The hospital is the largest in the Makoni district, as shown in Figure 3a), and is coordinated at 18° south and 32° east (GeoDatos 2019). As seen in Figure 3b) the building is also located along the main road between Mutare and the capital city Harare. The maternity ward is a part of the hospital and provides healthcare for new-borns, mothers and children who are HIV positive and also education support was held to prevent the disease (Engineers Without Borders Sweden n.d.). Power outages occurred almost on daily basis due to the unreliable power grid and thus exposed the patients to life-threatening danger. The backup diesel generators, whose main purpose was to cover the energy demand during power outages, lead to high fuel costs. Another challenge was that the generators do not always work at all which have left the hospital without electricity [1]. In order to afford the fuel, funds that could finance vital vaccines or other medicine related equipment must be used instead (ibid.).



a) Makoni district marked in grey (Andersson Djurfeldt 2002)

b) Location of Rusape General Hospital (Google Maps 2019)

Figure 3: Map showing a) the Makoni district and b) the location of Rusape General Hospital

1.3.1 Identified departments and area

Rusape General Hospital in Zimbabwe consists of two buildings, as seen in Figure 4. Furthermore, the main building holds all different departments except the maternity ward and is marked with a white circle down below. The maternity ward is the biggest department and focuses on women and childcare and is marked with a red circle.

The identified departments are the maternity ward, which was located in a separated from the main building, the children's ward, the X-ray department, the kitchen and the O.R. Figure 5 shows the maternity ward from the outside. Apart from the aforementioned departments there were also two operating rooms, the biggest was located at the maternity ward and the smaller was in the main building. Currently the hospital is provided with electricity from the grid and uses diesel generators during power outages.

[1] L. Nyafesa, District medical officer, Rusape General Hospital, meeting 2019-03-25

Figure 4: Map of the main building (white circle) and maternity ward (red circle) from above (Google Maps 2019)

Figure 5: Maternity ward seen from the east

1.3.2 Roof properties

After visiting Rusape General Hospital, it was found that the existing roof of the buildings consists of sheet metal as shown in the picture below. The tensile and yield strength of sheet metal increases with the thickness of the sheet (Goijaerts, A M. et.al 2001). The thickness of the roofs was difficult to determine when neither ladder nor measurement tools were available. The panel slope will have the same tilt as the roof, which was 22° according to EWB.

A metal roof could be a challenge for an installer who was used to comp shingle or tile roofs (Pickerel 2018). Metal roof can both differ in type of metal and roofing system. Depending on the roofing system, the installation difficulty can vary (ibid.). For instance a solar installation is easier if the ceiling has a structure of a standing seam rather than trapezoidal or corrugated metal roofs since they often requires an attachment direct to the roof as can be seen in Figure 6 (ibid.).

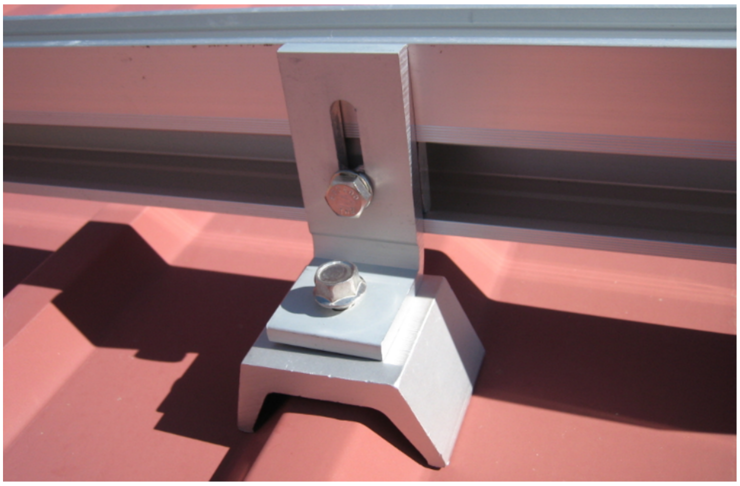


Figure 6: Example of mounting system on sinusoidal, corrugated and trapezoidal metal roofs (Pickerel 2018)

1.3.3 Current energy system

Currently Rusape General Hospital consists of two buildings where the maternity ward department is separate from the main building as seen in Figure 7. The electricity supply primarily comes from the 11kV grid which is based on hydro- and coal power (Makonese 2016). When the power grid was shut down and no electricity could be generated to the hospital the diesel generators were operating in order to generate electricity to the most critical areas where electricity supply is crucial for the lives of the patients. A simplified schematic model of the current energy system can be seen in Figure 7.

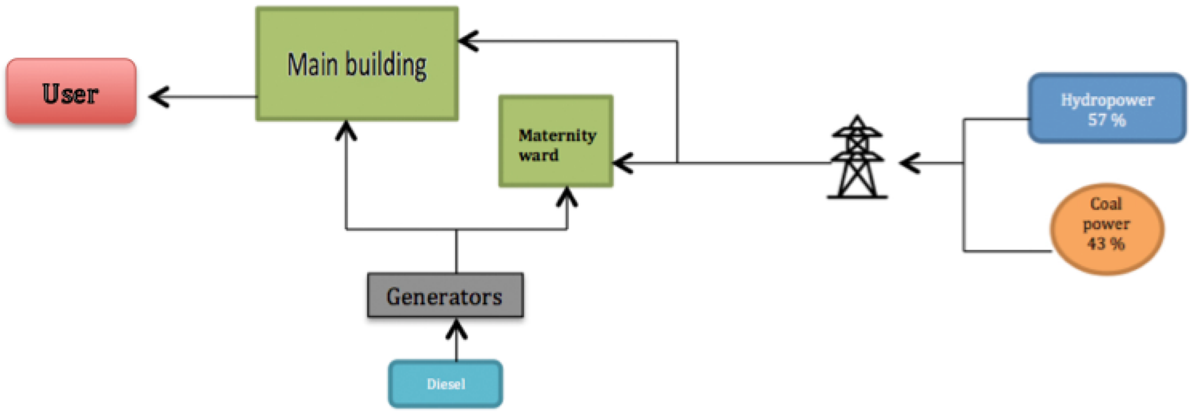


Figure 7: Current energy system

1.3.4 Climate

Zimbabwe is located southeast of Africa and have a various climate, where the north is sub-equatorial and the south is tropical. The rain season is from the middle of October to April whilst June and July are the coldest months (Seasons of the Year 2019). The high mountains of Zimbabwe create great altitude differences that make the climate subtropical and sunny (Nationalencyklopedin 2017). These are good conditions for developing production of solar power.

1.3.5 Energy consumption

An extract obtained from ZESA's office[2] showed the hospital's energy consumption, bought from ZESA, during 2018 and is shown in Figure 8 and Table 2. The numbers that were given indicates approximately 60% of the energy consumption was during the nights while the remaining 40% was needed during the day. The diagram in Figure 8 shows that the energy demand is at its highest during April and August with an energy demand of 357.4 MWh annually which corresponds to almost 52 700 $. This excludes the electricity produced by the diesel generators.

[2] ZESA, Rusape, meeting 2019-03-28

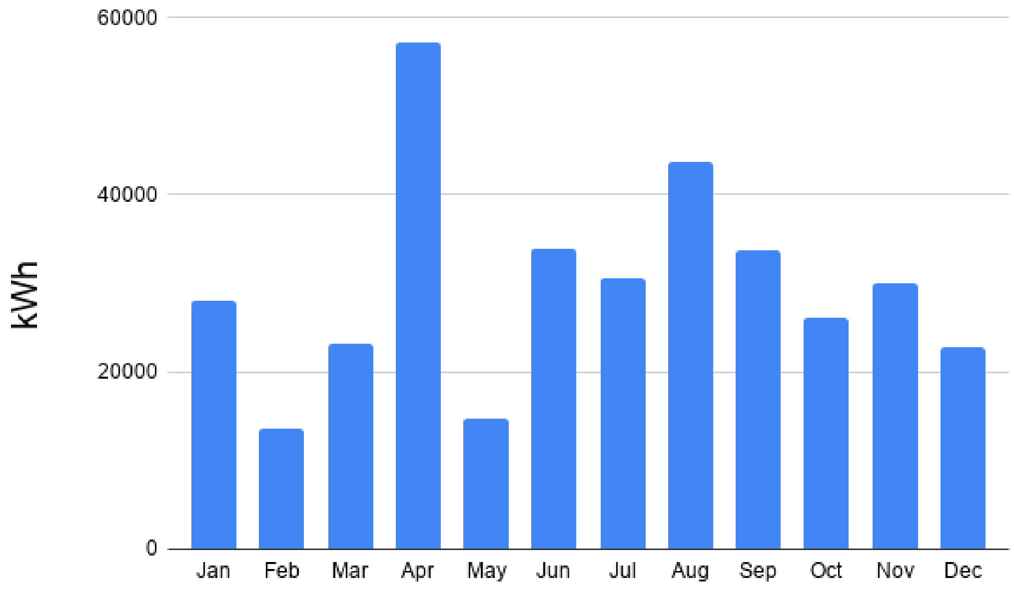


Figure 8: Monthly energy consumption 2018 at the Rusape General Hospital from ZESA

Table 2: Energy consumption during 2018 from ZESA

Time period	Energy consumption [kWh]	Cost [$]
Monthly average	28 339	4 555
Total for 2018	357 388	52 670
Day | Night	4 700 | 7 051	1 645

2 Methods

Before departure to the hospital in Zimbabwe a literature study was made in order to obtain knowledge and facts about solar-powered systems as well as similar activities. When studying the hospital itself, a feasibility study was performed since the system was complex and contained several different elements. To be able to determine the energy consumption and carrying out load analyses parameters, as much data as possible was collected. Parameters such as lighting and number of electricity consuming devices were examined and observed. Also, the interviews with the employees were made to understand the current energy situation and their opinions of how to improve the existing system, safety of the patients and how to achieve a satisfying working environment. During the study visits at the hospital, the goal was to collect as many viewpoints and parameters as possible in order to create a solid ground to further analysis of the material. Also, integrating with the locals was of great importance in order to further the cultural understanding and the perspective towards solar energy.

The simulation program HOMER Pro and the National Renewable Energy Laboratory (NREL) were used to calculate the collected data. HOMER Pro presented the most cost-efficient energy production and found an optimized system dependent on the selected constrains whilst NREL showed values of solar radiation throughout a certain time frame. The correct areas and sizes for the hospital were not available. To examine the roof area an approximation was made by using Google's measure tool called Google Maps Area Calculator.

