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Designing a Sustainable Energy System for a Nut Processing Plant in Mozambique

A Study in Energy System Modeling

Master's thesis in Sustainable Energy Systems

RASMUS BUSSE
FELIX DAVIDSSON

DEPARTMENT OF ELECTRICAL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
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Supervisor and Examiner: Jimmy Ehnberg, Department of Electrical Engineering

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Department of Electrical Engineering
Division of Electric Power Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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RASMUS BUSSE

FELIX DAVIDSSON

Department of Electrical Engineering

Chalmers University of Technology

Abstract

Mozambique is one of the least developed countries in the world, where only a few percent of the rural population have access to electricity, and those who have access face substandard service as the grid is prone to outages. This project is done in collaboration with a company in Mozambique that harvests macadamia nuts and wants to process them to increase their value. The company has its plantation in the rural areas of northern Mozambique, Niassa province, and plans to build a processing plant and have sustainable, on-site, energy generation to supply demand. The aim of this report is to investigate how the energy demands of the processing plant can be met using renewable and sustainable generation technology. This was done by creating a linear cost optimization model in GAMS to determine the energy mix and size of each technology. Different cases were created and evaluated based on different factors such as annual cost, practicality and energy usage. Large economic gains were noticed for grid connected systems and the solutions had cheaper annual costs but were highly dependent on the possibility to sell electricity. If the possibility to sell electricity was removed, but the ability to buy remained, installed generation capacity decreased and more electricity was instead purchased from the grid. Grid connected solutions had no investments in energy storage but to handle outages, it was necessary to have batteries, where outage duration and time of day were deemed most crucial on battery sizing. Variations in solar radiation had a significant effect on off-grid systems while grid connected solutions were barely affected. Based on the observed cases and their results, the energy system with the lowest total annual cost is a grid connected system with solar PV for electricity generation and pyrolysis for heat generation. Unless the grid becomes more reliable or demand side management can be utilized, a battery should be added to ensure processing during outages. For an off-grid solution, the same technologies would be used but the size of the battery should be increased.

Keywords: Africa, biochar, cost optimization, Mozambique, off-grid, outages, pyrolysis, solar, sustainable, waste utilization

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Rasmus Busse, Felix Davidsson, Gothenburg, June 2023

Contents

1	Introduction	1
1.1	Background	2
1.2	Aim	3
1.3	Scope	3
1.4	Limitations	4
2	Theory	5
2.1	Cultivating and utilizing the macadamia nut	5
2.1.1	The macadamia tree	5
2.1.2	Macadamia nut processing stages	6
2.1.3	Utilizing waste from the nut processing	6
2.2	Technologies	7
2.2.1	Solar photovoltaics	7
2.2.2	Diesel generator	7
2.2.3	Biomass heat only boiler	8
2.2.4	Bio pyrolysis	8
2.2.4.1	Biochar	9
2.2.5	Heat pump	9
2.2.6	Electric boiler	10
2.2.7	Battery	10
2.2.8	Grid in Mozambique	11
2.2.9	Summary of key technology data	11
2.3	Carbon credit market	12
2.3.1	Negative emissions	13
3	Method	15
3.1	Energy system modelling	15
3.1.1	Modelling the cases	16
3.1.2	Evaluating how outages affect the energy systems	17
3.1.3	Varying yearly solar radiation	17
3.2	Determining model input values	18
3.2.1	The energy content in macadamia shells	18
3.2.2	Calculating the biochar yield and determining its value	19
3.2.3	Determining biofuel prices in Mozambique	19
3.2.4	Determining the price of electricity	20
3.3	Evaluation of the different energy systems	20

4	The energy system model	21
4.1	Technology constraints	21
4.1.1	Solar PV	21
4.1.2	Storage	21
4.1.3	The grid connection	22
4.1.4	Generation, capacity and ramping constraints	22
4.2	Supply and demand	23
4.2.1	Energy balance - Electricity	23
4.2.2	Energy balance - Heat	24
4.3	Economic considerations	24
4.3.1	Investing	24
4.3.2	Expenditures and revenues	25
4.3.2.1	O&M costs	25
4.3.2.2	Revenues	26
4.3.3	The objective function	26
5	Results and analysis	27
5.1	Cases without grid connection (Off-grid)	27
5.1.1	Case A-1	28
5.1.2	Case A-2	30
5.1.3	Case A-3	32
5.1.4	Case A-4	34
5.1.5	Case A-5	36
5.2	Grid connected cases with the ability to purchase and sell electricity	38
5.2.1	Case B-1 and B-2	38
5.2.2	Case B-3 and B-4	41
5.3	Grid connected cases with the ability to purchase but not sell electricity	44
5.3.1	Case C-1 and C-2	44
5.3.2	Case C-3 and C-4	47
5.4	The effect of outages on the energy systems	50
5.4.1	Effect of outages on case B-1	50
5.4.2	Effect of outages on case B-3	53
5.4.3	Effect of outages on case C-3	56
5.5	The effect of small changes in solar radiation	59
6	Discussion	61
6.1	Case evaluation	61
6.1.1	Cases without grid connection (Off-grid)	61
6.1.2	Grid connected cases with the ability to purchase and sell electricity	62
6.1.3	Grid connected cases with the ability to purchase but not sell electricity	63
6.2	The effect of outages on the energy system	64
6.3	The effect of small changes in solar radiation	65
6.4	The value of having a grid connection	66

6.5	Demand side management	66
6.5.1	Different operating hours	67
6.5.2	Batteries vs altering the production	67
6.6	Uncertainties affecting the result	67
6.6.1	The energy demand of the processing plant	67
6.6.2	The cost of buying and selling electricity	68
6.6.3	Linear costs in the model	68
6.6.4	Weather affecting plant growth	68
6.7	Societal aspects	69
7	Conclusion	71
7.1	Final recommendation	72
8	Future work	73
A	Appendix 1	I
A.1	Modeling sets, indices, variables, and parameters	II
A.2	PVWatts®Calculator settings	IV
A.3	Case summary	V

1

Introduction

Energy poverty has been shown to negatively impact a wide range of development indicators, including, but not limited to health, education, food security, gender equality, livelihoods, and poverty reduction [1]. Currently, over half of the population living in the least developed countries (LDCs) still lack basic access to electricity [2], and even those that have access to electricity might suffer due to its high price or low reliability.

