A techno-economical analysis of a solar PV system and a feasibility study for biogas production for cooking

– A case study of the Tumaini Open School in Tanzania

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En tekno-ekonomisk analys av ett solcellssystem och en förstudie för biogasproduktion för matlagning: En fallstudie av Tumaini Open School i Tanzania

Sammandrag

Detta examensarbete är en fallstudie av Tumaini Open School för gravida studenter och studerande mödrar i Tabora, Tanzania. Genom den ideella organisationen Ingenjörer utan gränser Sverige genomförde författarna en Minor Field Study i Tanzania för att fastställa efterfrågade eltjänster, det resulterande elbehovet och den maximala dagliga effektkurvan för skolan vid fullskalig verksamhet. Vidare prioriterades eltjänsterna och användes för att konstruera och utvärdera tre scenarier för elförsörjningen, som kombinerade en självstädig solcellsanläggning med elektricitet från elnätet. Dessutom utvärderades möjligheten att producera biogas för matlagning. Metoden innefattade en litteraturstudie, intervjuer med studenter från skolan och olika experter, en enkät för prioritering av eltjänsterna, studiebesök på solcells- och biogasanläggningar och allmänna observationer under fältstudien. Vidare genomfördes optimeringar av solcellssystemen, beräkningar och kostnadsanalyser. Det framtida faktiska elbehovet och nödvändiga eltjänster kommer med största sannolikhet att skilja sig från det uppskattade och rekommenderas att justeras (1) för att undvika de lågprioriterade och energikrävande eltjänsterna, (2) för att undvika höga effekttoppar samt (3) för att anpassa belastningen efter elproduktionen. Prioriteringen av eltjänsterna resulterade i Automatiskt prioriterade eltjänster följt av fyra prioriterade steg där prioritets steg 1 innehöll de viktigaste eltjänsterna och steg 4 innehöll de minst viktiga eltjänsterna. Utifrån de bedömda scenarierna ansågs Scenario 2 (där de Automatiskt prioriterade eltjänsterna och steg 1-2 försörjdes av solenergi och steg 3-4 av elnätet) vara det mest lämpliga elsystemet för skolan utifrån de tekno-ekonomiska begränsningarna i förhållande till vilka steg av de prioriterade eltjänsterna som uppfylls. Det rekommenderas att ytterligare undersöka den faktiska implementeringen och platsen för montering av solcellsanläggningen. Möjligheten att producera biogas för matlagning är genomförbar för skolan men kräver noggrant övervägande och bedömning av planeringen för biogasanläggningarna, val av installatörer och tillgång till tillräcklig kunskap om drift och underhåll samt de sociala och miljömässiga fördelarna med att använda biogas och biogödsel. Det rekommenderas att ytterligare undersöka gasbehovet och -produktionen från de tillgängliga substraten, ihop med en mer specifik plan för implementering och en kostnadsanalys. Genom att använda solenergi i elsystemet och producera biogas för matlagning kommer skolan att närma sig de Globala målen för hållbar utveckling om god hälsa och välbefinnande samt hållbar energi för alla studenter och lärare, som mål 3 och 7 strävar mot.

Nyckelord

elbehov, eltjänster, elförbrukning, elbelastningsprofil, mikro/off-grid/fristående solsystem, solenergi, solenergioptimering, PV-optimering, batterioptimering, biogas, biogasanläggningar i utvecklingsländer, Tabora , Tanzania, skola, MFS, Minor Field Study, biogödsel, biogödsel, EWB-SWE, Engineers Without Boarders, Ingenjörer utan gränser, SDG 3, SDG 7

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Abstract

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Keywords

electricity demand, electricity services, electricity consumption, electricity load profile, micro/off-grid/standalone solar system, solar energy, solar optimisation, solar optimization, PV optimisation, battery optimisation, biogas, biogas plants in developing countries, clean cooking, Tabora, Tanzania, school, MFS, Minor Field Study, biofertiliser, biofertilizer, EWB-SWE, Engineers Without Boarders, SDG 3, SDG 7

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Abstrakt

Detta examensarbete är en fallstudie av Tumaini Open School för gravida studenter och studerande mödrar i Tabora, Tanzania. Genom den ideella organisationen Ingenjörer utan gränser Sverige genomförde författarna en Minor Field Study i Tanzania för att fastställa efterfrågade eltjänster, det resulterande elbehovet och den maximala dagliga effektkurvan för skolan vid fullskalig verksamhet. Vidare prioriterades eltjänsterna och användes för att konstruera och utvärdera tre scenarier för elförsörjningen, som kombinerade en självstädig solcellsanläggning med elektricitet från elnätet. Dessutom utvärderades möjligheten att producera biogas för matlagning. Metoden innefattade en litteraturstudie, intervjuer med studenter från skolan och olika experter, en enkät för prioritering av eltjänsterna, studiebesök på solcells- och biogasanläggningar och allmänna observationer under fältstudien. Vidare genomfördes optimeringar av solcellssystemen, beräkningar och kostnadsanalyser. Det framtida faktiska elbehovet och nödvändiga eltjänster kommer med största sannolikhet att skilja sig från det uppskattade och rekommenderas att justeras (1) för att undvika de lågprioriterade och energikrävande eltjänsterna, (2) för att undvika höga effekttoppar samt (3) för att anpassa belastningen efter elproduktionen. Prioriteringen av eltjänsterna resulterade i Automatiskt prioriterade eltjänster följt av fyra prioriterade steg där prioritets steg 1 innehöll de viktigaste eltjänsterna och steg 4 innehöll de minst viktiga eltjänsterna. Utifrån de bedömda scenarierna ansågs Scenario 2 (där de Automatiskt prioriterade eltjänsterna och steg 1-2 försörjdes av solenergi och steg 3-4 av elnätet) vara det mest lämpliga elsystemet för skolan utifrån de tekno-ekonomiska begränsningarna i förhållande till vilka steg av de prioriterade eltjänsterna som uppfylls. Det rekommenderas att ytterligare undersöka den faktiska implementeringen och platsen för montering av solcellsanläggningen. Möjligheten att producera biogas för matlagning är genomförbar för skolan men kräver noggrant övervägande och bedömning av planeringen för biogasanläggningarna, val av installatörer och tillgång till tillräcklig kunskap om drift och underhåll samt de sociala och miljömässiga fördelarna med att använda biogas och biogödsel. Det rekommenderas att ytterligare undersöka gasbehovet och -produktionen från de tillgängliga substraten, ihop med en mer specifik plan för implementering och en kostnadsanalys. Genom att använda solenergi i elsystemet och producera biogas för matlagning kommer skolan att närma sig de Globala målen för hållbar utveckling om god hälsa och välbefinnande samt hållbar energi för alla studenter och lärare, som mål 3 och 7 strävar mot.

Muhtasari (Swahili)

Tasnifu hii ya uzamili ni utafiti mahususi uliofanywa kwenye Shule Huria ya wasichana wajawazito na wanafunzi wazazi ya Tumaini iliyopo mkoani Tabora, nchini Tanzania. Kupitia shirika la Wahandisi Wasio na Mipaka la nchini Sweden, waandishi wa tasnifu hii walifanya utafiti mdogo nchini Tanzania ili kubaini huduma za umeme zinazohitajiwa na shule ya Tumaini, kiwango cha mahitaji ya nishati ya umeme inayohitajika na kiwango cha juu cha nishati kwa siku wakati shule ikiwa kwenye uendeshaji kamili. Zaidi ya hayo, huduma za umeme zilichambuliwa kwa kuzingatia kipaumbele na vipaumbele vilitumika kuweka hali tatu ya mifumo ya usambazaji wa umeme inayojumuisha, mfumo huru wa nishati ya jua isiyo ya gridi ya taifa utakaofanya kazi sambamba na umeme wa gridi kuu kutathminiwa. Pia, upembuzi yakinifu kuhusu uwezekano wa kuzalisha bayogesi safi kwa ajili ya kupikia ulitathminiwa. Mbinu zilizotumika katika utafiti huu zilijumuisha urejereaji wa tafiti zilizotangulia, mahojiano na wanafunzi wa shule ya Tumaini na wataalam mbalimbali, uchunguzi wa kuweka vipaumbele vya huduma za umeme, ziara za kitafiti kwenye mitambo ya nishati ya jua na bayogesi na uchunguzi wa jumla wakati wa utafiti wa nje ya darasani. Pia, ilijumuisha uboreshaji wa mifumo ya nishati ya jua, mahesabu na uchambuzi wa gharama. Huduma za umeme zinaohitajika katika siku za usoni na matumizi ya umeme yatatofautiana na makadirio yaliyopendekezwa hiyo watafiti wanapendekezwa yanyumbuliswe ili (i) kuepusha kuwekwa kwa vipaombele vya chini dhidi ya uzalishaji wa juu wa nishati, (2) kuepusha viwango vya juu vya nishati na (3) kuwianisha mzigo wa matumizi ya nishati na uzalishaji wa nishati. Uwekaji vipaumbele vya huduma za umeme ulisababisha vipaumbele vya huduma kujipanga vyevyewe kiotomatiki kwa kufuata hatua nne za vipaumbele. Kutoka kwenye hali zilizotathminiwa kuhusu mifumo ya usambazaji wa umeme, hali namba 2 (ambayo ni kipaumbele cha huduma iliyowekwa kiotomatiki na hatua ya 1-2 inatolewa na nishati ya jua na hatua ya 3-4 inatolewa na gridi kuu) zilibainika kuwa mfumo unaofaa zaidi wa usambazaji wa umeme kwa shule kwa kuzingatia vikwazo vya teknolojia na kiuchumi kuhusiana na hatua za kipaumbele za huduma ya umeme ilifanikiwa. Inashauriwa kuchunguza zaidi kikamilifu utekelezaji na eneo la uwekaji mfumo wa nishati ya jua. Uwezekano wa kuzalisha bayogesi kwa madhumuni ya kupikia unawezekana kwa shule lakini inahitaji shule kuzingatia kwa makini na kutathmini mpango wa uwekaji wa mfumo wa bayogesi hiyo, uchaguji wa wafungaji wa mfumo huo na upatikanaji wa ujuzi wa kutosha wa uendeshaji na matengenezo ya mfumo pamoja na manufaa ya kijamii na kimazingira ya kutumia bayogesi na malighafi yake. Inapendekezwa kuchunguza zaidi mahitaji ya gesi na uzalishaji kutoka sabustrate zinazopatikana, pamoja na mpango mahususi zaidi wa utekelezaji na uchanganuzi wa gharama. Kwa kutumia nishati ya jua katika mfumo wa usambazaji wa umeme na kuzalisha bayogesi kwa madhumuni ya kupikia, shule itahakikisha jitihada zake za kuelekea afya njema na ustawi pamoja na upatikanaji nishati nafuu na safi kwa kila mwanafunzi anayehudhuria masomo na mwalimu anayefanya kazi, kwa kuzingatia ufikiwaji wa lengo namba 3 na 7 la Mpango wa Maendeleo Endelevu.

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First and foremost, we would like to give special thanks to our hosts who received us in Tabora, Tanzania; Mr. Ezekiel Kassanga, Mr. Marius Simon and Mrs. Sweetberther William John. Your warm welcome and support made it possible for us to investigate and gather the information needed to write this report. Additionally, we would like to give special thanks to the students and members of the Tumaini Education Initiative for their willingness to share their thoughts and experiences with us. We would also like to express our gratitude to the project group and the experts at Engineers Without Borders Sweden for the willing assistance and expertise received during our work.

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We would also like to extend our gratitude to the Executive Director and Renewable Energy & Energy Efficiency Expert from TAREA, who provided us with important insights to the renewable energy sources in Tanzania and valuable contacts to possible study visits as well as solar and biogas companies. Thank you to the sisters at St. Ann Catholic Mission Hospital for enthusiastically showing us the hospital's PV system. Thank you to the biogas experts from Afrihands Tanzania for sharing your knowledge and taking us around several biogas plants in Arusha. An additional thank you to the hosts for the warm welcome at all of the study visits to biogas plants. Thank you also to the solar experts at Photons Energy Ltd., GadgetroniX and Power Providers for always offering your services and answering all of our questions. Finally, we want to send our gratitude to the Senior Engineer at TANESCO for providing us with useful information about grid connection and electricity prices in Tanzania.

Without the support from all of the above, our master thesis would not have been this interesting to perform. Finally, thank you to our friends and families for supporting us throughout this entire process.

Abbreviations

- AD = anaerobic digestion
- AC = air condition
- AM = air mass
- C = carbon
- CHP = combined heat and power
- DoD = Depth of Discharge
- DM = dry matter
- DNO = distribution network operator
- DSD = Diluted State Digester
- EWB = Engineers Without Borders
- EWURA = Energy and Water Utilities Regulatory Authority
- GTZ = German Agency for Technical Cooperation
- HRT = Hydraulic Retention Time
- IEA = International Energy Agency
- IPP = independent power producer
- K = potassium
- kWh = kilowatt hours
- kW_p = kilowatt peak
- LCOE = Levelized Cost of Electricity
- LPG = liquefied petroleum gas
- MFS = Minor Field Study
- MPPT = Maximum Power Point Tracking
- MW = megawatt
- N = nitrogen
- NEP = National Energy Policy
- NGO = non-governmental organisation
- NPV = Net Present Value
- NREL = National Renewable Energy Laboratory
- OLR = Organic Load Rate
- O&M = operation and maintenance
- P = phosphorous
- PV = photovoltaic
- PWM = Pulse Width Modulation
- REA = Rural Energy Agency
- RQ = research question
- SAM = System Advisor Model
- SDG = Sustainable Development Goals
- Si = silicon
- SPD = small power distributor
- SPP = small power producer
- SRT = Solids Retention Time
- SSD = Solid State Digester
- SSP = Shared Socioeconomic Pathway
- TANESCO = Tanzania Electric Supply Company Limited
- TAREA = Tanzania Renewable Energy Association
- TS = Total Solids
- TWh = terawatt hours
- TZS = Tanzanian shillings
- VAT = value-added tax
- VS = Volatile Solids
- ZECO = Zanzibar Electricity Corporation

Glossary

- Anaerobic Digestion = Degradation of organic compounds by microorganisms in a oxygen free environment, which produces biogas.
- Azimuth angle = The horizontal orientation of the solar panels in relation to the equator-
- AM = A body of air with horizontally uniform levels of temperature, humidity, and pressure.
- CAMARTEC plant = the biogas plant most utilised in east Africa and also the design of the plants at the study visits.
- Digestate = The solid and/or liquid material remaining after undergoing anaerobic digestion; often still high in nutrient content and can be used as fertiliser.
- Digester = A part of the biogas plant which is an enclosed tank, cylinder or silo in which anaerobic digestion of organic wastes (the substrates) takes place.
- Diluted State Digester = A digester design that do add additional water to the substrate before it enters the digester.
- Mesophilic = Microbial processes that take place in the moderate temperature range of 20–45°.
- Peri-urban = Mixed rural and urban areas.
- Substrate = The biomass suitable for digestion such as food, agricultural, sewage or human waste and animal manure.
- Solid State Digester = A digester design that do not add additional water to the substrate before it enters the digester.
- Tilt angle = The vertical tilt of solar panels.
- Ugali = A white, dough-like, traditional food made from maize.

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1 Introduction

This case study is about the Tumaini Open School for pregnant and mothering students located in Tabora, the United Republic of Tanzania, which is one of the country's most impoverished regions. Through the volunteer organisation Engineers Without Borders (EWB) Sweden, which have a partnership with the local organisation Tumaini Education Initiative and contribute with expertise to the school, the authors conducted a Minor Field Study (MFS) in Tanzania from March to May 2023. The goals of the school are to help vulnerable young women regain their education and reduce the stigma around teenage pregnancy in Tanzania. The school will accommodate day students, of which some will live on the premises with their children, with child care facilities, farming area, kitchen and other necessities available. Within this framework, the case study specifically addresses the electricity demand, possible electricity supply systems of solar energy and electricity from the main grid as well as biogas production for clean cooking purposes at the Tumaini Open School.

The energy from the sun is what keeps everything on earth alive, from humans and animals to plants and crops. It is the primary source of all other energy sources on earth, and is more abundant than any other energy source (UN n.d.). The number of people that have access to electricity globally have increased since 2010, which has especially been possible thanks to technologies that can make use of decentralised renewable energy sources. However, this increase has not been equal across regions. In fact, the amount of people without electricity access increased in Sub-Saharan Africa (The World Bank 2022a). In 2021, only 41 % of the population in Tanzania had access to electricity (The World Bank 2020). While the electricity generation in the country comes mostly from natural gas, petrol and hydro power, the favorable geographical location of the country near the equator and applied subsidies for renewable energy makes solar energy a compelling energy source that can be utilized both on- and off-grid. The off-grid energy is mostly consumed by households in peri-urban and rural areas but also by institutions such as hospitals and schools (SmartSolar Tanzania 2018a).

More than 95 % of cooking fuels in Tanzania came from firewood, charcoal and liquefied petroleum gas (LPG) in 2019. Clean cooking fuels on the other hand was almost none existent according to The World Bank (2022b) and IEA (2022). Access to clean cooking has been mostly stagnant since 2010 globally, and in 2021, only 7 % of Tanzania's population had access to clean cooking methods (The World Bank 2022a; The World Bank 2020). One possible option for clean cooking is biogas production, which can be implemented on both domestic and institutional level. Biogas was first introduced in Tanzania in 1975 and during the 1980s a new biogas plant design, the CAMARTEC plant, was developed by the The Centre for Agriculture Mechanization and Rural Technology (CAMARTEC) and the German Agency for Technical Cooperation (GTZ). They facilitated the installation of approximately 6 500 biogas plants until 2019, mostly concentrated to the region of Arusha (Africa Biogas Partnershop Program 2019; Energypedia 2014).

1.1 Purpose

The purpose of this master thesis is to determine the energy demand for electricity usage and cooking, as well as propose a feasible energy supply system based on solar PV and biogas production at the Tumaini Open School for pregnant and mothering students in Tabora, Tanzania. This is accomplished by determining the requested electricity services and maximum daily load profile of the school at full-scale operation as well as prioritising the electricity services. It also involves evaluating different scenarios of electricity supply systems of solar energy in combination with the main grid from a techno-economical perspective. Additionally, the case study aims to evaluate the feasibility of producing biogas for clean cooking at the school. The result of this master thesis will assist the Tumaini Open School in its pursuit of Sustainable Development Goals (SDGs) 3 and 7 regarding good health and well-being and access to affordable and clean energy.

1.1.1 Research Questions

To fulfill the purpose of this master thesis, the following research questions (RQs) will be answered:

1. What will the requested electricity services, the resulting electricity demand and maximum daily load profile at the Tumaini Open School in Tabora be during full-scale operation?
2. Which electricity services are of higher priority to the facility and its inhabitants?
3. Which of the assessed electricity supply scenarios is most suitable to fulfill the electricity services from a technical and economical perspective?
4. Is biogas production a feasible option for cooking at the Tumaini Open School in Tabora with regards to technical and cultural restrictions?

1.2 Delimitations

The case study of the Tumaini Open School in Tabora only consider the full-scale school in full operation. The electricity demand and the electricity supply system scenarios of the school will therefore cover only this and not consider the construction period. However, the effects of the construction period will be discussed in various aspects. The scenarios will only consider an off-grid solar system providing electricity for the facilities at the school. Grid connected solar panels are not part of the study, nor is other separate smaller solar installations on the school premises such as solar water pump systems or independent outside lighting with its own solar cells. Only silicon (Si) photovoltaic (PV) solar cells is considered, and solely the two most common battery types for standalone PV systems: lithium-ion (Li-ion) batteries and lead-acid batteries. All other technologies are disregarded, as well as other energy sources for electricity generation such as various types of generators, wind power, geothermal and fossil fueled electricity generation.

When evaluating the feasibility of biogas production for cooking purposes at the school only technical and cultural restrictions will be considered. No regard to costs or economical feasibility will be considered. Only substrates from human, animal, food and fruit waste will be considered and not agricultural waste.

1.2.1 Electricity supply system scenarios

The study will assess three different scenarios for electricity supply, each system consisting of different ratios of electricity provided by solar power and the main grid. The base case of solely grid electricity will be used for comparison reasons. The solar power system in the different scenarios will be designed to fulfill various steps of the prioritised electricity services. The electricity service priority steps are a result of interviews and surveys with the students and staff of the Tumaini Open School, as well as other members of the organisation Tumaini Education Initiative. Electricity services such as outside lighting and security cameras were Automatically prioritised while services like projectors, computers and air conditioning (among other things) were categorised as more or less important based on the surveys and interviews. Priority step 1 is

Table 1: *Electricity supply system scenarios for solar power optimisation and economical calculations, based on the steps Auto, 1, 2, 3 and 4 of the prioritised electricity services.*

Scenario	**Priority step**				
	Auto	1	2	3	4
Base	Main grid				
1	Solar	Main grid			
2	Solar			Main grid	
3	Solar				Main grid

considered the most important and priority step 4 the least important services. The construction and design of the electricity service prioritisation steps is further explained in Sections 3.2.3 and 3.3.3.

Table 1 below illustrates how the scenarios are constructed from the priority steps. For example, in Scenario 1, only the Automatically prioritised electricity services are meant to be provided with electricity from the PV system, while the rest of the services are powered by the main grid. Additionally, two system sizes of the PV system in each scenario will be assessed, referred to as "Bigger Battery" and "Bigger PV".

1.3 Assumptions

Several assumptions have been made during the calculations of the electricity demand, the electricity supply systems, economical analysis and biogas calculations. The electricity demand calculations and the load profiles are based on assumptions of the future need of electricity services. The power usage of devices for the services are based on the upper margin of western standard devices. It is also assumed that the school kitchen will only use gas, charcoal or firewood as cooking fuels. For the load profiles, time steps of one hour have been used and the assumed usage of services are based on school breaks, daily variations within one week and seasonal variations between wet and dry season.

For the electricity supply systems, it is assumed that the solar system will not be connected to the main grid and therefore can not sell excess electricity, and that electricity prices from the main grid will remain the same over the assumed system lifetime. It is also assumed that there is space available on the school premises to install a centralised solar system.

For the biogas calculations the available amount of substrates at the school is assumed based on discussions with the Centre Director.

2 Tumaini Open School

The Tumaini Education Initiative describe their vision for the Tumaini Open School for pregnant and mothering students in the following way: (Tumaini Open School 2023):

"*We create a stigma-free second chance for underserved and unserved teen mothers; we enable them to regain their education goals, self-esteem and self-confidence, and eventually access higher education, vocational and other technical training*"

The vision and purpose of the Tumaini Open School works towards the Sustainable Development Goal 4: *Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all* and 5: *Achieve gender equality and empower all women and girls* (United Nations 2023a; United Nations 2023b).

The Tumaini Open School is located about 10 km south of Tabora in Tanzania. Tabora is the capital of the Tabora Region, a city of around 145 000 people (Worldometer 2023). Tabora is located in the west-central part of Tanzania, far inland at 1 200 m above sea level as seen in Figure 1.

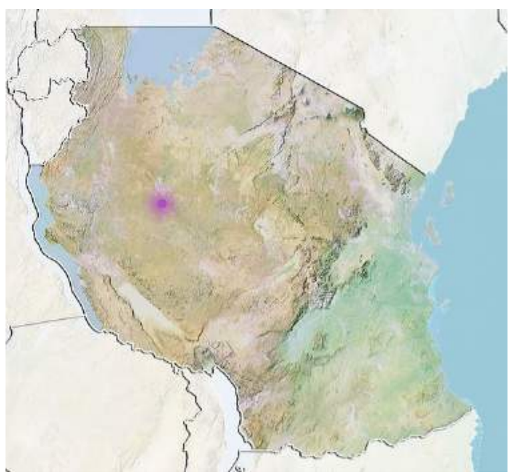


Figure 1: *Map of Tanzania with a mark of Tabora, edited from Encyclopædia Britannica ImageQuest (2023).*

The idea of The Tumaini Open School emerged during Mr. Kassanga's, now Centre Director of the school, thesis research within his postgraduate studies, when the President increased restrictions on adolescent mothers. Discriminatory policies against pregnant girls in public schools have been prevalent since independence in 1961, with limited advocacy for reforms by non-governmental organisations (NGOs). Despite efforts to educate both girls and boys, the education of adolescent mothers has been overlooked, and many of them are already out of school. This raises concerns about the lack of support for those who are already excluded from the formal education system, as policy reforms often take considerable time to be realised (Centre Director 2023).

The Centre Director's research involved an investigation of the activities of NGOs in supporting girls who have been expelled from school and need to regain access to education. It included an examination of alternative pathways aimed to identify advocacy and interventions undertaken by NGOs to facilitate the completion of primary or secondary education for expelled girls. However, the findings revealed that the assistance provided by NGOs was minimal, with a staggering 97 % of the girls receiving no help in 2019 (Centre Director 2023).

As a result of these findings, the Centre Director originated the concept of the Tumaini Open School for pregnant and mothering students, with a vision of a stigma-free and inclusive educational environment. While there are other NGOs that have established open schools for vulnerable girls, there is a gap in addressing the specific challenges faced by adolescent mothers. As the Tumaini Open School especially caters to their unique needs, it makes it the first of its kind. The Centre Director shared his idea with fellow founders who donated their own funds to establish classrooms for the school. Despite challenges, the school has received support and donations, and envisions a self-sustaining future, concerning both energy and food production (ibid.).

Since the Tanzanian government changed their policies in 2021, adolescent mothers are no longer banned from continuing their education in public schools. However, the systematic discrimination and the stigma that has been created is hard to eradicate. In December 2021 only approximately one-sixth of the adolescent mothers in Tanzania returned to their studies. For the communities and families of adolescent mothers to overcome this, collective effort and time is needed and eventually, reforms that benefit the vulnerable adolescent mothers can be initiated (Tumaini Open School 2023).

Since 2022 EWB Sweden and Tumaini Education Initiative has had a partnership. Through the wishes of Tumaini Education Initiative and the expertise provided by EWB Sweden, a land use plan was constructed and confirmed in May 2023. This can be seen in Figure 2a, where all buildings and other land uses for the school is represented. In Figure 2b, the same plan can be seen but with the planned rooms in all the buildings. The two parking lots situated in the northern and southern parts of the facility will be of the size 113 m^2 and 175 m^2 respectively.

The Tumaini Open School will be able to accept 450 students, out of which 250 will live in dormitories on the school premises out of which 100 may bring their child to live with them (Centre Director 2023).

(a) *Land use plan of the Tumaini Open School focusing on buildings.*

(b) *Land use plan of the Tumaini Open School focusing on interior.*

Figure 2: *Land use plan of the Tumaini Open School, exterior and interior (EWB Sweden 2023).*

A building with three classrooms and connection to the main grid has already been built and an extension of it is planned, see Figure 3a. Also, an accommodation house was in the process of being built in April 2023 as seen in in Figure 3b. These buildings can also be seen in the land use plan in Figure 2a above as "CLASSROOM" and "REST HOUSE", both down to the left.

(a) *Existing classroom building.* **(b)** *Accommodation house (in progress).*

Figure 3: *Existing buildings at The Tumaini Open School in April 2023 (Lovisa Magnusson Ericsson, 2023).*

During the field study, the students of the school were not attending the Tumaini Open School, but were instead spread out at different schools until sufficient facilities were ready at the start of the semester in July 2023.

3 Methodology

In this chapter, the overall research methodology is described followed by a presentation of the data collection, processing and calculation methods. The sections on methodology and data collection, along with some calculation sections, include a theoretical part before the actual methods used in this case study are described. The final part outlines the data processing methods and all calculation methods.

3.1 Research methodology

The research methodology of this case study is developed to systematically answer the formulated research questions as accurately as possible and to make sure that the end result is of use for the Tumaini Open School in the future. Since it is a case study and includes a minor field study, it is important that the research methods chosen are within the limitations of the field study and yet still suitable for the purpose of the report.

Research methodology does not only include the research methods themselves, but the logic behind why these methods are chosen for this particular research study. It includes every step from the reason why the study is conducted and how the problem formulation was defined to the data collection methods and data processing and analysis techniques (Kothari 2004, pp. 7–8).

3.1.1 Qualitative research

The purpose of qualitative research is to seek answers to more complex issues and highlight the "human side" of a research problem such as behaviours, opinions, emotions, beliefs and relationships (Northeastern University n.d. P. 1). In combination with quantitative research, the qualitative findings can help with the interpretation of quantitative data and provide a broader understanding of what that data means (ibid., p. 2).

There are three common qualitative research methods: *In-depth interviews*, *participant observations* and *focus groups*. Variations of the first two, interviews and observations, have been used in this study. Interviews are meant to collect data on personal experiences and perspectives which were necessary for parts of this study, while participant observations were necessary to collect data of the existing environment, conditions and behaviours without active involvement (ibid., p. 2). Qualitative methods always results in textual data and provides more flexibility than quantitative methods (ibid., p. 3).

A purposive sampling method was appropriate for the purpose of this study. The data collection continued until the objective of the study was achieved within the available resource and time limitations during the field study. This means that a certain quota of interviews does not need to be fulfilled. Therefore it is important to review and analyse the data continuously and in parallel to collecting it (ibid., p. 5).

3.1.2 Quantitative research

Quantitative research aims to explain or answer a certain question or problem in numerical terms. Statistics and mathematical methods are often applied for analysing the obtained data. Even data that does not naturally occur in a numerical form, such as opinions and behaviours, can be quantified by using surveys and questionnaires. In this way, such properties can be rated and measured and translated into numbers (Watson 2015). Structured observations is another way to quantify naturally occurring events and describe characteristics of, for example, a sub-population (Northeastern University n.d. P. 3). In-person surveys as well as digital surveys, and structured observations were both used in this study.