2.1 Literature survey

The conducted literature study was based on news, scientific articles, lectures and earlier studies that were in line with this subject. It was important to be critical to the source to determine whether it was true and false and to determine the author's intentions (Lunds Universitet 2019). Therefore, the sources of the literature were critically reviewed to determine its credibility and purpose as well as the year of publication since technology, guidelines and laws can be developed and renewed. The information that was considered relevant and reliable was carefully analysed before it was processed in order to create an understanding for both the authors and the readers.

Technical information such as the information about batteries, diesel generators, power production and PV system were based on lectures from the courses Batteries and Storage, Solar Energy respectively Power Engineering from Uppsala university and the software HOMER Pro. EWB has also shared information such as quotation for the pilot project at the hospital in Zimbabwe. To obtain knowledge and understanding for these areas combined, literature studies have been made on similar projects and articles.

2.2 Field visit

Valuable information was collected in order to understand the hospital's current system. The people at the organization Family Action for Community Empowerment in Zimbabwe (FACE Zimbabwe), which is a partner organization with EWB, made it possible to contact electricians, employees, managers and authorities in order to answer questions throughout the project. Information of significance to the project was obtained through meetings and practical analyses together with the hospital's operating technician. As mentioned, some of the information was sensitive and thus confidential, which could usually be solved by going directly to the area's principal. Such information could be facts that were considered to risk the hospital's reputation and the safety of the patients.

2.3 Questionnaire

A questionnaire was made to examine the hospital staff's knowledge and perspectives on renewable energy. It was also designed to see which departments, according to the staff, have the highest energy demand and thus would primarily need energy from a PV system. This was important to know since it copes with UN's SDGs, especially *Good health and well-being.*

Seventeen randomly selected employees answered questions about renewable energy and some personal information such as age, profession and education etc. Every participant answered anonymously. See all questions in Appendix, Table A.3. In addition, a response form was issued to the hospital where employees were asked to note when a power failure occurred. This was done over a week to identify how often the power outages occurred.

2.4 Techno-economic assessment

2.4.1 HOMER Pro

The simulation results were from the software HOMER Pro. The simulations were divided into two systems, one before adjustments and one after adjustments. The one before adjustments simulated the hospital at its present, without renewable energy and the simulation after adjustments simulated the hospital with different combinations of energy system solutions. Both systems were adopted in the simulations to be connected to the grid since it reflected the real situation. The location was set to the exact coordinates for Rusape General Hospital in order to import correct data such as solar irradiance. By writing *Rusape General Hospital* as the location of object, HOMER Pro could found the coordinates for the hospital.

Converter A converter is needed whenever there are components in the system that use alternating current (AC) or direct current (DC). For example, solar cells and batteries use DC while the grid and the generators use AC. The converter used in the simulations was a generic converter taken from HOMER Pro's catalogue called *System converter*. The parameters were constant except *Capacity Optimization* where an optimizer called *HOMER Optimizer* was selected. Also the box called *Parallel with AC generator* was ticked. After the changes, the *Rectifier Input* should still have a *Relative Capacity [%]* set to 100% and an *Efficiency [%]* at 95%. Furthermore, the *Inverter Input* had its *Lifetime [years]* set to 15 years and its *Efficiency (%)* set to 95%.

Diesel generators The current system is connected to the grid and it has diesel generators as a backup system. To make sure the generator only operated during power outages the diesel fuel price can be set to a high value, then it was expensive to use the generator and the grid will be used as much as possible. The costs can be amended after the simulations. The fuel price in Zimbabwe was already at a high value, 3.3 $/litre, and it does not have to be amended for the simulations to work properly. The value of the fuel price was from observations during the stay in Rusape which was between February and April in 2019.

There were two existing generators at the hospital of different brands and various volume capacities and they never operated at the same time. The one with the highest volume capacity was not running due to the high diesel prices that made it too expensive to use. Since the smaller generator was mostly used, the bigger generator was not included in the simulations. From a catalogue in HOMER Pro a generator called *Generic Small Genset (size-your-own)* was used as a base and represented the operating generator of the brand Volvo. The power size was at first set to 50 kW, but this value was changed to 40 kW to match the actual size of the generator. Also the *Reference generator capacity* was changed to 40 kW because that was the largest capacity. At *Fuel resource* the selected fuel was *Diesel*. The lack of information about the generator specifications resulted in default values being used for the remaining parameters set by HOMER Pro, such as fuel curve and emissions. The generator will only operate during power outages and therefore an operating mode for the generator called *Optimized* was selected.

Power outages The hospital is connected to the grid. Unfortunately, the grid cannot provide electricity around the clock. When adding a grid to the system in HOMER Pro the *Scheduled rates* was selected since the access of electricity varied. Under *Parameters*, *Include the grid in all simulations* was chosen. Under *Rate definition* the price for the electricity was set to 0.14 $/kWh which reflects the actual electricity price from ZESA, as can be seen in Table A.6. The sellback was set to zero since the hospital at present do not sell any electricity. The electricity price of O.14 $/kWh/month was also the value for the demand under *Demand rates*. In section *Reliability*, the power outages could be determined. In *Random outages* the parameter *Mean outage frequency (1/yr)* showed how frequent power outages occurred annually. Through interviews it was found that power outages mostly varied between 2-3 times per week which was calculated to approximately 100-150 times per year. The *Mean repair time (h)* described how long the power outage usually lasts and was given in hours. The employees also said that how long a power outage lasted could differ very much. This variation was simulated by adding a value to *Repair time variability (%)*, in this case it was set to 50% with a mean repair time of 2 hours. The section *Emissions* in HOMER Pro used standard values and was based on the diesel fuel.

Electric load The total electric load for the hospital and how it varied during a day was not documented. ZESA had information about how much electricity they had sold to the hospital in 2018 and three months in 2019 but there was lacking information about how many power outages there had been during the year, how much the hospital had used the diesel generator and how many times there had been a total blackout at the hospital. To get an approximation of how much energy demand the hospital has every month the power outages must be monitored. Interviews with the hospital employees gave an approximation of how many times a power outage could occur. To know more precise how much it varied it would be better to monitor the power outages for a couple of weeks and thereby calculate an average value. In Zimbabwe, there was only for one week the power outages got monitored. That was the reason the estimated observation was used for power outages since an average value could not be calculated. The amount of energy produced, and the efficiency differed between different types of generator brands.

In HOMER Pro, the electric load for the entire hospital was formed after a chosen profile called *Community*. The profile represented the hospital's electric load better than the other options since some departments were shut down during the night, for instance the X-ray department. This part was one of the bigger sources of error but without any documented electric loads for a 24-hour time period, it was difficult to approximate an hourly energy demand. Especially since the energy demand was often greater than the energy supply, where the energy supply from the diesel generators was not documented. Through the data from ZESA, the monthly average electric load was scaled to 24 hours and divided according to the electric load scheme for *Community*. The obtained data showed that the bought energy was highest during April, but HOMER only allowed the user to choose between January or June, see Figure 8. Since April was not an alternative in the software, no peak month was chosen. For the maternity ward the electric load was approximated together with EWB and more detailed information from the interviews. Thereafter it was divided into the electric load set up shown in Appendix, Figure 13.

Resources In order to specify the electricity production and weather conditions to the chosen location, resources were added. Under the section *Resources*, the *Solar GHI* was chosen and monthly average solar global horizontal irradiance (GHI) data from the library was imported by choosing *NASA Surface meteorology and Solar Energy database*. The values were monthly averaged over 22 years, between July 1983 and June 2005. Even though this can be seen as a source of error since the values were old, the time period was long and could therefore be reliable. In this section, the *Temperature* could also be chosen. The value were imported the same way as for *Solar GHI* from *NASA Surface meteorology and Solar Energy database*. The data was used when calculating the electricity production from PV panels.

PV system PV panels was added to the system by choosing *Generic flat plate PV* from the catalogue. The parameters within this model were changeable and it was chosen to get a good base. Since one of the purposes of this project was to determine how many cells were needed to provide electricity to the hospital with certain constraints, the sizing of the PV system would be decided by *HOMER Optimizer*. Since the incoming solar energy will give DC in the PV system, the box *DC* was ticked and could be found in *Electrical Bus*. The cost section was changed according to the quotation, see Table A.8. The *Capacity (kW)* was changed to 2.6 kW while *Capital ($)* and *Replacement ($)* was changed to the sum of the solar panel, the frame and the installation cost. The sum of these was 5 408.55$. By entering the part called *Advanced*, parameters like efficiency could be changed and was set to 15%. In this part it was possible to choose the PV panels to have a temperature coefficient and make the efficiency depend on the temperature, by ticking the box *Consider temperature effects?* under *Temperature*. Under *Orientation*, the panel slope was set to 22° and the default azimuth was used to simplify the calculations. When using a default azimuth, the panels will be orientated towards the equator, which is 180° azimuth in the southern hemisphere (HOMER Pro 2019d). The other values stayed the same.

Batteries To replace the diesel generator as a backup system, a more sustainable storage was examined which was batteries. Currently there are two common batteries: a Lithium-Ion (Li-Ion) battery and a Lead-Acid (LA) battery. It was interesting to examine which one of these battery types would suit the hospital through simulations. When choosing the battery type from the catalogue, there were a lot of batteries to choose from. The *Generic 1kWh Lead Acid* was chosen to simulate the LA battery. Thereafter, a battery called *Generic 1kWh Li-Ion* was chosen when simulating the Li-Ion battery. In order to decide what battery gave the better result, the two different backup systems were compared. For the same reason as for the PV panels, the sizing was set to *HOMER Optimizer*. Under *Site Specific Input* the string size was changed to 4 and led to a voltage of 48 V for the LA battery. This is a normal voltage value for a battery.

2.4.2 Load assessment

Through observations performed on the maternity ward the main energy consuming units could be identified and thus a load assessment was done. The studied objectives were machines at the hospital such as anaesthesia machine, lighting and incubators. The electric properties of each unit were taken to consideration in order to determine the total energy demand of the department. The properties of the electrical units refer to how much power was needed in order for the device to operate properly. On e.g. lamps and other equipment where such information was unknown an estimation was made based on similar products.

2.4.3 Cost analysis

When investing in a PV system with batteries as backup for private use, there are three important components: PV panels, batteries and converters. A converter was needed to change the current between AC and DC. For a micro grid like the hospital there was probably no need for so many converters since the solar system was quite small. To determine the installation cost for a future project a quotation from the pilot project was used, see Table A.8. From the quotation the cost per installed Watt for solar energy was calculated by including the actual PV panel, PV panel frame, installation of material and protection accessories. The cost for the frame per installed Watt does not always increase linearly but to simplify the calculations it varied with a constant value. For the battery, the cost per nominal capacity included the battery and the labour. The installation of material and protection accessories costs were mainly associated with PV panels because the installation of PV panels on the roof are a more complicated method than the installation of the battery system. Since labour was needed in the installation of the batteries the cost for it was included in that category and to simplify the calculations it was not included in the PV panel system, since it already had a cost for the installation. Other costs like insurance were not included in the price. The calculations can be found in Appendix, Table A.9.