Mozambique is considered a LDC and faces significant challenges regarding its energy sector as 70% of the population still lives without modern energy services [3]. The access to electricity is unevenly distributed throughout the country and the northern provinces are especially affected [3]. Large parts of the population living in rural areas lack connection to the national grid and lives without electricity in their daily life. Even the urban population faces struggles as 34% of urban households are considered energy poor [3]. Those who are connected and can afford the electricity still face substandard service as the grid is prone to outages, in some parts of the country reaching 400 interruptions per year, lasting an hour on average [4].

When access to electricity is poor, locally sourced firewood is commonly used to cook food. This seriously impacts the population as women and children in the rural population, which corresponds to two thirds of the overall population in Mozambique, have to walk several kilometers to collect the firewood, on average occupying 1.4 hours daily [3]. In addition to spending time collecting the firewood, the domestic pollution attributed to preparing food using the firewood negatively affects health and is estimated to cause nearly two million deaths annually throughout the developing world [5]. With a growing population, firewood usage is also making the country face challenges regarding deforestation [6].

Further, lacking reliable access to electricity can have a severe impact on emerging businesses utilizing more advanced value-adding processes, which will be less likely to establish in the afflicted countries and in the long term damage the country's economy as a whole. However, as a measure to lessen the risk of blackouts affecting production, companies can choose to end their reliance on the national grid by building their own generation instead, enabling them to generate their own electricity. To help struggling countries towards more reliable and sustainable energy systems, billions of international dollars in support of clean and renewable energy are being used as renewable energy capacity per capita has increased by 57.6% in developing countries since 2015 [7].

This project investigates how the Mozambique based company, Niassa Macadamia Limitada, can provide sustainable energy to a processing plant at the lowest cost in a country that is plagued by many issues, both regarding electricity and biofuels, while still providing a marketable product in the form of macadamia nuts.

1.1 Background

The popularity of the macadamia nut is currently increasing and as of 2019, macadamia nuts account for 2% of the global nut market [8]. The macadamia market consists of two different kinds of products which are; nuts in shell (NIS) and kernels. As of 2021, nuts in shell accounted for 32.3% of total export revenue while the remaining 67.7% consisted of nuts without shell [8]. Most consumer countries purchase macadamia as a kernel, but in China, the market for NIS is large as they themselves process the nut further. Overall, the market is bigger for kernels but the price still roughly follows the same scaled price trend [9] (price for NIS is scaled to match the cost per kg of kernels, to make them comparable). However, in the case of Mozambique, all nuts are sold as NIS since there are no processing facilities which limits the country to a smaller market share.

The Mozambique based company, *Niassa Macadamia Limitada* (NML), has secured land that will be used in a macadamia plantation. Out of the 5150 hectares that will be a part of the plantation, 1233 hectares are currently in use and macadamia nuts are being harvested. The macadamia kernel is surrounded by a soft but tough husk and a wood-like hard inner shell. Since August 2022, NML is operating a processing facility that is used to dehusk the macadamia nuts. In addition to dehusking the nuts, there is also a drying unit in place to dry the dehusked nuts. Both the dehusking and the drying process are currently powered by a diesel generator. Eventually, as the macadamia trees mature and the planted area expands to the planned 5150 hectares, the energy demands of processing the nuts will increase. The production of the farm is expected to reach 4000 tonnes of macadamia nuts annually and the processing plant should be able to process 1.5 tonnes of macadamia nuts per hour. In addition to the processing demand increasing due to the larger annual volume of harvested nuts, it will also increase as NML plans to process the nuts even further by investing in nut cracking equipment to remove their shells and sell them as kernels. Currently, the company expects to crack 90% of their nuts.

To handle the increased demand from processing and to move towards a sustainable energy system, NML will need to invest in new ways to supply their heat and electricity demand. The processing plant only has an energy demand during the harvesting season which is assumed to last from the 1st of April to the 1st of January. The energy demand consists of a constant heat load of 280 kW and a constant electricity load of 30 kW that increases to 400 kW during working hours. The working hours are assumed to be from 08:00 to 16:00 during all weekdays. Figure 1.1 below shows the weekly electricity demand for the processing plant.

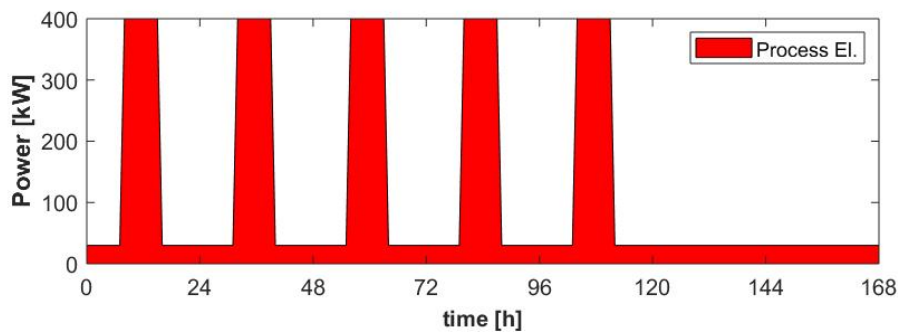


Figure 1.1: The electricity demand of a week of production for the processing plant NML plans to build.

The company wants to investigate the most cost-effective way to provide the processing plant with energy. This could be achieved either by purchasing electricity from the existing grid, as a study conducted by NML has shown that a grid connection of 480 kVA can be constructed, by investing in their own on-site energy generation, or by building a hybrid system that utilizes both the grid and on-site generation. However, if the grid is to be utilized in any way its low reliability has to be taken into account.

The company has been offered funds that can be used to build energy generation from renewable resources. Due to high levels of solar radiation, the company expects that the primary source of energy will be based on the sun and the use of photovoltaic panels. Another area of interest is to utilize the agricultural byproducts from the plantation to meet the heat demand of the processing and thus lower the electricity demand. In addition to utilizing waste resources from their own production, other local waste resources exist such as woodchips and sawdust from a nearby sawmill. If this could be utilized to fuel the processing demands of NML, biofuel usage will not affect the current risks of deforestation. Further, NML would like to know if it is beneficial to invest in energy storage and finally, if it is worth connecting their processing plant to the national grid.