3.1.3 The chosen research methodology

The reason for this case study originates from when one of the authors reached out to EWB Sweden on the 17th of October 2022 and got in contact with Tommy Lindström, Head of the the Energy and Waste management competence group. Following a meeting, the project at the Tumaini Open School, with partner organisation Tumaini Education Initiative, was suggested to be the subject of a master thesis. After discussions with the Project Manager at EWB Sweden, Karin Carlsson, a pre-study for electricity demand and supply was decided to be a part of EWB Sweden's pre-study of the school. From this, the problem formulation and research questions were developed in cooperation with both supervisor Max Åhman and examiner Henrik Davidsson at LTH to fulfill the requirements of a Master of Science in Engineering thesis, and with the Head of the the Energy and Waste management competence group, the Project Manager and the Centre Director of the Tumaini Open School, to ascertain the usefulness for the organisation in question. Assumptions and delimitation's have been established in agreement with and based on inputs from the Centre Director during early meetings and discussions. A common understanding regarding the time limitations of the field study has also been a foundation to the framework of the study.

The first step of this case study was to determine the electricity demand for the school facilities at full scale, and to do this, step one was to identify the requested electricity services. Step two was to quantify when these services wished to be fulfilled. Step three meant determining the energy use of all devices. Combining these three steps resulted in a maximum daily load profile which revealed power peaks over the day on which to base the optimisation and evaluation of the final electricity system on. Also, a prioritisation of the electricity services were made and categorised into steps through interviews and a survey. This data was used to create three electricity supply system scenarios.

The next step was to evaluate different ways to incorporate solar panels, batteries and the main grid into a functioning electricity supply system. A literature study was made to obtain theoretical knowledge about solar power systems such as generating process, technical specifications, installation requirements, capacity and components. Interviews with solar experts were conducted and two solar power installations were visited. The solar systems for each scenario were optimised and the Levelized Cost of Electricity (LCOE) calculated, as well as the electricity cost per kWh from the main grid for each scenario. After this, the total cost for each scenario was calculated and later compared.

Parallel to these steps a literature study was made to obtain theoretical knowledge about biogas production in developing countries and more specifically in Tanzania. During the field study, interviews with the Centre Director, the Tumaini Education Initiative Member and Interpreter Mr. Simon and biogas experts were conducted regarding the feasibility of using biogas for cooking at Tumaini Open School. Additionally, three biogas plants were visited as well as a school utilising a gas kitchen. Calculations were also made regarding the future biogas demand and production, which were also compared to determine the balance, additionally the possible digester size of the biogas plants at the school was calculated.

3.2 Data collection

Data collection can be categorized into two sources: primary and secondary data. Primary data is collected and sourced for the first time and is by default original and fresh. Secondary data is collected and processed by another person. By deciding which type of data is necessary for the purpose of the study, the appropriate data collection methods can be chosen (Kothari 2004, p. 95). This report was in need of both primary and secondary data, and hence, the following data collection methods have been used: *literature study*, *interviews*, *surveys* and *observations*.

3.2.1 Literature study

A literature study is an appropriate starting point for any research study. By gaining an overview of the available data and material on the topic, it is easier to develop the problem formulation and what data needs to be collected to answer it. The literature studied can be categorized into two types: conceptual (theories and concepts etc) and empirical (previous studies) (ibid., p. 12). For this report, the conceptual literature involved theories, models, concepts and regulations, among other things, that was necessary for further calculations and analysis of the primary data. To gain a better understanding of the conditions and local context of a case study in a developing country, empirical literature in the form of previous studies within the similar topic were reviewed.

The sources for conceptual literature were scientific papers, publications and guidelines from governments, international organisations, NGOs, interest organisations, technical journals, online magazines, books and public records and statistics. Empirical literature was found in the form of previous similar thesis reports, case studies and other Minor Field Studies within the same field and geographical region. Particularly interesting reference projects were studied more in-depth and inspired the methodology of this report. The main search engines that have been used are LUB-search and Google.

Some of the keywords that were used during the literature study were: Minor Field Study, Rural biogas plants, Anaerobic Digestion, Developing countries, Standalone PV systems, Grid Connection, Climate Change, Legislative Energy Framework in Tanzania, Energy in Tanzania, Tabora, TANESCO, EWURA, TAREA, Optimisation of standalone PV systems, Subsidies and LCOE, fixed dome plant, CAMARTEC.

3.2.2 Interviews

This section begins with a theoretical summary of interview techniques to give an introduction to this method of primary data collection. Secondly, the chosen interview method is described more in detail. Finally, all the interviews conducted in this case study are presented.

Theory on interview techniques

Qualitative research often employs unstructured or semi-structured interviews, which can be used as standalone methods or in conjunction with ethnographic research or other qualitative techniques. To capture the interviewee's perspective, it is advisable to maintain an unstructured or semi-structured interview format. Although an interview guide may be utilised, it should not be rigidly enforced as this can impede flexibility (Bryman 2011, p. 445). Whenever possible, interviews should be recorded and transcribed (ibid., p. 445), and field notes should be taken when necessary to preserve the freshness of one's impressions (ibid., p. 396).

In qualitative interviews, allowing the interview to wander in various directions can be advantageous as it can reveal what the interviewees consider significant. When employing a qualitative interview guide, it is common to deviate significantly from it during the interview by posing spontaneous or follow-up questions, altering the order or wording of questions. The guide is meant to be used as a tool and not as a strict protocol. The goal is to elicit comprehensive and detailed responses, and an interviewee may be interviewed multiple times to accomplish this (Bryman 2011, p. 413).

Unstructured interviews resemble normal conversations where only one or no questions are pre-planned, and a memorandum may be used as an aid to recollection. On the other hand, semi-structured interviews involve the use of an interview guide in which different themes are predetermined. When the study's purpose is relatively clear, or when there are multiple researchers, semi-structured interviews are typically employed (ibid., pp. 415–416).

To ensure that the fieldwork remains open to diverse perspectives, the research questions should not be excessively narrow or restrictive. It is important to begin the investigation with an open mind and avoid overly rigid preconceptions. Interview questions should be designed to effectively address the research questions while avoiding excessive specificity. It is essential that the questions are understandable to the interviewee and avoid leading or biased phrasing. Moreover, it is important to gather relevant background information, such as the interviewee's name, age, sex, and title, to contextualize the interviewee's responses (ibid., pp. 419–423).

The interview environment is also a crucial factor in obtaining accurate and candid responses, including ensuring the interviewee's safety, minimizing distractions, and preventing eavesdropping. Numerous strategies can assist in conducting a successful interview including maintaining awareness of the interview's focus and steering it as necessary, describing the interview structure to the interviewee and exhibiting consideration and respect. It is equally important being ethically conscious by clearly communicating the study's purpose and ensuring that information is handled confidentially. Additionally, the language used in formulating questions should be precise and unambiguous. It is crucial to exhibit sensitivity by actively listening and exhibiting empathy, and being critical when discrepancies arise in the interviewee's responses. Effective recall of prior discussion topics is important for connecting previously mentioned concepts throughout the interview process. Notes that are beneficial to write after the interview include the interviewee's state of mind, where the interview took place, other experiences and the environment (ibid., pp. 419–423).

Implementation of interview techniques

The qualitative method of semi-structured interviews were chosen for this case study as it provides flexibility to the interviewer. The necessary information regarding the future plan of Tumaini Open School, the desired electricity services, estimated electricity usage and local conditions were considered to be most easily obtained through interviews at site. The questions were pre-determined to fulfill the purpose of the interview, but the interviewer also asked follow-up questions depending on the answers. The interview questions were formulated in such a way that, despite translation through an interpreter, misunderstandings were to be minimized as much as possible. The interviews of the students were audio recorded after consent from the interviewee to document all answers through the interpreter in case it was needed at a later stage. When necessary, field notes were taken in conjunction with the interviews.

All interviews and what information was obtained are presented in Table 2. Interviews with the Centre Director, the Member and Interpreter, the students of Tumaini Open School and TANESCO were conducted in person while the remaining interviews were online since they were situated in other parts of Tanzania.

Table 2: *List of interviewee's and the information obtained during the meetings or interviews.*

Interviewee	Information obtained
The Centre Director - Centre Director of Tumaini Open School	Multiple meetings to obtain information about the project, present status, future goals, assumptions on electricity usage, etc
Member of the Tumaini Education Initiative & Interpreter	General information about the school and the project
7 students from Tumaini Open School	Electricity usage habits, prioritisation of the electricity services
Executive Director and Renewable Energy & Energy Efficiency Expert from TAREA	Subsidies and regulations for solar and bio energy, general information and advice etc.
Solar expert from Photons Energy Ltd. 2023	Advice, solar optimisation suggestions and cost estimates
Solar expert from GadgetroniX 2023	Advice and cost estimates
Solar expert from Power Providers 2023	General information about solar energy and advice
Senior Engineer at TANESCO	Frequency of power outages, power grid connection of solar systems and main grid costs
Biogas expert from Afrihands Tanzania	General information about biogas production in Tanzania

During the interviews with the seven students, the Member and Interpreter from the school was translating between the interviewer and interviewees. The Interpreter was well known to the authors and the students beforehand. The interviewer made sure several times during the interview that the interviewee had understood the question correctly and asked relevant follow-up questions based on the interviewee's answers. See an extended description of the execution of the interviews in Appendix A.1 and the interview templates in Appendix A.2 and A.3.

3.2.3 Survey

For the purpose of prioritising the electricity services, the quantitative method of a survey was used to decide which electricity services were of greater priority to the school. The target group for the survey was the students and teachers at the Tumaini Open School, as well as the Centre Director and other members of Tumaini Education Initiative. Through discussions with the Centre Director, a number of electricity services were decided to automatically be put at the highest priority (referred to as "Auto"), and the rest of them became part of the survey to be prioritised from 1-4. For the students and teachers, the survey was translated into Swahili by the Centre Director and the Interpreter. The survey contained the relevant electricity services for each target group and the subjects of the survey got to choose the ten, five and three most important services to each one of them. See the survey templates in Appendix B.1 and how the survey was used to create the Priority steps in Section 3.3.3.

In conjunction with performing interviews with the students, the survey was also carried out among them. The decision to perform the interview first and the survey second was based on the idea that the students would then be given an oral introduction to the purpose of the study and not just read an instruction which could be harder to understand and less motivating. Also, the interview provided them with questions to reflect on their electricity usage. The survey was then thoroughly explained to the first interviewed student with the help of the Interpreter, and one by one, the students answered the survey after being interviewed by the authors and presented to it by the first student. The teachers and other members of Tumaini Education Initiative received the survey through email since the there were no possibility of interviewing them. It was administered by the Centre Director along with instructions, also translated into Swahili.

3.2.4 Observations

Observations can be categorised in several different ways. The most relevant categories for this study were *structured* vs. *unstructured observations* and *controlled* vs. *uncontrolled observations*. Structured observations can for example have predetermined "boxes to tick" and a protocol of units to be filled in (Kothari 2004, p. 96). This method was used during study visits for reference projects, for example when visiting a solar power installation or biogas plant where field notes and photographs were taken. Unstructured observations do not require these predetermined protocols but instead allows observations to be of a more exploratory nature, with the purpose of answering the questions of the report (ibid., p. 96). These kind of observations were made continuously throughout the field study to gain understanding of the local context. Photos and notes were taken when interesting observations of technical and cultural limitations were discovered. The authors kept an open mind during the field study to be susceptible to additional information that could add any value to the report in a later stage.

In the case of controlled vs. uncontrolled observations, only the latter is applicable to this study since the former refers to observations in a controlled environment such as a laboratory. Uncontrolled observations on the other hand take place in a natural environment, undisturbed and without precision instruments. It is suitable for studying behaviours and natural sequences of events. However, these observations are vulnerable for subjective interpretations but at the same time, they provide a more complete overview of the context (ibid., p. 97).

At every study visit, notes were taken of relevant sightings and overheard information. Pictures were taken during study visits, particularly of technical specifications when possible. Table 3 presents all study visits conducted during the field study.

Table 3: *Study visits made by the authors.*

Study visits
Solar water pump system at the Centre Director's garden
Solar power installation at St. Ann Catholic Mission Hospital
Sikonge Folk Development College
Biogas plant at Site 1: St. Mbaaga Spiritual Formation Centre
Biogas plant at Site 2: St. Monica School
Biogas plant at Site 3: Convent of Carmelite Missionary Sisters

3.3 Data processing and calculations

This section describes the different methods of data processing that have been used to convert literature findings, interview answers, survey results and observations into qualitative and quantitative results. First comes a section on data processing theory. This is followed by sections on electricity demand and electricity service priority steps which laid the foundation for the rest of the study. These results were used to optimize the solar systems for the different electricity supply scenarios. After this, LCOE calculations of the solar systems and main grid costs per kWh were conducted for all scenarios. Finally, the total economical cost for each scenario were determined to be compared and analysed. The biogas demand, time needed for cooking, the possible biogas production and calculations for sizing the digesters is presented in the final section.

3.3.1 Data processing theory

After the data collection is completed the data processing can begin. The first step is to edit any errors and identify omissions in the raw data material. The data needs to be accurately entered and in the correct format for further processing and calculation. Editing should take place as soon as possible in conjunction with the occasion for data collection (Kothari 2004, pp. 122–123). The next step is to continue with classification of data and calculations where necessary. Finally, tabulation and proper illustration of the resulting data concludes the data processing (ibid., p. 127).

3.3.2 Electricity demand calculations

To identify the electricity demand the information was gathered in three main steps, as described in Section 3.1.3. The requested electricity services in each building and room on the school premises was established through interviews and discussions with the Centre Director, as was the estimations of number of hours and during what hours of the day each electricity service in every room needed to be fulfilled. Additionally, the answers from the student interviews were also taken into consideration. The hours of usage often varied with wet and dry season and between weekdays and weekends. To make sure the peak power and daily electricity demand would be covered, the hours of usage were set to the upper limit of the suggested range when considering maximum daily load profile.

The third and final step was to decide the power output of all the devices used to fulfill the required electricity services. The wattage of the devices were found from various online sources. The wattage of devices were selected in the upper range of devices in western countries because of lack of data for developing countries and Tanzania. The input values for the devices can be seen in Appendix C.1. In addition, the Digitisation expert from EWB Sweden was consulted to help with the power usage of computers and the server.

Based on the gathered information, a maximum daily load profile was calculated to display the maximum power peaks over the day. To determine the yearly electricity demand, the variations over the week and yearly seasons as well as the school breaks were taken into consideration. What is included and excluded during the weeks are presented in Table 4 below, along with the seasons and weeks of breaks over the year. The excel sheets for the electricity demand calculations and load profiles can be received upon request.

Table 4: *Services and buildings taken into consideration in the weekly and yearly electricity load profiles. Green colour means it is included and red colour means it is excluded. Days of the week is presented at the top of the table and weeks of breaks during each month at the bottom. Based on interviews with Centre Director (2023).*

Weekly load profile			
	Weekdays		Weekends
Day	1-2	3-5	6-7
Dry season	All	Computer & tailor laboratories, conference hall	Computer & tailor laboratories, classrooms, administration, conference hall, child care
Wet season	AC	Computer & tailor laboratories, conference hall, AC	Computer & tailor laboratories, classrooms, administration, conference hall, child care, AC
Breaks	All		

Yearly load profile												
Dry season	February, June-October											
Wet season	November-January, March-May											
Breaks	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	2			1	1	4	2		1			4

3.3.3 Prioritisation of the electricity services

The results from the survey, explained in Section 3.2.3, resulted in five priority steps: Automatic, 1, 2, 3 and 4. The Automatically prioritised services were as mentioned before determined through discussion with the Centre Director. Furthermore is Priority 1 the highest priority and 4 is the lowest. The survey was answered by seven students, six teachers, the Centre Director and three other members of Tumaini Education Initiative (in total seventeen people). The electricity services were prioritised according to:

Automatic: services automatically prioritised
Priority 1: services prioritised as top 3 among at least 5/17 of the target group
Priority 2: services prioritised as top 5 among at least 1/17 of the target group
Priority 3: services prioritised as top 10 among at least 1/17 of the target group
Priority 4: all the remaining services

Based on the resulting priority steps, three scenarios were created and a yearly load profile for each scenario was developed using the conditions shown in Table 4. The illustration of the scenarios can be seen in Section 1.2.1.

3.3.4 Optimisation method of the solar system

First, based on the reports of Qazi (2017) and Shenawy, E. T. El, Hegazy, A. H. and Abdellatef, M. (2017), a calculation was made to decide the necessary installed PV capacity. These results are referred to as the "PV capacity". Inputs for the PV capacity were the maximum daily load, sun hours at the specific site and loss factors. The sun hours were defined by the average number of hours per day with 1 kW/m^2 of solar irradiation on average. For example, if a site receives 7 kWh/m^2 in a day, it has received on average 7 hours of sun at 1 kW/m^2. The formula used can be seen in Equation 1 (Qazi 2017; Shenawy, E. T. El, Hegazy, A. H. and Abdellatef, M. 2017).

$$P_{PV} = \frac{Load}{H_S \cdot \eta_{tot}} \tag{1}$$

Where:

P_{PV} = Installed PV capacity (kW)
$Load$ = Daily electricity load (kWh/day)
H_S = Sun hours (h/day)
η_{tot} = Total loss factor

The results of RQ 1 and 2 were used as input values for the daily electricity load (plus 10 % load in the Bigger PV cases) and World Bank Group (2023) provided the values for sun hours. Furthermore, the total loss factor η_{tot} was a product of the following loss factors:

η_{access} = Average solar access (weather conditions)
$\eta_{soiling}$ = Module soiling rate (dirt on PV modules)
$\eta_{availability}$ = System availability rate (O&M losses)
η_{inv} = Inverter efficiency
η_{bat} = Battery efficiency
η_{TC} = Module temperature loss

Where η_{TC} was based on the temperature coefficient T_C described in Section 5.1.2. All input values for the loss factors came from the two reports by Qazi (2017) and Shenawy, E. T. El, Hegazy, A. H. and Abdellatef, M. (2017) and from Section 5.1.2 where the temperature coefficient is discussed. The input values for the PV capacity optimisation can be seen in Appendix D.1.

The second step in the optimisation process was to determine the electricity production by the solar panels. To do this, the hourly PV production was determined by using the simulation tool System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL). The simplified model PVWATTS and No financial model was used, with the PV capacity and a weather data file from National Renewable Energy Laboratory (n.d.[a]) for Tabora as inputs along with inverter efficiency, tilt angle, azimuth angle and other loss factors set according to the reports of Qazi (2017) and Shenawy, E. T. El, Hegazy, A. H. and Abdellatef, M. (2017) and the theory described in Section 5.1.2. The hourly electricity production from the PV system (referred to as "hourly production profile") was chosen as output from SAM and used in the next step.

The last step was to determine the installed battery capacity for the six system sizes, which are referred to as "battery capacity". The yearly load profiles and the hourly production profile were used as inputs in an Excel file based on a file from Davidsson, H. (2023). To avoid over sizing the battery, the PV production was set to zero during school breaks. The Excel file was prepared to give an account for electricity balance per hour, i.e. if electricity was missing, used or dumped compared to the load. After some iteration, an allowed limit of 10 % annual electricity shortage was set and used to decide the appropriate battery capacity. Part of the Excel sheet to optimise the battery capacity can be seen in Appendix D.2.

3.3.5 Economical calculations

In this section the theory of LCOE is presented as well as the method for economical calculations of the solar LCOE, the main grid cost for the base case and the scenarios and finally, the resulting total cost for all scenarios. All prices stated in Tanzanian shillings (TZS) were converted to USD using the same conversion factor: 1 TZS = 0.00043 USD (from 2023-04-13) (OANDA n.d.).

Theory of LCOE

LCOE is the most common method for comparing cost of energy. It shows the needed price of electricity for the revenues to equal the costs of an investment. If the electricity price is above the LCOE it would mean a bigger return on the investment while a price below it would mean a lower return and a loss on the investment. Equation 2 is a simplified LCOE equation (Badouard et al. 2020), where the *Total lifetime cost* and the *Total lifetime output* can be described as *The sum of costs over lifetime* and *The sum of output produced over the lifetime*, respectively.

$$\text{LCOE} = \frac{\text{Total lifetime cost}}{\text{Total lifetime output}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2}$$

Where:

I_t = Investment and expenditure cost

M_t = Fixed and variable operation and maintenance (O&M) expenditures for the year t, such as administration and technical salary, system maintenance, etc.

F_t = Fuel expenditures for the year t

E_t = Electrical/energy output for the year t

r = Discount rate

n = Expected lifetime of the power system

Because the LCOE is standardized some parameters are hard to predict, for example the variable costs during the long lifetime of the energy system, especially in a dynamic market (Energy Education n.d.). Additionally, some aspects are not taken into account such as the level of competition, the revenue streams of the systems and financial indicators for investment decisions. Furthermore, the reliability of a technology is not taken into account (Badouard et al. 2020).

LCOE for the solar system

To calculate the LCOE for the solar systems in the electricity supply scenarios, inquiries to three different solar power companies in Tanzania were made where two of them responded. The cost offers can be seen in Appendix E.1. From these the most suitable and cheapest solar panels, batteries and hybrid inverter/chargers were chosen, as well as the cheapest installation, transport and other costs to be used in the calculations. The exact costs used for calculations can be seen in Appendix E.2.

The LCOE was then calculated according to Equation 2 above, where a degradation rate was included for the yearly O&M costs, see Equation 3.

$$M_t = M_y \times (1 + d)^{t-1} \tag{3}$$

Where:

M_y = O&M cost for one year

d = O&M degradation rate

The Excel sheet with all calculations for Scenario 1: Bigger Battery can be seen in Appendix E.3.

Main grid electricity cost for the base case

To compare the total electricity cost for the scenarios, the cost for supplying the entire system from the main grid was first determined (referred to as the "base case"). The electricity price from 2016's tariffs was assumed to remain the same during the entire lifetime of the system, which was based on the historic tariffs and the statement from TANESCO (2023b), presented in Section 4.2.6 that predicted the changes to be small in the future, along with literature sources. The results from the electricity demand determined the choice of tariff, and in calculations, the tax was also included. Based on the results for hourly electricity demand for one full year (with regard to both wet and dry season as well as different loads on weekdays and weekends), the monthly electricity demand and maximum power demand was obtained. Using this, the electricity cost per month was calculated using Equation 4. See the used values in Appendix E.4.

$$\text{Electricity cost per month} = \text{Service charge (USD/month)} + \text{Energy charge (USD/kWh)} \times \text{Monthly energy demand (kWh/month)} + \text{Maximum power charge (USD/kW/month)} \times \text{Maximum power demand (kW)} \tag{4}$$

All monthly costs were then added to obtain the yearly cost to be used as year one ($t = 1$) in Equation 5. Even though the electrical load and cost for the main grid was assumed to be constant over the assumed lifetime, the same methodology as for LCOE was used to be able to compare and combine them later. This meant discounting both the electricity load and electricity cost over the assumed system lifetime.

$$\text{Total base case cost} = \frac{\text{Total electricity cost}_{\text{lifetime}}}{\text{Total electricity load}_{\text{lifetime}}} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{L_t}{(1+r)^t}} \tag{5}$$

Where:

C_t = Electricity cost for the year t

L_t = Electricity load for the year t

r = Discount rate

n = Expected lifetime of the power system

Main grid electricity costs for Scenario 1-3

As a result of the scenarios covering different many electricity services, the remaining electricity that was not supplied by the solar panels had to be bought from the main grid (both electricity shortage for the prioritised services included in each scenario and the excluded services). To calculate the cost for the electricity bought from the main grid, the electricity consumed from the solar panels or batteries were subtracted from the base case load on an hourly basis, which gave the monthly main grid load and maximum power demand. The same method as for the base case was then used to obtain the total cost for electricity bought from the main grid for each system size. See Equation 5.

Total electricity cost

To obtain the total electricity cost for the all system sizes, Equation 6 was used and the results were compared with each other and the base case, where the $Total\ NPV\ of\ main\ grid\ cost_{\ lifetime}$ for the base case was used for comparison.

$$\text{Total cost} = \text{Total NPV of solar cost}_{\text{ lifetime}} + \text{Total NPV of main grid cost}_{\text{ lifetime}} \tag{6}$$

Where:

Total cost = Total cost of the full system (solar panels and grid electricity) (USD)
Total NPV of solar cost $_{lifetime}$ = Total Net Present Value (NPV) of the solar PV system (USD)
Total NPV of main grid cost $_{lifetime}$ = Total NPV of the main grid cost (USD)

3.3.6 Biogas calculations

In this section the calculation method for biogas demand, time for cooking, biogas production and the balance of the demand and production are presented, along with the needed digester size for the plants with different substrates.

Biogas demand and time needed for cooking

To determine the biogas demand per day for the Tumaini Open School, the biogas demand per person per meal and meals per day was used (Afrihands Tanzania 2023b). From Afrihands Tanzania (ibid.), an average consumption rate of the gas stoves was also obtained and used to calculate the amount of time needed for cooking per meal per day using 1-6 stoves. See Equation 7 and all used values in Appendix F.1.

$$U = \frac{Q_{bio}}{Q_{stove} \times n_{stoves}} \tag{7}$$

Where:

U = Hours of gas usage per day (h)
Q_{bio} = Biogas production (m^3/day)
Q_{stove} = Consumption of biogas per stove (m^3/h)
n_{stoves} = Number of stoves

Biogas production

For each type of substrate available, the biogas production was calculated using Equation 8.

$$Q_{bio} = M_{tot} \times Y \tag{8}$$

Where:

M_{tot} = Average generation of substrate (kg/day or kg VS/day)
Y = Biogas yield (m^3/kg or kg VS)

The number of waste generating animals and humans were based on interviews with Centre Director (2023). Two sets of data were used for biogas yield and substrate generation from two different sources: (1) An average of several literature sources, and (2) Data obtained from the study visit with Afrihands Tanzania (2023b). The input values of datasets (1) and (2) can be found in Appendix F.2. This gave two sets of results that were later compared.

Balance

To compare the biogas demand with the possible biogas production from the available substrate the balance was calculated and discussed.

Sizing of the digesters

The method used to calculate the digester volume for the different substrates was provided by Afrihands Tanzania (2023b). Before calculating the digester volume, the volume of the substrate input had to be calculated. This was done by using Equations 9 and 10 with the assumption that 1 kg of substrate equals 1 l, and that the water to substrate ratio is 0:1 (ibid.). The input values that were used can be found in Appendix F.3.

$$\mathrm{Q} = \mathrm{M} \times (y + x) \tag{9}$$

Where:

Q = Substrate flow rate (m^3/day)
M = Average generation of substrate (kg/day)
x,y = Ratio y:x of water to substrate

$$V_{input} = \mathrm{Q} \times \mathrm{HRT} \tag{10}$$

Where:

V_{input} = Input of substrate and water to the digester (m^3/day)
HRT = Hydraulic Retention Time (days)

To determine the volume of the digester Equation 11 was used.

$$V_{digester} = V_{input} \tag{11}$$

Where:

$V_{digester}$ = Volume of the digester (m^3)

4 Background

This section includes the weather of Tabora, Tanzania where Tumaini Open School is located and Tanzania's legal and regulatory framework for sustainable energy.

4.1 Weather conditions

In this section the weather conditions of Tabora, such as the temperature, precipitation, hours of sun and the occurrence of extreme weather and natural hazards, is presented.

4.1.1 Temperature

During the years 1991-2021, the lowest average monthly min-temperature was 14 °C in July, while the highest average monthly max-temperature was 32 °C in October (see Figure 4). The lower night time temperatures are in general around 18 °C over the year with a drop between May and September. The higher day time temperatures stay around 28-29 °C throughout the year except an increase between August and November (World Bank Group 2021c).

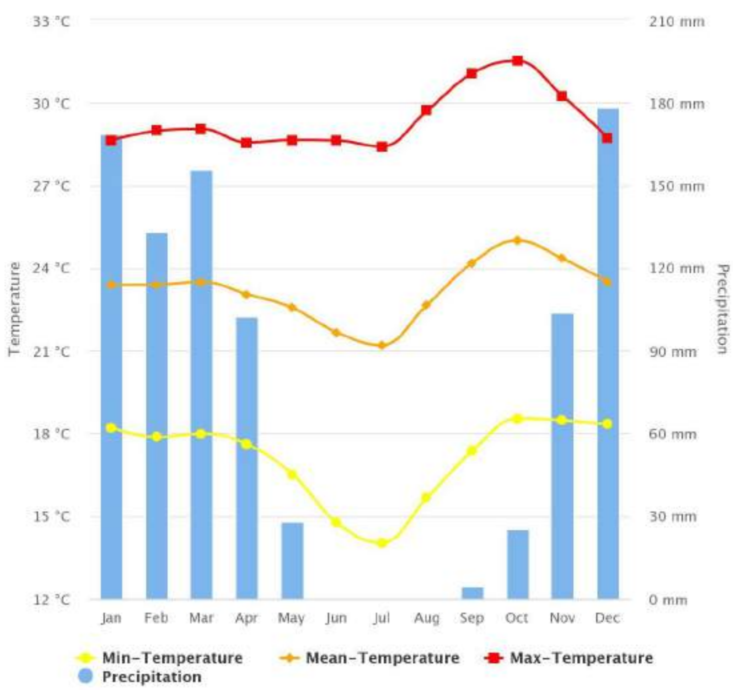


Figure 4: *Monthly Climatology of min-temperature, mean-temperature, max-temperature and precipitation 1991-2021 in Tabora, Tanzania (World Bank Group 2021c).*

Looking at trends and variability over a longer period of time illustrates the anthropogenic effects more clearly since natural variations occur on a year to year basis. The mean temperatures throughout the whole year has increased with about two degrees over the last 70 years (ibid.).

Projections for Tanzania's future climate depends on the Shared Socioeconomic Pathways (SSPs) (World Bank Group 2021b) which were developed by researchers in the late 2000s. They take factors like population growth, economic growth and urbanisation into consideration for modelling the future society which in turn is used for climate projections (Hausfather 2018).

The mean daily temperature between the years 2040-2059 seems to be increasing with about 0.5-1.5 °C throughout the year in all SSPs according to World Bank Group (2021b). Modesta, L.P. and Elias, S.A. (2020) confirms this statement, claiming that the minimum and maximum temperatures are both expected to increase during 2011-2040 in the Lake Victoria Region, which is slightly northwest of the Tabora Region. The minimum temperature is expected to increase 1.0-1.5 °C during the coldest months (June-September) while the maximum temperatures are expected to increase 0.7-1.2 °C on average over the year (ibid.).