In the software HOMER Pro, there are four costs presented in the results and analysed in the discussion: NPC, COE, operating cost and initial capital. The total net present cost (NPC) of a system is the present value of all the costs that the system incurs over its lifetime, minus the present value of all revenue that it earns over the project lifetime. The levelized cost of energy (COE) is defined as the average cost per kWh of useful electrical energy produced by the system. The operating cost is the annualized value of the total NPC, minus the annualized capital cost. The initial capital is the total installed cost of a component at the beginning of the project. The program also used initial capital costs which are the same as investment cost. (HOMER Pro 2019e)

2.5 Criticism of method

There was several limiting factors during the field study that could affect the results. The duration of the field study was within a two-month period which led to a load assessment only was performed on the maternity ward instead of the entire hospital. More time could have made it possible to do more observations and interviews and thus a more accurate result could have been achieved. Lack of tools and information of some areas at the hospital resulted in that estimations had to be made which in turn affects the final outcome. Even though the estimations were based on interviews with the employees, technical investigations and facts, it still caused uncertainties. The monitoring of power outages could also been done during a longer period and more usage of instruments and machines could have been monitored for even more accurate results. Some of the sources could be considered as old, but they were nevertheless chosen with an awareness of that. Some of the old sources that were used contained facts that does not change significantly over time. For example, the definition of power.

In HOMER Pro, there were factors and values which were standardized in the simulation program since there was no information about the real values. What kind of batteries and solar cells were not decided at first, and that was why the capacity and characteristics may differ a bit. Also, the operating generators at the hospital differed in volume size and are in this section addressed as the "smaller generator" and the "bigger generator". The smaller generator which was used the most at the hospital does work automatically compared to the bigger generator. This means that the smaller generator needs to manually get switched on by the electrician. In some occasions the diesel fuel was not available which prevented the generators from working properly. In turn, the lack of fuel led to energy production delays which could not be simulated by the software. That means that HOMER Pro will show better results for the energy system which include the diesel generator than what reflects the real situation.

The hospital's roof was directed in all cardinal points. The simulations in HOMER was simplified by calculating all PV panels as if they were all in the same direction to the north. The entire roof will not be covered with PV panels and in order to maximize the energy uptake from the sun, panels should primarily be mounted on roofs facing north. Another source of error was the shadowing from the surrounding. It was not considered since shading from trees was estimated to not affect solar panels on the studied roofs. No information of future construction projects nearby was available.

3 Technical information

3.1 Definition of power

The power is calculated as the product of voltage (U) and DC whilst the product of voltage and AC is the apparent power (S). Apparent power can also be described as the sum of active power (P) and reactive power (Q). In order to determine the active power, the phase angle φ or the power factor cos(φ) is required. The formula for active and reactive power is shown in equation 1 and 2 below:

$$P = |U| \cdot |I| \cdot cos(\varphi) = |S| \cdot cos(\varphi) \;\; [W] \tag{1}$$

$$Q = |U| \cdot |I| \cdot sin(\varphi) = |S| \cdot sin(\varphi) \;\; [VAr] \tag{2}$$

In most cases the generator distributes a three phase voltage whilst smaller loads, such as lights, only requires a single phase (Fregelius 2018). To create balance between the three phases the loads have to be equally distributed. Complete balance is usually not achieved in practice (ibid.). In this case both phase angle and power factor for the devices were unknown and therefore the power factor was set to 1. This means that the electrical units are assumed to have no losses. When the value of the power factor is 1, the apparent power only consists of active power and has no reactive power.

3.2 Solar energy

Solar energy is described as the energy that can be utilized from solar radiation. The power produced from the sun is defined as the electricity produced from a PV system and the source is considered to be renewable since it does not end unlike coal and oil. (Vattenfall n.d.)

3.2.1 PV systems and maintenance

Solar energy is emitted energy from the sun by heat and radiation. A PV cell is a semiconductor device that converts solar energy into DC electricity (Scragg 2018). A numerous PV cells are interconnected in series or parallel and together they form a module with a power capacity up to 200 W (International Energy Agency 2010; Chahuruvaa and Dei 2017). When PV modules are connected to appurtenant applications such as converters, batteries and mounting systems it is called a PV system (International Energy Agency 2010).

Like most products it is of great importance to take care of the PV panels in order to obtain not only a longer life span but also allow the panel to operate at its maximum power. The main reasons why the panels cannot operate at its maximum power are covering layers of dust or particles as well as high temperatures (Rehman and El-Amin 2012). These factors are proven to impair the efficiency of the PV panel (ibid.). The efficiency of a PV panel will slowly deteriorate and in turn affect its long time performance and the resulting electricity converting capacity (ibid.).

3.2.2 Irradiation and radiation

There are three main types of radiations used in terms of incoming solar radiation and those are spectral irradiance, irradiance and radiation. The spectral irradiance is the received power per area and wavelength differential [$W/m^2\mu m$] and the irradiance can be described as the received power per square meter [W/m^2]. Radiation integral of irradiation with respect of time with the unit [Wh/m^2]. The solar radiation varies and depends on parameters such as weather conditions, time of the day and location. (Silvestre and Castañer 2002)

The annual variety of solar radiation is shown in Figure 9 which showed that the solar radiation was higher in September to Mars whilst it was lower during April to August. It is a result of Zimbabwe being in the southern hemisphere and thus below the equator (Time and date 2019b).

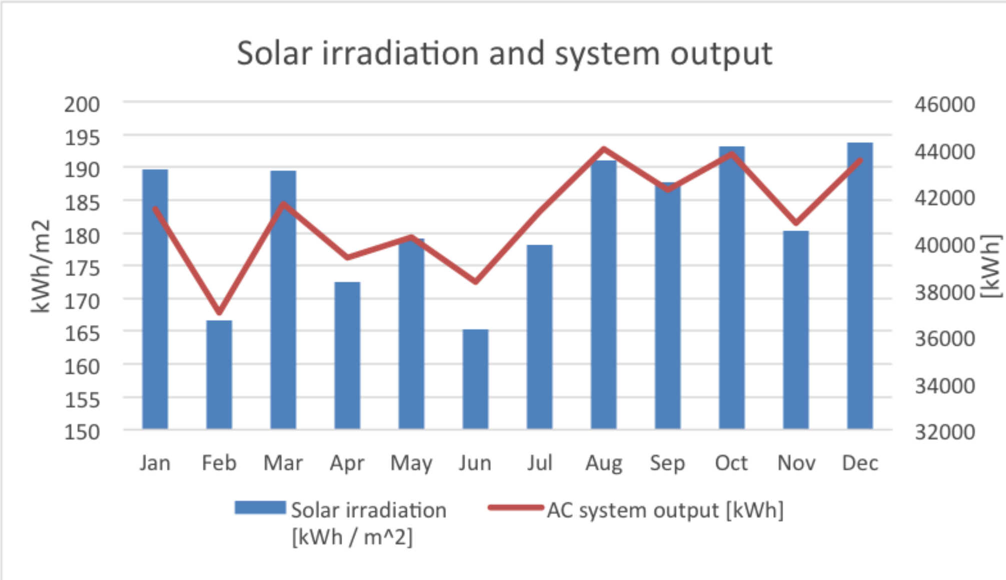


Figure 9: Monthly PV performance data during a year calculated by NREL

3.2.3 Azimuth

The azimuth angle is the east-west orientation of the PV array and is expressed in terms of degrees. It is common that the azimuth value in calculation tools for PV energy systems is zero when facing south. The azimuth angle is determined by the position of the sun that is measured relative south on the northern hemisphere and relative north on the southern hemisphere and is shown in Figure 10. (Dhimish and Silvestre 2019; PV Education 2019)

In other words, solar placement in the northern hemisphere should facing the geographical south since panels will receive most of the direct sunlight during a day and the opposite applies for panels on the south hemisphere. This was the reason why modules in the southern hemisphere should be facing north as can be seen in Figure 10. (Dhimish and Silvestre 2019)

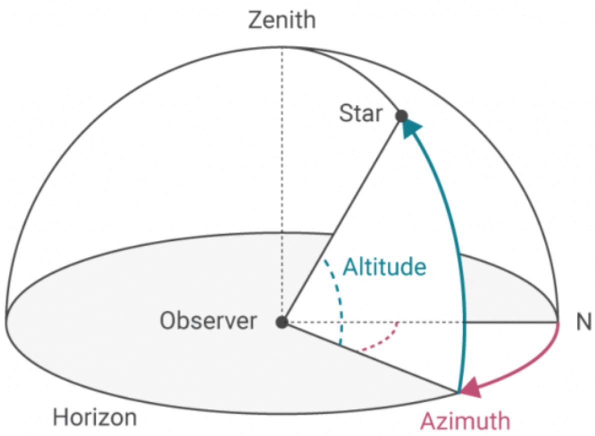


Figure 10: Schematic picture showing azimuth and altitude relative zenith and celestial objects (Time and date 2019a)

3.2.4 Areas

It is better to mount solar panels on a roof, compared to place them directly on the ground, as it reduces the risk of damaging the panels from both animals and humans. In addition, the risk of shading is less if the panels are placed on the roof than if placed on the ground. One of the main focusing of this report was to investigate the possibility to have enough solar energy to cover the energy demand during power outages. By using a measuring tool called Google Maps Area Calculator, the total roof area for the maternity ward was calculated to 518 m^2 and the main hospital was 3660 m^2. See calculations in Appendix, Figure A.1. It was not possible to cover the entire roof with PV panels in relation to the solar panel frame, the tilt of the roof and chimneys. If the simulations give a result with greater solar panel area than the roof area, some of the solar panels must be on the ground. This situation was not eligible.

3.2.5 PV technologies

The two main types of solar cells existing are the first and the second generation of solar cells. The first generation is the traditional silicon wafer based solar cell, which is the oldest technology of solar cells and covers around 80% of the solar market. The sunlight that comes in contact with the solar cell's surface can get the photons energy converted into heat, absorbed into the cell and converted into electricity or lost. The second generation is the thin film solar cell. It comprises different absorption layers and buffer layer and this leads to a better efficiency. They are 100 times thinner than the silicon solar cell which makes the absorbing layers very thin but it is also more material efficient. (Kaur and Singh 2016)

3.3 Diesel generators

A generator consists of a stator and a rotor. From the rotation created by the engine an electromotive force is induced in the stator and thus generates a current (Mahon 1992). According to the Administration department[3] in Rusape, there were three diesel generators connected to the hospital, but only one was used as a backup system during power cuts. The operating generator differed in size, brand, model and capacity and are presented in Table 3. Since these only operated during power cuts the diesel consumption differed each day.