1.2 Aim

The purpose of the project is to investigate how the energy demand of *Niassa Macadamia Limitada's* processing plant can be supplied with the lowest total annual cost, utilizing renewable sources and the electricity grid.

1.3 Scope

In order to investigate how the energy demand of *Niassa Macadamia Limitada's* processing plant can be met with the lowest total annual cost, a linear optimization model is to be created. The optimization model will be using collected data from

energy generation technologies that are deemed suitable for the location. Based on the load of the processing plant and technology costs, the model will invest in the system with the lowest total annual cost. Different cases will be created and evaluated based on different factors such as annual cost, investment cost, fuel source, practicality and energy usage.

- The cases will be subject to three scenarios, off-grid, on-grid with the ability to buy electricity, and on-grid with the ability to both buy and sell electricity.
- As the national grid of Mozambique is prone to outages [4], it will further be investigated how the grid connected cases can be made to sustain production while there is an outage. The effects of both a low and a high outage frequency will be evaluated based on the same factors as previously mentioned.
- As the cases likely will make use of electricity generation from solar PVs, which generation will vary from year to year, the impacts of a slightly higher or lower yearly solar radiation will be investigated based on the same factors.
- The nut processing plant will produce waste during processing. It should be investigated if the waste products can be utilized.

1.4 Limitations

The following limitations were put in place to limit the scope of the project

- The resolution of simulations will be set to hours due to uncertainty in input data with finer resolution.
- Site-specific labor and maintenance costs will not be considered due to a lack of data.
- Will not consider the angle of solar PVs but instead assume solar PVs can be placed at the angle which yields the highest power output.
- To prioritize technology diversity, only general values will be used for the different technologies, that is, no competition between brands within the same technology. This would allow the project to look into more kinds of technologies instead of focusing on a few.

2

Theory

This chapter presents the theory about macadamia nuts and technologies that can be used to supply energy to the processing plant. Further, the concept of carbon credit markets and negative emissions are explained.

2.1 Cultivating and utilizing the macadamia nut

This section describes how the macadamia nut can be grown, processed, and used.

2.1.1 The macadamia tree

The macadamia tree is indigenous to the subtropical rainforests of Australia but has been introduced to several parts of the world where the climate allows, such as southern Africa, South America and Hawaii [10]. Studies have shown that the trees are best suited for low elevation areas as the kernel recovery rates and tree growth and health are increased compared to high elevation. However, the amount of precipitation and temperature will have a relatively larger effect on the kernel recovery rates, which makes it beneficial to grow macadamia at higher elevations if the temperature and amount of rainfall during the wet growing season are decreased [10].

Even though the kernel recovery will be decreased if the trees are subject to large amounts of rainfall during the wet growing season, there can still be a benefit of additional irrigation as the trees can be highly affected by water deficits. During early fruit growth, nut yields have been observed to decrease by 45% if subject to water deficits. During other stages in nut maturation such as during the oil accumulation stage, the kernel recovery rate was decreased by around 25% when water deficit stresses occurred, showing that water deficit stresses can have a large impact during several stages of nut maturation [11].

The trees have a long life cycle and need at least 5 to 7 years before the first harvest [9]. After the first harvest, full maturity and production will be achieved when the tree reaches an age of 12 - 15 years [12] and if grown in suitable locations, the trees can remain productive for over 100 years [12]. The long infancy stage and overall lifetime of the trees make them suitable as a long term investment.

2.1.2 Macadamia nut processing stages

The Macadamia nut consists of a green fibrous husk that encloses a tough wood-like shell, which contains the macadamia kernel. The husk has a thickness of 3.2 - 6.4 mm, and should be removed within 24 hours of harvest to preserve kernel quality [13] [14]. Compared to the shell, the husk is relatively easy to remove using mechanical forces.

After having the husk removed, the NIS has a moisture content of around 30% and requires drying before it can be further processed or sold. The NIS is dried until it reaches a moisture content of 1 - 2%, which is done in multiple steps and will take anywhere from 7 to 17 days [14] [15]. Usually, the NIS is dried by hot air with temperatures around 30 – 60°C, where most of the drying time is spent with the hot air below 45°C [14] [15]. The NIS is dried to increase the kernel recovery and prevent flavor deterioration during storage [14] [16].

After the NIS is dried to the right moisture content, they can either be sold as nuts in shell or further processed and cracked to remove the dry shell and retrieve the kernel. The kernel can be sold as a natural kernel or after being roasted and seasoned, commonly using salt. In Figure 2.1 below, the nut is shown in its different processing stages.

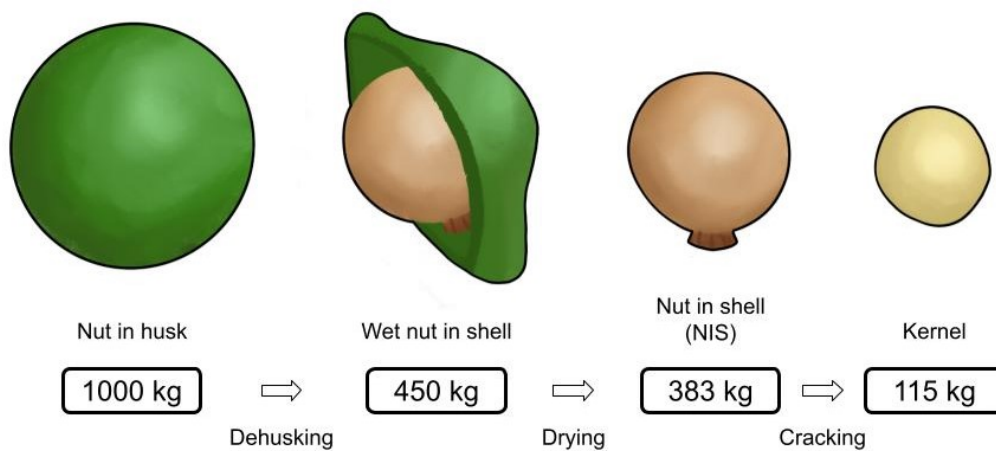


Figure 2.1: A simplified schematic of the different processes the Macadamia nut goes through and how much mass is lost during dehusking, drying and cracking respectively [9].