4.1.2 Precipitation

When it comes to precipitation, Tanzania has historically had very reliable wet seasons but lately they are getting more unpredictable due to climate change (Southern Africa Drought Resilience Initiative 2021). The recurring wet seasons can also be seen in Figure 4, where the heavy rains fall from March to May and the shorter rains between November and January. Tabora however is in one of the more arid areas since it is on the higher mainland (Natural Habitats Adventures 2023; World Bank Group 2021c).

The future amount of precipitation is also affected by climate change and changes vary from -18 % rain in September-November (SSPs1-1.9 scenarios, 2040-2059) to +6.4 % rain in December-February (SSPs3-7.0 scenarios, 2040-2059). It is hard to draw any definite conclusions about increased or decreased precipitation because it varies between different SSPs, both more and less rain during different wet seasons and years in projections. What is certain though is that changes in rainfall and consecutive dry days will appear and scenarios contain ambiguities that can not be foreseen (World Bank Group 2021b).

4.1.3 Hours of sun

Since Tabora (and Tanzania) is located very close to the equator, the city always get approximately 12 h of daylight every day throughout the year (it only differs ±20-25 min) (Weather Spark 2023). The solar insolation is at its highest in the central parts of the country which makes Tabora particularly suitable for solar power. The exact location for Tumaini Open School can be put into the tool called Global Solar Atlas from World Bank Group (2023) which gives the theoretical average global horizontal irradiation of 6.13 kWh/m^2/day and average solar PV output of 4.88 kWh/kW$_p$/day. The optimum tilt from horizontal for the PV module is 10°, and optimum azimuth angle is 0°(facing north) (ibid.).

4.1.4 Extreme weather and natural hazards

Extreme weather events are such events that differ from the normal mean climate. It occurs when a certain combination of conditions are fulfilled simultaneously which is relatively rare, but climate change and rising temperatures increase the risk of extreme weather events happening. It is especially true for precipitation since for every 1 °C warmer air temperature, its potential to carry water goes up by 7 %. This is called the "Clausius-Clapeyron-Relationship". So not only does climate change increase the probability of extreme rainfall to occur, it also increases the amount of rain that falls (World Bank Group 2021a).

Tabora is considered a hotspot regarding the increased risk for droughts in the future. In the last 30 years, six major droughts has struck Tanzania and climate change projections are pointing towards even longer and more frequent droughts in the arid central region which Tabora belongs to. Agriculture is deemed to be strongly affected with double amount of crop losses from intensification of droughts (Southern Africa Drought Resilience Initiative 2021).

4.2 Tanzania's legal framework and electricity sector

This section will describe the energy authorities, organisations and NGOs in Tanzania, policies in Tanzania regarding energy, licensing requirements and subsidies, interconnection with the main grid, the electricity price for main grid electricity and the grid reliability.

4.2.1 Energy authorities, organisations and NGOs

The former President of Tanzania created a Ministry of Energy through a Notice on Assignment of Ministerial Functions in 2016. The ministry is responsible for formulation and monitoring of the policies for energy, oil and gas in the country (Ministry of Energy 2023). The regulatory framework for the energy sector in Tanzania is overseen by the Energy and Water Utilities Regulatory Authority (EWURA). This regulatory body has been granted various powers in order to effectively govern the electricity supply industry. Specifically, EWURA is authorized to issue licenses to entities operating within this sector, as well as to review and enforce the tariffs and fees charged by these licensees. Additionally, EWURA is responsible for approving the terms and conditions of electricity supply offered by these licensees, as well as for initiating the procurement of new electricity supply installations (EWURA 2023; Mramba, C., Zervos, N. and Ngalinda, S. 2019).

TANESCO has mandate in power generation, transmission, and distribution. The state owned company generates electricity through its own plants and also receives power from independent power producers (IPPs) to supply the national grid and isolated areas. The company is responsible for power transmission, including the O&M of the grid, which is interconnected with TANESCO's generation and distribution systems. Furthermore, TANESCO is responsible for power distribution activities and general customer service issues (TANESCO 2023a).

The Rural Energy Agency's (REA) goal is to promote and facilitate rural energy development in collaboration with various organisations. REA's functions include promoting, stimulating and improving modern energy access for productive uses in rural areas, financing eligible rural energy projects and providing technical assistance to project developers and rural communities. The agency also works to promote the rational and efficient production and use of energy, prepare and review application procedures and guidelines for grants allocation and facilitate the preparation of documents for rural energy projects (Devex 2023).

CAMARTEC is a Government Institution under the Ministry of Industry and Trade and has programs within Agricultural Mechanization and Rural Technologies (CAMARTEC 2023b). CAMARTEC describe their mission as *"To promote agricultural development and agro-based industrialization through improved agricultural mechanization, agricultural processing technologies and rural energy."* (CAMARTEC 2023a).

Tanzania Renewable Energy Association (TAREA) is a non-profit organisation with over 900 members that aims to promote the accessibility and use of renewable energy and energy efficiency technologies. Their mission is to develop a network of stakeholders and advocate for increased use of renewable energy while emphasizing good quality and the best practices. The association conducts various activities such as forging partnerships, lobbying for policies and regulations, providing advisory services, conducting research and education, as well as disperse information (TAREA 2021).

4.2.2 Policies

The National Energy Policy (NEP) was updated in December 2015 with the aim of providing Tanzanians with sufficient, dependable and affordable energy in a sustainable manner. The policy advocates for the scaling up of renewable energy sources such as solar, biomass, wind, small-scale hydro and geothermal, while also promoting alternatives to wood for cooking and regulating the use of petroleum. In addition, the document seeks to enhance institutional, legal and regulatory frameworks and human resources to support the development of a sustainable energy sector (Grantham Research Institute 2023).

4.2.3 Licensing requirements

According to EWURA regulations, all operators of mini-grids with an installed capacity of more than 1 MW must obtain a licence from the regulator before commencing operations. The projects can also require a provisional licence. All operators who are exempted from licensing requirements for renewable energy projects, with an installed capacity of less than 1 MW at a single site, as well as off-grid distribution and supply activities with a maximum demand under 1 MW, must register with EWURA and obtain a Registration Certificate upon completion of the project's commissioning. However, mini-grids below 100 kW do not need to obtain the Registration Certificate (Mramba, C., Zervos, N. and Ngalinda, S. 2019; Zigah, E., Barry, M. and Creti, A. 2023).

4.2.4 Subsidies

To increase the competitiveness of renewable energy technologies, some taxes and import duties have been eliminated (Zigah, E., Barry, M. and Creti, A. 2023). The value-added tax (VAT), customs and excise duties do not apply to components and parts of solar energy systems and PV cells (Mramba, C., Zervos, N. and Ngalinda, S. 2019; SmartSolar Tanzania 2018b). The components included are PV modules, DC charge controllers, DC inverters and deep cycle batteries which use and/or store solar power (The United Republic of Tanzania 2014; The United Republic of Tanzania 2019).

4.2.5 Interconnection with the main grid

If a mini-grid power station is constructed to meet the necessary standards for interconnection with the main grid, its operators may seek permission from the authorities to operate it as such. The mini-grid can operate in various ways such as (1) selling, or (2) purchasing and reselling electricity to retail consumers from a distribution network operator (DNO), as a small power producer (SPP) or a small power distributor (SPD), respectively. Alternatively, (3), a combination of (1) and (2) is possible or the mini-grid operator can (4) eliminate some or all of their assets that are involved in generating and distributing power or (5), they can decide to sell some or all of their distribution assets to the DNO, usually TANESCO (Mramba, C., Zervos, N. and Ngalinda, S. 2019; Zigah, E., Barry, M. and Creti, A. 2023). The feed in tariffs are technological and size specific, where there is a feed in tariff for SPPs of small hydro and biomass projects, while solar and wind projects apply an auction system (SmartSolar Tanzania 2018b).

According to the experience of the TANESCO (2023b), the smallest IPP connected to the main grid was 500 kW producing electricity through hydro power. TANESCO believes that there is no profit from buying from smaller IPPs (TANESCO 2023b; TAREA 2023). Additionally, to be allowed to connect to the main grid the electricity must be supplied in the same high voltage as the main grid which can be hard to produce for an SPP. If an IPP were to sell directly to other consumers it would make them competitors with TANESCO. Because of this, (additionally to requiring a licence from EWURA) a separate grid between the IPP and the consumer is needed since TANESCO do not allow competitors to be connected to the main grid (TANESCO 2023b).

4.2.6 Electricity price

According to TANESCO (ibid.), the electricity price in Tanzania depends on which customer category the buyer belongs to. The applied tariff depends on electricity demand and was last changed in 2016 (ibid.). There are three main customer categories; *T1*, *T2* and *T3*. Additionally, there is one prior to these called *D1*, or *"Low Usage Tariff"*, that applies for domestic customers and provides electricity at low voltage and single phase (230 V) (EWURA 2016, p. 8).

T1 is also called the *"General Usage Tariff"* and provides low voltage power in single (230 V) or three-phase (400 V) (ibid., p. 8). Users must exceed 75 kWh/month during three consecutive months (TANESCO 2016). It includes, among others, residential customers, small commercial business and light industries (EWURA 2016, p. 8). T2 applies for consumers exceeding 7500 kWh/month for three consecutive months, with maximum power demand below 500 kW at 400 V . T3 is divided into *T3-MV* (Medium Voltage) and *T3-HV* (High Voltage). T3-MV applies for users exceeding 500 kW, and T3-HV includes large business and electricity consumers like Zanzibar Electricity Corporation (ZECO), gold mine Bulyanhulu and Twiga Cement (TANESCO 2016).

In Table 5, the tariffs for 2016, 2013-2015 and before 2013 is presented. The increasing and decreasing changes are represented with red and green coloring to highlight the changes during these years. The numbers are based on "Tanzania Electric Supply Company Limited ("TANESCO") Tariff Adjustment Order, 2016." (EWURA 2016, p. 8) and "Tanzania Electric Supply Company ("TANESCO") Electricity Price Adjustment Order for Three Years, 2013." (EWURA 2013, p. 11), both approved by EWURA in 2016 and 2013 respectively. All prices are excluding 22 % tax (18 % VAT, 3 % for rural electrification, 1 % to EWURA) (TANESCO 2023b). As can be seen in Table 5, the tariffs have both increased and decreased since before 2013, and some have even been removed.

According to TANESCO (2023b), the changes in electricity prices have been small in percentage historically. Changes depend on multiple factors such as policy changes, production costs and opinions from consumers and stakeholders, which is the government since TANESCO is owned by the government. The government is aiming to increase electricity access in rural areas by, among other things, making electricity affordable for everyone (ibid.). Based on this, TANESCO (ibid.) predicts only small changes in the future.

Table 5: *Tariffs for electricity consumers approved by EWURA in from prior to 2013 until 2016 (EWURA 2013; EWURA 2016).*

Customer category	Component	Unit	Tariff before 2013	Tariff 2013-2015	Tariff since 2016
D1	Service charge	TZS/month	-	-	-
	Energy charge (0-75 kWh)	TSZ/kWh	60	100	100
	75 kWh	TSZ/kWh	273	350	350
T1	Service charge	TZS/month	3 841	5 520	-
	Energy charge	TSZ/kWh	221	306	292
	Maximum power charge	TZS/kW/month	-	-	-
T2	Service charge	TZS/month	14 233	14 233	14 233
	Energy charge	TSZ/kWh	132	205	195
	Maximum power charge	TZS/kW/month	16 944	15 004	15 004
T3-MV	Service charge	TZS/month	14,233	16 769	16 769
	Energy charge	TSZ/kWh	118	163	157
	Maximum power charge	TZS/kW/month	14 520	13 200	13 200
T3-HV	Service charge	TZS/month	14 233	-	-
	Energy charge	TSZ/kWh	106	159	152
	Maximum power charge	TZS/kW/month	12 079	16 550	16 550

4.2.7 Main grid reliability

Tanzanians suffer from frequent power outages and according to a report by The United Republic of Tanzania (2020), there were 1 407 power outage hours on average per year with a frequency of 1,548 times per year during the three year period 2016-2019. Old electricity infrastructure including cables (conductors) and transformers (substations) were listed as the main reasons for these outages. During 2022 the momentary and sustained feed interruption frequency per year for Sikonge, Tabora was 28 and 196, respectively (TANESCO 2023b). This part of the Tabora Region is located next to Tumaini Open School and can therefore give an indication of the interruption frequency at the school. Additionally, the authors who resided in Tabora Town for two months experienced frequent power outages (sometimes a few per day and sometimes a few per week) which occurred especially during the rains and lasted for approximately a few minutes up to six hours.

5 Technology options and local context for electricity and fuels

In this section, the theory for solar PV technologies for electricity production and biogas technology for cooking purposes will be described as well as the study visits made by the authors during the field study.

5.1 Solar PV systems

In 1839, Edmond Becquerel discovered the photovoltaic effect, where an electron is displaced by the energy from light, which generates an electrical current. This is the basic physical property for today's PV cells (Dincer, I. and Bicer, Y. 2018, pp. 731–732). The first electricity generating solar cell was a silicon solar cell created in 1954 by Bell Laboratories scientists (National Renewable Energy Laboratory n.d.[b]). More specifics and important characteristics of PV technology and other components of a PV system is described in this section.

5.1.1 Solar PV technology

Today, several kinds of solar PV cells are available on the market. The most common technologies are silicon solar cells (mono-crystalline and poly-crystalline) followed by thin-film solar cells (National Renewable Energy Laboratory n.d.[b]; Wallender, L. and Allen, S. 2022). New, more effective but often more expensive, upcoming technologies such as III-V solar cells, hybrid tandem III-V/Si solar cells and organic material or hybrid organic-inorganic solar cells (called perovskites) are being developed (National Renewable Energy Laboratory n.d.[b]; Mukhopadhyay 2020). Researchers are continuously pushing the limits and setting new records for solar cell efficiency.

Regardless of solar cell technology, the material is cut into thin slices which makes up the essential electricity producing layer of a solar panel. Each solar panel can have a varied number of solar cells arranged and wired together. The layer is protected by a glass cover and surrounded by a metal frame (Wallender, L. and Allen, S. 2022). There is also two layers of plastic film on both sides of the silicon solar cell layer, in addition to a backsheet at the bottom. The backsheet protects the solar panel from moisture and dirt and provides electrical insulation. Finally, a junction box connects the multiple panels to each other into a solar panel array (Svarc 2020).

Mono-crystalline vs. poly-crystalline solar cells

Silicon PV cells can, as mentioned above, be categorized in mono-crystalline and poly-crystalline cells. Mono-crystalline solar cells are made of slices of a single crystal of silicon grown into a cylindrical log shape in a lab. This process is carried out specifically for solar cell production and makes mono-crystalline cells more expensive than poly-crystalline cells. The poly-crystalline solar cells are made of randomly fragmented silicon crystals that are melted in the oven and formed into cubes. There is no arranged structure as in a mono-crystalline cell but instead, many crystals create an unstructured pattern which makes the poly-crystalline cell less effective. Poly-crystalline solar panels therefore require more area than mono-crystalline panels to generate the same amount of electricity. Average efficiency for both types of silicon PV cells can be seen in Table 6 below (Wallender, L. and Allen, S. 2022).

In general, mono-crystalline solar panels are more suitable in areas with less incoming sunlight and where efficiency is the priority. Poly-crystalline cells are, because of the lower efficiency, more suitable for areas with

Table 6: *Efficiency of mono- and poly-crystalline solar cells (Wallender, L. and Allen, S. 2022).*

Mono-crystalline	**Poly-crystalline**
15 % - 20 %	13 % - 16 %

a high rate of sunlight and where a cheaper price is of greater importance. One downside with poly-crystalline panels are that they are less heat tolerant. However, both technologies have approximately the same lifetime (Wallender, L. and Allen, S. 2022).

5.1.2 Orientation and installed capacity

The installed capacity of a solar system is measured in watt peak (W_p), where 1 kW_p will produce 1 kWh of electricity under standardised test conditions. For solar panels to be comparable, they are all tested under the same three conditions:

1. Irradiance of 1 000 W/m^2
2. 25 °C module temperature
3. Solar spectrum of 1.5 air mass (AM)

In reality, the amount of kWh that is generated depends on shading, amount of irradiation, incidence angle of sunlight, surrounding temperature and size of system, among other things (EvoEnergy 2018). Solar panels always have a temperature coefficient among its technical specifications. The temperature coefficient states how the maximum efficiency is affected by the change of module temperature by one degree Celsius from the standard test condition 25 °C (Boston Solar 2019). For example, a temperature coefficient of -0.4 % means that for every degree above 25 °C, the solar panel's maximum efficiency will decrease by -0.4 %, while it will increase by 0.4 % for every degree below 25 °C.

5.1.3 System components

Beyond the solar panel itself, other important parts of a solar power system are the inverter, the racking, batteries and the charge controller (Go Green Solar 2021).

Inverter
The inverter converts the generated DC power from the solar panels to AC power to be used in the connected appliances or exported to a connecting grid. It also monitors the electricity flow between different system components. Which type of inverter that should be used depends on the system design such as size, capacity of the connected battery and if shading is a problem or not.

Racking
Racking is the solar panels' mounting structure and can be either for rooftops or on the ground. It usually consists of rails to carry the panels and flashings to keep railings in place (ibid.). For roof-mounted systems it is crucial that the roof structure is of sufficient quality to withstand the weight of the panels and O&M. The orientation and pitch of the roof is equally important for maximum output of the panels (SmartSolar Tanzania 2018c). For ground mounted installations, a concrete foundation holds a structure of metal pipes to the ground. Ground mounts do not have the same restrictions as rooftops, because they can be installed

in any azimuth and tilt angle. Rooftop mounting is usually a cheaper option since no new structure needs to be built. It is also a more space effective choice and safer against theft and vandalism. However, access for maintenance and cleaning is usually easier for installations on the ground depending on the height of installation (Go Green Solar 2021).

Battery

The two battery types mentioned most frequently in connection to standalone PV systems are Li-ion batteries and lead-acid batteries (ECOFLOW 2022; Qazi 2017; Renogy United States n.d.). Li-ion batteries have a higher efficiency and storage capacity than lead-acid batteries (Renogy United States n.d. Wolf n.d.), where the storage capacity for Li-ion and lead-acid batteries are 150 Wh/kg and 25 Wh/kg respectively (Qazi 2017, p. 60). Another important characteristic of batteries is the Depth of Discharge (DoD), i.e. the percentage of kWh stored in the battery that can be used before it needs to be recharged (ECOFLOW 2022; Wolf n.d.). Li-ion batteries have an average DoD of up to 80 % while, for lead-acid batteries, it is usually around 50 % (Wolf n.d. Wolf n.d. Renogy United States n.d.).

The effect of temperature changes are another important factor that needs to be considered. At low temperatures the battery's capacity is negatively affected while in higher temperatures, the lifetime is reduced (Qazi 2017, p. 70). Lead-acid batteries are more sensitive to extreme temperatures than Li-ion batteries and are recommended to be operated between 5 °C and 27 °C while Li-ion batteries can handle a wider range of -18 °C to 60 °C (Wolf n.d. Renogy United States n.d.). Regardless of battery type they should be stored in a protected environment with a relatively controlled temperature to avoid overheating and damage (Wolf n.d.).

Charge controller

In a standalone solar system with battery storage, a charge controller is an essential component. It prevents the battery from overcharging during excess production and over-discharging during periods of low or no production and high electrical load. Both overcharging and over-discharging can damage the battery and affect its lifetime, performance and safety. Also, it prevents reverse flow of current when the solar panels are not producing electricity and automatically monitors the connection to the load during night time (Qazi 2017, pp. 51–52).

Different types of charge controllers have different characteristics; they are either designed to maximise the efficiency of electrical output from the solar panels or to extend the lifetime of the batteries as much as possible. The two main types of charge controllers on the market today are based on Maximum Power Point Tracking (MPPT), which maximizes efficiency of the solar panels, and Pulse Width Modulation (PWM) which prolongs battery lifetime thanks to lower electricity output from the panels (Solar Power Secrets n.d.[b]). Which charge controller to choose depends on the design of the solar system. Some additional characteristics of the two types of charge controllers to consider are presented in Table 7 where the interference with TV and radio devices comes from sharp charging pulses generated by the PWM charge controller (Solar Power Secrets n.d.[a]).

Table 7: *Comparing characteristics of PWM and MPPT charge controllers (Solar Power Secrets n.d.[a]).*

Characteristics	PWM	MPPT
Pricing	Cheap	Expensive
Size suitability	Smaller off-grid system (<150 W_p)	Larger off-grid system (>150 W_p)
Climate suitability	Warmer sunny weather	Colder cloudy weather
Scaling capability	Low	High
Interference with TV and radio	Yes	No

5.1.4 Degradation rate and lifetime of components

In this section the degradation rate and lifetime of the solar panels, inverters, batteries and charge controllers are presented.

Solar panels

In a solar power system, of all the components, the solar panels have the longest expected lifetime. This means that in a life cycle perspective, the other components must be replaced to match the lifetime of the solar panels to maximize the system's lifetime. The expected lifetime of solar panels is 25-30 years (Sodhi et al. 2022, p. 786). However, if well maintained, they will continue to produce electricity far beyond 30 years but with lower efficiency due to degradation of the solar panel. According to Jordan, D.C. and Kurtz, S.R. (2011), the result of a study during 40 years on 2 000 degradation rates gave an average annual degradation rate of 0.8 %. This means that after 25 years, a solar panel is still producing electricity at 82 % efficiency. The degradation rate is affected by factors such as weather, thermal stresses, oxidation and corrosion (Branker, K., Pathak, M.J.M. and Pearce, J.M. 2011, p. 4476).

Inverters

The inverter is less affected by heat stresses since high ambient temperature reduces PV efficiency and therefore reduces the stress on the inverter (Brito et al. 2018, p. 1023). However, equivalently, higher solar irradiation leads to higher electricity production in the solar panels and hence, increases the stress in the inverter. Inverters are expected to last 10-15 years which means, during the lifetime of the solar system they will have to be replaced 2-3 times (Branker, K., Pathak, M.J.M. and Pearce, J.M. 2011; Saddler 2022).

Batteries

When it comes to batteries, the lifetime depends greatly on type of battery, number of cycles (charged and discharged), maintenance and the environment in which it is installed. Li-ion batteries are superior to lead-acid batteries regarding lifetime and temperature endurance, but they are more expensive. However, from a life cycle perspective it can still be worth investing in Li-ion batteries thanks to the longer lifetime (Renogy United States n.d.). It depends though on how often the batteries are being used. For example, if they are used regularly, say every night when the sun is gone, they will need to be replaced sooner than if they are only used during power outages (Wolf n.d.). Nonetheless, Li-ion batteries are designed for and more suitable for frequent usage (ECOFLOW 2022). That is why battery lifetime is hard to predict since it depends on various factors (Kinzy 2023; ECOFLOW 2022; Wolf n.d. Renogy United States n.d.). Lead-acid batteries have a shorter lifetime in general, averaging 3-5 years (Renogy United States n.d. ECOFLOW 2022), while Li-ion batteries can last 5-15 years (ECOFLOW 2022).

Charge controllers

According to both Solar Power Secrets (n.d.[b]) and Renogy Australia (n.d.), the average lifetime of charge controllers are 15 year even though it can vary between different types. This means it has to be replaced once during the solar system's lifetime. It is not said which factors affect the lifetime of the charge controller, but since the batteries are the most expensive part of a solar system, a well functioning and efficient charge controller is essential to keep the battery well maintained and avoid unnecessary costs.

5.2 Biogas in developing countries

Biogas is produced through the process of anaerobic digestion (AD), which involves the decomposition of organic matter such as animal manure, food waste, sewage, agricultural waste and human waste in specialised digesters and biogas plants. The resulting products of the process are biogas, which mainly consists of methane and carbon dioxide but also contains small amounts of hydrogen sulfide and ammonia. The residual product is called digestate, which is a nutrient-rich residual material (Svenskt Gastekniskt Center AB 2012; Aamodt 2020).

5.2.1 Anaerobic digestion

The microorganisms responsible for the biogas production are affected by certain operation parameters. The temperature in the digester must be above 15 °C. For the mesophilic microorganisms, the ideal temperature is in the range of 30-40 °C, which is also more stable as they can better withstand changes in environmental parameters and consume less energy. For the thermophilic microorganisms, a range of 45–60 °C is optimal and they have a shorter retention time to maximise biogas yield but is less stable. As the carbon dioxide solubility is lower in higher temperatures, a higher concentration is found in thermophilic ranges. In developing countries, mesophilic ranges are preferable, because there is no need for additional energy and the process is more stable. The temperature variations between night and day or between seasons can also affect the biogas production which is why several models of biogas digesters are buried underground, as it uses the temperature buffer capacity of the soil (Vögeli et al. 2014).

The pH in the digester should be in the range of 6.5–7.5 as the different processes of the anaerobe digestion occur in different ranges. The hydrolysis and acidogenesis occur at pH 5.5–6.5, and the methanogenic phase at pH 6.5–8.2. The C:N ratio (ratio between carbon (C) and nitrogen (N)) indicates consumption of nitrogen, where the optimal range is between 16-25:1. This can be achieved by mixing substrates with high and low C:N ratios. Organic solid waste materials have a high ratio whereas sewage or animal manure has a low ratio. During the startup of a biogas plant the digester needs to be inoculated with the right bacteria and it can take a few weeks before methane will be produced. A high quality biogas will contain 55-70 % methane. Inhibitors such as oxygen, organic acids, hydrogen sulphide, free ammonia, heavy metals, tannins/saponins/mimosine, herbicides, insecticides, disinfectants and antibiotics should be avoided in AD (ibid.).

The duration when liquid fraction remains in the digester is named the Hydraulic Retention Time (HRT) and in mesophilic digesters, the optimal time is 10-40 days. For digestion of solid wastes, the Solids Retention

Time (SRT) and HRT can be assumed to be the same (Vögeli et al. 2014).

The biological conversion capacity of the AD system is named the Organic Load Rate (OLR) and describes the volume of substrate input to the digester. The optimal range for non-continuously stirred AD digesters, which are predominant in developing countries, is below 2 kg Volatile Solids (VS)/m^3 of digester/day, and if the system is overloaded it can lead to system failure. The stirring in the digester keeps the temperature constant within the digester, inoculates new substrate input with the microorganisms and prevents scum formation that can otherwise cause malfunctions in the system (a shallow top layer is acceptable). In the technologies most used in developing countries (fixed- and floating dome) a passive mixing is achieved by feeding the digester with digestate outflow which corresponds to the normal daily feeding load (ibid.).

5.2.2 Technical specifications

Substrates

The substrate, also called the feedstock, is the biomass which is inserted into the biogas plant. It can include food, animal, agricultural or industry waste such as human excreta, manure or sewage waste. The VS is the organic material from the total dry matter (DM) content, or the Total Solids (TS), and it is this fraction that contributes to the biogas production. For the biomass to be suitable as substrate the VS needs to be between 70-95 % of the TS. The biogas yield can be indicated by:

m^3 CH4/kg VS
Nm^3 CH4/kg VS
m^3 biogas/t (wet weight) substrate
m^3 biogas/kg TS
m^3 biogas/kg VS

Where Nm^3 stands for m^3 under normal conditions; 0 °C, 1.01325 bar and relative gas humidity 0 % (ibid.).

The substrate needs to undergo a pre-treatment where non-biodegradable materials are removed and the particle size of the biodegradable materials are reduced to ⌀5 cm or less depending on the size of the inlet pipe. This gives the microorganisms more area to be degraded. The separation is either manual or magnetic and the size reduction can be grinded manually or power driven (ibid.).

The cow manure is a highly suitable substrate as it contains the bacteria for producing methane and the homogeneous consistency makes it easy to use in a continuous plant. However, the methane gas yield is low because of the digesting which has already occurred in the cow's stomach. It requires a liquid ratio of water or urine of 1:1. If the pigs are kept in a unpaved area the manure can be used and must also be mixed with water. Then, the sand and other unwanted particles needs to be allowed to sediment in the mixing tank. Manual mixing is often neglected as the odour is very potent and therefor mechanical mixing can be a solution. The bird droppings can be used together with the cow manure but only if the sand ratio is not too high in the collection of the droppings. The droppings are very dry so mixing with water is necessary. If human waste is to be used the toilets should be directly connected to the biogas plant both because of hygiene and stigma related reasons. The water amount in flushing should be minimised (Kossmann et al. n.d.).

Digestate from the outlet can be mixed with new substrate and in wet digestion, water will also be mixed in, which supply the digester with an appropriate bacterial population and total TS, respectively. With too much TS the pipes may be clogged and with too little the biogas production will be low (Vögeli et al. 2014). The available substrate must enter the digester as soon as it is available to avoid pre-digestion outside the digester (Kossmann et al. n.d.).

Depending on the substrate, the time before the initial start of biogas production can vary from a few days to several weeks. For cow dung it only takes a few days (ibid.) while for human waste it can take several weeks (Afrihands Tanzania 2023a). If the plant is not fed for a few months, for example during school breaks, the up start of the plant should be gradual, meaning that input of the substrate should be gradual. A guideline could be to limit the input the first two weeks with 20 %, the second two weeks with 50 % and finally the fifth week with 100 %. During the pause in use of the AD system the digestate should be recirculated to the digester to prevent scum production (Vögeli et al. 2014).

Plant designs

Biogas plants are highly flexible and can be designed and scaled to suit various needs (Svenskt Gastekniskt Center AB 2012). The digester design is classified as dry if the TS content is >16 %, and semi-dry or dry if the TS content is between 22-40 %. Dry digestion needs a smaller digester volume, less handling of material and the digestate can easily be used as a fertiliser or be pelletized for fuel use. However, in developing countries, this has some practical difficulties among other things because of the batch-wise feed of the digesters. In a batch fed digester the substrate is fed to the digester, then stays for the entire retention time, and then they are emptied. This technology is cheaper than continuous systems but can lead to gas production and quality fluctuations, and there is a risk that seals, which need to be airtight, leak. This can lead to biogas losses or an explosion can occur when the doors are opened between batches as the methane mixes with air (Vögeli et al. 2014). A continuous plant is both fed with substrate regularly and emptied of digestate regularly, and because of this the gas production is both higher than for batch systems and constant. A semi-batch system is also possible for example if the substrates are straw and cow manure. Then the straw is fed batchwise twice a year while the manure is fed continuously (Kossmann et al. n.d.). As AD requires different processes that are optimal in different conditions, it is possible to have the biogas plant in two or multi-stage systems. However, this is more expensive (Vögeli et al. 2014).