The smaller generator, Volvo, was operating more often than the bigger generator, John Deere, due to lack of diesel accessibility in the country. John Deere, here labeled as generator 2, needed 48% of its full tank in order to operate[4]. The high fuel price was also a limiting factor. Generator 2 was automatically switched on when blackouts occurred while generator 1, Volvo, was operating manually. One of the main challenges during a blackout was to get the generator to start fast enough and in some cases the generator did not work at all[5]. It was two electricians who had the main responsibility for the maintenance of the generators and thus the ones who started the manual generator 1 during blackouts. If they were not available, the hospital could suffer from power cuts that lasted for hours which put patients at great risk that in turn can lead to death[6].

Table 3: Diesel generators at the hospital

Generator	Brand	Voltage [kV]	Capacity [l/h]
1	Volvo	330	10
2	John Deere	-	20

3.4 Batteries

Energy storage is a good solution since the energy supply does not match the energy demand. Renewable energy, such as solar power, produces irregular electricity supply which requires energy storage. An energy storage enables the hospital to use the stored energy as backup power and thus increases the resilience against crises. This leads to higher energy efficiency, peak shaving and load levelling which in turn reduces the operating costs. The energy can be stored in e.g. batteries in order to meet the energy demand during the nights or when power outages occurs. In addition, batteries will also ensure that power demand and available power was synchronized whilst it prevents voltage fluctuations that could damage power consuming units. (Norbäck and Sparr 2014)

There are several different types of batteries but batteries that cannot be recharged will not be investigated. A non-rechargeable battery is called a primary battery. A secondary battery has a galvanic process for discharging and then an electrolysis for charging. The two most important characteristics of a good battery are high rechargeability and high energy density. Energy density depends on both voltage and capacity and if they have a high value the energy density will also be high. The energy density tells how much energy a battery can store whilst specific power is a measure of how fast a battery can deliver energy. The voltage is the difference in electrode potential between anode and cathode. Higher difference gives higher voltage. Other aspects that makes a battery better are long cycling, effective current transmission, fast recharge, low self-discharge, made of non-toxic material and low-cost material, small

[3] Administration department, Rusape, meeting 2019-02-20
[4] L. Nyafesa, District medical officer, Rusape General Hospital, meeting 2019-03-25
[5] H. Gutukunhuwa, Electrician, Rusape General Hospital, meeting 2019-02-14
[6] L. Nyafesa, District medical officer, Rusape General Hospital, meeting 2019-03-25

weight, small volume and high safety with no side reactions. The most common battery technologies are LA battery and Li-Ion battery. The benefits of choosing LA battery instead of Li-Ion battery are the low price, high safety and temperature range. The disadvantages are the toxic material needed and low energy density. (Younesi 2018a; Younesi 2018b)

Table 4: Battery differences (Younesi 2018a; Kurzweil and Garche 2017)

Battery type	LA	Li-Ion
Specific energy [Wh/kg]	30-40	90-240
Energy density [Wh/L]	60-75	200-500
Specific power [W/kg]	180	500
Charge/discharge efficiency [%]	70-92	100
Self-discharge [%/month]	3-20	5-10
Lifetime [cycles]	500-800	>1000
Nominal Cell Voltage [V]	2	3-4.2

4 Economical analysis

The initial capital costs for a PV system depends on the inflation rate which in turn affects the payback period. Recently, in July 2019, the inflation in Zimbabwe was at its highest peak in history when it reached +176% (Trading Economics 2019). Before it escalated the inflation rate was around 0% (ibid.). The electricity generation cost for PV systems mainly depend on the annual irradiation from the sun combined with the efficiency of the panels (International Energy Agency 2010). It is also affected by the interest and eventual discounts (ibid.). Since PV systems only consists of fixed parts, both the operational and maintenance costs is relatively low (ibid.). When investing in PV systems, a payback period can be calculated. The calculation estimates the time it will take to reach a "break-even point" which is when the investment is repaid (Ross et al. 2002).

Net Present Cost (NPC), or life cycle cost, the current value of all installation- and operating costs the component during its lifetime minus the present value of the total revenues it earns during the corresponding time span. The software program calculates the NPC of each component in the system and then the total system itself. It makes the NPC opposite to the Net Present Value (NPV) but it differs only in sign. (HOMER Pro 2019e; HOMER Pro 2019c)

Levelized Cost of Energy (COE) is also a term used in this project. HOMER Pro defines levelized cost of energy as COE and is the ratio between annual cost of produced electricity and total electric load delivered according to Equation 3. It enables a comparison of different renewable technologies such as solar- and wind power with different conditions such as life span, total capital and capacities. (U.S. Department of Energy, Office of Indian energy 2015; HOMER Pro 2019b)

$$COE = \frac{C_{ann,tot} - c_{boiler} H_{served}}{E_{served}} \tag{3}$$

Where:
$C_{ann,tot} = total\ annualized\ cost\ of\ the\ system\ [\$/yr]$
$c_{boiler} = boiler\ marginal\ cost\ [\$/kWh]$
$H_{served} = total\ thermal\ load\ served\ [kWh/yr]$
$E_{served} = total\ electrical\ load\ served\ [kWh/yr]$

Payback period is a calculation of how long time, expressed in years, it takes to recover an investment, or reach a "break-even point". payback tells you how many years it takes to recover an investment. The payback period depends on a numerous different parameter such as the panels financial life, power production, area covered by modules and calculation rate etc. In summary, the repayment time is determined as the ratio between the total investment and the payment surplus. (Larsson and Strid 2017; Hedborg 2011)

In the simulations in this project, the selected base case system must have a lower initial capital value and a higher operating cost than the system it was compared against. If it does not match the criteria, the software returns a term called n/a. The payback time depends on the selected base case system.

Operating costs are the expenses associated with an ongoing business's daily operations such as sold goods and labour costs. In general, the lower a business operating costs are, the more profitable it is. It must also consider that some industries have higher operating costs than others. Therefore, this type of measurement is best applicable among companies or business's within industries with similar occupation. The Equation 4 below shows how the operating costs are calculated by HOMER Pro is presented. (InvestingAnswers 2019)

$$C_{operating} = C_{ann,tot} - C_{ann,cap} \tag{4}$$

Where:
$C_{ann,tot} = total\ annualized\ cost\ of\ the\ system\ [\$/yr]$
$C_{ann,cap} = total\ annualized\ capital\ cost\ of\ the\ system\ [\$/yr]$

Initial capital cost is in the HOMER Pro software defined as the total installation costs of a component from the beginning of the project (HOMER Pro 2019a). It was the installation costs for the PV system that corresponds to initial capital cost in this project.

5 Quantitative study

The social aspect of the hospital gives an overview of how the current situation affect the patients and the working conditions at the hospital. A quantitative study was done in order to explore the viewpoint and experiences of the hospital employees which is presented below. It is important to understand that the team who runs Rusape General Hospital are dedicated and hardworking people but their restricted budget and the lack of access to electricity are resulting in poorly medicine supply and non-working equipment (Engineers Without Borders Sweden n.d.). Besides what was asked in the questionnaire, more air conditioning were requested at the maternity ward[7].

From the questionnaire, the majority of the participants experienced that the two most limiting factors in their everyday work was high prices and lack of access to material. High prices refers to e.g. diesel, medicine and electricity costs. In the questionnaire, the participants where asked what critical areas they considered to be in most need of electricity supply. A summary of the answers are presented in Appendix, Figure 11. Furthermore, the questionnaire and all of the answers can be found in Appendix, Table A.3. Regarding the power outage frequency response form, it turned out that only one power outage had occurred during the week observed. Such information was not enough to establish an assumption of how frequent interruptions occur and therefore this result was not further presented in this project.

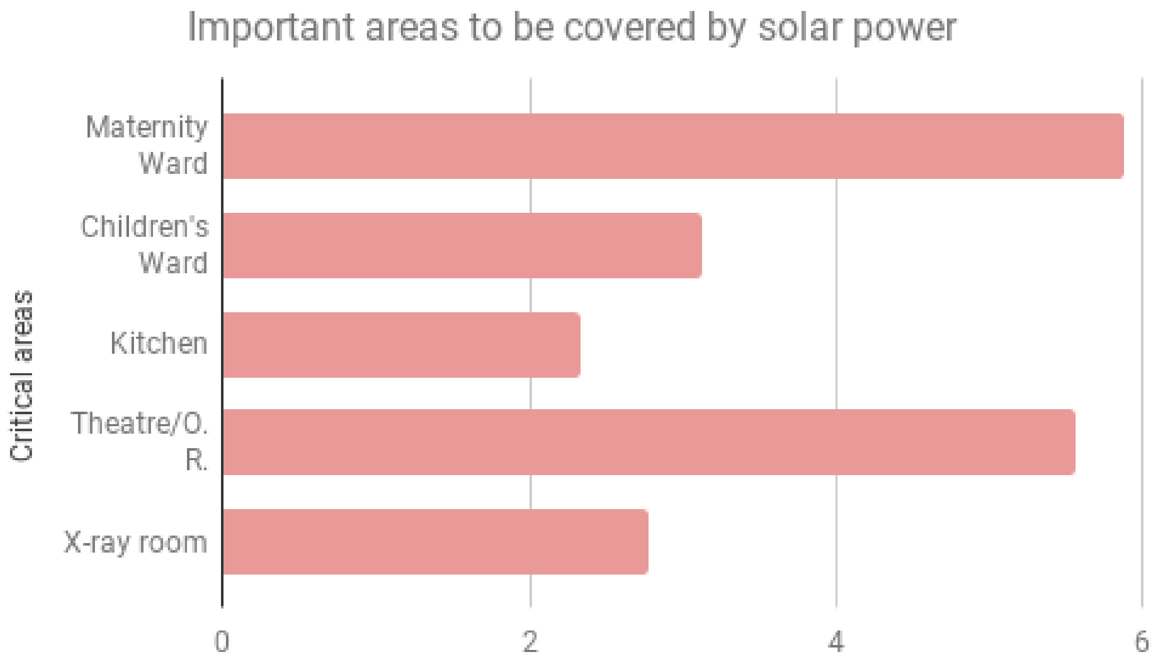


Figure 11: Answers from the questionnaire

[7]R. Mhlanga, Head nurse, Rusape General Hospital, interview 2019-02-14

6 Results

The simulation results were obtained from HOMER Pro. By implementing known parameters, collected from the field study, into the software program it simulated and showed the user the most cost-efficient energy system. Several scenarios, both in an economical- and technical aspect, were tested in order to analyse how the system would behave with different combinations of components within a PV system.