2.1.3 Utilizing waste from the nut processing

From the process, a significant amount of dried nutshell will be generated after cracking. The residual biomass could be suitable for other processes especially due to its low moisture content. Currently there are different use of the nutshell such as filler material in roads, hydrochars preparation and burning for energy recovery [17]. New ways of using agricultural solid waste is being discovered such as using

the macadamia nutshell to remove hexavalent chromium from aqueous solutions [18].

When visiting the plantation it was shown that the macadamia husk could have usage as well, to be used as a fertilizer and some trials had been carried out by the company. The trial consisted of fertilizing macadamia trees with husks and over time comparing them with nearby trees that had not been given any husk. The trial had been going on for some years and seemed to indicate that fertilizing the trees with the husk could increase tree growth and productivity, as the trees given the husk were visibly larger.

2.2 Technologies

In the following section, different technologies that could be used to supply the processing plant with energy will be described. Key parameters related to performance and economy will be presented. Due to the relatively small size of the energy system, some properties have been scaled down from larger units. Key parameters for all technologies will be summarised in tables at the end of this section, see Table 2.1 and Table 2.2.

2.2.1 Solar photovoltaics

Due to the current global transition from fossil fuels to sustainable, renewable energy generation, solar photovoltaics have gained increased interest over the last years. PVs offer advantages such as no noise, little maintenance, no requirement of fuel, absence of moving parts, and modularity, making it easy to expand generation to meet demand [19]. As the technology has become more popular, manufacturing levels and experience have increased, which has entailed decreased production costs [20]. The generation from PVs is directly related to the local solar radiation, which varies from year to year and is expected to slightly decrease over time [21] [22].

As solar PVs are modular, sustainable and do not require any fuel nor maintenance during operation, it has become a popular technology to have in off-grids and mini-grids [19] [23] [24]. However, solar PVs are rarely used alone due to their dependents on solar radiation and thus intermittency [23]. Key performance- and economic parameters related to solar PV are presented in Table 2.1.

2.2.2 Diesel generator

The most common off-grid generation technology in rural areas of developing countries is diesel generators [23], which is a mature and reliable technology. Diesel generators are recognized for their high flexibility and low investment cost but also their high operation cost because of relatively low efficiency and consumption of fossil fuel, thus also high emissions [25]. Further, in areas with poor infrastructure, it can be challenging to secure supply of fuel as it has to be transported to them.

Diesel generators are commonly used as peak generation technology due to quick ramp-up/down and expensive operation cost [19]. Key performance and economic parameters related to diesel generators are presented in Table 2.1.

2.2.3 Biomass heat only boiler

Biomass is one of the earliest fuels used to generate heat and it is still one of the primary sources, especially in rural areas [26]. A popular technology today, which utilizes biomass is biomass boilers, and their use is often considered sustainable and renewable, as emitted carbon originates from the air and biomass will regrow, capturing new carbon from the air [26].

The sustainability aspect of biomass boilers is debated and the origin of the biomass plays a big role in the discussion [27]. There are however cases where the use of biomass as fuel is accepted and affordable; when the used biomass has no other use and low value, such as waste wood and forest residue [28]. Generally, biomass boilers have a high versatility and can utilize most biomass. It is a mature and established technology widely used but primarily in areas with excess biomass and significant heat demand. Key performance and economic data for the biomass boiler is presented in Table 2.2.

2.2.4 Bio pyrolysis

In the pyrolysis process, organic material decomposes mainly into pyrolytic gas, pyrolytic oil, and biochar in the absence of oxygen [29]. Early use of pyrolysis was to produce tar from coal and charcoal from wood, while present pyrolysis boilers are primarily fueled by biomass to generate bio-oils, gases and biochar [30]. All of the residues have the potential to be used as fuel, either as produced or further processed to generate more suitable fuel [31].

There are different categorizations of pyrolysis; slow-, flash- and fast pyrolysis, where the difference between them is the heating rate, ranging from 0.1 °C/s to 2500 °C/s [30]. These different processes have different purposes where slow pyrolysis generates more biochar while flash pyrolysis generates more bio-oil [30], thus to increase biochar production a low temperature and low heating rate would be chosen [32]. Other than traditional biomass, alternative fuels such as municipal solid waste or macadamia nutshells have increased in popularity lately, to utilize waste to energy [33] [34] [35].

Different fuel properties promote different quantities and quality of the output whereas it is attractive to have low moisture and ash content and low fixed carbon but high volatile matter and elemental carbon [36] [37]. Additionally, it is attractive to have low water content and small particle size and Biomacon state that their pyrolysis boiler can accept a maximum water content of 30% [38]. Key performance and economic parameters are presented in Table 2.2.

2.2.4.1 Biochar

Biochar is produced during the pyrolysis process and is a porous and carbonous material that is applied in such a way that it can serve as a long term carbon sink or as a replacement for fossil carbon in manufacturing. Depending on its qualities, the half-life of biochar is calculated to range from 150 to 5000 years and in 2018 the IPCC classified biochar as a Negative Emission Technology [39].

Other than its usefulness as a negative emission technology, biochar has been shown to have several different beneficial properties in agricultural use and has been utilized in this application since as early as 400 BC, when it was used by the indigenous population in the Amazons to increase soil fertility. The exact properties of the biochar will depend on the original biomass type and conditions during the pyrolysis process such as temperature and duration, although all kinds of biochar share the following positive properties [39]:

- Biochar is chemically inert and will not react with its surroundings
- The porous structure will yield a high water retaining capacity
- The large surface area of biochar will increase nutrient retention in the soil
- Microscopic cracks and cavities in the biochar are suitable for the growth of desired microorganisms
- Can be added in animal feed to increase weight gained, wellbeing and decrease methane emissions

Biochar can be sold for around 750 EUR/ton in Sweden [40]. However, according to an official at the Swedish embassy in Mozambique, projects similar to NMLs that utilize pyrolysis could expect around 200 to 400 EUR/ton of biochar on the voluntary carbon market.

2.2.5 Heat pump

Heat pumps are a mature technology that extracts heat from a source and amplifies it before pumping it to somewhere where needed. Because heat pumps do not generate, but only transfer heat, they are far more efficient than conventional heat generation technology, such as electric boilers [41]. The output heat is normally higher than the power required to operate the heat pump and the coefficient of performance (COP) for typical heat pumps is around 4 [41] [42].