The most popular AD plants in developing countries are the fixed dome plant and the floating dome plant. They are wet digestion systems operated in continuous mode under mesophilic conditions. There are other plants that are also used in developing countries, such as the tubular plant or the garage-type plant, but they will not be described in this report (Vögeli et al. 2014; Kossmann et al. n.d.).

Fixed dome plant

The fixed dome plant consists of a mixing tank with an inlet pipe and a sand trap. There is an inlet for the substrate which leads to the dome shaped digester where the substrates are digested by bacteria and biogas is produced. The gas flows up to the rigid gas holder and through the gas pipe to the gas appliances. At the top there is an airtight hatch and as the gas production accumulates, digestate is pushed to the displacement pit, also called the compensation tank or expansion chamber. When gas is utilised the digestate moves back into the digester. As the gas pressure fluctuates, utilisation of the gas is less effective than for the floating dome plant, and a gas pressure regulator or a floating gas holder needs to be implemented if the appliances require it. However, the gas production is the same for both plants. See Figure 5 (Vögeli et al. 2014; Kossmann et al. n.d.).

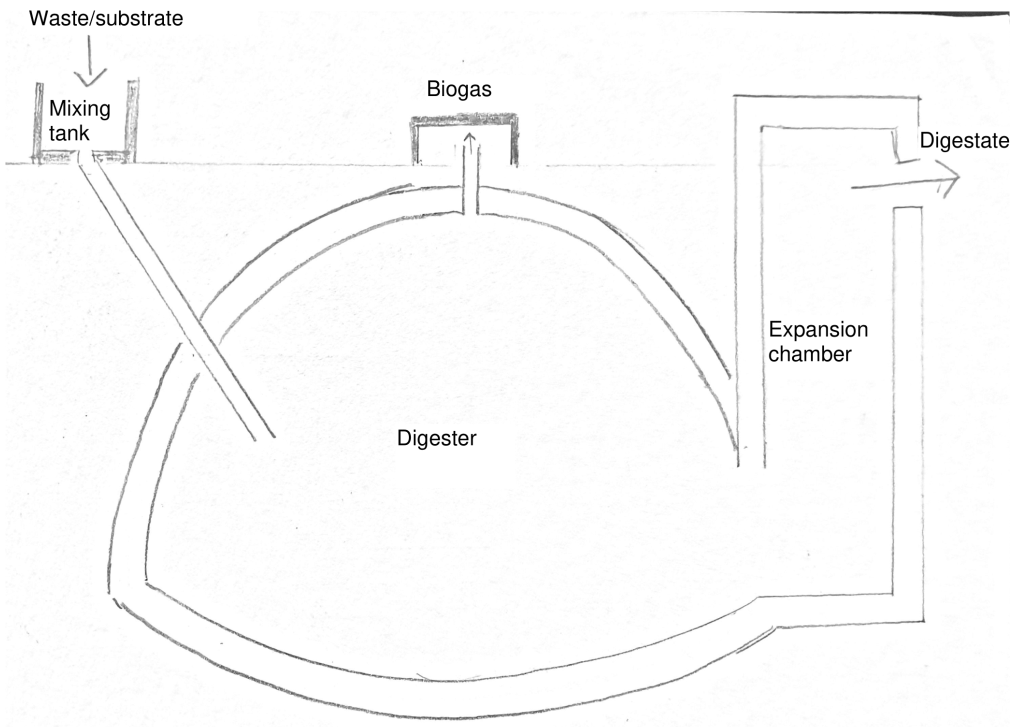


Figure 5: *Fixed dome biogas plant. Authors' own illustrations based on Kossmann et al. (n.d.) and Vögeli et al. (2014).*

There are several different models of the fixed domes, including the CAMARTEC model which was developed in Tanzania (Vögeli et al. 2014). It has a flat rigid foundation, a hemispherical structure and a calculated joint, also known as the weak/strong ring, which allow for movement and flexibility, making it more resistant to damage (Kossmann et al. n.d.). The CAMARTEC plant is described further in Section 5.3.4.

The fixed dome plant has a low cost, no moving parts, no steel parts that can rust and thus, low maintenance, and it has the benefits of a long operational lifetime. Additionally, the plant is underground which saves space and protects it from physical damage and temperature variations, and the soil covering the dome counteracts the internal pressure from the biogas production. As substrates, cow manure, food, agricultural or human waste can be utilised, separately or mixed. During construction, an experienced biogas technician is necessary to ensure that it is constructed without risk for leakages. It is also labour-intensive which creates opportunities for local employment. If any cracks in the dome occur it would be very difficult to repair (Vögeli et al. 2014; Kossmann et al. n.d.). Also, cracks means that the gas can leak, but also the digestate which may pollute nearby water. That is why there should be a specific distance to the nearest water sources (Vögeli et al. 2014).

Floating dome plants

The floating dome plant is constructed in a similar way to the fixed dome, however, there are some distinctive differences. The floating gas holder, also called the gas drum, rises or falls depending on the volume of gas which makes the availability of gas utilisation directly visible. Additional weights can be added on top of the gas holder to increase the pressure if needed. A guide frame for the gas is also required to keep the gas holder stable. See figure 6. The floating dome comes in several different models and can use both animal manure and human waste. The gas dome can float on the digestate directly or in a separate water jacket which reduces the risk of gas leakage. The water jack floating dome is easier to maintain, has a long operational lifetime and has a superior sealing of the substrate than the if the gas dome floated directly on the digestive (Vögeli et al. 2014; Kossmann et al. n.d.).

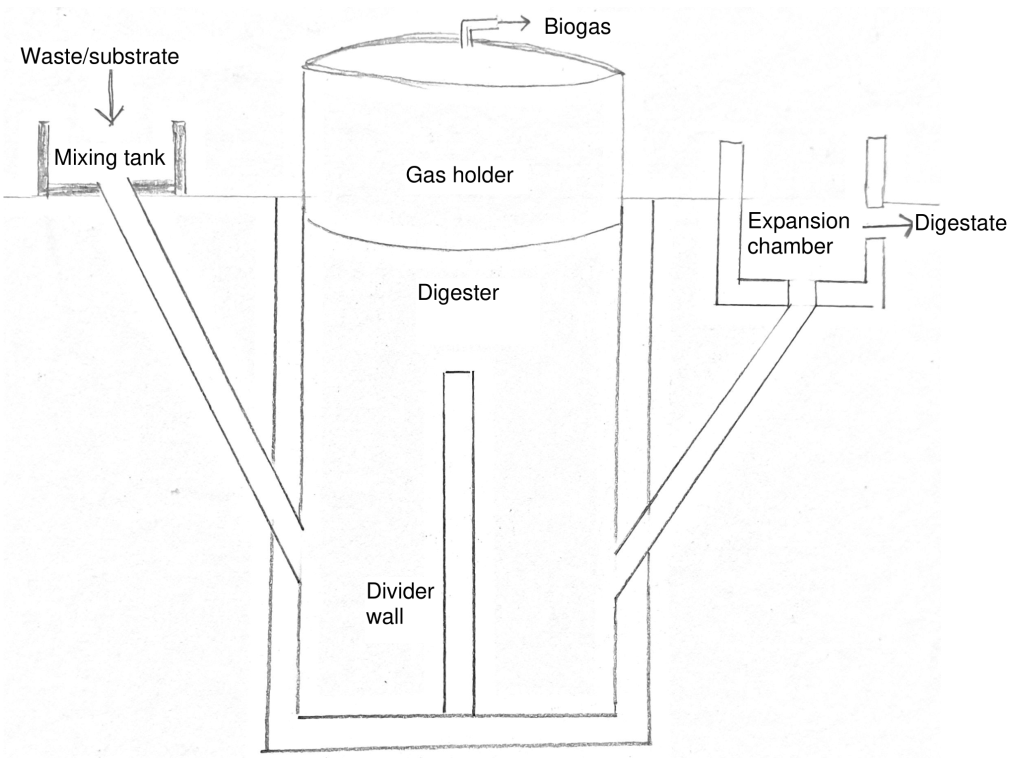


Figure 6: *Floating dome biogas plant. Authors' own illustrations based on Kossmann et al. (n.d.) and Vögeli et al. (2014).*

Floating dome plants are easy to construct, understand and operate, and the gas is at a constant pressure. However, it is more expensive because of the additional material costs, and requires higher maintenance than fixed dome plants, since the gas holder needs to be de-rusted and painted regularly. Additionally, floating domes have a shorter lifetime than fixed domes because of the moving parts (Vögeli et al. 2014; Kossmann et al. n.d.).

5.2.3 Operation & maintenance

To ensure an efficient gas production and a long lifetime of the plants, the O&M is of highest importance. Therefore, is it mandatory that not only the technology is implemented correctly but also that the knowledge is available, through for example training programs (Vögeli et al. 2014; Afrihands Tanzania 2023a; Kossmann et al. n.d.). It is not only necessary to know how the plant should be operated and maintained but also why it should be operated in a certain way for long term usage. The O&M responsibilities of the operators and owners needs to be clear, and strategic planning with schedules and control mechanisms of the O&M is vital

(Vögeli et al. 2014).

Daily operations

The substrate needs to be measured and fed into the digester on a daily basis to ensure a steady feed into the digester which provides a continuous production of biogas. That way the bacteria producing will be stable and likewise the gas production. Before the substrate is fed into the digester it needs to be pre-treated and if necessary be mixed with water or digestate from the plant to mix in the bacteria and streamline the process. Inorganic materials such as sand, glass, plastics or metals should not be fed into the digester (Kossmann et al. n.d. Vögeli et al. 2014).

The gas pressure requires checking every day to make sure the pressure is stable. If the pressure rises the gas needs to be utilised to avoid depressurising the system and if the pressure is too low it can indicate mismanagement or other disturbances in the system. If there is a low production of gas the problem needs to be identified immediately and solved (Kossmann et al. n.d.). Vögeli et al. (2014) states that there are no simple, reliable and inexpensive biogas flow meters available on the market and that monitoring the gas flow is often not considered essential by the operators in developing countries. However, as mentioned, gas monitoring is necessary to maintain the biogas system.

Weekly or monthly

Several appliances needs to be cleaned and checked regularly. The biogas stoves needs to be cleaned to avoid clogging of the air intake holes and to avoid corrosion. Grease should be applied and the air flow should be adjusted to create a suitable flame (ibid.). If the gas smells of rotten eggs there is a leak of the biogas which could originate from the pipes, joints, valves or the stove. The system and appliances should be air and gas tight when the valves are closed and needs to be checked regularly (Kossmann et al. n.d. Vögeli et al. 2014). If there is a strong odour originating from the digestate it means that the plant is operating at sub optimal levels and the digester could be overloaded with substrate or the microorganism population could be imbalanced. Kossmann et al. (n.d.) even suggests the odour to be checked daily.

The pH-value in the digester should never be below 5.5 and the feeding needs to be stopped if this occurs until the pH-value stabilises. After this the feeding can start gradually again (Vögeli et al. 2014).

Depending on the amount of gas being produced, the water trap needs to be emptied weekly or monthly to prevent clogging and corrosion of the pipes.

For the floating drum digesters, the gas holder must be maintained regularly to make sure it has a long lifespan. The gas holder should be removed, cleaned and repainted with anti-corrosive paint on an annual basis (Kossmann et al. n.d. Vögeli et al. 2014).

Long-term maintenance

There are examples where the plant operators do not use the mixing tank but instead, put the substrate directly into the digester which means the substrate does not go through the sand trap. The sand then reduces the volume available for digestion (Vögeli et al. 2014; Afrihands Tanzania 2023a). The digestate can also accumulate at the bottom of the digester over time. With a good operation and design of the plant it may need to be cleaned only every 5-10 years (Vögeli et al. 2014). The cleaning process is expensive which is a reason why some biogas plants are abandoned (TAREA 2023).

Common problems for low tech biogas plants

There are several problems that normally occur in low tech biogas plants in developing countries that have been observed and is associated to the O&M. The gas production can be low because of insufficient input of the substrate, or the gas pressure is low even when it is not used because of blockage in the pipe by digestate or leaks in the valve, pipes or dome. If condensed water has accumulated, the gas pressure can be non-consistent. Low pH, hazardous antiseptic or other toxins could inactivate the bacteria in the digester, which can cause both bad smell of the gas and make it inflammable. If the burner is malfunctioning by having too high air supply the gas can become odourless and inflammable, and if there is water in the gas pipe the flame can become uneven. If the flame is low, it can be because of leakages, low volume of gas or the nozzle of the burner being blocked or too small. On the other hand, a too high flame can be caused by a too big nozzle hole. If the flame ports are blocked it can also cause the flame to go backwards into the pipes (Vögeli et al. 2014).

5.2.4 Biogas utilisation

The utilisation of biogas is versatile, encompassing a range of applications such as space heating for domestic and commercial buildings, cooking, and water heating. Additionally, biogas can be utilised in combined heat and power (CHP) systems, or further refined to serve as a vehicle fuel. The local use of raw biogas is made possible through the establishment of pipelines, while the upgrading process entails pressurization and transportation via gas cylinders, or injection into existing gas networks (Energigas Sverige 2021). Burning the biogas on a gas stove is a common local utilisation of the gas in developing countries (Vögeli et al. 2014). Using biogas for cooking purposes in households and farms in developing countries is the best way to use biogas, considering the efficiency of using it in stoves, engines or lamps (Kossmann et al. n.d.). Household burners have a capacity of between 0.2-0.45 m^3 gas/h or more (Vögeli et al. 2014; Kossmann et al. n.d.), while industrial burners has a capacity of 1-3 m^3 gas/h (Kossmann et al. n.d.).

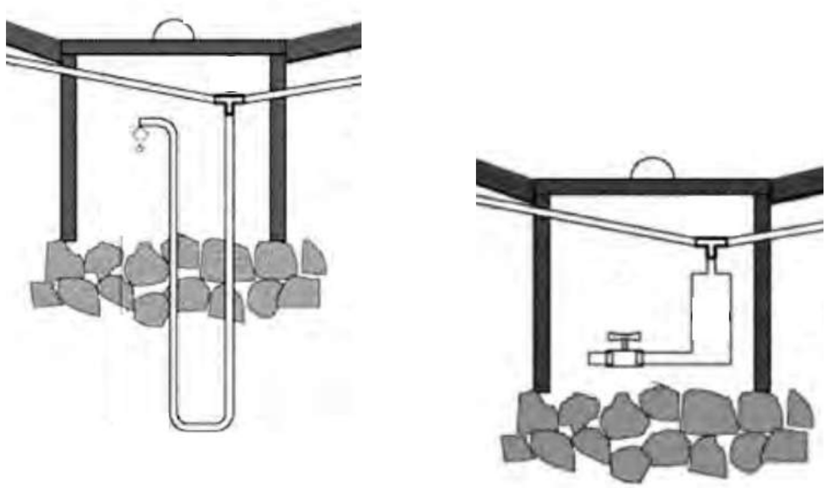
It is important to know that using biogas as an energy source for cooking purposes affects the cooking technique. In contrast to cooking with charcoal, the biogas is not able to reach the same heat level which some meals require and the cooking time can be longer. The taste also differs from cooking with firewood or charcoal and the food can not be kept warm in the same way as on the residual heat from the charcoal. If the available amount of biogas per day is not enough for the cooking demand, an additional energy source such as natural gas stoves, firewood or charcoal will also be needed (Vögeli et al. 2014). If biogas substitutes butane or propane gas the performance is reduced and more gas is needed (Kossmann et al. n.d.).

Post-treatment of the gas

Water removal

The gas that leaves the digester is almost 100 % saturated with water vapour which will condense on the equipment when cooled or pressurized which can lead to corrosion or blockage in the pipes. The water traps are located at the lowest point in the pipes as gravity will move the water there. If there are several depressions in the pipes there also needs to be water traps at these locations (Kossmann et al. n.d. Vögeli et al. 2014).

There are two kinds of water traps, automatic or manual, which can be seen in Figure 7a and 7b, respectively. The automatic water trap is U-shaped and gas pressure automatically pushes out the water (Kossmann et al. n.d. Vögeli et al. 2014). With these water traps there is a risk of gas leakage, however, with the manual water traps there is a risk of blockage if the trap is not emptied regularly (Kossmann et al. n.d.). Both traps are located underground in a solid container with a lid to avoid soil to fill up (Kossmann et al. n.d. Vögeli et al. 2014).



(a) *The U shaped automatic water trap is located at the T joint of the piping system, with a water column which is equal to the maximum gas pressure +10 %.*

(b) *The manual water trap is located at the T joint with a container for the water and a manual tap for drainage.*

Figure 7: *Figures of water traps. Illustrations edited based on Kossmann et al. (n.d.) and Vögeli et al. (2014).*

Hydrogen sulphide removal
When water and hydrogen sulphide react they create corrosive acids which can corrode the biogas system and the appliances such as the stoves. The removal of hydrogen sulfide is only necessary if the concentration is above 2 % in the biogas which it rarely is and is therefore usually not necessary. The purification is also unnecessary if the appliances are made of stainless steel (Kossmann et al. n.d.).

The dry box method comprises a gas-tight container with a ferrous material that the hydrogen sulphide can react with. The material can, by being exposed to atmospheric oxygen, be reverted to its original state, i.e. regenerated, but the reaction is highly exothermic and can not be repeated indefinitely (Kossmann et al. n.d. Vögeli et al. 2014). Many types of tropical soils, such as the lateritic soil in tropical regions, contain iron and are well-suited for utilisation as a purification medium (Kossmann et al. n.d.).

By pumping air at a rate of 2-5 % of the biogas production the biogas could also be purified of hydrogen sulphide. This works best if the gas holder is positioned above the digestate as the bacteria responsible for the purification process thrive in moist, warm and nutrient-rich conditions. However, given that this method requires electricity which can be unreliable in developing countries this method is not suitable (ibid.). According to Kossmann et al. (ibid.) manual pump is possible but also not suitable.

The high pressure water scrubber method is a physical process where the water is sprayed in the opposite flow of the gas. A large amount of water is required but can be treated and reused. Both hydrogen sulphide and carbon dioxide can be removed, because both have a higher solubility in water than methane does (Vögeli et al. 2014).

Carbon dioxide removal
The carbon dioxide can be removed by bubbling the gas through water containing any alkaline chemical. The content of carbon dioxide in biogas can be as high as 35–40 % and by removing it the energy content will increase in a unit volume of biogas. However, the carbon dioxide does not affect the cooking, except that it lowers the efficiency, and is therefore generally not removed in developing countries (ibid.).

Kossmann et al. (n.d.) writes that carbon dioxide removal is expensive, complicated and only advisable if the bottling capacity for high-pressure storage needs to be increased. The removal can be done using limestone but the process produces a large amount of lime "paste" that needs to be removed (ibid.).

5.2.5 Digestate utilisation

The digestate residual product, also called slurry or effluent in wet systems, depend on the substrate but is an excellent fertiliser for agricultural applications. Plants need nitrogen, phosphorous (P), potassium (K) and other trace elements which are all found in the digestate. Soils in different parts of the world contain different amounts of nutrients and the plants there have adapted to this environment. In lateritic soil, in tropical regions, P is often the limiting factor for plant growth. The C:N ratio is approximately 15:1 in the digestate, and the available P and K content of the digestate, which are not affected by the digestion, is approximately 50 % and 75-100 %, respectively, of the total amount (Vögeli et al. 2014). The digestate should be used on the agricultural fields right before the vegetation growth period (Vögeli et al. 2014; Kossmann et al. n.d.).

Pathogens in the digestate can be incapacitated in the digester with a high enough temperature. In mesophilic systems, the higher the HRT, the more effectively will the unfavorable environment work to incapacitate pathogens. Higher HRT also means a larger amount of reduction of the organic load, however, the decomposition will never fully be completed in the biogas plant (Vögeli et al. 2014).

The digestate needs to undergo post-treatment before it is discharged to a water body, or if the substrate used is human waste, and will be used as fertiliser. Spray irrigation without prior post-treatment should also be avoided due to the pathogen risk. The digestate from wet systems have a high water content since most of the organic material is digested. Post-treatment can include sedimentation of the digestate and aerobic/anaerobic treatment in wetlands or ponds. For dry digestate, post-treatment can include composting (ibid.).

The digestate can be collected in a tank as liquid with the benefit of little nitrogen loss but with the disadvantage that the large, waterproof storage tank can be expensive. In liquid form the digestate can be utilised as a fertiliser using gravity, mixed with the irrigation system or it can be distributed by several small channels. One should be careful not to over fertilize as this can lead to eutrophication and ecological damage.

Another solution is to dry the digestate in shallow basins which makes the digestate easier to transport and use as fertilisers at other locations. However, the nitrogen loss with this method is very high. The digestate can also be decomposed and mixed with other organic material, which will then provide a high nutrient content and also be easier to transport than if the digestate remained in liquid form (Kossmann et al. n.d.).

5.2.6 Stigma and acceptance

There can be resistance against using biogas or digestate from biogas production, especially if human waste or pig manure has been used as substrate, either because of hygiene, religious or other social reasons. Some may refuse to cook with biogas and some will not eat or buy crops which has been fertilised with the digestate (Aamodt 2020; Vögeli et al. 2014). Vögeli et al. (2014) gives an example of cooks initially refusing to cook with the biogas at a student's canteen at a secondary school in Dar es Salaam, Tanzania. The reason, however, was found out to be because the cooks used the charcoal for private use as well and were afraid that the school would not purchase it anymore.

5.3 Study visits

During the field study, two study visits to small-scale solar PV installations were made. One visit was to a very small solar water pump system without battery storage, and the other to a larger solar power system with battery storage at a hospital. Another study visit was made to Sikonge Folk Development College as well as three biogas plants around Arusha with Afrihands Tanzania (2023b). The visits are shortly described in the following sections.

5.3.1 Solar water pump system at the Centre Director's farm

On the 27th of March 2023, the authors visited a solar power installation at the Centre Director's farming area. It is located about 1-2 km northwest of the Tumaini Open School and was reached by foot from there. The solar system was connected to a water pump to supply the farming area's irrigation system with water from a 100 m deep borehole. The water pump was used for 8 hours per day and pumps water into a 1.8 m deep water storage well. This was the only function of the solar panels and therefore, no battery storage was included in the system. The total installed capacity of the system was 3 kW_p with ten poly-crystalline solar panels forming a total PV area of 19.5 m^2. The solar panels were ground mounted 3 m above ground as shown in Figure 8.

Figure 8: *Solar PV installation at the Centre Director's farming area (Lovisa Magnusson Ericsson, 2023).*

The authors learned that a similar solar water pump installation will most likely be used at the school facility. This means that the water pump would be supplied by an independent solar system without storage capacity, separated from the main solar PV system that is the focus of this study.

5.3.2 St. Ann Catholic Mission Hospital

On the 27th of April 2023, St. Ann Catholic Mission Hospital in Tabora was visited by the authors who were welcomed by the sisters of the hospital. The hospital had solar panels installed on the roof of one building which powers the lighting, computers and monitors for almost the entire hospital. High electricity demanding machines such as X-rays, anesthesiology machines and others were run on electricity from the main grid or from a power generator during power outages. A total of 72 poly-crystalline solar panels formed 140 m^2, with a total installed capacity of 23 kW_p were facing north, with a tilt of 10°.

The batteries and hybrid inverter/charger for the solar system were kept in a barred room with open air circulation, under a lid to cover them from dust. The circulation of air prevents them from moisture as well as overheating. The gel type batteries could power all the lighting for three days with a total storage capacity of 1070 Ah. They could also be charged from the grid when the solar panels were not generating enough electricity, and the switch between solar and grid power was manual. The solar system was installed in 2020 and financed by Clinica Sant Anna in Switzerland.

Swiss engineers come to visit the hospital in Tabora once every two years to monitor the system and evaluate the benefit of it. In addition, three sisters and two male workers have been trained to maintain the batteries and solar panels. There is also one local engineer to handle bigger problems. The batteries were vacuumed every week for removal of dust, and the solar panels were cleaned with water once a month during the dry season. The roof-mounted solar panels and the battery room can be seen in Figures 9a and 9b.

From the sisters, the authors learned that the hospital has greatly benefited from the solar power installation. It has eased their daily operations and working conditions significantly during power outages thanks to improved lighting and computer availability. Since it was installed only three years ago, no major problems to the system have occurred yet. They emphasised the importance of taking good care of the system and

(a) *Solar panel installation at St. Ann Catholic Mission Hospital.*

(b) *The battery room at St. Ann Catholic Mission Hospital.*

Figure 9: *Study visit at St. Ann Catholic Mission Hospital (Lovisa Magnusson Ericsson, 2023).*

training of hospital staff for O&M, but also the manager to make sure this knowledge does not disappear when workers come and go.

5.3.3 Sikonge Folk Development College

On the 10th of April 2023, Sikonge Folk Development College in Sikonge was visited by the authors, the Centre Director and the Member of Tumaini Education Initiative who were welcomed by a teacher at the school. The teacher showed the authors the kitchen, the greenhouse and the school premises.

Electricity supply

The school used electricity exclusively from the main grid. However, they described the difficulties with the many power outages that especially occurred during droughts when there is less water for the hydro power plants. The difficulty lies in fewer hours of study time for the students and outside lighting which is important, partly because of security and partly because of dangerous snakes in the area. They are keen to also have solar power but they cannot afford to buy the system.

Kitchen and food preparation

LPG and local firewood that was collected on the school premises was used as fuel for cooking. The gas kitchen was relatively new and had been provided and sponsored by the government. There were two 200 l gas ovens, two 50 l gas ovens and two gas stoves, see Figure 10. One 200 l gas oven could cook food for 300 students according to the teacher and the kitchen was managed by two cooks. The school also had a firewood kitchen in which there were five firewood stoves, see Figure 11.

(a) *The 50 l gas oven.*

(b) *The 200 l gas oven.*

(c) *The gas stove.*

(d) *The kitchen with gas ovens and stoves.*

Figure 10: *The gas kitchen and the stoves and ovens used at Sikonge Folk Development College (Lovisa Magnusson Ericsson, 2023).*

(a) *The school's firewood kitchen.*

(b) *Firewood collected at the school premises.*

Figure 11: *The firewood kitchen and the collected firewood from the premises at Sikonge Folk Development College (Martina Prpic Vucenov, 2023).*

Breakfast was prepared from 8:00-10:00, and directly after, lunch preparation begun, which was served at 14:00. The food prepared in the gas kitchen was usually porridge, ugali, meat and rice, while beans were cooked in the charcoal ovens since they took too long to prepare and therefore it was too expensive to cook in the gas kitchen. The gas stoves were used to cook vegetables or when there were few people to cook for.

On the day of the visit, the gas kitchen was not used since the personnel were gone for Easter Monday. The students themselves were cooking and they were only allowed to use the firewood stoves and not the gas kitchen when without supervision.

5.3.4 Biogas plants around Arusha

On the 9th of May 2023, the authors met with four biogas experts from Afrihands Tanzania and together visited three domestic biogas plants near Arusha. The experts consisted of two highly experienced engineers, one technician (still in training but experienced) and one artisan. The two engineers were part of the team who designed the CAMARTEC fixed dome plant which is one of the most widely used designs in east Africa and the neighbouring countries of Tanzania. The plants visited were all of the CAMARTEC design. Bellow follows a section of the general design of the biogas plant systems for all three sites and then the individual systems are described in the three following sections.

The design of the biogas plant systems

The first two biogas plants visited were of the type Diluted State Digester (DSD) where the substrate is mixed with water. The last plant was of the type Solid State Digester (SSD) which does not add additional water, see Figure 12. The digesters have a 30 year lifespan but according to Afrihands Tanzania (2023b), in reality they can last for generations if operated and maintained properly. There are some differences in the design of a DSD and SSD plants such as the mixing and inlet tank. Additionally the expansion chambers are designed differently as the outflow goes from the middle of the digester, instead of at the edge, to the digestate chamber. This makes it easier to remove sediments (solid parts) when needed. By having a sediment tank it is easier to handle solids and therefore, scum formation is less of a problem than for other plants.

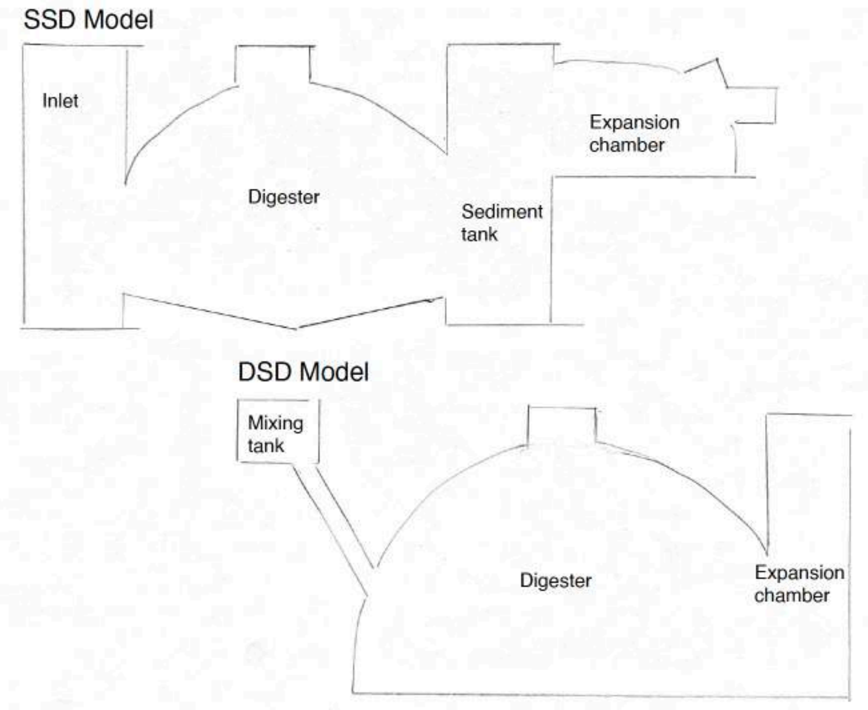


Figure 12: *Illustrations of the design for a DSD (above) and an SSD (below). Authors' own illustrations based on designs provided by Afrihands Tanzania (2023b) and Kossmann et al. (n.d.).*

All digesters are closed and on top there is a pipe valve. Above the expansion chambers a lid which can be opened is located where the digestate can be accessed if needed. From the expansion chamber the digestate flows out from the plant and the gas flows from the top towards the kitchen. The gas pipes should be located underground to avoid damage. If the pipes are located above ground they should be of metal, or if in the shade, of plastic since the sun corrodes the plastic. Before the gas enters the appliances in the kitchen the gas undergoes post-treatment and is purified at some of the sites.