6.1 Simulations of current system

Currently the hospital is connected to the grid and has a smaller and a bigger diesel generator as a backup system. The third generator was inoperative and was not considered in the result. Generator 2, John Deere, as can be seen in table 3 was not used since it needed a larger amount of fuel. To work properly the generator needed to be filled with fuel at a minimum of 48% of the total volume of the tank. The hospital could not provide enough diesel to the generator due to high fuel price and the lack of diesel availability. This was the main reason why generator 1, the smaller one, was used instead of generator 2, the bigger one, even though generator 2 was automatically controlled.

Table 5: The current system with 150 power outages/year and an inflation rate at 0%

Electric parameters	
Energy production [kWh/year]	359 609 *97.2% Grid / 2.77% DG*
Capacity shortage [%]	1.160
Unmet electric load [%]	0.869
Total fuel consumption [litres/year]	3 126
Average fuel consumption [litres/day]	8.560
Economic parameters	
NPC [$]	782 455
COE [$]	0.170
Operating cost [$/year]	59 644
Initial capital cost [$]	20 000

There are no solar panels or batteries installed at the moment and the current system generates an annual production of 360 MWh, as can be seen in Table 5. The simulations showed that about 3% comes from the backup system as of today consists of one smaller diesel generator. Among the 150 simulated power outages that happened during a year, the generator did not operate four times which in some cases can cause a lot of damage and endangered patients' lives.

6.2 System solutions

To simplify the simulations, the results in Table 6-9 have a constant inflation rate and a constant grid failure frequency. The grid failure frequency is the number of power outages that occurs annually. The inflation rate was set to 0% whilst the grid failure frequency was assumed to occur 150 times/year. The capacity shortage and unmet electric load should not exceed 0%, since the safety of the patients was put at high risk if outages occurs. Thus, this could also lead to higher investment costs. A capacity shortage of 1% was also considered to compare the economics to see how much it varies, but 0% is usually required for a hospital. Currently the hospital suffers from a higher capacity shortage at 1.16% due to the power outages and inadequate backup system.

Definitions of the grid-connected energy systems are presented as follows:
System 1: PV panels, batteries and a diesel generator
System 2: PV panels and batteries

6.2.1 System simulation for the entire hospital

Rated capacity is the installed capacity of PV panels while the nominal capacity shows how much batteries are needed for the chosen system. One battery has a nominal capacity of 1 kWh, which means that nominal capacity corresponds the number of batteries installed. It implies a nominal capacity of 100 kWh means 100 batteries were installed.

Table 6 shows the annual energy production for different system solutions connected to LA batteries as a backup system. The grid-connected System 1, containing PV panels, LA battery and small influence of diesel generators was the most cost- and energy efficient option. It can be stated since it had the shortest payback period, highest rated capacity from PV panels and needed the least number of batteries.

Table 6: Energy production and payback time for different combinations of energy systems for the entire hospital

System	Energy production [kWh/year]	Payback time [year]	PV: Rated capacity [kW]	LA battery: Nominal capacity [kWh]
1	383 728 *62.3% Grid / 36.9% PV / 0.832% DG*	10.33	88.3	212
2	375 730 *68.6% Grid / 31.4% PV*	15.07	73.6	396

Table 7 shows the corresponding annual energy production for different system solutions with Li-Ion batteries as a backup system. It can be seen since the same grid-connected system solution, as for LA batteries, was the most cost- and energy efficient option. The energy production differed between 373 MWh and 384 MWh while the payback time differed between 9.5 to 15 years.

Table 7: Energy production and payback time for different combinations of energy systems for the entire hospital with Li-Ion batteries

System	Energy production [kWh/year]	Payback time [year]	PV: Rated capacity [kW]	Li-Ion battery: Nominal capacity [kWh]
1	378 937 *65% Grid / 34.6% PV / 0.427% DG*	9.52	81.1	138
2	373 360 *69.8% Grid / 30.2% PV*	12.22	70.6	257

6.2.2 Suggested energy system

The suggested solution, obtained from simulations, is to supply the hospital with renewable energy from a PV system and keep using diesel generators as a backup system, which can be seen in Figure 12 below. The figure also shows that the incoming radiation hits the PV panels that can be mounted on the roof. The radiation, hitting the PV panels, will create electricity that can either be stored in batteries or redirected to the hospital. The hospital will still be provided with electricity from grid but the energy supply from the PV system will lower the grid dependency.

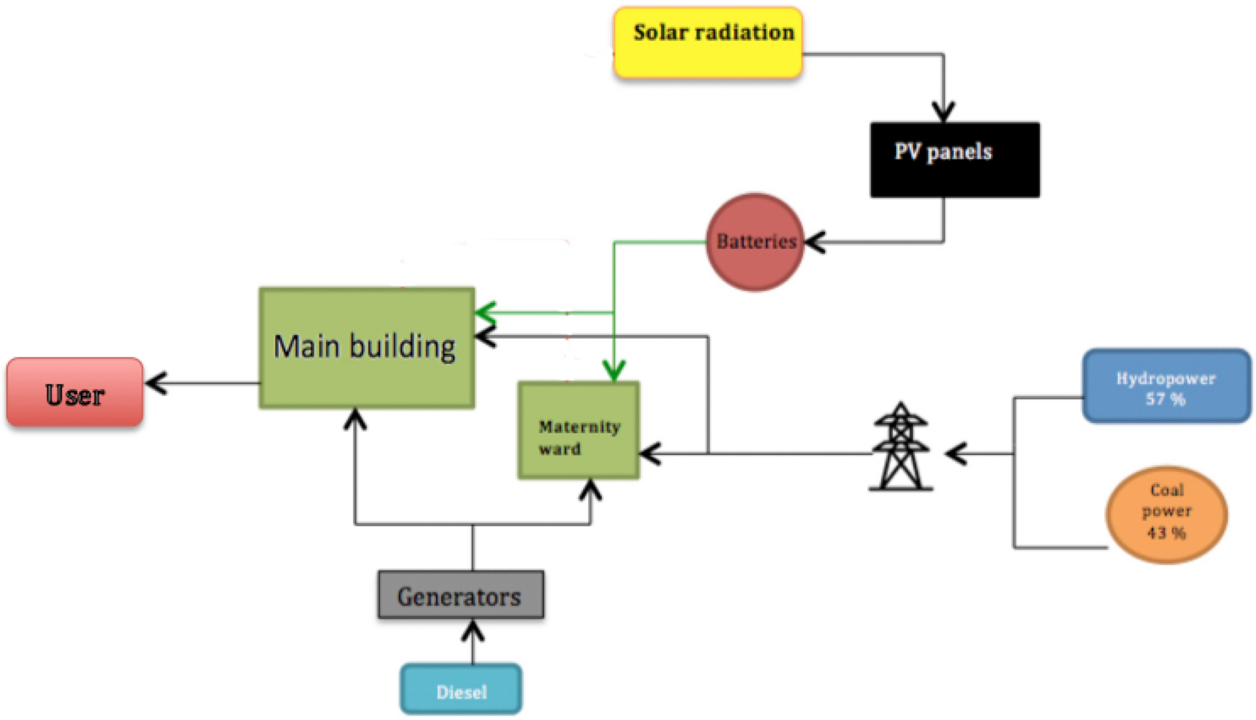


Figure 12: Energy system including PV panels and batteries

6.3 Maternity ward

6.3.1 Load assessment on maternity ward

The resulting load assessment for the maternity ward is presented in Figure 13. The different colours represents the total energy demand for each hour during a day and the numerical results from the assessment can be seen in Appendix, Table A.4. The figure below shows that the energy demand peak twice a day. According to employees[8], approximately two operations were performed per day and usually lasted for thirty minutes each. Electricity consuming devices that are used during surgeries could be the reason behind the two peaks seen in Figure 13. It can also be seen that the lowest energy consumption level is relatively high due to other electricity consuming machines that was used around the clock, such as vaccine storage's, freezers and refrigerators.

[8]P. Machocho, Nurse, Rusape General Hospital, interview 2019-03-01

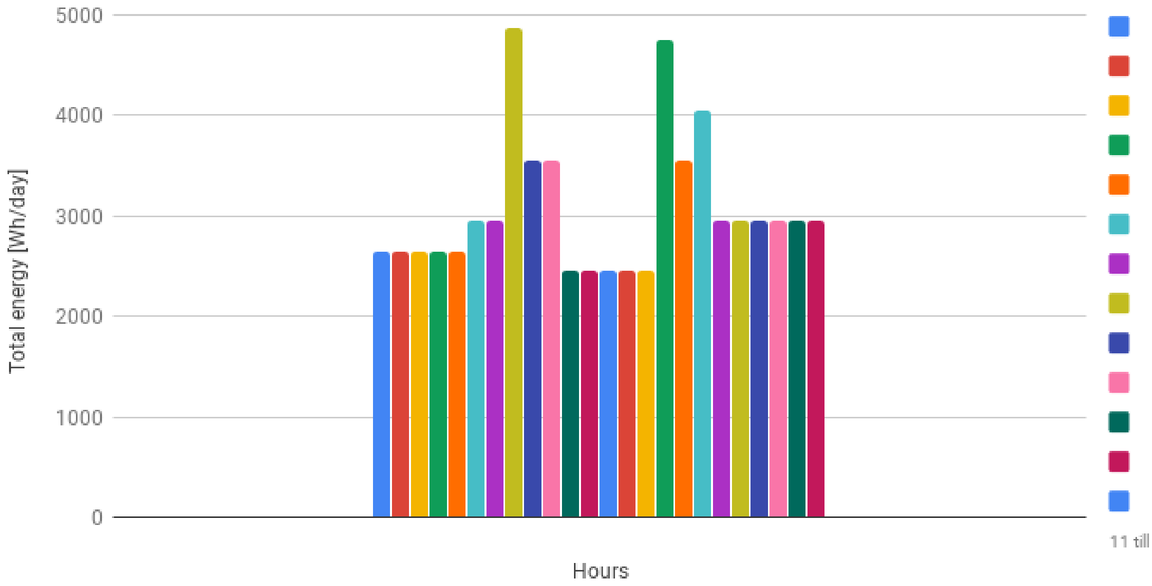


Figure 13: Load assessment at the maternity ward

6.3.2 System simulation for maternity ward

The results in this section was obtained by entering values from Figure 13 in section 6.3.1 as an electric load into HOMER Pro. **Table 8** below shows the annual energy production for different combinations of energy systems for the maternity ward when using LA batteries. The resulting simulations shows that System 2 with PV panels, grid and battery is the best option regarding both rated capacity from PV panels and payback time but requires more batteries than System 1. System 1, containing PV panels, DG, LA batteries and grid, gives a slightly higher annual energy production than System 2.