In most cases, heat pumps are more expensive than conventional fossil-fueled heating, such as gas or oil boilers, even if financial incentives are in place but due to their high energy efficiency, they usually have lower running costs and thus can be competitive [41]. Key performance and economic related parameters are shown below in Table 2.2

2.2.6 Electric boiler

The electric boiler is a mature and common power to heat (P2H) unit that comes in various sizes, from a few thousand watts up to 60 MW [42]. The technology utilizes electricity to supply heat but unlike the heat pump, electric boilers generate heat and thus have a lower COP than heat pumps. Efficiency is around 99% thus 100 kW of electricity generates 99 kW of heat.

Electric boilers have a very simple design with no built-in complex components and are easy to operate and maintain. Additionally, the boiler has quick load response and startup [42]. The boilers are relatively cheap to invest in and require no fuel but instead electricity to operate, therefore the operation cost is highly dependent on the cost of electricity. Because of the low power to heat ratio (compared to heat pump) but quick load response, electric boilers are primarily used to make use of excess energy [43]. Key performance and economic related parameters for Electric boilers are shown in Table 2.2.

2.2.7 Battery

Batteries are a commonly used technology to store electricity and their interest has increased over the last year due to the increase of intermittent variable renewable energy sources (VRES) and the electrification of homes and industry, primarily the automotive industry. They have grown to become one of the key technologies to enable the next phase of the energy transformation and the International Renewable Energy Agency believed installed capacity of battery energy storage (BES) would increase 17-fold from 2017-2030 [44].

There are different batteries with different properties and characteristics, whereas the most widely used battery in operating systems, is the Li-ion battery (LIB) [45]. Although Li-ion batteries are a relatively new technology, their high energy density, efficiency, versatility and decline in production cost, have made them very competitive [45] [46]. Thus LIB batteries are promising for a broad range of applications such as peak load shaving, renewable integration and frequency regulation [46].

As mentioned, LIB are flexible and versatile but have an upper limit to feasible storage periods due to self-discharge and a limited number of full charge-discharge cycles [46]. LIB used for frequency response have a quick response time and a short storage time of a few minutes while LIB used in battery energy storage systems (BESS) have a storage time of a few hours to a day, but the technology is currently less attractive for long-term storage beyond a few days [46].

Another parameter that is different depending on the application of the LIB is C-rate, which is the relation between installed charge/discharge capacity (W) and storage size (Wh). As such a C-rate of one indicates that the battery can charge/discharge within one hour and C-rate lower than one indicates a longer charge/discharge time and a C-rate over one can charge/discharge in under one hour [46]. Typically

LIBs used in BESS have a C-rate lower than one due to long-term energy management while LIB used for grid stability have a higher C-rate to ensure short-time power quality [46] [47]. Key performance and economic parameters are presented in Table 2.1.

2.2.8 Grid in Mozambique

To have an industry, factory, home etc. grid connected is attractive since more technologies can co-operate to increase reliability on the consumer end [48]. However, in Mozambique the grid is subject to frequent outages and it is therefore a risk for the consumer. In the northern part of Mozambique an average of 230 outages occur annually with an average duration of one hour [4]. The electricity tariffs in Mozambique vary from customer to customer and for medium voltage, the price ranges from roughly 0.04 EUR/kWh to 0.07 EUR/kWh, depending on the specific customer and their contract [49].

To be connected to the grid is a luxury in Mozambique and only a low percentage of the rural population have grid connection [4]. NML has been offered to connect to the grid and the cost of the cable and labor would correspond to roughly 220 kEUR. The specific cable that NML has been offered to purchase would have a capacity of 480 kW. For more information regarding the cable, see Table 2.1

2.2.9 Summary of key technology data

In the following section, tables with key performance and economic parameters of the used technologies are presented. The technologies related to the electricity supply are presented in Table 2.1 and the heat supplying technologies are presented in Table 2.2.

Table 2.1: A summary of the key technical and economic parameters for the electricity supplying units used in this project [42]. The included technologies are from left to right; Solar PV, Diesel generator, Li-ion battery size component, Li-ion battery charge capacity component and lastly the provided data for a grid connection.

Technology		PV	DG	Bat. size	Bat. cap	Grid
Fuel		None	Diesel			
Efficiency	[%]		35	100	95	100
Lifetime	[years]	20	25	20	20	40
Ramp up/down	[h]		1			1
Investment cost	[kEUR/kW]	560	343	232	270	458
Variable O&M	[kEUR/kWh]	0	0.006	0	0	0
Fixed O&M	[kEUR/year]	6.9	8.8	0	0	0

Note that the electricity demand related the pyrolysis (Pyro) and biomass boiler

(HOB) shown in Table 2.2, are conservative estimates based on data provided by Biomacon, regarding electricity demand to run pumps, fans, etc., for their bio-fueled pyrolysis [38]. Additionally, non-available data regarding the pyrolysis, such as O&M costs, have been assumed to be the same as for the biomass boiler.

Table 2.2: Key technical and economic parameters for the heat supplying units included in this project [38] [42]. The included technologies are from left to right; Biomass boiler, Pyrolysis, Heat pump and Electric boiler.

Technology		HOB	Pyro	HP	EB
Fuel		Biomass	Biomass	El.	El.
Energy demand	[kW _{el} /kW _{heat}]	0.021	0.021	0.25	1
Efficiency	[%]	99	40	100	99
Lifetime	[years]	25	20	25	20
Ramp up/down	[hours]	1	2	1	1
Investment cost	[kEUR/kW]	690	1625	1430	150
Variable O&M	[kEUR/kWh]	0.00119	0.00119	0.00269	0.0006
Fixed O&M	[kEUR/year]	32.5	32.5	2.0	1.07

2.3 Carbon credit market

The effects of global warming have increased in magnitude and frequency to have reached a state where current extreme climate events are life threatening [50]. Many instruments and actions have been introduced to brake the global warming and amount of carbon dioxide emitted to the atmosphere, such as the Paris agreement. One of the main instruments introduced in Europe to follow the Paris agreement, is the "European emission trading scheme" (EU ETS), which is a way to set a price on carbon emissions [51]. In EU ETS there is an emission cap and industries are given allowances to emit, following the total emission cap and companies need to have allowances to cover their emission or they face significant fines. However, emitters with more allowances than used are able to sell their permits to other emitters and this part of the market is called; cap-and-trade market [52]. The purpose of the market is to reduce overall emissions by reducing local emissions where it is the most economically favorable [53].