If the gas is not utilised it should still be combusted on the stoves for environmental reasons. However, if it is not, it will escape from the digester through the outlet pipe since it is located higher than the inlet pipe. This is because if it were to escape through the inlet pipe the person filling the substrate would risk being exposed to the gas.

Site 1: St. Mbaaga Spiritual Formation Centre

At St. Mbaaga Spiritual Formation Centre the biogas plant had been built by the artisan, the least experienced expert, and the plant utilised pig manure as substrate.

The pigs were in concrete stables with a sloping floor towards the channels in the middle corridor, see Figure 13a. The manure was first sweeped and moved in buckets to the mixing chamber, see Figure 13b. Then the stables were cleaned with a small amount of water which was drained through the small channels. In the mixing tank they estimated the ratio, and usually unnecessarily added more water than substrate. It was then manually mixed and let into the digester.

(a) *Concrete stables for the pigs with a sloping floor toward the channels in the middle corridor.*

(b) *Personnel sweeping the floor in the pig stables to manually collect the manure to use as substrate in the digester.*

Figure 13: *The pig stables at Site 1 (Martina Prpic Vucenov, 2023).*

The outlet for the digester had been blocked when it was noticed that the digestate was returning into the digester, which is a normal process as the digestate returns when the gas is used. However, this was not known by the owners and the personnel operating the plant. See the mixing tank and the system in Figure 14.

Figure 14: *Biogas plant system at Site 1 (Lovisa Magnusson Ericsson, 2023).*

The expansion chamber had been emptied the year before since it was thought that the plant was not working properly. They hired inexperienced personnel who did not recognize the reason and the solutions for the scum formation in the plant.

The plastic gas pipes that led to the kitchen were located above ground even if the artisan advised the clients to break apart the concrete and place them underground. This was to ensure a long lifetime of the pipes and avoid leakage. The gas kitchen is illustrated in Figure 15.

Figure 15: *Gas kitchen at Site 1 (Martina Prpic Vucenov, 2023).*

Site 2: St. Monica School (nursery, primary and secondary school)
At St. Monica School zero grazing cows were utilised, meaning that the cows only stayed in the stables. In the stables there was a channel where the manure was manually collected, similar to at Site 1, and afterwards the stables were washed with water. There had been an electric mixing device but as it corroded and broke it was not replaced for economical reasons and instead, the mixing was now done manually.

The cows had been generating more substrate than the plant was originally designed for and as a result, the operators overfed the digester which made it overproduce gas and form scum.

From the digester chamber the digestate flowed into compost pits where ash was added to increase the value of the compost. There were two compost pits, where one was broken and about to be repaired. A roof covered the pits to shield it from the sun and keep it from drying out. Since they produce too much compost to use themselves they sell the remaining compost. The experts claimed that there was a big market for the digestate as fertiliser. See the biogas system in Figure 16

They had a manual water trap which they drained once a month, as well as hydrogen sulphide removal in the kitchen.

Figure 16: *Biogas plant system at Site 2 (Lovisa Magnusson Ericsson, 2023).*

Site 3: Convent of Carmelite Missionary Sisters

At the Convent of Carmelite Missionary Sisters the biogas plant had been built by the technician, the second most experienced expert, in the beginning of 2023 (the same year as this field study was conducted). It utilised cow manure and urine as substrates and since it was an SSD, they did not mix it with water. According to the experts the SSD design is easier to operate, maintain and perform check-ups on. The plant does not need to be fed daily as the DSD plants do but can instead be fed every other day. Despite this, the owners of the plant feed it every day since they did not have any other storage space for the manure. See the biogas system in Figure 17a.

Urine is collected separately as it flows out from the stable on tilted floors to a collecting point. The urine provides enough liquid to mix with the substrate which means that the SSD plant is not completely solid as the name suggests.

Water and hydrogen sulphide is removed before the gas reaches the appliances. One of the engineers mentioned that the hydrogen sulphide removal should occur before the water removal as water facilitates the reaction. There was also a booster pump which could be used to increase the gas pressure to the appliances. See Figure 17b.

(a) *Biogas plant system at Site 3.*

(b) *The gas first flows through the (white) water removal box, second; through the (green) hydrogen sulphide removal box and lastly; through the (black) booster pump. A pressure gauge can also be seen to the left.*

Figure 17: *Biogas system at Site 3 (Lovisa Magnusson Ericsson, 2023).*

Four out of nineteen sisters were trained simultaneously as the construction of the plant by the technician. As the construction of the plant progressed the sisters were educated on understanding the system. The technician took pictures and then made notes on how to operate the specific parts as well as prepared a manual for the sisters. The four sisters have continued to train the remaining sisters on how to manage the plant.

The sister hosting us emphasised the benefits of using the biogas instead of having to buy and transport LPG which they used before. She mentioned that the plant was expensive but well worth the cost.

General notes

All hosts at the three sites were very welcoming and gladly showed us around, and all of the experts seemed very keen on sharing their knowledge.

At Site 1 the plant was installed by an inexperienced artisan outside of the company and therefore the construction of the plant and the training of the personnel suffered. The people operating the plant did not have the knowledge to operate it and did not inform the installer of problems that occurred as they should have. At Site 2 there was also some mismanagement in the form of overfeeding the digester. However, this was not because of lack of knowledge but because they did not have another way of handling the manure. The plant at Site 3, which was made just a few months before the visit, had the best management and best contact with the installer of the plant. They appeared to have received the best training and the best design, according to the experts. The fact that the sisters plan to educate all the other sisters will help to ensure that the knowledge of O&M stays at the site and that the plant will not be abandoned.

From the visit the authors got viable information about how the instalment of a biogas plant is done, what a (seemingly) successful training program should look like and how important it is to have a continued communication channel between the owner of the plant and the installers. It seems that it is important for the owners to maintain the communication especially when there are uncertainties about the O&M of the plant.

The biogas experts mentioned that the possible biogas plant design considered for the Tumaini Open School is the SSD desgin.

6 Energy demand and supply - results and analysis

This section describes the results and analysis of the case study, which includes interviews, survey and calculations.

6.1 Student interviews

In this section the results followed by analysis of the interviews with the students will be presented.

6.1.1 Results

A total of seven students were interviewed and a summary of the answers, as well as additional inputs from the survey, are presented in Table 8. See an extended description of the interview execution and the interview templates in Appendix A.

Table 8: *The results from the student interviews and part of the survey. Electricity use of the students, preferred electronic devices in classrooms, preferred food preparation method and additional information provided by the students in the survey is illustrated at the bottom.*

	No of students	**Time**
Electricity use		
Studying w. lighting outside school hours	7	16-18 and 19-22
Charging of mobile	3	3 h, morning or at night
Ironing	6	Afternoon/evening
Fan	4	
Lighting inside dormitories	4	
Lighting outside	2	
Lighting inside washroom	1	
Preferred electric devices in classrooms		
AC/Fan	7	
Lighting inside	6	19-22
Computer for every student	5	
Charging of devices	1	
Food preparation preferences		**Reason**
Electrical	2	Shorter preparation time Sweeter food
Gas	5	Shorter preparation time Easier to use
Charcoal	1	Sweeter food

Continued on next page

Table 8: *The results from the student interviews and part of the survey. Electricity use of the students, preferred electronic devices in classrooms, preferred food preparation method and additional information provided by the students in the survey is illustrated at the bottom.* (Continued)

	No of students	
Additional information	**From interviews**	**From survey**
Electricity is a necessity	1	1
Backup source is important	3	1
Renewable energy preferred	-	1
Solar energy preferred	2	5
Generator necessary	-	1
First aid service	1	2

The electricity use of the students is shown at the top of the table, where only studying with lighting outside school hours and mobile usage were asked specifically. From the three students who owned a mobile, two were broken and no longer in use so the result reflects the usage from before it was broken. One student mentioned that usage of fans is weather dependent, and one student preferred fans over AC.

In Table 8 above the *Additional information* the students provided from the interview and the survey is presented. This information was obtained from a voluntary final remark in the end of the interview and when answering the survey.

6.1.2 Analysis

The students were asked to mention the most important electric devices in the classrooms, and many students mentioned computers for the students. Then, they were asked directly about the importance of the AC/fans, and six out of seven were asked directly about the lighting. When interpreting the results, it is important to consider that the high number of students who did find these services important can be because of the way it was asked, namely as a direct question. It might therefore be more important to emphasise the importance of computers for the students because this was the answers to an open question.

The results show that most students preferred to have their food prepared with gas stoves/ovens. However, the question of how they preferred their food to be cooked was not asked in the same way to every student since it was not formulated clearly enough. The translator made his own interpretation of the question and modified it as the interviews went along. Therefore, there is a risk that some were asked which cooking method they prefer to use themselves rather than which cooking method used to prepare the food they are served they prefer. There were discussions about the cooking and food between the students and the translator which the authors could not follow. However, even if there was some misunderstanding one can conclude that no prejudice or resistance was found by the students using any of the stoves/ovens.

During the interviews the translator helped the students to feel comfortable by talking freely to them and making jokes with them. He sometimes rephrased the questions and talked with them until he found out the answer and then translated it back to the authors. This most likely resulted in better answers from the interviewees, however it also meant that the authors did not have access to all the information given by the students. The language barrier and the translation process possibly hindered the authors on elaborating on the discussion with the students or adding relevant follow up questions. This resulted in the interview being of a more structured than semi-structured nature.

The reliability of the answers from the students are considered to be high as the students understood that this case study was to their benefit and that none of the questions asked were of a sensitive nature to the students.

Since the first student were asked different questions and some were added after her interview, and since she was present during all the interviews, she was asked a supplementary question in the end about if she had something to add. She mentioned the importance of solar power because of the frequent power outages.

6.2 Electricity demand and load profiles for priority steps and scenarios

In this section the results followed by analysis of electricity demand and load profiles for the electricity service priority steps and scenarios are presented.

6.2.1 Results

The base case

The maximum daily load profile for the entire school is illustrated in Figure 18, which is also the load profile for the base case. The time use of the electricity services was, as mentioned in Section 3.3.2, a result of interviews and discussions with the Centre Director.

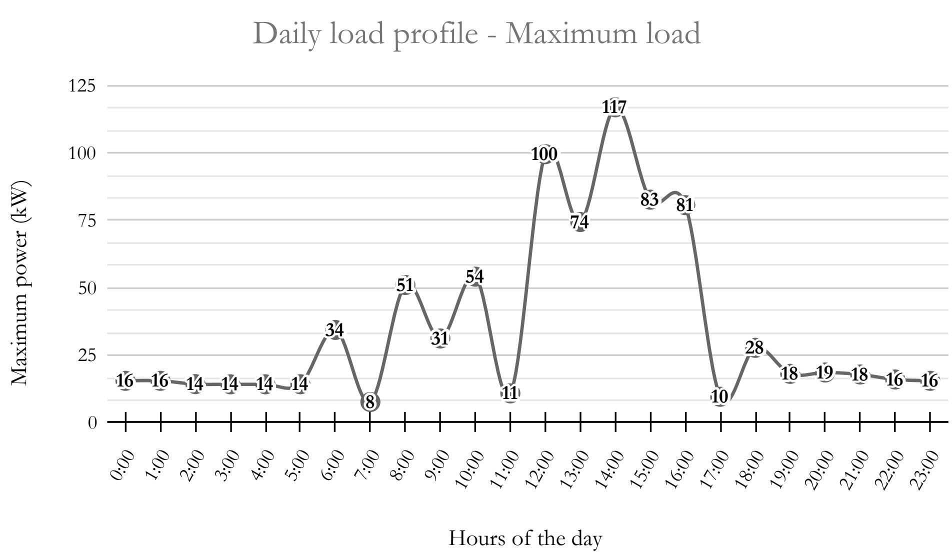
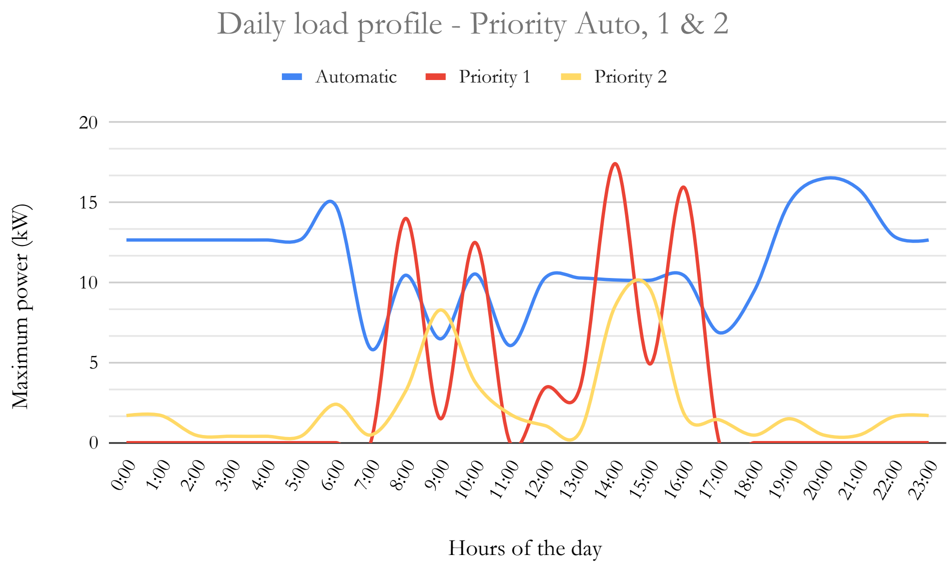


Figure 18: *The maximum daily electricity load profile (kW).*

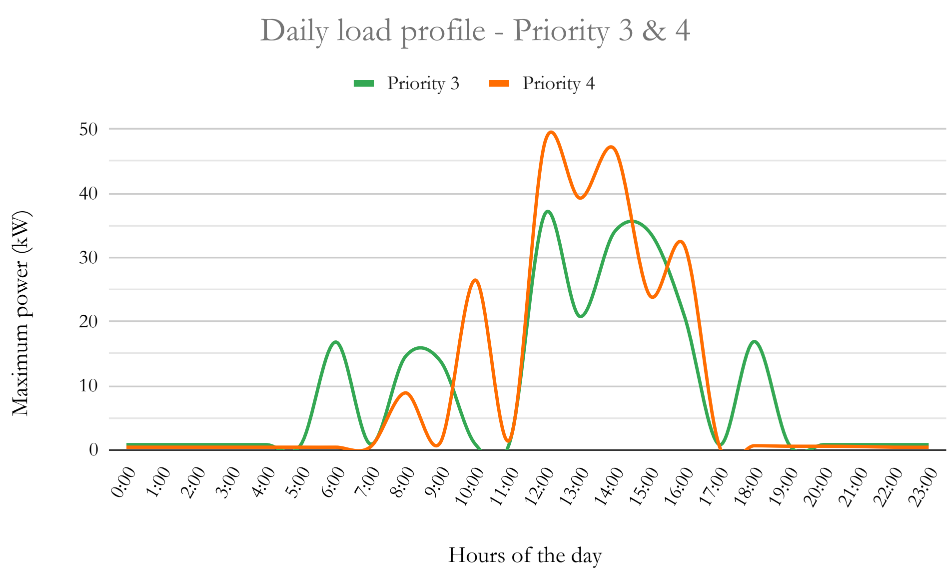
Electricity service priority steps

The daily load profiles for the electricity service priority steps are illustrated in Figure 19. The load profile for automatically prioritised services and priority step 1 and 2 are illustrated in Figure 19a and priority steps 3 and 4 in Figure 19b. The total daily electricity demand for all the priority steps are shown in Figure 20.

The priority steps are based on the automatically prioritised electricity services and the results from the survey, which can be seen in Appendix B.2.



(a) *The automatically prioritised, priority steps 1 and 2.*



(b) *Priority steps 3 and 4.*

Figure 19: *Daily load profiles in (kW) of the electricity service priority steps.*

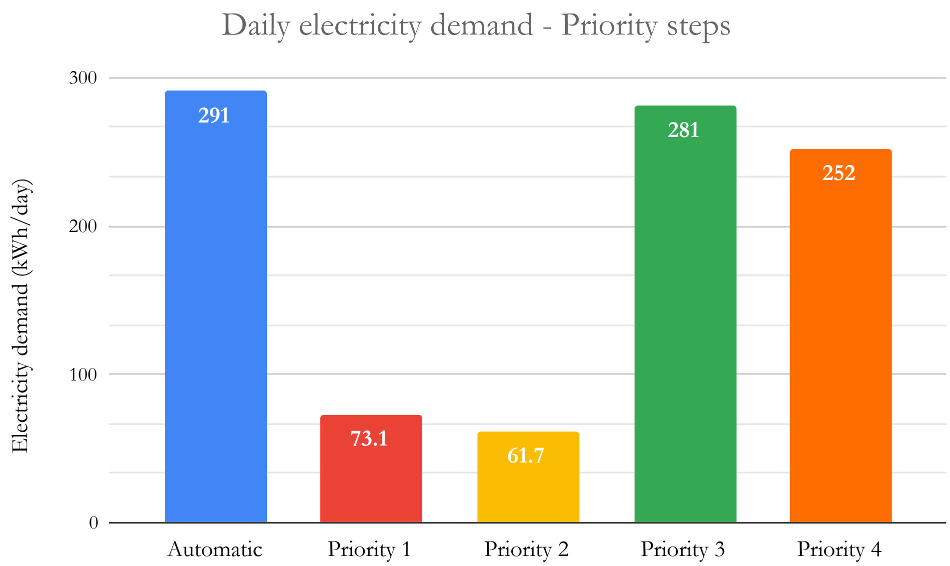


Figure 20: *Total daily electricity demand for all the electricity service priority steps (kWh/day).*

The scenarios

The daily load profile and electricity demand for the Electricity supply system Scenarios 1, 2 and 3 are illustrated in Figure 21 and 22, respectively. Scenario 1 consist of the automatically prioritised electricity services only, while Scenario 2 adds priority steps 1 and 2 and Scenario 3 adds priority step 3. See Table 1 in Section 3.3.4 for a visual presentation of the scenarios.

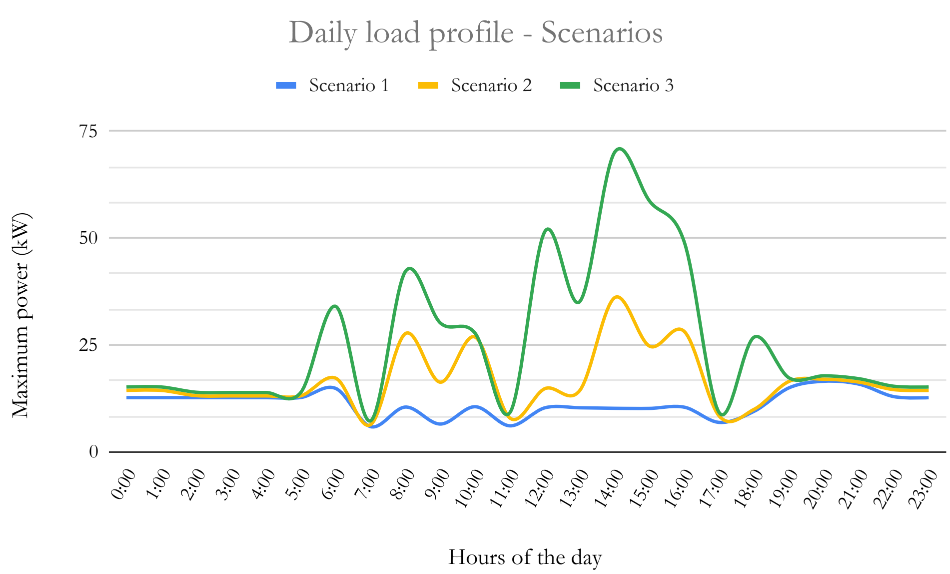


Figure 21: *Daily load profile for Scenario 1, 2 and 3 (kW).*

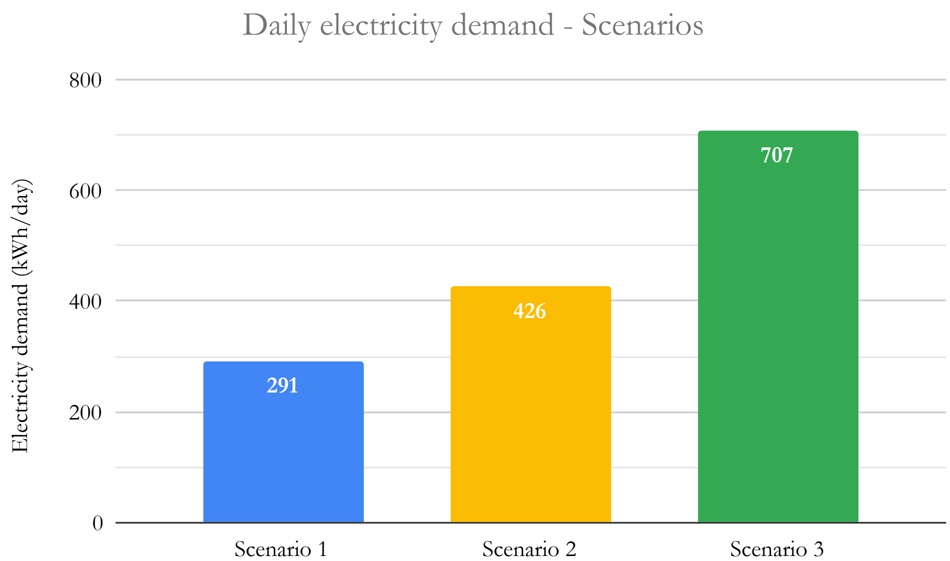


Figure 22: *Total daily electricity demand for Scenario 1, 2 and 3 (kWh/day).*

The total monthly electricity demand for base case and all the scenarios is illustrated in Figure 23.

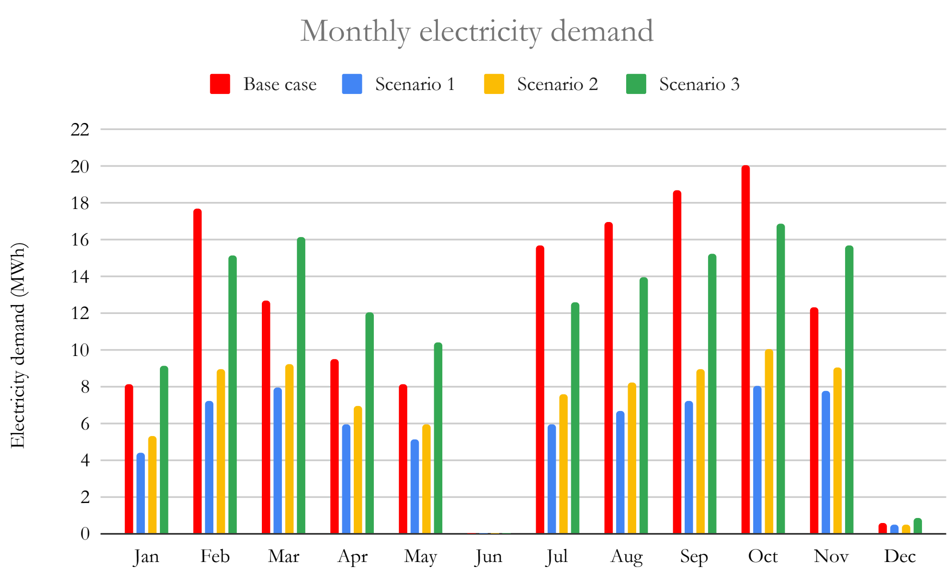


Figure 23: *Total monthly electricity demand for the base case and all the scenarios (MWh).*

6.2.2 Analysis

Electricity demand

The electricity demand is based on uncertain assumptions of the future need of electricity services for the buildings and rooms. The exact services that will be used, number of devices and hourly use are all assumptions, meaning that the calculations cannot be exact. Furthermore, some electricity services were not known such as for the plumbing and electrician vocational classrooms and are therefore excluded from the electricity demand.

While the electricity demand was calculated, the land use plan produced by EWB Sweden for the Tumaini Open School, including architectural plans for the buildings, was not yet determined. Therefore, the administration building assumed in the electricity demand is not consistent with the land use plan. In the land use plan there are more rooms but no bigger staff room and therefore it was decided with the Centre Director that the original plan for the administration building should be used in the calculations which included a larger staff room.

Choosing the electricity demand for the devices in the upper range in western countries may have resulted in an oversized system. However, in developing countries the devices used are often older and use more electricity which justifies the upper range choice. This may change in the future, although probably not within the next few years. Additionally, the startup power demand of the devices was neglected which may result in an undersized system and lower power peaks. However, since many of the devices might not be used at the same time, as assumed, the effect of this assumption may be reduced.

Electricity service prioritisation

The prioritisation of the electricity services is based on the automatically prioritised services and surveys answered by students, teachers and other members of the Tumaini Education Initiative. The sampling group for each target group was small but together with the interviews conducted with the students and the Centre Director the gained information is still considered to be applicable. The answers from the different target groups were all valued equally since all of them have different experiences, perspectives and priorities.

In the surveys the gas in science laboratories as well as some of the automatically chosen electrical services were mistakenly included and were also often chosen as a priority. The surveys were originally created to cover the entire energy demand and not only the electricity demand which is the reason why the gas was included. The automatically prioritised services were determined after the first draft of the surveys, and some services were missing in the second draft of the surveys. Without these extra electricity services there would have been more services included in priorities 1-3 and the resulting scenarios and load profiles would possibly have looked different, which in turn affects both the solar optimisation and the economical costs.

Daily, monthly and yearly electricity load profiles

Just as the electricity demand the daily load profiles are based on assumptions of the future use of the electricity services which are uncertain. The usage depends on for example the school schedule for the classrooms which were not known since this depends on available teachers and the curriculum of the attending students. However, based on the assumptions it can be seen that the load profiles are well suited to the sun hours of the day, except during the 5:00 and 18:00 peaks.

The daily load profile for the automatically prioritised services is the only curve with lower daily than nightly load. This is explained by the lighting outside that is only on during night time. Included in this priority step are also some services that are used continuously such as the WiFi, security cameras, the server and refrigerators. The peaks at 5:00 and 20:00 is a result of the inside lighting that is needed when the sun is not up.

The daily load profile for Priority 1 is especially determined by the usage of the desktops at 8:00, 10:00, 14:00 and 16:00. The peaks at 9:00 and 15:00 in the daily load profile for Priority 2 is mostly due to the usage of the sewing and overlock machines as well as some small power usage devices. The photo copy machine and the desktops usage also affects the peaks at 10:00 and 14:00.

The daily load profile for Priority 3 is determined by the usage of the electrical ovens and stoves in the teachers house at 6:00, 12:00 and 18:00. The usage of ACs is the reason for the remaining peaks. The daily load profile for Priority 4 is mostly due to the usage of electric tea kettles at 10:00 for breakfast and ACs during the afternoons.

The monthly and yearly load profiles are based on two standard weeks of operation, one for wet season and one for dry season, which are repeated with regard taken to school breaks. This can be seen in Figure 23 for the monthly electricity demand. The way the weeks are constructed, with two days with the maximum possible load, three days with medium load and load for weekends for each season, may result in load profiles that are not accurate and possibly over- or undersized. The load profiles will also be affected by the fact that the wet and dry seasons are not completely predictable and thus the usage of the ACs will also differ in reality. It may also be that not all of the ACs will be used every day as is assumed. Furthermore, it is assumed that no electricity will be used during the school breaks which most likely will not be the case as some teachers may be working during school breaks. Also, students living at the school might stay at the premises and not go home for the entire or parts of the break. However, this assumption was made as to not oversize the battery for the solar system.

6.3 Solar PV system optimisation

In this section the results followed by analysis of the solar PV system optimisation are presented.

6.3.1 Results

The results for each system size of the installed PV capacity, PV size and number of panels is presented in Table 9. The resulting battery storage capacity is also presented in the same table.

Table 9: *Results of PV capacity, PV size, number of panels and battery capacity from the PV optimisation.*

Scenario		PV capacity (kW_p)	PV size (m^2)	No of panels	Battery capacity (kWh)
1	Bigger Battery	59.9	286	111	155
	Bigger PV	65.8	315	122	148
2	Bigger Battery	87.6	418	162	157
	Bigger PV	96.3	460	178	154
3	Bigger Battery	145	695	269	184
	Bigger PV	160	764	296	181

The amount of saved electricity is presented in Figure 24 below. This is the electricity consumed from the solar panels and hence, does not need to be bought from the grid.