Table 8: Energy production and payback time for different combinations of energy systems with LA batteries

System	Energy production [kWh/year]	Payback time [year]	PV: Rated capacity [kW]	LA battery: Nominal capacity [kWh]
1	29 120 *67.2% Grid / 28.7% PV / 4.09% DG*	n/a*	5.22	20
2	27 588 *76.8% Grid / 23.2% PV*	8.35	3.99	24

***n/a** is a term used by HOMER Pro when the investment cost for a PV system never reaches a break-even point, meaning that the investment will not repay itself. In the software, the payback time was calculated by comparing two systems.*

Table 9 shows an annual production of approximately 27 000 kWh to 29 000 kWh, depending of the chosen energy system. System 2, consisting PV panels and Li-Ion batteries, gives the shortest payback time but need more battery capacity compared to System 1. Comparing the results in Table 8 and Table 9 it can be seen that Li-Ion batteries requires less installed capacity from solar panels, produces a slightly higher annual energy production as well as fewer batteries.

Table 9: Energy production and payback time for different combinations of energy systems with Li-Ion batteries

System	Energy production [kWh/year]	Payback time [year]	PV: Rated capacity [kW]	Li-Ion battery: Nominal capacity [kWh]
1	28 047 *72.1% Grid / 26.1% PV / 1.77% DG*	n/a*	4.57	12
2	27 741 *74.4% Grid / 25.6% PV*	8.70	4.43	15

6.4 Economical aspect after investments for the entire hospital

The inflation has a strong impact on the price development in the country and it is almost impossible to predict how it will vary. **Table 10** shows how four different inflation scenarios can affect the prices. In order to see how the economy depends on inflation, the power outages were assumed to occur 150 times per year with capacity shortage of 0%. The values in the tables 10 and 11 were based on System 1 that contains PV panels, LA batteries and diesel generators. This was done in order to see how the economy depends on inflation alone. During the summer of 2019, the inflation rate in Zimbabwe reached its highest peak at +176%. But before the that the rate was around 0%, which was the reason why the inflation rate was set to 0%. From the Table 10 below, it can be seen that a higher inflation causes negative net present cost, cost of energy and operating cost but a higher initial capital cost.

Table 10: Scenarios of possible inflation rates with 0% capacity shortage

Power outage [1/yr]	Inflation [%]	NPC [$]	COE [$]	Operating cost [$/year]	Initial capital cost [$]
150	0	860 922	0.18	44 639	290 289
150	100	-18,117 B	-0.997	-1.09 M	7.43 M
150	150	-5 327 575 B	-1.49	-1.48 M	7.29 M
150	200	-526 379 406 B	-1.73	-1.72 M	7.29 M

Table 11 shows how the costs varies depending on the amount of power outages. This also made it possible to see how the prices varies with respect to the number of power outages. The result shows that the more power outages at the hospital, the more expensive the system gets. This can be seen since all of the parameters in the Table 11 below rises when the amount of power outages was set to 150, compared to when it was set to 100 times.

Table 11: Scenarios of possible annual power outages with 0% capacity shortage

Power outage [1/yr]	Inflation [%]	NPC [$]	COE [$]	Operating cost [$/year]	Initial capital cost [$]
100	0	805 941	0.173	46 088	216 775
150	0	860 922	0.18	44 639	290 289

Table 12 shows how the prices changes depending on two different system solutions with LA batteries. The system solutions are defined on page 25. System 1, which includes PV panels, batteries and diesel generators, had the lowest net present cost, cost of energy and operating cost. The simulation showed that a system, containing diesel generators and batteries, resulted in the lowest initial capital cost.

Table 12: Economy analysis with the two different combinations connected to LA batteries

System	NPC [$]	COE [$]	Operating cost [$/year]	Initial capital cost [$]
1	860 922	0.18	44 639	290 289
2	922 201	0.197	48 238	305 559

Table 13 shows how the prices changes depending on two different system solutions with Li-Ion batteries. As in table 12, System 1 containing PV panels, batteries and a diesel generator resulted in the lowest net present cost, cost of energy and operating cost. By comparing Table 12 and 13 it can be seen that Li-Ion batteries result in lower investment costs and were more cost-efficient than LA batteries.

Table 13: Economy analysis with the two different combinations connected to Li-Ion batteries

System	NPC [$]	COE [$]	Operating cost [$/year]	Initial capital cost [$]
1	811 026	0.171	40 800	289 463
2	887 478	0.19	44 059	324 250

7 Discussion

In general, it should be considered not to oversize nor undersize the system. If its capacity is too high, the costs could be greater than what system will be able to utilize and thus it may lead to e.g. a longer payback period and lower NPC. However, if it is undersized the system may not deliver as much energy as the hospital need.

Regarding installation competency for solar cell systems, the study showed that it may not be enough solar installing expertise around the country. This assumption is because it was only a few existing isolated home solar systems in Zimbabwe during 2017. Another reason that could cause difficulties to install PVsystems is that the metal roof properties was not identified. This means that it can be hard for the population to be able to do solar installations themselves. However, through organizations and collaborative educational opportunities can be organized and held by knowledgeable people and thus people will learn and in turn pass it on.

Since the actual power factor was unknown, it was set to 1. This means that it was assumed that all electrical components were loss-free and that the voltage and current were in phase with each other and thus there was only active power. This was further explained in section 3.2. As a result of this assumption, the theoretical power output calculations result in a "better" output than the actual power output was since current transmission always involves heat losses.

7.1 Quantitative study

The current system at Rusape General Hospital receive its electricity supply mainly from the coal and hydropower-based grid. From interviews with the employees, power outages were said to occur on daily basis and during that time the hospital was completely dependent on its three generators. During the field visit, there was only two out of three generators that was in operation. The response form showed that only one power outage occurred during the week as employees were asked to note each break. This result does not match what the actual number was said to be. One reason could be that the hospital had unusually few power outages during that week or another conceivable opportunity could be because all breaks were not noted by the employees. Perhaps it would have been better to give the same person the task instead of sharing the responsibility on several different people. At the same time, the employees were working in shifts, which means that some power outages will be missed if the responsibility lies with only one person.

The maternity ward was one of the largest and most important department in the entire hospital, since children under-five mortality rate is relatively high. Also, the bigger O.R. was a part of that building. That could be a reason why most of the respondents of the questionnaire considered that the maternity ward was the most important area to cover for in the event of blackouts. The operating rooms had high priority as well since it was crucial that the power was working during surgeries. Lights, medical equipment and machines, such as the anaesthesia machine that keeps the patient asleep during the procedure, need electricity in order to work. The respondents also experienced that the most limiting factors within the business was high prices and lack of material. These go hand in hand, it was probably lack of material due to high prices. According to calculations and simulations, the power from renewable energy, generated from a PV system, could hopefully help. By redirect, the money from high energy and fuel costs can be invested in medical equipment and machines.

7.2 System design for the entire hospital

To obtain a better energy system, two main options were investigated for the hospital to follow. The first option, System 1, was to invest in a PV system with associated batteries and continue to use diesel generators as a backup system in the event of absence from batteries. The second alternative, System 2, was to invest in PV modules combined with batteries and shut down the diesel generators.

There were other system options which was not represented in the results. One of them was with only batteries installed. The idea would be to store energy when the electricity price was low. The batteries can be used during power outages or when the electricity price was very high, which results in lower costs. Without diesel generators as a backup the hospital would not have to rely on expensive diesel fuel and thereby lower their impact on the environment. An investment in batteries alone will make the hospital continue to rely on the grid, and even though the batteries will reduce the impact of the blackouts, the hospital will not be as independent as it would be with PV panels. This system would not be profitable because the batteries were too expensive to be a financially sustainable solution and did not have a payback time within the lifetime period for batteries. Also, since the grid was unreliable due to the low electricity production in the country, this system would not contribute to this major problem and can at best only help the hospital with its electricity demand.

To reduce the amount of batteries required for the previous system, a system with both diesel generators and batteries as electric reserves would solve this problem. The backup system becomes stronger and more robust since if one of the components cannot work properly, the other components can compensate and operate instead. For instance, if the generators would not have enough fuel available or if the batteries were not fully charged. The problem with this system was that the other disadvantages from the first mentioned system remain and it also add the fact that this solution would not follow the SDGs number 7, 12 or 13 as a result of keeping the diesel generators.

Another system which was not included was to only have a PV system. By having a PV system without batteries or diesel generators, the costs will be reduced since the self-supply of electricity enables the system to become less dependent on electricity prices. However, the initial capital costs for the PV system will be quite high. A negative aspect was the system will not have a backup system, which a hospital is obligated to have especially when the grid is unreliable. It was impossible to have a capacity shortage of 0% without a backup system and this was the reason why this system was not investigated further. An investment in a PV system without batteries will continue making the system dependent of the grid, and thereby vulnerable, to the weather conditions. Without any energy storage, the system is only able to utilize energy during daytime at the same time as energy production was lower under cloudy conditions.

A complete PV system, containing both PV panels and batteries (System 2), was the most expensive investment. By keeping the existing generators to complete the PV system (System 1), the costs were slightly lower compared to if they were removed. The reason was due to the higher price of the batteries compared to PV panels. More batteries are needed in a system with only PV panels and batteries since the diesel generators are non-existent and consequently more energy storage was needed in form of batteries. Hence higher initial capital cost for the batteries. System 2 enables both renewable power production and the possibility to store the energy and use it when the energy demand was high. Table 6 shows that the shortest payback time was obtained when combining PV panels, batteries and a diesel generator as in System 1. The energy production from the grid will then decrease with almost 35% compared to the current system for LA batteries and 32% for Li-Ion batteries. As for some of the earlier mentioned systems, System 1 do not contribute to the SDGs 7, 12 or 13 dues to its dependence of diesel fuel. In other words, the lowest investment cost alternative does not necessarily have to be the best option.

7.3 Maternity ward assessment

The energy peak demands, as can be seen in Figure 13, show that the energy demand peak twice a day. An explanation could be that the energy demanding surgeries on average were performed around two times a day. A surgery requires a lot of electricity supply since the medical equipment, such as the anaesthesia machine and the cooling needed must operate during this time. This is the reason why an energy storage, such as a battery, is favourable since it enables the user to utilize renewable energy generated from a PV system both during day- and night-time. An energy supply from installed batteries can contribute to reduce the power peaks.