The EU ETS is one of many implemented instruments in the world that focuses on the European market and is observed by the European Commission, a legal but non-political organization. There are more compliance markets that function roughly the same and are monitored by legal organizations but there are also carbon markets that are free (voluntary) markets and observed by non-legal organizations. On the free markets, companies can trade "emissions" with one another within or over country borders, without having a relation to their country. In a cap-and-trade market, there is a cap on emissions that parties have to adjust to while in a free

market, there is no requirement to reduce emissions [54]. There are however issues caused when the two markets operate without relation, emissions permits may be calculated twice, once by the emitter itself on the voluntary market and once by the country in which the company is located, on the compliance market. This issue causes confusion and entails increased emissions [53].

As mentioned, there are many different markets where emission allowances are granted and possible to trade. Mozambique is however not part of EU and thus not part of the EU ETS and hitherto there are no well established carbon markets operating in Africa, but there are instruments under development. Under United Nations Climate Change Conference 2022 (COP27), African Carbon Market Initiative (ACMI) was announced [55]. ACMI has the ambition to establish a voluntary carbon market to increase the production of carbon credits in Africa while ensuring transparency in revenue and creating jobs [55]. This framework aims to create a stable legal ground for companies to invest in the carbon market without fearing the political risk of the country where they operate to claim the carbon credits. The programs ambition is to have the market established by 2030 and fully developed by 2050, thus this market is not currently established but on its way [55].

2.3.1 Negative emissions

The current situation in the world and ongoing trends of emissions and global warming are critical. Targets of increased global temperature of 1-2 °C are believed to be very difficult, and even impossible to meet based on current trends, according to recent IPCC reports [56]. From the IPCC report, all scenarios that meet targets of global temperature increase less than 2°C have negative emissions. Negative emissions are generated when carbon is taken away from the carbon cycle by carbon capture and storage (CCS) technologies [57]. The most common ways of generating negative emissions is by either capturing carbon directly from the air (DACCS) or by using biomass as fuel and capturing the carbon in the emissions (BECCS) [57].

Negative emissions are relatively new and yet the framework of what is considered negative emissions, and its value, are not fully established. There are however possibilities to generate negative emissions by utilizing biomass and bio-waste from agriculture, such as biochar, which is generated when organic matter is composed in an oxygen free environment, such as in pyrolysis as mentioned in 2.2.4. There is however a debate regarding if biochar generates negative emissions or not and it is highly dependent on the source of biomass and the end use of the biochar, thus the value of biochar is yet to be determined [58] [59].

3

Method

To find the energy system that could supply NMLs processing facility with the lowest annual cost, a linear cost optimization model was developed to determine the size of the incorporated technologies, and to identify the general trend of the energy system. While creating the model, several different input values were unknown and had to be determined based on assumptions from literature and interviews. Using the model several cases with different technology combinations were examined and the effects of outages, and changes in solar variation, were taken into account while recommending NML a system that would be satisfactory under the local conditions of Mozambique. The model itself is described further in chapter 4.

3.1 Energy system modelling

A model of the processing plant was used to evaluate different energy systems. The model is presented in chapter 4. The purpose of the model was to, given the technologies in the technologies section, choose the technologies that would result in the energy system with the lowest total annual cost that manages to meet the demands of the processing plant. This was done by creating a linear optimization model of the processing plant and minimizing the objective function in equation 4.35.

The linear cost optimization model was chosen as a method to determine the size of the incorporated technologies, as it made it simple to evaluate several different technologies at once and to identify the general trend of the energy system. Although the cost estimates are approximate at best, the installed size and relations between the technologies should be correct which makes the resulting systems a good foundation on which to base further investigations and decisions regarding future investments.

A selection of cases was further investigated to determine how outages and changes in solar radiation would affect the technologies used in the energy systems. This was done to determine how NML could compensate for these occurrences in their energy system.

3.1.1 Modelling the cases

Different cases were created to investigate how limiting the use of certain technologies would affect the solution. The cases presented in table 3.1 were investigated. Note that even if several technologies are allowed, the model might choose to only invest in some of the technologies. The original energy system proposed by NML contained Solar PV, batteries, heat pump and electric boiler. To simplify the description, these technologies together were called the "base technologies" (BT). The other cases are built upon the base case but allow more technologies to choose from. The technologies mentioned under the technology column are added to the base case.

Table 3.1: Overview of the cases that have been analyzed and what technologies were allowed to be used in the respective cases. BT is the base technologies that were defined as solar PV, heat pump, electric boiler and batteries. The A cases are off-grid, the B cases are able to purchase and sell electricity and the C cases were allowed to purchase but not sell electricity.

Case	Technologies
A-1	BT
A-2	BT + Diesel generator
A-3	BT + Pyrolysis
A-4	BT + Pyrolysis + biomass boiler
A-5	BT + Biomass boiler
B-1	BT
B-2	BT + Diesel generator
B-3	BT + Pyrolysis
B-4	BT + Pyrolysis + biomass boiler
C-1	BT
C-2	BT + Diesel generator
C-3	BT + Pyrolysis
C-4	BT + Pyrolysis + biomass boiler

In all A cases, constraints 4.7 and 4.8 in the model was disabled at all hours to simulate off grid operation. In the B cases, the vector of both equations was enabled at all hours to simulate perfect grid connection and in the C cases, the constraint in equation 4.8 was deactivated, as to remove the models ability to sell electricity.

The model was run using various costs of biofuel to identify the breakpoints where it would be more beneficial to use the pyrolysis compared to the biomass boiler. The breakpoints depend on the investment costs of the technologies, the cost of biofuel and the selling price of the biochar. Based on discussions with parties in Mozambique it was found that when the parameters were used within the probable price range, the model preferred the pyrolysis over the biomass boiler. As such cases only containing the biomass boiler, were not further investigated during the B and C cases.