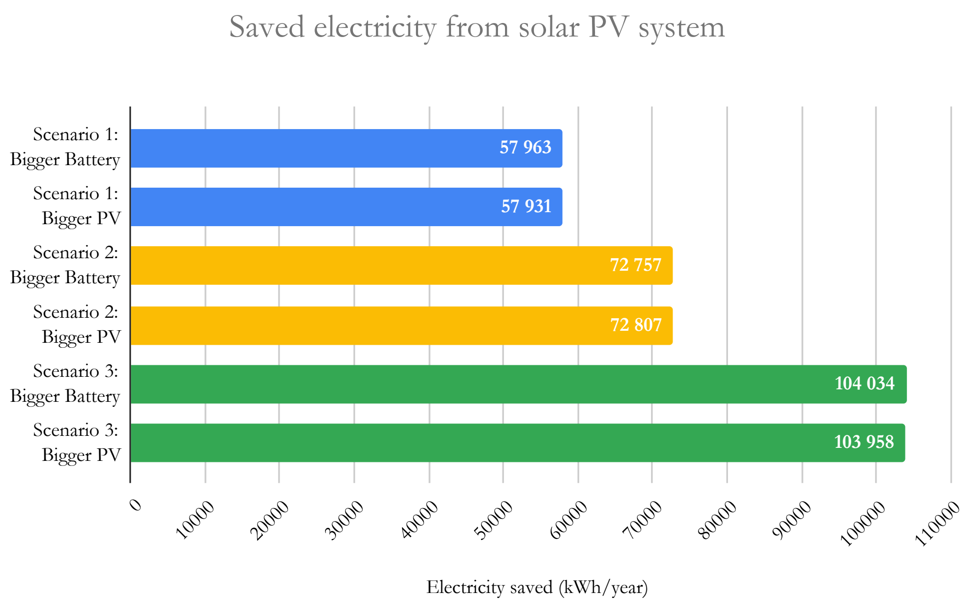


Figure 24: *Saved electricity from the solar PV system for each scenario and system size (kWh/year).*

The hourly production output results in 2-4 occasions per year of electricity shortage from the solar power system exceeding 12 h. In all but one of these incidents did the electricity shortage last about 13-14 hours. The electricity shortage exceeds 24 hours once per year in each system size, namely 27-28 hours and occurs on the same day in March.

6.3.2 Analysis

In the last column of Table 9 it can be seen that the battery capacity is smaller for the systems with Bigger PV, as it should be. With more installed PV capacity the battery capacity can be reduced since more production compensates for less storage in certain moments. However, the battery size is only slightly bigger in Scenario 2 than in Scenario 1 despite higher load. This is because the additional load in Scenario 2 appears almost exclusively during daytime (8:00-16:00) when the solar panels are producing electricity. Thus, there is no need for much more storage.

As can be seen in Table 9, the difference in battery capacity between Bigger Battery and Bigger PV is bigger for Scenario 1 (7 kWh) than for Scenario 2 and 3 (3 kWh). The reason is probably that Scenario 1 has a larger share of its electricity demand during night time, while in Scenario 2 and 3, the majority of electricity consumption occurs during day time.

In Figure 24, it can be seen that in Scenario 1 and 3, the amount of saved electricity decreases with Bigger PV while in Scenario 2, it increases. This could be explained by the difference in load distribution over the day between the scenarios. Since Scenario 1 has a bigger part of its load during night time (see Figure 21), it is not beneficial to invest in more solar panels since increased production would not cover the nightly load. Scenario 3 has additional load during day time but also two peaks in early morning and evening (5:00-7:00 and around 18:00, see Figure 21) when the panels produce less. Therefore, for these scenarios it might be more profitable to increase the battery capacity. In the opposite way, it seems more profitable to invest in more solar panels for Scenario 2 since the additional load is distributed mainly during day time (see Figure 21). On the other hand, available land area is limited which is disadvantageous for the Bigger PV case.

Looking at all scenarios, the load is well suited to the solar hours and hence, the battery capacity can be small enough to cover the lower nightly load. However, the battery is sized to make sure the yearly electricity shortage is below 10 %, not to cover the nightly load specifically. The reason for the occasion of electricity shortages exceeding 24 h in the hourly production output is not clear, but one explanation could be that the weather file used in SAM's simulations caused a drop in electricity output on this exact day. Despite the instances of electricity shortage exceeding 12 hours, the method of sizing the battery to limit electricity shortage to 10 % per year is still considered reasonable and justified. Since the power outages normally last between a few minutes up to 6 hours in the Tabora Region and only very rarely last a full day or longer, the results of electricity shortage from this study seem manageable.

Since all electricity demand assumptions and input values for calculations are chosen in the upper limit of the suggested range, the system has a margin for maximum electricity consumption. The Bigger PV case, where an extra 10 % load is to be covered, therefore risks causing an oversized system that might not be economically justified. On the other hand, the case of Bigger PV is interesting when it is compared with the Bigger Battery cases. Since batteries are the most expensive component in a solar PV system, the authors thought it would be an interesting approach to the economical analysis. This is discussed more in the analysis of the economical results.

The PV capacity (used as input in SAM) was based only on the total maximum daily electricity load which does not represent the changes in yearly load, which might result in an oversized system. The loss factor used in the PV capacity calculations also included many loss factors. Literature sources used different loss factors and it was therefore not clear which should be included. However, these loss factors are very small and do not greatly affect the results.

During school breaks, the electricity load was assumed to be zero. This will most likely not be the case in reality since teachers will work at the school during breaks and some students cannot go home during breaks. This of course affects the sizing of the battery since the PV system is assumed to be "turned off" during school breaks. In reality, it would be beneficial for them to be "turned on" a day or two before school starts again to charge the batteries in advance. These sort of adjustments were unfortunately not possible in this study, but could be a recommendation for future operation.

One big disadvantage of this study is the unrealistic assumption that the full PV system will be installed and put into operation all at once. It was necessary for the continuing calculations and long-term purpose of investigating the full-scale electricity demand, but in reality, the school will expand its facilities in many small steps as financing allows it. Therefore, scalability is an important factor to consider during implementation of the PV system. The assumption affects both electricity production and cost of the system. If the 10-15 years up-scaling period were included, the degradation of components would be more spread out in time which changes the need of replacing components.

6.4 Electricity cost for the scenarios

In this section the results followed by analysis of electricity cost for the scenarios are presented.

6.4.1 Results

The results of electricity cost for the solar LCOE for each scenario, with Bigger Battery and Bigger PV included, is presented in Table 10a while the cost of the electricity from the main grid, including the base case, are presented in Table 10b.

Table 10: *Solar LCOE and main grid cost per kWh for each of the six system sizes and the base case.*

(a) *Solar LCOE results.*

Scenario		Solar LCOE (US cent/kWh)
1	Bigger Battery	41.8
	Bigger PV	42.5
2	Bigger Battery	35.9
	Bigger PV	36.7
3	Bigger Battery	39.3
	Bigger PV	40.3

(b) *Main grid cost results.*

Scenario		Main grid cost (US cent/kWh)
Base case		15.4
1	Bigger Battery	18.2
	Bigger PV	18.2
2	Bigger Battery	18.3
	Bigger PV	18.3
3	Bigger Battery	15.3
	Bigger PV	15.3

The total cost for the electricity supply system over the assumed lifetime for each scenario, including both solar power and main grid electricity, is presented in Figure 25. The colors illustrates the share of solar power and main grid to the load distribution, and the numbers inside presents the total cost for the solar and main grid power. The percentage in parenthesis represents the share of the cost for each system size. The total cost per scenario over the assumed lifetime is presented in Figure 26.

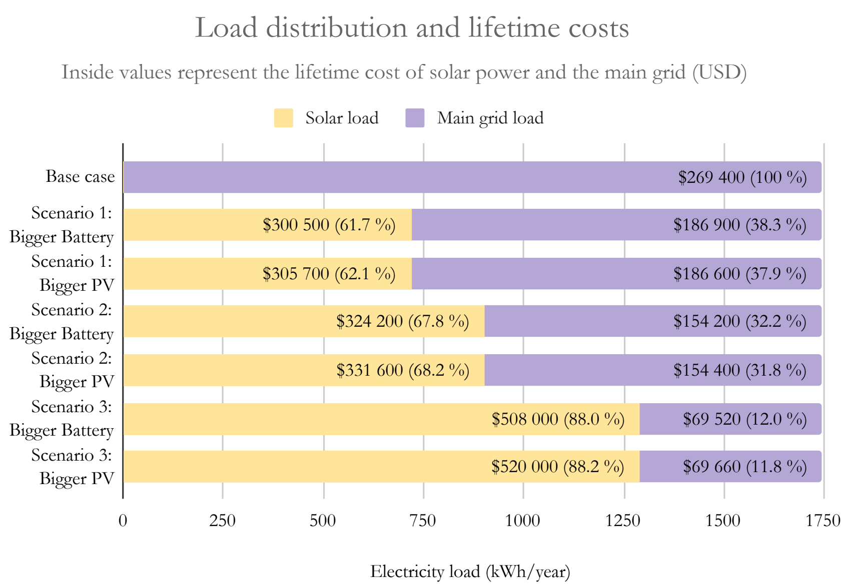


Figure 25: *Total load distribution (kWh/year), lifetime cost (USD) and share of the cost in parenthesis for solar power and the main grid.*

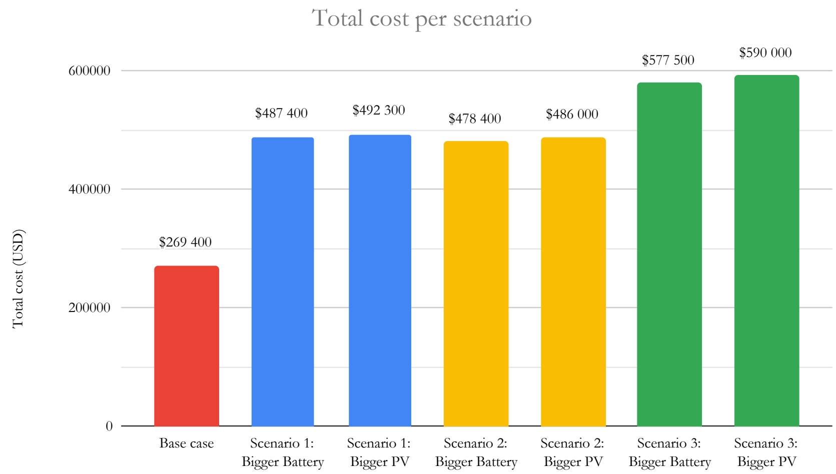


Figure 26: *Total lifetime cost for each scenario (USD).*

6.4.2 Analysis

Solar LCOE

From Table 10a it can be seen that the LCOE is higher for Bigger PV than for Bigger Battery in all scenarios. This is because the battery size that was needed to fulfill the calculated installed capacity is the same for Scenario 1 and 2, for both the Bigger PV and Bigger Battery cases. The 10 % increase in load for the Bigger PV case is not enough to make the battery size small enough to impact the choice of batteries and hence, the cost. However, it is worth noticing that the LCOE is lower for Scenario 2 than for Scenario 3 which is also unexpected. This could be due to a more optimum match between PV production and load profile for Scenario 2 than for Scenario 3. The additional batteries and components for Scenario 3 most likely is another explanation.

Comparing the LCOE results of this study with other LCOE reports gives some interesting insights. The LCOE are approximately two to four times higher compared to a study by Lazard (2023) for *Solar PV + Storage—Utility Scale* made for the United States market. This could partly be because of the offers received had approximately 30 % higher O&M costs compared to the same study. While the capital cost per kW are within the range presented in the report, it is not clear what system size is regarded or which components are included in the study by Lazard (ibid.). It is therefore not definite whether the results of this study are reasonable or not. However, the O&M costs used in this study were provided by the solar company Photons Energy Ltd. and represented a system they are already maintaining. The size of this system is unknown, and it is possible they increased the prices knowing the authors came from a developed country thinking that possible funding would come from Europe when making the enquiry (which is not the case). The same goes for all costs in the offers received. Also, both companies are based in Dar es Salaam which probably has a more developed market for PV systems than Tabora, and in addition, yields high transportation costs. Finally, comparing the markets of Tanzania with the United States is not reasonable since the market is much more developed in the United States than in a developing country such as Tanzania. A smaller market means fewer imports which results in more expensive components per device. The authors could not find an updated LCOE report for Tanzania or Africa for a more accurate comparison.

The costs are affected by the choice of components used, especially the chosen hybrid inverter/charger which may be oversized for the system sizes. This is because the enquiries from the solar companies were for the base case. If enquires were made for the six system sizes, it is possible that the hybrid inverter/charger would have been smaller and cheaper.

Cost of electricity from the main grid

The results of the cost of electricity from the main grid in Table 10b show the high effect of the tariffs. Since much less electricity needs to be bought from the grid in Scenario 3, it was charged through tariff T1 which has neither service charge nor maximum power charge. In Scenario 1 and 2 however, which were charged through T2, it shows that the less electricity that is bought from the grid, the more expensive the electricity becomes per kWh. This is due to the service charge, which is the same each month independent of electricity demand for T2. The base case therefore has the cheapest cost of electricity per kWh from the main grid of all the T2 cases, but once consumption falls below the limit for T1 (as for Scenario 3), it becomes even cheaper per kWh than the base case. Notice though that Bigger PV or Bigger Battery has no noticeable effect on the grid bought electricity cost per kWh.

Load distribution and total cost

Figure 25 shows that the cost for solar is more expensive than grid electricity in every scenario, independent of the load distribution between solar and grid. This is because of the solar LCOE being more than double the electricity price per kWh from the main grid. As for the LCOE, the total cost is higher for the cases with Bigger PV than for Bigger Battery, which corresponds to the LCOE results in Table 10a.

The total cost for each system size is illustrated in Figure 26, where the total cost for solar and grid electricity is added together. Scenario 2 have the lowest LCOE result, but combined with the highest cost of electricity from main grid it ends up being the second best scenario. Scenario 1 ends up being slightly more expensive since it has the highest LCOE and only slightly lower cost of electricity from the main grid than Scenario 2. It is clear that Scenario 3 is the most expensive option of the scenarios, despite having the lowest cost per kWh for main grid electricity.

In Figure 26 it is clear that the base case is the cheapest alternative for the electricity supply system. The difference between Scenario 1 and 2 is minimal which makes Scenario 2 more profitable, but it also means that the choice between these scenarios should be based on more than economical factors, such as the reliability of electricity supply or the O&M of the systems. Scenario 3 with Bigger PV is clearly the most expensive scenario.

Assumptions

Assumptions on degradation rate and life expectancy of components greatly affects the cost results, as it affects the need for replacing them and in turn, the lifetime cost of the system. For example, if the assumed lifetime for batteries and the hybrid inverter was 15 years instead of 10, they would only have to be replaced once instead of twice, which would result in a lower LCOE. In the same way, assuming the same electricity consumption for 30 years will also affect the economical costs, as well as assuming constant yearly electricity output from the solar panels. This is the result of assuming that the solar PV system is installed in one go.

This also affects the NPV of the investments and O&M costs since the cost of components could change in the next 10-15 years as well as labour costs. However, since the same assumptions are used in both LCOE calculations and main grid cost calculations, the total cost for all scenarios are consistent. This means the economical analysis and comparison between the scenarios are still relevant and justified. The final conclusion on what scenario is the most cost-effective option will most likely be true despite some potentially large assumptions.

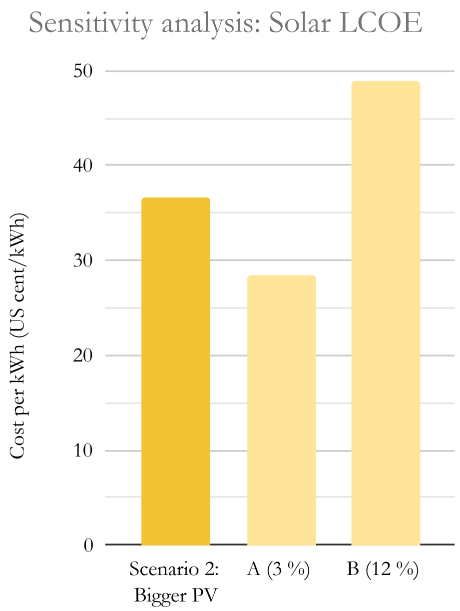
In the same way has the assumption of keeping the tariffs constant during 30 years an impact on the total cost, not only for the base case but for all scenarios. Most likely, the tariffs will be adjusted in the coming 30 years, but since the tariffs have been both increasing and decreasing historically, it is difficult to draw any conclusions on future tariff changes. Since the tariffs are regulated from the government with the goal to make electricity affordable there is a possibility that the tariffs could be even lower in the future. Based on this, and information from the interview with TANESCO (2023b) which stated that the tariffs most likely will stay the same in the foreseeable future, this was the most reasonable assumption.

6.5 Sensitivity analysis

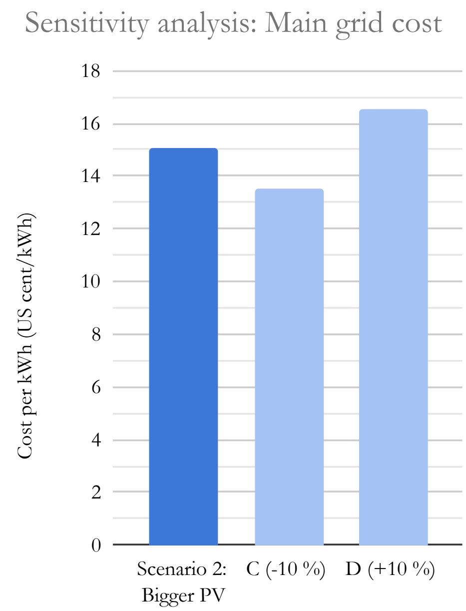
A sensitivity analysis was performed to investigate the impacts of two input values on the cost per kWh for LCOE of solar, grid bought electricity and the resulting cost per kWh for one chosen scenario. The two parameters are the discount rate (which affects the LCOE for solar) and the electricity price (which affects the cost for grid bought electricity).

6.5.1 Results

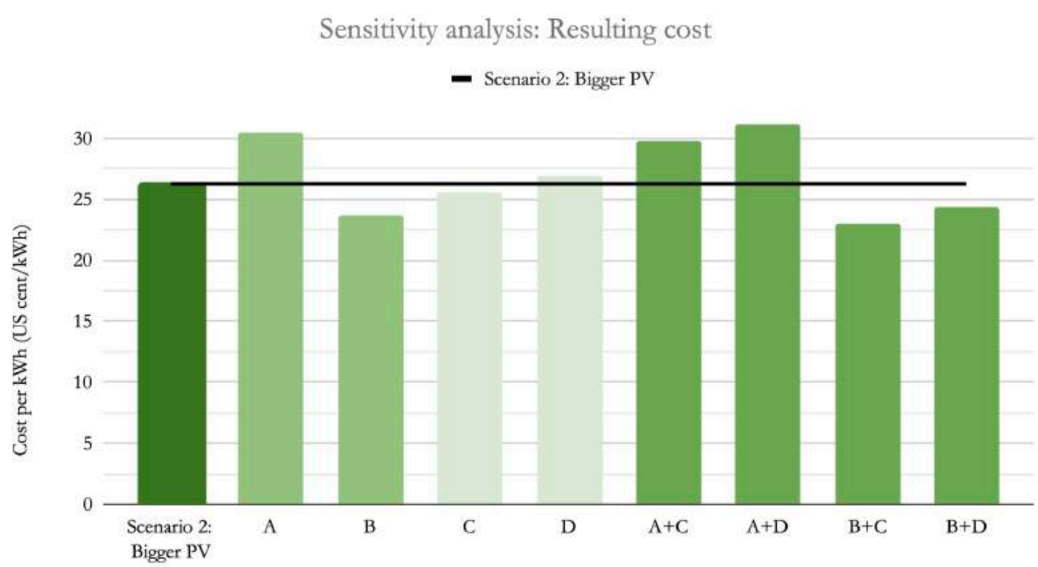
The chosen scenario for the sensitivity analysis is Scenario 2: Bigger PV with all results presented in Figure 27. The discount rate is changed from the original 7 % to the lower 3 % and higher 12 %, with the resulting LCOE for solar presented in Figure 27a. The energy charge and maximum power charge is varied with ±10 % (with the service charge kept constant). The grid costs are presented in Figure 27b. Finally, by combining these changing parameters, the resulting costs are obtained and presented in Figure 27c. This is done by adding the total lifetime costs for solar and grid bought electricity and dividing the sum on the total electricity demand during the lifetime of 30 years.



(a) *Solar LCOE where A represents a discount rate of 3 % and B represents 12 %, compared to 7 %.*



(b) *Main grid cost per kWh where C and D represents a 10 % lower and higher electricity price respectively.*



(c) *Resulting cost per kWh where all combinations of discount rate and electricity price are represented.*

Figure 27: *Sensitivity analysis of discount rate and electricity price, with Scenario 2: Bigger PV as a reference case.*

6.5.2 Analysis

Looking at Figure 27a, it is clear that the discount rate has a great impact on the LCOE for solar. For case A, the 3 % discount rate raises the NPV of total output more than it raises NPV of total cost, which results in a lower LCOE compared to case B. 12 % discount rate brings down NPV of total output more than NPV of total cost which, in the opposite way, results in a higher LCOE. The ratio between NPV of total cost and NPV of total output is lower for A than for B. However, it is worth remembering that the NPV of total cost is higher for A than B, which becomes evident in the resulting cost in Figure 27c.

The change in electricity price affects only the grid bought electricity with approximately the same percentage as the price variation, as seen in Figure 27b. The results are reflected on the resulting costs in Figure 27c, where the cost for case A+D and B+D is higher than A+C and B+C respectively.

Since the LCOE for solar is higher than cost per kWh for grid electricity, the discount rate has a bigger impact on the resulting cost than electricity price. As Figure 27c shows, half of the cases are below the reference case and half are above, but the best combination is a discount rate of 12 % and 10 % lower electricity price (case B+C).

6.6 Biogas system

In this section the calculation results followed by analysis of the biogas system are presented.

6.6.1 Results

Biogas demand

The total biogas demand for the daily cooking was calculated to be 177 m^3/day, and the time used for cooking using 1-6 of stoves are presented in Table 11.

Table 11: *Time used for cooking using different number of stoves.*

No of stoves	**1**	**2**	**3**	**4**	**5**	**6**
Total cooking time (h)	77.8	38.9	25.9	19.4	15.6	13.0

Biogas production

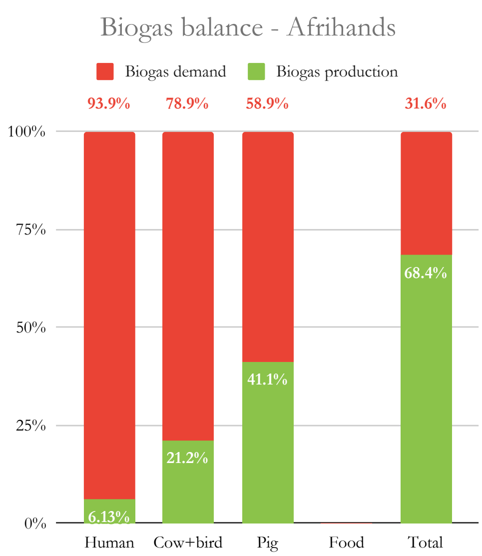
The results for biogas production from different types of substrates are presented in Table 12 below, where the results based on data obtained from both Afrihands Tanzania and averages of literature sources are presented for all substrates except for food waste since no data was obtained from Afrihands Tanzania for food/fruit. The available substrates that the calculations are based on can be seen in Tables **??**, 19 and 20 in Appendix F.

Table 12: *Results for biogas production per day per substrate from Afrihands Tanzania and from literature sources.*

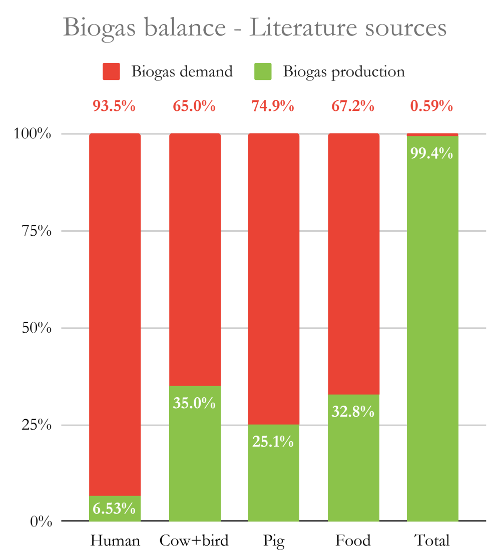
Substrate	Afrihands (m^3/day)	Literature sources (m^3/day)
Cow	21.9	33.7
Bird	2.80	7.07
Pig	48.0	29.3
Human	7.16	7.62
Food/fruit	-	38.3
Total	**79.8**	**116**

Biogas balance

Based on the results presented in Tables 11 and 12, the balance between biogas demand and production can be seen in Figures 28a and 28b. The green represents how much of the total biogas demand that can be covered by the produced biogas for cooking at the school. The red represents how much of the demand that can not be covered by the production.



(a) *Results based on Afrihands Tanzania.*



(b) *Results based on literature sources.*

Figure 28: *Balance of biogas demand and production per day (m^3/day).*

Sizing the digesters

The results for sizing of the digester for different substrates based on information obtained from Afrihands Tanzania are presented in Table 13.

Table 13: *Results of digester size for fixed dome for different types of substrates.*

Substrate	Afrihands (m^3)
Human waste	7.16
Cow + bird manure	33.3
Pig manure	40.0
Food waste	12.0

6.6.2 Analysis

Biogas demand

To calculate the biogas demand for the school an average amount of biogas demand per person was used which means that the result can not be exact since it depends on the efficiency of the stoves and the amount of food needed to be prepared. However, the average usage was based on experience from Afrihands Tanzania (2023b) and is therefore considered to be reasonable in these calculations. The average was based on usage for three meals per day while some of the students and teachers will not eat dinner. While this was considered in the calculations the biogas demand might be overrated as the three meals, breakfast, lunch and dinner, do not need the same amount of gas to be prepared.

The time needed for cooking per day is highly dependent on the assumed gas consumption rate (m^3/h) of the stoves. This parameter was also based on experience from Afrihands Tanzania (ibid.) and when compared with gas consumption rates from IRENA (2016), it was within a reasonable range. While the gas consumption rate of the future stoves at Tumaini Open School may differ, it will most likely only be a small difference. The number of stoves needed at the school will be more than six which based on the visit at Sikonge Folk Development Collage, where they used four big ovens and two small stoves as well as charcoal stoves for almost the same number of people, is reasonable. If they use stoves with a higher gas consumption rate the necessary number of stoves will of course be smaller.

Biogas production

To calculate the biogas production from the substrates (human, animal and food wastes), several different sources were used to get an average of the generation of substrate, the percentage of VS and gas yield from either the VS or the total substrate. The chosen sources were all based on biogas production plants in developing countries, however, for some values there was only one source and in some cases the values differed significantly. The biogas production was also calculated based on values from Tanzania given by Afrihands Tanzania (2023b). These sources were based on the local conditions and are therefore most appropriate even if the design and operation of the biogas plant may result in a different biogas production.

All the generated substrate of the animal manure per day was assumed to be collected in the calculations, however, for this to be true all animals needs to be kept in a stable. If the animals are kept grazing in fields and moved around it will be harder to collect all the manure. Additionally, the stables should preferably be cemented so that the collection becomes more simple and so that the urine from the animals, which gives a higher gas yield, can be collected. By using a cemented stable, the sand and soil interference can also be minimized.

The biogas production results from the two sources, Afrihands Tanzania and the literature sources, gave somewhat different results which can be attributed to variations in the underlying conditions specified within the literature. The biogas digester type, water ratio and other relevant factors are unknown, as well as type and handling of substrate utilised. However, despite these discrepancies, the results are still similar. Afrihands Tanzania has experimentally determined the substrate generation and biogas yield that is used to calculate the biogas production in conditions that resemble those at Tumaini Open School and can therefore be argued to be the most reliable and relevant for estimating the biogas production.

The total biogas production cannot be compared as the biogas production from food and fruit is not included in the Afrihands Tanzania results. It can, however, if the production from food and fruit is excluded. Here, the resulting production is about 11 % higher from Afrihands Tanzania than from the literature sources. As Afrihands Tanzania's values are experimentally determined they are considered more reliable and thus, the higher calculated production is more likely.

Balance

The balance of the biogas demand and production in Figure 28 shows that the Tumaini Open School will be unable to meet the entirety of its cooking requirements with solely the available substrates. However, since both the demand and production are based on estimations, actual values may deviate. There might be different amount of animals available or fewer students living at the school using the toilets or required to cook dinner for. Furthermore, the literature sources, which include food waste as Afrihands does not, show that the demand is in close proximity to being fully met. What can be concluded is that the school will require multiple biogas plants for the different substrates to sufficiently meet their biogas demand for cooking. They might also have to complement with other cooking fuels.

Sizing of the digesters

The sizing of the digesters are highly dependent on the HRT and the average generation of substrate and therefore the quality and reliability of the data employed in these calculations is of the utmost importance. The digester size is calculated with the values for HRT for the human and animal manure provided by the biogas expert from Afrihands Tanzania (2023a), while Gylapo, T. (2010) was referenced for the food waste. Using these sources for the data and using the digester sizing method provided by Afrihands Tanzania (2023b) ensures a more accurate reflection of the practises in Tanzania which enhances the reliability of the results.

The method of determining the digester size corresponds with the methods described in the literature sources Kossmann et al. (n.d.) and Vögeli et al. (2014), however there are some differences. For example in the literature sources the OLR was calculated to determine if the plant is within the optimum range for non-continuously stirred AD digesters. Additionally, the digester in the literature sources are designed with a third of the volume in the digester for the biogas which it is not in the method provided by Afrihands Tanzania (2023b). The digester design is instead based on the CAMARTEC design and utilises the fact that the gas pushes the digestate out as it is produced. In the literature it is also advised to mix some substrates with water while the plant desgin of the SSD do not require this.

7 Discussion

In this section the results of the electricity and biogas system are discussed further around plausibility of the results, the effect of assumptions and future challenges for implementation and maintenance, among other things. Furthermore, a discussion around the methodology used in this master thesis is conducted.

7.1 Electricity system

This section presents the discussion of the results of the electricity demand and supply system.

7.1.1 Electricity demand and load profiles

The estimated electricity services, the electricity demand and the maximum daily load profile at the Tumaini Open School in Tabora during full-scale operation are based on several assumptions and delimitations which are elaborated upon in Section 6.2.2. Consequently, due to these factors as well as the level of ambition when determining the electricity services the future electricity demand and the resulting maximum daily load profile may deviate significantly from the estimations in this report. However, the estimations primarily rely on over-estimations effect and time used by devices and therefore, the actual future electricity demand will probably be lower. Additionally, the amount of electricity services are very ambitious when comparing with other schools visited by the authors. Furthermore, both the Digitisation expert from EWB Sweden and the solar experts from GadgetroniX (2023) expressed surprise over the system size and demand. A feasibility assessment of the system was recommended, with emphasis on cutting down on services and electricity peaks specifically. For example the number of computers can be argued to be abundant as well as the amount of ACs and other high electricity consuming devices. By scaling back on the number of services and size of some services the cost of the system will be significantly reduced and easier to operate and maintain for the school's staff, even though the standard of living may be affected.