The results as can be seen in Table 8 show that System 2, combining PV modules with batteries, gives the most optimal system solution. This was because System 2 have the shortest payback time in relation to both rated capacity and nominal battery capacity. It had a slightly lower energy production than System 1 that contains PV panels, batteries and a diesel generator. The main reason why the prices differed between System 1 and 2 was the high diesel price that System 1 was affected by since it contained a generator which consumed diesel fuel. In addition, System 2 requires 4 more LA batteries, or 3 more Li-Ion batteries, compared to System 1. In an environmental and accessible aspect, it was better not to depend on the diesel generators since the fuel was hard to access and the pollution from diesel have a negative impact on the environment. That was why generators should be avoided, and thus shut down, if possible. Hence System 2 was more favourable.

EWB has financial resources to install 2.6 kW of PV panels at the maternity ward which means the simulated system was a bit far away from the actual investment, especially for the one with Li-Ion batteries. On the other hand the Li-Ion batteries were close to the investment, with a planned installed nominal capacity of 10.08 kWh. For more details see Appendix, Table A.8. For LA batteries there were more than double the amount of batteries needed compared to the planned nominal capacity. Thus, the System 2 with LA batteries required less installed rated capacity for PV panels than for Li-Ion batteries.

7.4 Choice of battery

From Table 4 a comparison between the properties of LA batteries and Li-Ion batteries was made. Li-Ion batteries has higher energy density and power density than LA batteries, meaning that it has larger energy storage capacity and are able to deliver the stored energy at a faster rate. Li-Ion batteries also have longer lifetime and can thus go through more cycles without losing efficiency. But LA batteries are cheaper and also safer during its operations than Li-Ion batteries. The Tables 6-9 show that Li-Ion batteries give shorter payback time and that less installed capacity from PV panels was needed compared to LA batteries. It could be a result of its profitable energy storage properties. Due to the profitable properties of a Li-Ion battery, it can be recommended for this project.

7.5 Financial impact

As shown in Table 10, the inflation have a strong impact of the different costs. Recently, the inflation increased significantly and showed no signs of slowing down. That is why Table 10 represents simulations with various inflation. It shows that increasing inflation gives negative NPC, COE and operating cost whilst the initial capital cost increases. A negative net present cost (NPC) means that the investment cost will be refunded, and the hospital will also earn money on the investment. This is due to that a positive value of the inflation causes the value of the currency to drop over time and a hyperinflation will make the value to drop very fast. The initial capital cost increased because HOMER Pro simulates the most cost-efficient solutions and then suggest an alternative where it recommends investing in a certain amount of PV panels. This was due to the self-production of electricity that will increase and hence consume less electricity from the grid, which in turn lowers the operating cost.

In order to obtain results independent of the inflation rate the simulations was simplified. Table 11 presents two scenarios where no inflation was assumed. The result shows how much impact the power outages have on the economy. Almost all costs increase with increasing power outages. More power outages resulted in that more nominal capacity of the energy storage was needed. It can be seen that the operational costs decrease when the power outages increase due to the fact that the solar cells were utilized during the blackouts. The more energy generated from the PV system; the more money can be considered saved in terms of electricity costs which was why it was reasonable that the operating costs decrease as the power outages increase.

7.6 Achieving the Sustainable Development Goals of UN

System 1, containing grid, PV panels, Li-Ion batteries and diesel generators, was the best solution for the entire hospital whilst System 2, containing grid, PV panels and Li-Ion batteries, was the optimal solution for the maternity ward. This can be seen in Table 7 and Table 9. Matching these results to the SDGs of UN it showed that System 1 fulfilled all of the chosen goals except three, namely:

7: Affordable and clean energy
12: Responsible consumption and
13: Climate action

The reason for not fulfilling these goals is due to that the generators are retained in System 1 and thus a fossil dependency will be continued as well as pollution emissions. By choosing System 2 all five of the SDGs from UN was fulfilled. This implies more self-sufficiency and less impact from changes in fossil fuel price or its inaccessibility. It also follows the goals of REP.

Even though the payback time is lower for System 1 than System 2 when looking at the entire hospital, it might be a better investment to choose System 2, in an environmental perspective and fulfilling the global goals of UN. But in an economical and financial aspect, System 1 is a better option for the entire hospital.

7.7 Difficulties with the chosen systems

The difficulties with the chosen systems could be the lack of competency of solar installers and to finance PV panels, converters as well as batteries. Another challenge is the continued reliance on fossil fuel for System 1 which includes a diesel generator. It can also be difficult to predict the variation within the electric load and thus cope with the fluctuating energy demand. Batteries can help smoothen the power peaks and shift the load. Hence if the power peak is too high, especially when the grid and PV panels are not operating, the batteries might not be able to cover for the demanding electric load and will not provide the requested electricity. The system is also sensitive to the rising temperatures, caused by climate changes, since its efficiencies decreases in high-temperature environments. The simulations use older temperature data which showed accurate results today. A challenge is that the average outdoor temperature not only might rise, but also rise faster and higher than expected, which in turn might cause poor electricity generation. Finally, the high investment cost for PV panels and batteries could give rise to financial challenges for the chosen systems. The high initial capital costs have resulted in a payback time within the components lifetime. However, the expenses for the system needs a liquidity, the ability to pay for the investment. Currently the expenses exceed the assets.

7.8 Sources of error

It should be noted that simulation results in HOMER Pro, may differ from the actual result will in practice. The program has limiting factors since HOMER Pro is a software program designed for constructing PV systems through simulations and thus the parameters could differ. For instance, the efficiency of the actual panels can differ from the ones that HOMER Pro uses and the electric load of the hospital could have a lot of variations. Another source of error could be the operating panel temperatures that highly affects the efficiency of the PV panels. This means that if the simulated temperature coefficients do not match the actual temperature on the location, it could affect the simulated energy output of the PV system. How the average temperature will be in Rusape in the future is impossible to predict but it can be stated that it will be affected of the global warming, which the software does not consider.

One factor which has not been discussed was the sold electricity to the grid. In the current system the hospital has no electricity generation and therefore there are no information about how much the hospital can earn by selling electricity to the grid. It is unknown whether Zimbabwe's electricity system has enough capacity to enable surplus sales to the grid. The electricity bought from the grid was 0.14 $/kWh and if it is assumed that it is possible to sell electricity to the grid, then the price of the electricity sold would probably be slightly lower, depending on if there is an abundance of electricity within the grid or not. Even though it might not be a lot of money, in the long run the hospital can save money and the payback time for the investment could then decrease. A renewable energy system will most likely decrease the dependency of backup generators and thus the money that would be spent on diesel could then be redirected to buy more hospital supplies. However, the simulations give a good idea of the extent to what types of related equipment needed in a PV system to optimize the power production and the corresponding costs.

8 Conclusions

- *The most cost-efficient electric energy system*, regarding the entire hospital, is to use a grid-connected system containing PV panels, Li-Ion batteries and a small influence of diesel generators. The maternity ward is a part of the entire hospital and simulations showed that the optimized solution, both with respect to energy and economy, is to use a grid-connected system containing only PV panels and Li-Ion batteries.

- *The installed capacity needed* from the optimal PV system, with Li-Ion batteries, was 81.1 kW, which corresponds to a sustainable electricity supply of around 378 973 kWh annually. This applies to the entire hospital. Looking at the maternity ward, it requires an installed rated capacity of 4.43 kW which corresponds to an annual electricity supply of 27 741 kWh. The installed nominal capacity for the entire hospital was 257 kWh whilst for the maternity ward it was 15 kWh.

- *The electricity generated from PV panels alone* for the entire hospital is 131 112 kWh/year for System 1 and 112 755 kWh/year for System 2. This is showed in Table 6-7 where the PV panels alone corresponds to 34.6% of the total annual energy production from System 1 and 30.2% for System 2. In the same way as above, Table 8-9 show that the PV panels stand for 26.1% of the total energy production in System 1 and thus the PV panels alone are able to generate 7 320 kWh/year. For System 2, the energy production from PV alone is 7 102 kWh/year, which corresponds to 25.6% of the total production. This applies for the optimized system on maternity ward.

- *The challenges* would be the lack of installers, unpredictable load variations, global warming that affects the temperature sensitive components and the high investment costs.

- *The optimized energy system differed* between the maternity ward and the entire hospital due to the fact that the main building required much more energy supply than the maternity ward. The differences in the optimized energy systems were that the software recommended keeping the diesel generators when simulating the entire hospital and the maternity did not. In other words, System 1 was recommended for the entire hospital and System 2 was recommended for the maternity ward.

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A Appendix

A.1 Area calculations by using Google Maps Area Calculator

Roof area of maternity ward:
518 m^2

Roof area of main building:
$4180\ m^2 - 259.76\ m^2 \cdot 2 = 4180 - 519.52 = 3660.48\ m^2$

Total roof area of the entire hospital:
4178.5 m^2

Figure A.1: Measuring roof area of maternity ward with Google Maps Area Calculator

A.2 Solar radiation calculations by NREL

Table A.1: Monthly solar radiation calculated by NREL

Month	Solar Radiation (kWh / m^2 / day)
January	6.12
February	5.95
March	6.11
April	5.75
May	5.78
June	5.51
July	5.75
August	6.16
September	6.26
October	6.23
November	6.01
December	6.25
Annual	5.99

A.3 Annual solar radiation and output

Table A.2: Annual solar radiation and AC output calculated by NREL

Month	AC system output [kWh]	Solar radiation [kWh/m^2]
Jan	41387.6	189.72
Feb	36975.9	166.6
Mar	41626.5	189.41
Apr	39319.1	172.5
May	40200.4	179.18
Jun	38289.6	165.3
Jul	41315.6	178.25
Aug	43984.3	190.96
Sep	42220.4	187.8
Oct	43736.6	193.13
Nov	40796.6	180.00
Dec	43500.5	193.75

A.4 Questionnaire

Table A.3: Answers to the questionnaire

Participants	Age	Sex	Education	Profession	Knowledge of renewable energy scale [1-5]	Limiting factors	Desired investment in resources *-If other, specify*
1	38	Male	Bachelor's	-	5	Price	Vaccine storage
2	-	Female	Secondary	Nurse	5	Price	Vaccine storage
3	55	Male	Secondary	Nurse	5	Price	Other
4	-	-	Other	Nurse	5	Price	Vaccine storage
5	-	-	Other	Nurse	5	Price	Vaccine storage
6	53	Female	Secondary, Diploma and General nursing	Nurse	1	Other Reason not explained	Lamps + vaccine storage
7	43	Male	Professional	Accountant	3	Price	Lamps
8	32	Female	Diploma	Dental therapist	4	Access to material	Air conditioner
9	47	-	Secondary	Assistant nurse	3	Access to material	Air conditioner
10	50	Male	Specialist diploma	Medical laboratory scientist	5	Access to material	-
11	-	Female	College credits	Nurse	5	Other, I think it wasn't considered of late	Lamps
12	-	Male	Secondary	Nurse	5	Price	Other *-Refrigerators*
13	-	Male	Diploma	H.F.S.S	5	Price	Other *-Boilers*
14	-	Other	Secondary, college credits and diploma	Nurse	3	Access to material	other *
15	36	Female	Secondary college credits	Nurse	5	Price + Material access	Vaccine storage
16	57	Female	Bachelor's	Nurse	1	Price	Other *-Solar energy*
17	34	Male	Bachelor's	Administration	1	Other, We had reliable electricity and supplement generator	Other **

**Some of depths are not attached to alternative power when power was available all dept be attached in case of emergencies,laundry, all wards and administration block.*

***Connection to Green House (students home). 2)Connection of the compound. 3) Connection of TB unit and maternity. 4) Incinerator and mortuary coldators.*

Questions about solar energy

This is a questionnaire of what you think about solar energy. It is voluntary and anonymous to participate. The answers are only for use in our and future project and your answers can never be used against you.