While running the model for the B cases it was seen that B-1 was identical to B-2 and B-3 was identical to B-4. This is due to the fact that it was not beneficial to utilize the extra technologies provided in B-2 and B-4 compared to B-1 and B-3 respectively when the cases were connected to the grid. The same occurrence was discovered in the C cases as C-1 was identical to C-2 and C-3 was identical to C-4.

3.1.2 Evaluating how outages affect the energy systems

The grid in Mozambique can be subject to frequent outages [4]. To determine how the energy systems would behave and if certain technologies would be more advantageous under these circumstances, the model was run with a fixed number of outages on randomized hours of the year.

To investigate how the cases would perform during outages, cases B-1 and B-3, which are identical to B-2 and B-4 respectively, were re-run while only allowed to invest in battery size and capacity to not fail during the outages. This was based on [60] where it was seen that limiting the installed capacity of solar PV did not have a large effect on the optimal energy system if it was allowed to sell electricity. As such the constraint in equation 4.10 was changed to an equality for all technologies except the battery. The fixed values were based on the case results to not change the energy system composition.

Case C-3 was also evaluated although it was allowed to invest in solar PV capacity in addition to the battery size and capacity. This was done as this case was significantly impacted in terms of costs by not being able to increase its installed solar PV capacity. No other cases from scenario C were investigated as case 3 was deemed the most promising case based on the previous simulations.

The number of outage hours was randomly distributed throughout the year and set to 100 h for a low outage scenario and 1000 h for a high outage scenario. Each case was simulated ten times for the low outage scenario and ten times for the high outage scenario.

3.1.3 Varying yearly solar radiation

The cases were subjected to changes in solar radiation to investigate how small changes would affect the solutions. To determine the effect of solar variations, ε in equation 4.1 was increased or decreased with the amount that was supposed to be investigated.

Again, the invested technologies would be fixed based on previous results although, for the off-grid cases, the battery size was allowed to change to still make the solutions feasible. When the solar radiation was changed for the on-grid cases, all technology sizing was fixed as the grid could compensate for the increase/decrease in solar radiation.

3.2 Determining model input values

This section describes how important input parameters were determined to model the energy system as realistically as possible. The values used in the model are based on the information provided by NML in the background and the technology data from section 2.2.9. However, all values needed were not known and had to be determined based on calculations or literature. These values are presented in this section.

3.2.1 The energy content in macadamia shells

The equations below describe how the mass of the macadamia nuts changes during the different processing stages [9]. The mass of the raw nuts is denoted as m_{NIH} , the dehusked nuts as m_{WNIS} , the dried nuts in shell as m_{NIS} and finally the macadamia kernels as m_{KRNL} .

$$m_{NIS} = m_{NIH} \cdot HF \quad (3.1)$$

$$m_{DIS} = m_{WNIS} \cdot DF \quad (3.2)$$

$$m_{KRNL} = m_{NIS} \cdot SF \quad (3.3)$$

HF , DF , and SF are process parameters that determine the mass loss in the different stages. $HF = 0.45$ is the husking factor, $DF = 0.85$ the drying factor and $SF = 0.3$ the shelling factor [9]. Utilizing the previous equations 3.1 - 3.3, the mass of the dried nutshell that can be retrieved from the raw nuts and be used to fuel the drying process, is described as

$$m_{MNS} = m_{NIH} \cdot HF \cdot DF(1 - SF) \quad (3.4)$$

Assuming that nut processing will only occur when the processing plant is running and that the amount of processed nuts is proportional to the energy demand of the processing plant, the total amount of nutshell produced during a year can be described as

$$m_{MNS} = \sum_t (\bar{d}p_t^e \cdot m_{NIH} \cdot HF \cdot DF(1 - SF)) \cdot \beta \quad (3.5)$$

Where $\bar{d}p_t^e$ is a normalized vector of the nut processing plants electricity demand, and β is the share of processed nuts that will be sold as kernels (90 %).

The nutshells produced in the process can be used as a heating source for the drying of macadamia nuts. Using the higher heating value of macadamia nut shells HHV_{MNS} [61] (19.367 MJ/kg) and assuming total combustion, the total energy contained in the yearly supply of nutshells could be calculated as

$$E_{MNS} = HHV_{MNS} \cdot m_{MNS} \quad (3.6)$$

3.2.2 Calculating the biochar yield and determining its value

According to the manufacturer of the pyrolysis boiler, a rough estimation of the biochar dry weight yield can be achieved by assuming that 40% of the energy in the fuel gets converted into biochar. If it is assumed that biochar has the same energy density as elemental carbon the dry weight yield α can be calculated as

$$\alpha = \frac{m_{biochar}}{m_{MNS}} = 0.4 \cdot \frac{HHV_{MNS}}{HHV_{carbon}} \quad (3.7)$$

Using this assumption, a dry weight yield (α) of roughly 22 % is achieved, meaning that 1 kg of nutshells yields 0.22 kg of biochar. This aligns with conservative estimates as the dry weight yield from different sources of biomass is commonly stated to range from 20 % to 40 % [62]. As the value is conservative and a true test firing of the fuel in a pyrolysis boiler is needed to determine the actual dry mass yield, this value was used in the model.

The value of biochar will depend on different factors, such as source and usage. As mentioned in section 2.2.4.1, if the biochar is used as a way to carbon compensate on the voluntary carbon market, the value is stated to be around 200 to 400 EUR/ton. However, due to other positive impacts of the company such as creating jobs for locals and utilizing organic practices in parts of the plantation, it is probable that NML will be able to negotiate for a value in the higher end of the range. Further, a study of charcoal prices in Tanzania, which is a neighbouring country to Mozambique, found that the cost of buying charcoal, which is a similar product to biochar, was slightly more than 300 EUR/ton [63]. Due to this, a value of 300 EUR/ton was used for the biochar in the model.

3.2.3 Determining biofuel prices in Mozambique

When a study about biofuel usage in urban areas of Mozambique was conducted, it was found that the prices could vary regionally [64]. The two largest cities close to Lichinga which were studied were Nampula and Beira. In Nampula, the city closest to Lichinga out of the two, one bakery and one hospital were studied. The bakery and the hospital paid 0.006 EUR/kWh and 0.002 EUR/kWh for their biofuel respectively [64]. In Beira, a bakery was studied that paid 0.014 EUR/kWh for its biofuel [64]. In the model, a biofuel price of 0.0125 EUR/kWh was used as it is at the high end of the costs that were found. It is likely that the processing plant can utilize lower quality fuels than a bakery which makes it reasonable to have a slightly lower price.