The most important energy services for the students, teachers and other members of Tumaini Education Initiative, which can be seen in Appendix B.2, are projectors and fans in the classrooms, gas in the science laboratories and desktops in the computer laboratories. The prioritisation of the electricity services should be taken into account when determining the future electricity services for the school. The gas in the laboratories are not part of the electricity system but can still be noted as important for the energy demand of the school. The priority steps and what electricity services are included in each step can be seen in Appendix C.2.

When determining Scenario 1-3, the prioritised electricity services along with the resulting electricity demand and load profiles were taken into consideration. Scenario 1 only included the automatically prioritised services as these services were considered essential and created the smallest possible PV system to explore. The automatically prioritised services also displayed relatively low power peaks which makes the resulting solar system interesting to investigate. There are very few services in Priority 1 and thus the electricity demand is quite low. The difference between Priority 1 and 2 in electricity demand and power peaks were minimal. Therefore, Scenario 2 comprised of the automatically prioritised services and both step 1 and 2. Scenario 3 were determined to not include the last step of electricity services as these were considered the least important and had very high electricity demand and power peaks.

7.1.2 Solar PV system

The assumptions made for components such as cell technology and battery type have a big impact on the resulting calculations. Regardless of technology, the same installed capacity is needed to fulfill the electricity demand for each scenario, but with poly-crystalline cells it would require more land area than with mono-crystalline. Since there is a shortage of available ground surface for solar panels, it motivated the choice of mono-crystalline cells. Although, at both study visits, the solar cells were of poly-crystalline type. Observations made by the authors during the field study also implies that poly-crystalline cells are the most common technology in Tabora. However, both the solar experts from Photons Energy Ltd. (2023) and GadgetroniX (2023) proposed mono-crystalline cells in their offers, so the assumption is still reasonable. Furthermore, based on experts from EWB Sweden, solar experts and the interview with TAREA (2023), it was indicated that the final cost were similar regardless of PV technology since the size and amount of panels evens out the price difference in technology.

Similary, the specifics of lead-acid and Li-ion batteries motivated the choice of battery type. Li-ion batteries have longer lifetime, higher efficiency and storage capacity which means that they require less space. Additionally, lead-acid batteries are more sensitive to higher temperatures which is an important factor in this case study. Despite being more expensive, Li-ion batteries were chosen as the more suitable alternative for the conditions in question, and they will most likely pay off economically in a lifetime perspective.

The solar PV system was assumed to not be connected to the main grid based on the interview with TANESCO (2023b) even if it is a possibility legally. The smallest system ever connected to the grid for selling excess electricity was 500 kW, which is about three times greater than the biggest proposed system of this study (160 kW_p for Scenario 3: Bigger PV). Presumably, it would be more profitable to invest in batteries and consume the excess electricity themselves. However, this could be worth investigating further since the batteries are the most expensive part and the electricity price is low compared to the LCOE for solar. From an economical perspective it might be beneficial to buy more electricity from the grid during night time and only use electricity from the PV system directly when it is produced. It does not however solve the problems of power outages and the reliability of electricity supply during night time and cloudy days. This is an important factor to consider according to interviews, conversations with the Centre Director of the school and the teacher from Sikonge Folk Development College.

Another assumption that needs to be discussed is the possibility of having centralised PV system concentrated to just one solar park. The current land use plan does not take the necessary land area for solar panels into consideration (which can be seen in Figure 2). It only allows for larger ground mounted installations above two parking lots. There the solar panels could be mounted in a similar way as at the solar pump at the Centre Director's garden, however, with a more robust construction that allows for more stability and parking of cars below the panels. However, the results for the required PV size need more space than there is available for all system sizes except Scenario 1: Bigger Battery. If no more land is allocated for the project, the solar panels would have to be roof-mounted and spread out over many buildings. This would require additional components and cables which in turn would become more expensive and make the system more complicated to manage and maintain. Most likely, the solar panels will be roof-mounted and installed gradually for every new building constructed at the facility. This makes the results of this report less accurate and applicable, but as mentioned before, the comparison between the scenarios are still valid and of bigger importance to this case study than the specific numbers of the result. One problem during implementation that has to be considered is the system design for batteries and remaining components, and also the storage of these components. They also require space and maintenance from the start of operation. The location for a storage room must be carefully considered for future up-scaling of the system.

Proper maintenance is a key factor for a successful PV system and optimal return on investment. During the study visit to St. Ann Catholic Mission Hospital, the sisters emphasised multiple times how important proper maintenance and knowledge of the system is. The sisters took great responsibility and care, and were proud to show all parts of the system. This testifies to the impression the authors got during the field study, namely that solar panels are widely accepted as a reliable source of electricity. The study visit to Sikonge Folk Development College and interviews with the students further confirms this hypothesis. No observations of malfunctioning or mismanaged solar power systems were made during the field study.

7.1.3 Comparison of scenarios

The reason for the base case being the most affordable scenario has to do with the very low electricity prices. Since the government in Tanzania aims to increase electricity access, it is important for them to keep electricity prices low for everyone to afford it. However, despite being economically unprofitable, solar panels offer the advantage of reliability against the grid. Due to the frequency of power outages, both solar panels and the main grid can be considered intermittent electricity sources. However, the weather conditions in Tabora make solar power very predictable. As mentioned before, power outages normally last from a few minutes up to six hours according to observations during the field study. It is important for many reasons to have reliable electricity access, for example a better study environment and a sense of security for the young mothers and their children. Since the sun sets around 18:30-19:00 all year round, evening study hours are limited without access to lighting. This is just one of many benefits from reliable electricity access, and by achieving this, SDG 7 (affordable and clean energy) is also closer to being reached within the project. This is why solar panels are still worth the investment, despite not being economical.

When it is time to start installing the PV system, hopefully some costs could be decreased, for example O&M costs and the costs marked as "Other" in Appendix E.3 where part of the Excel sheet for the LCOE calculations are presented. It is likely that as the Tanzanian market for PV systems grows the prices and LCOE will decrease and become more comparable with Lazard. As mentioned before, the offers received from the solar companies might not be fully accurate, and it is possible that the school can negotiate a better price when they are making the enquiry in the future.

The sensitivity analysis highlights the relatively small impact of changes in electricity price. 10 % lower or higher tariffs would not make a big difference on the electricity cost for the school in the future, which should be considered as a positive outcome. The discount rate however has a greater impact. Both the discount rate and electricity price are hard to predict for the coming 30 years, but what can be concluded, once again, is that the exact numbers in the results should not be the centre of analysis. Focus should be on the comparison between the scenarios to make sure that the most important services to the school are fulfilled within their financial capacity.

The scenario that should be considered the most suitable option depends on a number of factors, since the economic analysis does not give a definite answer. The number of occasions with energy shortages greater than twelve consecutive hours could be one factor but no scenario stands out to be better than the other. The rate of reliability increases with the higher ratio of electricity services being covered by the solar panels, since the risk of being affected by power outages is reduced with a bigger PV system. In this regard, Scenario 2 stands out for covering more electricity services without an increase in total price compared to Scenario 1. Scenario 3 however covers more electricity services, but at the cost of a higher price.

Technical restrictions such as O&M and challenging weather conditions have a greater effect on a larger system. The difference in system size between Scenario 1 and 2 is much smaller than between Scenario 2 and 3, which once again makes Scenario 2 the most promising alternative. When it comes to cultural restrictions on solar panels, the authors did not notice any resistance or distrust in PV technology during the field study. On the contrary, solar panels were widely used on a small-scale basis and the common opinion seemed to be very in favour of solar power. The results from the interviews and surveys presented in Table 2 confirm this, where the importance of renewables and solar energy were mentioned by the majority of the students. This speaks in favour of all scenarios except the base case, which instead represents a system of much criticism and resistance from users due to power outages, according to the authors' experience.

7.1.4 The future electricity system

As previously discussed in Section 7.1.1, it is hopefully possible to cut down on some electricity services to lower the demand and power peaks of the system. By doing this, a larger part of the system can be covered by the solar power system, without increasing the cost. Another way of changing the demand would be to plan the electricity consumption according to the supply and not the other way around, for example by not using all computers simultaneously as sewing and overlock machines, or by avoiding using any high electricity demanding devices simultaneously. One could also exclude all the high electricity demanding services in Priority 4, since they are considered the least important services.

There are governmental and non-profit organisations such as REA and TAREA, as well as policies such as The National Energy Policy, that work towards increasing electricity access in Tanzania, and especially advocate investments in renewable energy sources. In the future, these forces may lead to increased and more efficient subsidies and investments for solar and bio energy. However, governmental processes are time consuming and sometimes very inefficient. Furthermore, some laws and regulatory frameworks may not work as they are intended to.

Depending on the electrical load during school breaks, the PV system may or may not need to be turned off to avoid damage to the electrical components. If they are turned off it is important to turn the system back on a few days before full operation starts to achieve optimum performance of the system. This is to ensure that the batteries are fully charged ahead and ready for the maximum daily load when needed.

When making future predictions and estimations to electricity demand, there are many unknown answers to the questions; What will the electricity services be? How much electricity will be required for the devices? How will the electricity tariffs change? How will climate change affect electricity output from the solar panels? The answers to all these questions and many more needs to be assumed, which increases the potential for inaccuracy, as with any study that relies on future assumptions.

The future, actual electricity supply system may be similar to one of the scenarios presented in this case study. It may also exclude batteries or include other energy sources such as generators or other renewable sources, but this will not be discussed further in this report as they are delimited.

7.2 Biogas system for cooking purposes

The balance of the biogas demand and production showed that the demand was almost fully met with the available substrates. To fully meet the demand, some adjustments to the parameters would be needed such as acquiring more animals or lowering the daily gas demand by changing the prepared food to foods that require less gas usage. If there is a biogas shortage, there might be a need to complement the biogas with additional cooking fuels such as LPG or charcoal. However, the required amount and time used for buying and transporting the additional cooking fuels will substantially decrease with the usage of biogas. If food and human waste are utilised, the amount of substrate available will differ during the year as there will be fewer people that eat and live on the school premises during school breaks (see specifications for start up after school breaks in Section 5.2.2.) In contrast, the substrate from animal waste will be continuous because they will be on the school premises permanently. Likewise, after the school breaks it would take some time before the biogas plants operate under optimal conditions and the biogas production is maximal. Even if the biogas production cannot fully meet the demand, having a biogas plant provides other benefits such as waste handling, free and organic fertiliser and other environmental benefits.

The utilisation of biogas provides several environmental advantages over traditional fuels such as firewood and charcoal, including the reduction of greenhouse gas emissions and air pollution. Utilising biogas instead of firewood decreases deforestation and thereby land degradation, soil erosion, associated flooding and degradation of ecosystems. Additionally, the utilisation of digestate produced from the biogas production process provides further environmental benefits, such as a decrease in nitrogen loss to water and air, an increase in soil carbon reserves, and a reduction in emissions from energy-intensive mineral fertiliser production. The successful application of digestate as a fertiliser is heavily dependent on the composition and quality of the substrate, as these factors significantly impact the resulting composition and quality of the digestate. The nutrients will increase health and resilience in the soil, which will benefit the planted crops.

In addition to its environmental benefits, the use of biogas offers health and social advantages, such as a decrease in harmful smoke inhalation or eye diseases associated with traditional fuel-based cooking and a significant reduction in the time and effort required to operate gas stoves. By producing their own biogas, the school will not only ensure access to affordable, sustainable and modern energy for cooking, but also improve working conditions and the health of those working at the school, which is in line with SDG 3 and SDG 7.

Considering the long lifetime of the biogas plants, it is reasonable to assume that the investment required for installing the plants will eventually pay off as there will no longer be a need to buy the necessary fuel for cooking. The cost for fertiliser needed on the fields will also be avoided, as well as the cost of emptying the septic tanks if human waste is used as a substrate. If the biogas demand decreases or production increases compared to the estimations of this report, it might even be possible to sell excess biogas to make a profit. Additionally, if all the digestate cannot be used as fertiliser, it could also be used to generate revenue. However, it is possible that the market for the digestate will be non-existent or very small, because there are currently no biogas plants in the vicinity of the school or Tabora Town. The market and potential buyers would be interesting to investigate.

When investigating the feasibility of producing biogas for cooking purposes at the school, it is very important to consider the technical and cultural restrictions. The planning phase of the biogas plant is critical and includes various factors such as the location of the plant relative to nearby buildings and activities. The issue of odour needs to be considered, as well as the design of the pipe systems for the plant. The transportation of substrates, in addition to the distribution of biogas and transportation of digestate to the fields, should be automatic or easily handled manually. A storage solution for the digestate may also be necessary during non-growing seasons. By planning the design correctly, several O&M aspects can be facilitated. From the study visit at the biogas plants around Arusha, the authors observed that it is critical that the designer and installer of the plant has enough knowledge to anticipate the flow of the plant and problems that can occur. Someone who is experienced and will be available for future communication and follow-up is highly recommended.

From the study visits it was also apparent that the O&M of the plant (which are described in Section 5.2.3) is a crucial factor for success, along with the transfer of knowledge regarding operation and the benefits of the system. Training programs for the owners and operators of the plants are recommended by both the literature sources; Kossmann et al. (n.d.) and Vögeli et al. (2014) , as well as Afrihands Tanzania (2023a). To achieve proficient management of the plant, an individual who is in charge and possesses the necessary knowledge and competence to oversee the daily routines of the biogas system is mandatory. Often the knowledge is lost when the personnel operating the plant moves away, like at Site 1 of the visited plants. This is very plausible at the Tumaini Open School, because it is a non-profit organisation and teachers and personnel may leave if offered a better paid position elsewhere.

The weather conditions at the biogas plant is another important factor for success. Inside the digester, the environment needs to be within a certain pH level and meet mesophilic conditions (temperature between 20-45 °C). The acidity is affected by the operations of the plant while the temperature inside the digester is affected by the outside temperature, even if the soil around the dome somewhat isolates the digester. Climate change predictions around Tabora seems to indicate that the mean daily temperature between the years 2040-2059 will increase with about 0.5 °C - 1.5 °C throughout the year in all climate change scenarios and will therefore only marginally affect the temperature inside the digester. However, the fact that Tabora is considered to be a hotspot for increased risk of droughts will affect the crop production and potentially the health of the animals. If the school decides to utilise agricultural waste as substrate for a biogas plant this will affect the substrate flow. Agricultural production will also affect the food waste and thus also the substrate flow to a plant utilising food waste as substrate. Higher temperatures and unpredictable precipitation in the future may cause droughts that will affect biogas plants if water is needed for mixing during pre-treatment. However, as the biogas experts from Afrihands Tanzania stated, an SSD with the CAMARTEC design would be recommended for Tumaini Open School, which does not require additional water.

The possibility that stigma of using biogas or the digestate will hinder the usefulness of the biogas plants should not be underestimated. The literature sources describe in detail several occasions where the stigma is a considerable hindrance of the success of the plants. Some teachers or students might not want to eat the served food and therefore not even attend the school. However, when interviewing the students it was evident that there was no stigma about the use of biogas, so the potential problems may not be as great as stated in the literature. Biogas as a fuel was not expressly mentioned but the results from the interviews can still be considered an advantage for biogas as cooking fuel. Based on literature sources and the interviews with TAREA (2023) and Afrihands Tanzania (2023a), there may be stigma about using biogas from animal substrate and especially human waste from a hygienic point of view. This can be overcome with time and education but since there are no other known biogas plants in the region it might be difficult to change the minds of the people in the neighbouring villages. Another possible obstacle for utilising biogas for cooking purposes is the fact that people usually adhere to their established habits and routines as they feel and perceive them to be the most convenient. From field observations it was noticed that even if gas ovens and stoves were available, the usage of a charcoal stove was sometimes preferred, especially for some specific foods. Some do not realise the health and environmental problems of using firewood or charcoal, or simply enjoy cooking with these fuels despite the problems and will tend to prefer traditional methods.

To increase the chances of the implementation of biogas plants at the Tumaini Open School to be successful, it would be beneficial if the participants show enthusiasm and interest in the project. Additionally, the school needs to carefully assess all the critical factors and possible hindrances mentioned above before moving forward with any installations. By carefully considering all these aspects the school can overcome potential obstacles and enjoy a successful biogas system for cooking purposes and, at the same time, increase their share of clean energy. An experienced biogas installer will be needed as both the literature sources Kossmann et al. (n.d.) and Vögeli et al. (2014) and the biogas experts from Afrihands Tanzania (2023b) emphasise.

Since Afrihands Tanzania will most likely construct the biogas plants if the school decides to install them, the digester size calculations were conducted using their equations. The results showed that the plants will all be relatively small, but together their cumulative area requirement and the additional space needed for mixing tanks, expansion chambers and digestate storage area, the total land area will be larger. It is however important to realise that the plants are mostly underground and if the plants are managed properly any potential odours can be mitigated, then the area can be repurposed for other activities. The most suitable placement of the plants would be in the south area of the school premises, where the farming and animal keeping area is situated, as seen in the land use plan in Figure 2a. It would be even more suitable to have the biogas plants near the substrate generation, the human waste plants near the toilets and the food and fruit waste near the kitchen but, as the land use plan does not allow the space for this, all plants should be located together. This will also help the O&M of the plants as most likely there will be one person in charge of the plants and the personnel operating the plants.

To achieve an effective substrate collection, the human waste should flow directly to the digester, whilst the animals should be kept in concrete stables with channels to collect urine. The transportation of the food and fruit waste should be a daily routine to facilitate the operation of the plant. The appropriate conditions for optimal biogas production should be pursued such as the correct pH level, C:N ratio and temperature. Inhibitors such as organic acids, disinfectants and antibiotics (see Section 5.2.1), as well as inorganic materials should be avoided. The gas pipes from the pipes can merge and thus the gas from all plants can be post-treated at one location. Whether sulphide removal is necessary or not is not known as the literature source, Kossmann et al. (n.d.), and the biogas experts from Afrihands Tanzania (2023b) contradict each other. The kitchen may look similar to the gas kitchen found at Sikonge Folk Development School, because that kitchen was made for a similar amount of people.

7.3 Reflections on methodology

Overall the authors find the method of this case study relevant and suitable for the aim and answering the RQs. However, there are several elements that would have improved the results that will be discussed below.

The execution of the interviews could have been improved in several ways. Firstly, the interview structure could have been improved by starting with the open questions for their electrical usage and their preferred way of having their food prepared, followed by the direct questions. Secondly, the questions could have been discussed with the interpreter beforehand to make sure that they were fully understood and more adjusted to the interviewees. This would probably have led to the first student not being asked different questions compared to the rest. Furthermore, additional questions about the frequency of power outages and their way of handling the difficulties it brings would have been interesting to ask all the students. Finally, more specific questions about the usage of biogas as cooking fuel and the digestate as fertiliser would have been relevant in order to discuss the possible stigma around this even more.

The execution of the survey for prioritising the electricity services could also have been improved. If the process of making the survey had been planned to a later time, the included electricity services could have been more accurate and thus the results would not have had as many errors. The intention was to also interview the teachers and conduct the survey on site, but unfortunately this was not possible and the survey was sent by email. By not being interviewed first, the teachers and other members of the Tumaini Education Initiative which received the survey did not have the same introduction to the subject and the case study, or the possibility to reflect in the same way as the students. This might cause misunderstandings or omissions, but it is also possible that by answering the survey independently, without influence from the authors or other teachers, the answers are more truthful. Furthermore, another defect of the survey method is the fact that the survey was distributed to the teachers and other members late in the process and thus, the answers were obtained too late for other parts of the case study. For example, had all responses from the survey been obtained earlier, the scenarios could have been constructed earlier which would have made the cost enquiries to the solar companies more accurate, instead of solely requesting information corresponding to the base case.

Furthermore, an obstacle to the process of the case study was the slow response time from external parties and the inefficient use of time compared to the authors' standards. For example, agreements made during meetings were often not fulfilled within the agreed timeline, and follow-ups were often delayed. This was expected as the authors were warned beforehand, but it still affected the possibility of changing the methodology as there was not enough time to complete the task. Additionally, it resulted in some further delimitations that were not intended at the start of the project.

An alternative to constructing the priority steps, the survey and the resulting scenarios would have been that the automatically prioritised services only were chosen by the authors and had not been determined through discussions with the Centre Director as he also answered the survey. Another alternative would have been to not have any automatically prioritised services and expand the number of services to choose from in the survey. As a result, Priority 1 would have included more services and there would have been a Scenario 1 encompassing Priority 1 and Scenario 2 encompassing Priority 1-2 etc. This way, the construction of the scenarios would have been entirely objective from the authors' perspective.

If there had been more time available, the optimisation of the PV system could also have included the inverters, since these were an important source of error to the following choice of components and economic calculations. This would have made the cost results and perhaps, the comparison between the scenarios, more exact. SAM could have also been utilised more efficiently, since a more simplified tool was used for the hourly production profile. SAM contains many additional features that could have improved the output, but it would not necessarily have had a vital impact on the results. The comparison between the scenarios are still valid since the same simplified tool was used for all the scenarios. Furthermore, the authors learned more about the optimisation process by not relying too much on data simulation tools.

During early research, it was found that there are several methods for optimising the storage capacity. The Excel sheet for hourly energy balance enabled the method of sizing the battery according to the yearly load profile instead of only considering the daily load profile. The alternative would have been to only cover nightly loads or a certain number of hours and size the battery accordingly, which seemed less accurate with regard to changing weather seasons and school breaks. However, an improvement to the method would have been to increase the variation between Bigger Battery and Bigger PV, which would have made a big difference to the cost results and a more interesting comparison.

LCOE was chosen as the cost evaluation method for solar power, because it is the most common and widely used method for evaluating the cost of renewable energy sources. However, during the study it was realised that the standard LCOE method was not fully appropriate for the applicable conditions. No interest from loans or return on investments needed to be considered since financing will come from donations or interest free loans (according to discussions with the Centre Director). Furthermore, excess electricity will not be sold to the grid and hence, no revenues will be generated which is assumed in the LCOE formula. The actual method used took these factors into consideration and the LCOE formula was adjusted, but a more accurate result could have been obtained if a more suitable method was adhered to.

By conducting an MFS, the authors gained valuable knowledge and insights that would not have been possible had this case study been completed from Sweden. The discussions with the members of the Tumaini Education Initiative, the visits to the Tumaini Open School, meeting the students and visiting solar installations and biogas plants made it possible to understand the local conditions, possibilities and restrictions as well as provide useful contact information. Many assumptions and preconceptions based on partiality have been invalidated or disproved while studying the local context during the field study, which is an important part of the purpose of doing an MFS.

8 Conclusions

This case study aimed to help the Tumaini Open School for pregnant and mothering students in Tabora, Tanzania, to strive for the SGDs 3 and 7, regarding good health and well-being and access to affordable and clean energy. This was achieved by first determining and prioritising the electricity demand and services, followed by comparing different electricity supply systems of solar energy in combination with the main grid. Finally, an investigation on the feasibility of producing biogas for cooking purposes was conducted.

The required electricity services and the resulting electricity demand and maximum daily load profile at the Tumaini Open School during full-scale operation have been determined and presented in this report. However, the future, actual required electricity services and electricity consumption will most likely differ from the determined and is recommended to be adjusted to avoid the low prioritised, high electricity demanding services and to avoid high power peaks. It is also recommended to adjust the electricity consumption to fit the electricity supply system, as opposed to the reverse, because the consumption can be controlled, whilst the supply often can not. This way the efficiency can increase and the cost can be lowered. As mentioned, the services have been prioritised by its inhabitants and the prioritisation steps should be valued when planning for the electricity system.

Based on the above discussion of the comparison between the scenarios, Scenario 2 would be the most appropriate alternative. However, it is not possible to recommend one of the cases Bigger PV or Bigger Battery, because the results are too similar to make any final conclusions. The variations on panel and battery size must be larger and evaluated again to see if it is economical to size the components differently. Some of the most important takeaways from the discussion is the importance of sufficient training and O&M knowledge of the management and staff of the Tumaini Open School in the future.

It is possible to have a successful biogas production system for cooking purposes at the Tumaini Open School, but it involves careful consideration and assessments of the critical factors and possible hindrances. Some of the important factors identified during the field study are the planning stage, the choice of installers and the knowledge of and training regarding O&M as well as the environmental and social benefits of utilising biogas for cooking purposes and digestate as fertiliser.

The members of the Tumaini Open School, met by the authors, have shown great interest and commitment to this case study and its related topics, which is a good sign for future success of the PV system and biogas production. By using solar energy in the electricity supply system and producing biogas for cooking purposes the school will ensure its pursuit towards access to good health and well-being along with affordable and clean energy for every attending student and working teacher, as the SDG 3 and SDG 7 aspires towards.

Future research relevant to the Tumaini Open School would be to further investigate the electricity demand with regard to the prioritised services determined in this case study. Regarding the PV system it is recommended to evaluate the implementation process more in detail and location of the solar panels as well as other components. Regarding biogas production for cooking purposes, future research regarding the gas demand and production from the available substrates is recommended, along with a more specific implementation plan and cost analysis. Finally, an investigation of the digestate market in the area around the school would be beneficial before implementation.

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A Appendix: Student interviews

A.1 Execution of interviews

The students of Tumaini were temporarily placed at different schools until Tumaini Open School was ready to receive them. The seven girls that were interviewed were placed at Sikonge Folk Collage. The execution of the interviews was as follows. First all the girls were gathered and the authors of this report introduced themselves shortly. Then followed a longer explanation by Mr. Kassange of the progress of the cooperation between Tumaini and EWB, the land use plan was presented and the authors work was explained. They were also told that they would be able to start at Tumaini in July since their accommodation would have been built. Possibly they can start even in June.

Author Lovisa Magnusson Ericsson conducted the interviews and author Martina Prpic Vucenov took notes and asked follow-up questions when clarification was needed. After consent by all the girls the interviews were also recorded. All interviews followed a semi structured way but the question template was edited after the first interview to better suit the recipient. The first interview was also different because all the other girls could listen to the answers. They were sent out after about half the interview. After the interviews all the girls answered the survey. The Translator explained the survey to the first girl who then explained it to all the other girls after their interviews. As the first girl was present during all the interviews she was asked one more question at the end.

A.2 Template 1

Interview student no X
Name:
Age:
Children:
Date: 2023-xx-xx
List of people present:

Start:
Present ourselves, who we are:
Engineering students from Sweden helping Tumaini Open School with how much energy you will need and also what kind of energy system is possible
We would like to ask you a few questions, is that all right?
Could we record it? It is only for our use, nobody will hear except us.

Questions:
Please describe what your day is like, from waking up to going to sleep.
How many hours do you study with lighting outside of school hours?
Do you have a phone? If so, how many hours and when do you charge it?
Do you use electricity for anything else?
Is it important to have AC/fans in the classrooms?
Food and kitchen:
Do you have any preferences about how you want your food prepared?

Is it important what kind of stove it is prepared on?

End:
Is there anything else that you would like to share with me?
Do you have any questions for us?
Thank you for your time

Comment:
Environment
Other

A.3 Template 2

Interview student no X
Name:
Age:
Children:
Date: 2023-xx-xx
List of people present:
Interpreter:

Start:
Present ourselves, who we are: Engineering students from Sweden helping Tumaini Open School with how much energy you will need and also what kind of energy system is possible.
We would like to ask you a few questions, is that all right?
Explain that the interview and survey will take about 10 minutes each.

Questions:
How many hours do you study with lighting outside of school hours?
Do you have a phone? If so, how many hours and when do you charge it?
Do you use electricity for anything else?
What is important energy wise in the classrooms?
Is it important to have AC/fans in the classrooms?
Is it important to have lights in the classrooms?
Food and kitchen:
Do you have any preferences about how the food you are served is prepared?

End:
Is there anything else that you would like to share with me?
Do you have any questions for us?
Thank you for your time

Comment:
Environment

Other

B Appendix: Survey

B.1 Template

The survey template for other members of Tumaini Education Initiative can be seen in the pdf below. This is the most extensive survey template since they got to pick from all electricity services (the students' and teachers' survey contained fewer electricity services to choose from).

Survey energy demand

Please write your name, age and occupation:

____

<u>Automatically prioritized:</u>
- The kitchen
- First Aid House
- Security building
- Server in library (for all computers)
- Toilets
- Lighting inside
- Lighting outside
- Security cameras
- Solar water pump

Instructions:
1. Please start by choosing the 10 most important energy services at Tumani Open School.
2. Next, from those 10, chose the 5 most important energy services.
3. Finally, from those 5, chose the 3 most important energy services.
4. If an energy service is missing please fill it in under "Other" at the bottom.

Energy services	10	5	3	Comment
Classrooms:				
Projector				
Charging of laptop				
Sound system				
Fan				
Wifi				
Laboratories:				
Charging of laptop				
Projector				
AC				
Gas				
Vocational training:				
Computer labs				
Desktops				
Projector				
Printer				
Photocopy machine				
Sound system				

AC				
Fan				
Tailoring				
Electrical sewing machines				
Electrical overlock machine				
Charging of laptop				
Projector				
Library:				
Desktops				
Charging of laptop				
AC				
Library office				
Printer				
Photocopy machine				
Fan				
Electric kettle				
Administration building:				
Wifi				
Staff room				
Charging of laptop				
Electric kettle				
Refrigerator				
TV set				
Microwave				
Head office				
Refrigerator				
TV set				
Assistant office				
TV set				
Secretary room				
AC				
Charging of laptop				
Electric kettle				
Printer				
Photocopy machine				
Office for accountant				

AC				
Charging of laptop				
Academic officer				
AC				
Charging of laptop				
Matron office				
AC				
Charging of laptop				
Dining hall:				
Charging of laptop				
Projector				
TV set				
Sound system				
Child care facility:				
AC				
Dormitories students:				
Charging of mobile				
Teacher's house:				
Living room				
Charging of laptop				
TV set				
Charging of mobile				
Ironing clothes				
Sound system				
Kitchen				
Refrigerator				
Electric ovens/stove				
Blender				
Electric kettle				
Volunteer house/Hostel:				
Washing machine				
Bedrooms				
Charging of mobile				
Kitchen				
Refrigerator				
Electric ovens/stove				

Blender				
Electric kettle				
Living room				
Charging of laptop				
Other:				

B.2 Summary of results

The total results from the survey can be seen in the pdf below. This is a summary of the results from students, teachers and other members of Tumaini Education Initiative.