Background information

Age: ____, prefer not to answer ☐

Sex: Male ☐ Female ☐ Other ☐ Prefer not to answer ☐

Education: What is the highest degree or level of school you have completed? *If currently enrolled, highest degree received*.

- ☐ No schooling completed
- ☐ Primary school
- ☐ Middle school
- ☐ Secondary/high school
- ☐ Some college credit, no degree
- ☐ Bachelor’s degree
- ☐ Master’s degree
- ☐ Professional degree
- ☐ Doctorate degree
- ☐ Other: ____________________
- ☐ Prefer not to answer

Current profession: What do you work as?

- ☐ Doctor
- ☐ Nurse
- ☐ Assistant nurse
- ☐ Administration
- ☐ Cleaner
- ☐ Janitor
- ☐ Receptionist
- ☐ Guard
- ☐ Other: _________________
- ☐ Prefer not to answer

Have you heard about renewable energy?

- ☐ Yes
- ☐ No

If yes, how much do you know about it? *Answer on a scale from 1 to 5*

- ☐ 1, only heard of it
- ☐ 2
- ☐ 3, I can briefly describe what the term “renewable energy” means
- ☐ 4
- ☐ 5, I know what is considered renewable energy and can explain it

If no, do you want to know more about it?

- ☐ Yes
- ☐ No
- ☐ I don’t know

The General hospital of Rusape

What do you think about the current electricity situation at the hospital? *Answer on a scale from 1 to 5*

- ☐ 1, I don’t think there is a problem
- ☐ 2
- ☐ 3, Power cuts occur but nothing that stop me from doing my job
- ☐ 4
- ☐ 5, The power cuts cause problems in my work and put the patients at high risk

What areas do you think should be covered by potential solar power? *Rank the areas from 1 to 5, where 1 is the most important area and 5 is the least important area among these alternatives.*

- ☐ Maternity ward
- ☐ Children ward
- ☐ Kitchen
- ☐ Theatre/O.R.
- ☐ X-ray room

What do you think is the most limiting factor for the hospital to use solar energy? *Tick one of the boxes below or write your own answer.*

- ☐ Price
- ☐ Access to material
- ☐ I don’t know what solar energy is
- ☐ Other

If you choose “Other”, please specify:

Are you being part of the decision on what the hospital's money is used for?

☐ Yes
☐ No

If the hospital would have access to more electricity, what do you think they should invest in? *Tick one of the options below or write your own answer.*

☐ More lamps and lights
☐ More air conditioner
☐ More refrigerators, freezer and storage for vaccines
☐ Nothing, it's good the way it is today
☐ Other

If you choose "Other", please specify:

What could make the hospital buy solar panels (for electricity production)? *Write any suggestions you can think of.*

A.5 Load assessment calculation sheet

The load assessment on the maternity ward was calculated over a 24 hour period in Excel. The total power [W] for each of the energy consuming appliance was the product of rated power and number of units for each device as can be seen in the figure below. The lower image represents how much time these devices were used hourly. For instance, 0.5 corresponds to 30 minutes per hour and 1 was one hour per hour. This was done for all 24 hours of the day. The resulting energy production [Wh] was the sum-product of total power and time which can be seen as the bold marked numbers at the bottom of the lower image.

Table A.4: Load assessment calculations on the maternity ward

Application	Brand	Number of	Rated power	Total	AC or DC	Where
Lamp		1	60	60	DC	Incubator room
Infant incubators	DAVID YP-90A	4	850	3400		Incubator room
Resuscitator		1	1100	1100		Kangaroo room
LED lamps		7	20	140	DC	Pre/post deliver room
Lamp		2	60	120	DC	Operating Room
Air condition, cooling		2	1555	3110		Operating Room
Air condition, heating		2	1440	2880		Operating Room
Surgical lamp		1	150	150	AC	Operating Room
Emergency lamp		3	60	180	DC	Operating Room
Surgery table		1	300	300		Operating Room
Anastesia machine	WATO TMEX – 65/55	1	1100	1100		Operating Room
Fluorescent lamp		1	60	60	DC	Labour room/delivery room
Resuscitator		1	1100	1100		Labour room/delivery room
Refrigerator	Capri C420	1	240	240	AC	Hallway
"Blue box" medicine refrigerator		1	250	250	AC	Hallway
"Blue box" medicine freezer		1	180	180	AC	Hallway
Fluorescent lamp		3	60	180	DC	Pre-labour house
Wall socket, mobile charging?		8	5	40		Pre-labour house

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
0,5	0,5	0,5	0,5	0,5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0,5	0,5	0,5	0,5	0,5	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0,5	0,5	0,5	0,5	0,5	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0
0,5	0,5	0,5	0,5	0,5	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0
0,5	0,5	0,5	0,5	0,5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
2640	**2640**	**2640**	**2640**	**2640**	**2950**	**2950**	**4870**	**3550**	**3550**	**2450**	**2450**	**2450**	**2450**	**2450**	**4755**	**3550**	**4050**	**2950**	**2950**	**2950**	**2950**	**2950**	**2950**

Table A.5: Resulting load assessment for the maternity ward

	Energy [kWh]	Power [kW]
Daily need	73.38	
Peak demand		4.87
Annual energy consumption	26 784	

A.6 Energy consumption

Table A.6: Spread sheet of the monthly energy consumption and costs 2018

12 MONTHS 2018				KWH		$
	DATE	LAST READING		CONSUMPTION		AMOUNT CHARGED
	Dec	73650		22848		$3 722,61
	Nov	50802		30026		$4 502,40
	Okt	20776		26095		$3 852,49
	Sep	994681		33735		$4 769,10
	Aug	960946		43593		$6 273,44
	Jul	917353		30533		$4 469,66
	Jun	886820		33855		$4 986,46
	May	852965		14715		$2 154,88
	Apr	838250		57154		$8 207,83
	Mar	781096		23196		$3 323,44
	Feb	757900		13609		$1 910,16
	Jan	744291		28029		$4 497,50
TOTAL				357388		$52 669,97

Energy consumption:
$357388 kWh/year \longrightarrow 979.145 kWh/day \longrightarrow 40.798 kWh/hour$

Power outages:
2-3 $h/week = 2.5h/week \longrightarrow 0.357h/day$

Lost energy due to power cuts:
$40.798 \cdot 0.357 = 14.571 kWh/day \longrightarrow 0.6071 kWh/hour$

Table A.7: Hourly energy consumption for the entire hospital during a day

Hour	Bought energy from ZESA [kWh]	Total energy consumption incl. power cuts [kWh]
1	11.519	12.128
2	11.519	12.128
3	11.519	12.128
4	11.519	12.128
5	11.519	12.128
6	17.279	17.888
7	28.799	29.408
8	40.318	40.927
9	46.077	46.686
10	46.077	46.686
11	46.077	46.686
12	46.077	46.686
13	46.077	46.686
14	46.077	46.686
15	46.077	46.686
16	46.077	46.686
17	51.837	52.446
18	57.596	58.205
19	69.117	69.726
20	69.117	69.726
21	69.117	69.726
22	69.117	69.726
23	51.837	52.446
24	28.799	29.408

A.7 Quotation

Table A.8: The quotation for the pilot project

Description	Quantity	Excl. Price	Disc %	VAT %	Excl. Total	Incl. Total
Zim-stp325W24V - 325W Suntech, 24V Solar panel	**8**	$241.00	0.00 %	15.00 %	$1,928.00	**$2,217.20**
ZIM-GWSPF5KVA - Growat, 48V, 5KVA, Pure Sine Wave Inverter Charge with 60A in-built Charge Controller	**1**	$890.00	0.00 %	15.00 %	$890.00	**$1,023.50**
ZIM-8G4DLTP - Deka 210ah 12v battery	**4**	$721.00	0.00 %	15.00 %	$2,884.00	**$3,316.60**
FRA001 - Solar Panel Frame	**1**	$625.00	0.00 %	15.00 %	$625.00	**$718.75**
MAT001 - Installation Material & Protection Accessories	**1**	$2,150.00	0.00 %	15.00 %	$2,150.00	**$2,472.50**
LAB001 - Labour	**1**	$200.00	0.00 %	15.00 %	$200.00	**$230.00**
MIL001 - MILEAGE (Harare to Rusape)	**348**	$0.38	0.00 %	15.00 %	$132.24	**$152.08**
FBC001INS - FBC Insurance Annual Premium	**1**	$372.00	0.00 %	0.00 %	$372.00	**$372.00**

Table A.9: Cost per installed capacity

PV panel system	Battery system
PV panel: $\frac{241\$\cdot 1.15}{8\cdot 325W} = 0.1066\$/W$	Battery: $\frac{721\$\cdot 1.15}{4\cdot 210Ah\cdot 12V} = 0.08226\$/Wh$
Frame: $\frac{625\$\cdot 1.15}{8\cdot 325W} = 0.2764\$/W$	Labour: $\frac{200\$\cdot 1.15}{210Ah\cdot 12V} = 0.09127\$/Wh$
Installation: $\frac{2150\$\cdot 1.15}{8\cdot 325W} = 0.951\$/W$	
Total: 1.334 \$/W	Total: 0.1735 \$/Wh

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