Energy services	Top 10	Top 5	Top 3	Tot:
Classrooms:			Total answers:	17
Projector	9	6	6	21
Charging of laptop	3	2	2	7
Sound system	1	0	0	1
Fan	7	6	5	18
Wifi				Auto
Lighting inside				Auto
Lighting outside				Auto
Laboratories:				
Charging of laptop	1	1	1	3
Projector	2	1	0	3
AC	1	0	0	1
Gas	13	11	8	32
Lighting inside				Auto
Lighting outside				Auto
Vocational training:				
Lighting outside				Auto
Computer labs				
Desktops	14	10	9	33
Keyboards, mouse, monitor	14	10	9	33
Projector	3	0	1	4
Printer	2	2	1	5
Photocopy machine	1	1	0	2
Sound system	1	1	0	2
Wifi				Auto
AC	0	0	0	0
Fan	0	0	0	0
Lighting inside				Auto
Lighting outside				Auto
Tailoring				
Electrical sewing machines	11	6	3	20
Electrical overlock machine	1	1	0	2
Charging of laptop	0	0	0	0
Projector	1	0	0	1
Lighting inside				Auto
Plumbing				
Lighting inside				Auto
Electrician				
Lighting inside				Auto

Energy services	Top 10	Top 5	Top 3	Tot:
Library:				
Desktops	13	7	2	22
Keyboards, mouse, monitor	13	7	2	22
Charging of laptop	1	1	0	2
Server				Auto
Wifi				Auto
AC	2	0	0	2
Lighting inside				Auto
Lighting outside				Auto
Library office				
Printer	3	1	2	6
Photocopy machine	3	1	0	4
Fan	2	1	1	4
Electric kettle				
Admin:				
Wifi				Auto
Lighting outside				Auto
Staff room				
Charging of laptops	7	2	2	11
Electric kettle	0	0	0	0
Refrigerator	1	1	0	2
TV set	0	0	0	0
Microwave	0	0	0	0
Lighting inside				Auto
Head office				
Refrigerator	0	0	0	0
TV set	0	0	0	0
Lighting inside				Auto
Assistant office				
TV set	0	0	0	0
Lighting inside				Auto
Secretary room				
AC	0	0	0	0
Charging of laptop	2	0	0	2
Electric kettle	0	0	0	0
Printer	1	0	0	1
Photocopy machine	0	0	0	0
Lighting inside				Auto
Office for accountant				

Energy services	Top 10	Top 5	Top 3	Tot:
AC	0	0	0	0
Charging of laptop	1	1	0	2
Lighting inside				Auto
Academic officer				
AC	0	0	0	0
Charging of laptop	1	1	0	2
Lighting inside				Auto
Matron office				
AC	0	0	0	0
Charging of laptop	0	0	0	0
Lighting inside				Auto
Kitchen & dining hall:				
Kitchen				
Gas ovens/stoves				Auto
Refrigerator - big				Auto
Electric kettle				Auto
Blender				
Fan				Auto
Lighting inside				Auto
Lighting outside				Auto
Dining hall				
Charging of laptop	1	0	0	1
Projector	0	0	0	0
TV set	12	4	1	17
Sound system	0	0	0	0
AC				
Fan				
Lighting inside				Auto
Lighting outside				Auto
Conference hall:				
Projector				
Charging of laptops				
Fan				
AC				
Wifi				Auto
Sound system				
Lighting inside				Auto
Lighting outside				Auto
Health & nursing:				

Energy services	Top 10	Top 5	Top 3	Tot:
Lighting outside				Auto
Resting room				
Fan				Auto
Lighting inside				Auto
Office for nurse				
Charging of laptop				Auto
Fan				Auto
Lighting inside				Auto
Storage room				
Refrigerator				Auto
AC				Auto
Lighting inside				Auto
Child care facility				
AC	5	0	0	5
Lighting inside				Auto
Dormitories:				
Bedrooms				
Charging of mobile	7	2	0	9
Lighting inside				Auto
Lighting inside w children				Auto
Lighting outside				Auto
Washing room				
Lighting inside				Auto
Teacher's house:				
Lighting inside				Auto
Lighting outside				Auto
Bedrooms				
Lighting inside				Auto
Living room				
Charging of laptop	2	0	0	2
TV set	2	1	0	3
Charging of mobile	0	0	0	0
Ironing clothes	1	1	1	3
Sound system	0	0	0	0
Lighting inside				Auto
Kitchen				
Refrigerator	1	0	0	1
Electric ovens/stove	1	0	0	1
Blender	0	0	0	0

Energy services	Top 10	Top 5	Top 3	Tot:
Electric kettle	0	0	0	0
Lighting inside				Auto
Bathrooms				
Lighting inside				Auto
Washing room				
Lighting inside				Auto
Volunteer house/Hostel:				
Washing machine	1	0	0	1
Lighting inside				Auto
Lighting outside				Auto
Bedrooms				
Charging of mobile	1	1	0	2
Lighting inside				Auto
Bathrooms				
Lighting inside				Auto
Kitchen				
Refrigerator	4	0	0	4
Electric ovens/stove	4	0	0	4
Blender	0	0	0	0
Electric kettle	0	0	0	0
Lighting inside				Auto
Dining room				
Lighting inside				Auto
Living room				
Charging of laptops	2	1	0	3
Lighting inside				Auto
Agriculture				
Water pumps				Auto
Toilets:				
Lighting inside				Auto
Lighting outside				Auto
Secutiry building:				
Fan				Auto
Charging of mobile				Auto
Lighting inside				
Lighting outside				Auto
Other:				
Security camera				Auto

C Appendix: Electricity demand and electricity service priority steps

C.1 Electrical devices

The effect of all devices used for electricity demand calculations, including sources, can be seen in the pdf below.

Device	Effect demand (Wmax/device)	Source	Date
Charging of laptop	80	Digitalisation expert from EWB Sweden	2023-03-13
Desktops	100	Digitalisation expert from EWB Sweden	2023-03-13
Keyboards, mouse, monitor	25	Digitalisation expert from EWB Sweden	2023-03-13
Projector	500	Digitalisation expert from EWB Sweden	2023-03-15
Sound system	100	https://geekmusician.com/do-speakers-use	2023-04-16
Printer	500	https://energyusecalculator.com/electricity_	2023-03-26
Photocopy machine	2000	https://letsavelectricity.com/printer-power-c	2023-04-07
TV set	72	https://www.jackery.com/blogs/news/how-m	2023-04-07
Mobile phone	16	https://support.apple.com/en-us/HT210133	2023-04-07
Wifi	20	https://news.energysage.com/how-many-w	2023-03-26
Fan	95	https://atomberg.com/blog/post/power-cons	2023-04-07
AC	4000	https://news.energysage.com/how-many-w	2023-04-07
Electrical sewing machines	110	https://sewingmachinetalk.com/electricity-s	2023-04-07
Electrical overlock machine	110	https://sewingmachinetalk.com/electricity-s	2023-04-07
Refrigerator	400	https://www.coastappliances.ca/blogs/learn	2023-04-07
Refrigerator - big	800	https://news.energysage.com/how-many-w	2023-04-07
Electric oven	5000	https://news.energysage.com/how-many-w	2023-04-07
Electric stove	3000	https://news.energysage.com/how-many-w	2023-04-07
Electrical stove/oven total	8000	Sum of the two above	
Gas oven/stove	0	-	
Blender	1000	https://www.gadgetreview.com/how-many-v	2023-04-07
Electric kettle	1500	https://www.electricalclassroom.com/power	2023-04-07
Microwave	1200	https://www.cnet.com/home/energy-and-uti	2023-04-07
Security camera	15	https://www.thehomehacksdiy.com/how-mu	2023-04-07
Lighting inside	40	Mr. Ezekiel Kassanga's estimation	2023-03-38
Lighting outside	40	Mr. Ezekiel Kassanga's estimation	
Iron	2000	https://www.homehackerdiy.com/how-much	2023-04-16
Server	300	Digitalisation expert from EWB Sweden	2023-04-18
Water pump	0	-	
Washing machine	500	https://www.daftlogic.com/information-appli	2023-04-16

C.2 Electricity service priority steps

Table 14: *The resulting priority steps based on survey answers.*

Priority 4	**Priority 3**	**Priority 2**	**Priority 1**	**Auto**
AC: computer lab, accountant office, academic officer, matron office, secretary room, dining hall, conference hall,	Sound system: classrooms	Charging of laptops: classrooms, laboratories, library, staff room, accountant office, adacemic officer, volunteer house	Projector: classrooms	Wifi: everywhere
Fan: computer lab, dining hall, conference hall	AC: in laboratories, library, child care room	Projector: laboratories	Fans: classrooms	Lighting inside: everywhere
Charging of laptops: vocational training, matron office, conference hall	Projector: computer lab, vocational training	Printer: computer lab, library office	Gas: laboratories	Lighting outside: everywhere
Electric kettle: library office, staff room, secretary room, volunteer house	Charging of laptops: secretary room, dining hall, teachers house	Photocopy machine: computer lab, library office	Desktops: computer labs	Server: computer labs
TV set: staff room, head office, assistans office	Printer: secretary room	Sound system: computer lab		Kitchen: everything except blender
Microwave: staff room	Refrigerator: teachers house, volunteer house	Electrical sewing machines and overlocking machines		Fans: resting room, nurse office
Refrigerator: head office, teachers house	Electric ovens/stove: teachers house, volunteer house	Desktops: library		Charging of laptop: nurse office
Photocopy machine: secretary room	Washing machine: volunteer house	Fan: library office		Refrigerator: child care room
Blender: kitchen, volunteer house		Refrigerator: staff room		AC: storage room in admin building
Projector: dining hall, conference hall		TV set: dining hall, teachers house		Security building: everything
Sound system: dining hall, conference hall, teachers house		Charging of mobiles: dorms, volunteer house		Security cameras: everywhere
Charging of mobile: teachers house		Ironing clothes: teachers house		
Electric ovens/stove: teachers house				

D Appendix: Solar PV system optimisation

D.1 PV capacity optimisation inputs

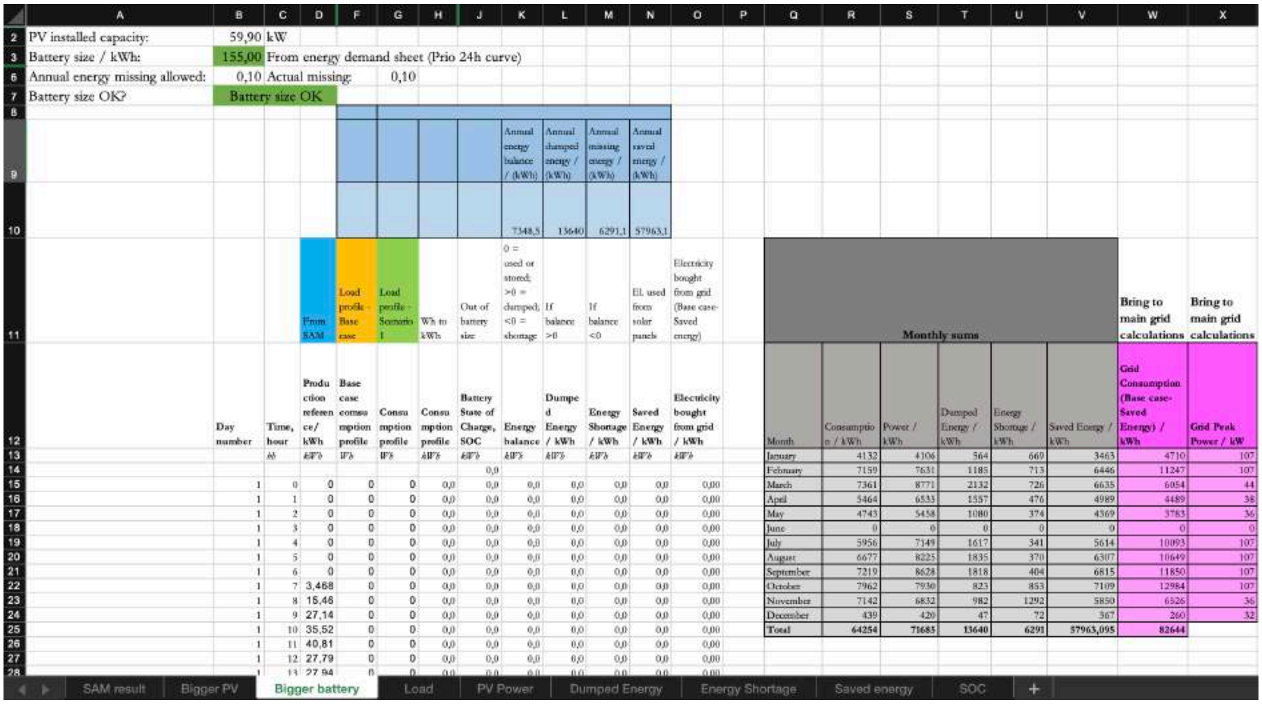
Input values for calculating the PV capacity are presented in Table 15.

Table 15: *Input values for PV capacity calculations.*

PV capacity inputs	Same for all	Scenario 1	Scenario 2	Scenario 3
Total load (kWh/day)		291	426	707
Scale factor (-) (10 % extra load)	1.1	320	468	778
Sun hours (h/day)	6.13			
Global irradiation (kWh/m^2/day)	6.13			
Total loss factor (product of those below)	0.79			
Average solar access	*0.95*			
Module soiling rate	*0.95*			
System availability rate	*0.99*			
Module temperature coeff.	*0.984*			
Inverter efficiency	*0.95*			
Battery efficiency	*0.95*			
Panel area (m^2/panel)	2.58			
Panel capacity (kW$_p$/panel)	0.54			

D.2 Excel sheet for PV capacity optimisation

A part of the Excel sheet used for optimising the battery capacity for Scenario 1: Bigger Battery is presented in Figure 29.



PV installed capacity:	59,90	kW
Battery size / kWh:	155,00	From energy demand sheet (Prio 24h curve)
Annual energy missing allowed:	0,10	Actual missing: 0,10
Battery size OK?	Battery size OK	

Annual energy balance / (kWh)	Annual dumped energy / (kWh)	Annual missing energy / (kWh)	Annual saved energy / (kWh)
7348,5	13640	6291,1	57963,1

Day number	Time, hour	From SAM: Production reference/ kWh	Load profile - Base case: Base case consumption profile	Load profile - Scenario 1: Consumption profile	Wh to kWh: Consumption profile	Out of battery size: Battery State of Charge, SOC	0 = used or stored; >0 = dumped; <0 = shortage: Energy balance	If balance >0: Dumped Energy / kWh	If balance <0: Energy Shortage / kWh	El. used from solar panels: Saved Energy / kWh	Electricity bought from grid (Base case-Saved energy): Electricity bought from grid / kWh
	h	kWh	Wh	Wh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
						0,0					
1	0	0	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	1	0	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	2	0	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	3	0	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	4	0	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	5	0	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	6	0	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	7	3,468	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	8	15,46	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	9	27,14	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	10	35,52	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	11	40,81	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	12	27,79	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00
1	13	27,94	0	0	0,0	0,0	0,0	0,0	0,0	0,0	0,00

Monthly sums: Month	Consumption / kWh	Power / kWh	Dumped Energy / kWh	Energy Shortage / kWh	Saved Energy / kWh	Bring to main grid calculations: Grid Consumption (Base case-Saved Energy) / kWh	Bring to main grid calculations: Grid Peak Power / kW
January	4132	4106	564	669	3463	4710	107
February	7159	7631	1185	713	6446	11247	107
March	7361	8771	2132	726	6635	6054	44
April	5464	6533	1557	476	4989	4489	38
May	4743	5458	1080	374	4369	3783	36
June	0	0	0	0	0	0	0
July	5956	7149	1617	341	5614	10093	107
August	6677	8225	1835	370	6307	10649	107
September	7219	8628	1818	404	6815	11850	107
October	7962	7930	823	853	7109	12984	107
November	7142	6832	982	1292	5850	6526	36
December	439	420	47	72	367	260	32
Total	**64254**	**71685**	**13640**	**6291**	**57963,095**	**82644**	

Figure 29: *Part of the Excel sheet for battery optimisation for Scenario 1: Bigger Battery.*

E Appendix: Economical calculations

E.1 Received offers from solar companies

All offers from Photons Energy Ltd. and GadgetroniX are presented in Figure 30 and 31, respectively. The summation of all battery costs can be seen in Figure 32.

Photons Energy					
Option 1		**QNT**	**COST (USD)**	**COST (USD/device)**	**COST (SEK)**
Solar array 540 Wp, tot 278.19kWp installed including Mounting structure		517	162,282.1	313.9	1,677,996.7
BYD premium LVL 15.4 kWh (total 647 kwh)		42	382,952.0	9,117.9	3,959,724.0
Fronius Eco 25 PV inverters		6	26,008.6	4,334.8	268,928.7
Victron Quattro 15kVA inverters		12	95,182.8	7,931.9	984,190.0
Charger controller 450/200		6	20,662.7	3,443.8	213,651.9
Balance of System Estimate			42,902.9		443,616.4
Installation charges			21,270.4		219,935.8
Transport charges			3,798.3		39,274.2
Total:			**755,059.8**		**7,807,317.8**
Option 2		**QNT**	**COST (USD)**	**COST (USD/device)**	**COST (SEK)**
Solar array 278.19kWp including Mounting structure		517	162,282.1	313.9	1,677,996.7
Battery Bank - 480kWh Lithium-ion Phosphate batteries (120 kWh/battery)		4	283,261.8	70,815.5	2,928,927.0
2 ATESS 150KW Hybrid inverters with inbuilt charge controller		2	76,978.5	38,489.3	795,958.1
Balance of System Estimate			45,132.3		466,667.8
Installation charges			21,270.4		219,935.8
Transport charges			3,798.3		39,274.2
Total:			**592,723.4**		**6,128,759.6**
O&M	**Year 1**				**COST (USD)**
	Service 1	**Service 2**	**Service 3**	**Service 4**	
Routine Visits fee - Solar Power System	550	550	550	550	**2,200**
Routing visits - Transport and Travel costs	600	600	600	600	**2,400**
Accessories that might be required for servies	80	80	80	80	**320**
Unplanned visits (Call out estimate)			900		**900**
Total:					**5,820**

Figure 30: *Solar installation offers from Photons Energy Ltd. (2023).*

GadgetroniX offert:				
APPLIANCE	**QNT**	**COST (USD)**	**COST (USD/device)**	**COST (SEK)**
Solar panel: JA Solar Panel 540W - JAM72S30-525-550-MR	352	75,996.8	215.9	785,806.9
Batteries: Freedom won LiTE Commercial 200/160	2	154,634.4	77,317.2	1,598,919.7
Solar Connector MC4 - Pair (1 Male, 1 Female)	4	24.0	6.0	248.2
Hybrid inverter: ATTESS HPS150 165KVA hybrid Inverter/charger	1	28,454.4	28,454.4	294,218.5
Protective devices, earthing materials, balance of materials and accessories	1	30,465.0	30,465.0	315,008.1
320 kWh * 2 Batteries Inverter mounting board	1	210.0	210.0	2,171.4
Aluminium Ground Mounting Frame	190	45,144.0	237.6	466,789.0
P400-3 CALG Basic generator FG Wilson 350kVA Prime Perkins Diesel Engine	1	61,650.0	61,650.0	637,461.0
GX Energy Service Charges	1	12,500.0	12,500.0	129,250.0
Delivery, Installation, programming, testing, training and commissioning of the system	1	29,000.0	29,000.0	299,860.0
Total excl VAT		438,078.6		4,529,732.7
VAT (18%)		37,340.5		386,101.1
Total:		**475,419.1**		**4,915,833.8**

Figure 31: *Solar installation offers from GadgetroniX (2023).*

Batteries		Model	Size (kWh)	COST(USD/kWh)	COST (USD/de
		LV flex lite	5	500	2500
BYD		LV Premier	15.4	592	9117
			5	530	2650
			100	530	53000
			80	530	42400
		LV	60	530	31800
			100	590	59000
			700	590	413000
Freedom won		HV	300	590	177000
		LV	4.95	580	2871
WECO		HV	5.3	588	3116
Batteries: Freedom won LiTE Commercial 200/160			200	387	77,317.2

Figure 32: *Summation of all battery cost offers from Photons Energy Ltd. (2023) (purple) and GadgetroniX (2023) (yellow).*

E.2 Solar LCOE inputs

The following lifetime for all components was used in the LCOE calculations:

- Solar panels: 30 years
- Batteries: Li-ion batteries: 10 years (replaced 3 times)
- Hybrid inverter/controller: 10 years (replaced 3 times)

According to theory, inverters have a lifetime of 10-15 years and charge controllers 15 years. Based in this, a lifetime of 10 years was assumed for the hybrid inverter to have a margin in the calculations.

The used costs for all scenarios are presented in Figure 33.

Used costs						
	Scenario 1		Scenario 2		Scenario 3	
	Bigger Battery	Bigger PV	Bigger Battery	Bigger PV	Bigger Battery	Bigger PV
Other	67972	67972	67972	67972	67972	67972
PV modules and racking	34793	38273	50908	55999	84531	92984
Batteries year 1	77317	77317	77317	77317	127200	127200
Batteries year 11	36733	36733	36733	36733	60432	60432
Batteries year 21	18673	18673	18673	18673	30720	30720
Hybrid inverter year 1	28454	28454	28454	28454	56909	56909
Hybrid inverter year 11	13518	13518	13518	13518	27037	27037
Hybrid inverter year 21	6872	6872	6872	6872	13744	13744

Figure 33: *The used costs in the solar LCOE calculations for all scenarios.*

E.3 Excel sheet for LCOE

Part of the excel sheet that the solar LCOE for Scenario 1 with Bigger Battery is presented in Figure 34

INPUTS	Value	Unit	Source	Comment
Discount rate	0.07	-		
Degredation rate	0.000	-	https://img1.wsimg.com/blobby/go/32d5f267-4f2e-473e-9	
Life expectancy	30	years	4.3. System life for solar PV	
Total costs				
Other	67972	USD		Includes: Balance of System Estimate, Installation charges, Transport charges
PV modules and racking	34793	USD		
Batteries year 1	77317	USD		Lifetime 10 years, replaced 3 times (Li-
Batteries year 11	36733	USD		
Batteries year 21	18673	USD		
Hybrid inverter year 1	28454	USD	https://www.igs.c	Lifetime 10 years, replaced 3 times
Hybrid inverter year 11	13518	USD		
Hybrid inverter year 21	6872	USD		
Capital cost per kW (exkl battery)	2532.9			
Capital cost	**284333**	USD		Includes all costs above
Fixed O&M	1244	USD		
Variable O&M		USD		
Total O&M	**1244**	USD		
O&M degredation rate	0.005		https://www.researchgate.net/publication/230551090_Ph	
Total energy production				
Power production for direct use	57963	kWh/year		Kommer från Saved energy från Henrik
Power production for storage				
Total power productior	**57963**	kWh/year	Saved energy	
CALCULATIONS				
Year	0		1	2
Discount factor		*(1+discount rate)^Year*	1.07	1.14
Total cost				
O&M costs per year		*O&M cost (year) * (1+degredation rate)*	1244	1250
Present value of costs	**284333**	*O&M costs per year/discount factor*	1163	1092
NPV of total cost	**300553.5**			
Total energy Output				
Degradation factor		*(1+degredation rate)^Year*	1.00	1.00
Power production per year		*Total power production / degredation factor (=1.0*	57963.1	57963.1
Present value of Costs		*Power production per year / discount factor*	54171.1	50627.2
NPV of Total Output	**719266**			
LCOE	**0.42**	**USD/kWh**		
	42	**US cent/kWh**		
	418	**USD/MWh**		

Figure 34: *Part of the excel sheet to calculate the solar LCOE for Scenario 1: Bigger Battery.*

E.4 Main grid cost inputs

The T1 and T2 prices, including 22 % tax, converted into USD are presented in Table 16 below.

Table 16: *Pricing for tariff 1 and 2 for main grid electricity, including 22 % tax.*

Charge category	Unit	Cost T1	Cost T2
Service charge	(USD/month)	0	7.47
Energy charge	(USD/kWh)	0.15	0.15
Maximum power charge	(USD/kW/month)	0	7.87

F Appendix: Biogas system calculations

F.1 Biogas demand

The amount of people that will be attending and living at the school during full-scale operation can be seen in Table 17.

Table 17: *Amount of people at the Tumaini Open School.*

People living at the school	
Students	300
Children	100
People not living at the school	
Students	150
Teachers	25
Total	**575**

The calculated biogas demand at Tumaini Open School at full-scale using the parameter "Gas demand per day" from the biogas experts from Afrihands Tanzania (2023b). The total gas demand was calculated using Equations 12 and 13 and the valued can be seen in Table 18.

$$(c) = (a) + (b) \times 2/3 \tag{12}$$

$$\text{Total gas demand} = (c) \times \text{gas demand} \tag{13}$$

Table 18: *The values used to calculate the biogas demand.*

Gas demand		
Gas demand per day	0.250	m3/student eating three meals
No of people eating three meals (a)	350	
No of people eating two meals (b)	175	
No of people (c)	467	
Total gas demand	**117**	**m3/day**

F.2 Biogas production

The biogas production was calculated using specific values for the number of animals and waste generation at Tumaini Open School presented in Table 19 and 20.

Table 19: *Number of animals at Tumaini Open School at full-scale.*

Animal	No of animals
Birds	1 000
Pigs	200
Cows	50

Table 20: *Amount of food, fruit and vegetable waste, based on Gylapo, T. (2010).*

Waste material	Total kg/day
Food/leftover/kitchen	153
Fruit/vegetables	38.2
Total	**190.91**

The specific biogas yield and substrate generation values and the resulting biogas production from Afrihands Tanzania (2023b) and the following literature sources; Vögeli et al. (2014), Kossmann et al. (n.d.), IRENA (2016), Mukumba, P. Makaka, G., Mamphweli, S. and Misi, S. (2013), and Pilloni, M. and Hamed,T.A. (2021) are presented in the following Figures. Figure 38 presents the Afrihands Tanzania results and Figures 35, 36 and 37 presents the results from the literature sources.

	Result of avarages for human waste			
	Avarage of Mukumba et.al. 2013 & IRENA 2016 & biogas expert		Avarage gas yield Mukumba et.al. 2013 & biogas expert	
People at Tumaini	**Human waste/day**	**Total Human waste/day**	**Gas yield m3/kg**	**Gas production m3/day**
Students living	0.3	90	0.065	5.85
Students	0.3	22.5	0.065	1.4625
Children	0.1	1	0.065	0.065
Teachers	0.3	3.75	0.065	0.24375
Total		117.25		**7.62**

Figure 35: *Biogas production per day from human waste using literature values.*

Result of avarages for food waste						
	Gylapo, T. 2010	Linked to "Energy demand" sheet for total amount of people	Vögeli et.al. 2014, Pilloni 2021 et.al. Gylapo, T. 2010 & IRENA 2016		First one: Pilloni 2021 et.al. & Gylapo, T. 2010, Second: Pilloni 2021 et.al.	
Food waste	kg/day for 110 students	**Total kg/day**	VS %	**Total VS kg /day**	Gas yield m3/kg VS	**Biogas production m3/da**
Food/leftover/kitchen	32	152.73	0.45	69.0	0.52	36.18
Fruit/vegetables	8	38.18	0.15	5.6	0.38	2.11
Total		**190.91**		**74.6**		**38.28**

Figure 36: *Biogas production per day from food waste using literature values.*

Animal waste	Results of avarages for animal waste								
	Mukumba et.al. 2013 & IRENA 2016 & biogas expert		Mukumba et.al. 2013 & biogas expert		Pilloni 2021 & IRENA 2016 & Kossmann n.d.		Pilloni 2021 & Kossmann n.d.		Avarage!
Animal	**kg/day**	**Total kg/day**	**Gas yeild m3/kg**	**Gas production m3/day**	**VS %**	**VS kg/day**	**Gas yield VS kg/day**	**Gas production m3/day**	**Gas production m3/day**
Birds	0.09	**93.33**	0.06	5.69	0.38	**35.13**	0.24	8.44	7.07
Chicken									
Ducks									
Taki									
Guineafowls									
Pigs	4.00	**800.00**	0.06	44.80	0.04	**34.53**	0.40	13.73	29.3
Rabbits									
Cows	12.50	**625.00**	0.04	23.75	0.31	**194.38**	0.23	43.73	33.7
Calf	5.00	100.00							
Total		**1518**		**74.24**				**65.90**	**70.1**

Figure 37: *Biogas production per day from animal waste using literature values.*

Gas generation				
Substrate	**Generation kg/animal/day**	**Generation kg/day**	**Gas yield m3/kg**	**Gas generation m3/day**
Cow	12.5	625	0.035	21.9
Bird	0.04	40	0.07	2.8
Pig	4	800	0.06	48.0
Human	0.3	119	0.06	7.2
Total				**79.8**

Figure 38: *Biogas production per day from food waste using values from Afrihands Tanzania.*

F.3 Sizing of digesters

The values from Afrihands Tanzania (2023b) to calculate the digester size for the different substrates along with the equations used are presented in Figure 39.

Digester sizing	*Daily feeding = substrat generation*		*V (m3) =HRT (days) * Daily feeding / 1000*
	Daily feeding kg/day	**HRT (days)**	**Volume (m3)**
Cow	625	50	31
Bird	40	50	2
Cow + bird	665		**33**
Pig	800	50	**40**
Human	119	60	**7**
Food	191	63	**12**

Figure 39: *The digester volumes for the different substrates using values from Afrihands Tanzania (2023b).*