3.2.4 Determining the price of electricity

The electricity tariffs in Mozambique vary for different consumers [49]. However, as mentioned in section 2.2.8 the electricity price for customers utilizing medium voltage roughly ranges from 0.04 EUR/kWh to 0.07 EUR/kWh. During an interview with a sawmill close to the plantation it was stated that they usually pay around 0.07 EUR/kWh for their electricity. Due to the close proximity between the companies and a comparable energy demand, it was assumed that NML would pay the same price and 0.07 EUR/kWh was used as the electricity price in the model.

During private communications with an employee at the Swedish embassy, it was stated that the electricity selling price could range between roughly 0.04 EUR/kWh to 0.08 EUR/kWh. This price also has to be negotiated together with EDM and is based on the cost of service. When selling electricity in the model, the selling price was assumed to be equal to the buying price (0.07 EUR/kWh). It was deemed unrealistic to have a higher selling than purchasing price and due to this, the purchasing price was chosen to present a best case scenario of selling at the purchasing price, instead of the mentioned high end price of 0.08 EUR/kWh. The high electricity selling price was chosen as it could provide an interesting extreme when compared with results where the model could not sell electricity as the real but uncertain value would be somewhere in between the two extremes.

3.3 Evaluation of the different energy systems

The cases were evaluated based on which technologies and how the technologies were used to meet the demand of the processing plant. The resulting energy systems were compared in terms of annual costs to find the system that would be most beneficial for NML to invest in, although the actual practicality of the systems was also considered as some systems were more significantly affected by the simplifications used in the model. While determining the energy system that should be recommended to NML, the effects of outages, changes in solar variation, and uncertainties in the input values such as the electricity price were taken into account. This was done to provide them with a system that would be satisfactory while under the local conditions of Mozambique and be built on conservative estimates.

4

The energy system model

This chapter presents the equations and constraints that govern the energy system model of the processing plant. The used sets, vectors, parameters, constants and variables are listed in the appendix.

4.1 Technology constraints

This section presents the constraints that limit and controls the behavior of the technologies.

4.1.1 Solar PV

The following constraint was used to model the electricity generation of the solar PV's.

$$e_{PV,t} \leq k_{PV} \cdot sun_t \cdot \varepsilon \quad \forall t \in T \quad (4.1)$$

sun_t is a vector that is gathered from *PVWatts® Calculator* [65]. The vector is based upon the closest available location to *Niassa, Mozambique* and uses a simulation based on measured solar radiation data to estimate the average part load of a solar PV plant each hour. Further, $e_{PV,t}$ is the generation of the solar PV's each hour and k_{PV} the installed solar capacity. As $e_{PV,t}$ can be smaller than $k_{PV} \cdot sun_t$, the model is allowed to curtail excess energy. ε is set to 1 but can be changed to investigate how increases or decreases in solar radiation impact the model.

4.1.2 Storage

The following constraints were used to model the state of charge of the battery energy storage system

$$SOC_t = SOC_{t-1} + bat_{charge,t} \cdot \eta_{bat} - bat_{disch,t} \quad \forall t \in T \setminus \{1\} \quad (4.2)$$

The constraint causes the battery storage level SOC_t to be equal to the storage level from the previous hour SOC_{t-1} plus the charged amount times the charging efficiency $bat_{charge,t} \cdot \eta_{bat}$ minus the discharged amount $bat_{disch,t}$. The constraint is valid for all hours except the first which is governed by the following constraint which determines that the first hour of the year is preceded by the last hour of the year, thus enabling the battery to have a realistic charge level during the first hour

of the year.

$$SOC_1 = SOC_{8760} + bat_{charge,1} \cdot \eta_{bat} - bat_{disch,1} \quad (4.3)$$

Furthermore, the following constraints limit the storage level SOC_t to the installed storage capacity k_{store} and the discharge $bat_{disch,t}$ and charge $bat_{charge,t}$ to the installed size of the battery's power component k_{power} .

$$SOC_t \leq k_{store} \quad \forall t \in T \quad (4.4)$$

$$bat_{disch,t} \leq k_{power} \quad \forall t \in T \quad (4.5)$$

$$bat_{charge,t} \leq k_{power} \quad \forall t \in T \quad (4.6)$$

4.1.3 The grid connection

The following two constraints were added to correctly model the grid connection.

$$grid_{bought,t} \leq k_{grid} \cdot O_t \quad (4.7)$$

$$grid_{sold,t} \leq k_{grid} \cdot O_t \quad (4.8)$$

$e_{bought,t}$ and $e_{sold,t}$ are variables that will contain the amount of bought respectively sold electricity each hour of the year, k_{grid} is the installed capacity of the grid and O_t contains the grid availability for each hour of the year. If O_t would contain only ones, the system would have a perfect connection, and if O_t would contain only zeros the system would be off-grid. When the model was tested for outages, a number of zeros corresponding to the number of total outage hours were randomly inserted into the vector, effectively simulating outages.

Niassa Macadamia is already in discussions with a company that is supposed to build a grid connection. Because of this, the installed capacity of the grid was fixed to the grid size discussed in the deal.

$$k_{grid} = K_{grid} \quad (4.9)$$

4.1.4 Generation, capacity and ramping constraints

The installed capacity k_i of all investments has to be equal to or lower than a maximum limit K_i . As such K_i can be changed to limit investments in certain technologies.

$$k_i \leq K_i \quad \forall i \in I \quad (4.10)$$

Further, the generated electricity $e_{s,t}$ or heat $h_{s,t}$ has to be equal to or lower than the installed capacity at all hours of the year

$$e_{s,t} \leq k_s \quad \forall t \in T, \quad \forall s \in S \quad (4.11)$$

$$h_{h,t} \leq k_h \quad \forall t \in T, \quad \forall h \in H \quad (4.12)$$

All plants have ramping constraints that determine how fast they can go from no load to full load and full load to no load. The ramp up constraint for the plants is presented below

$$e_{s,t} \leq e_{s,t-1} + \delta_s \cdot k_s \quad \forall t \in T, \quad \forall s \in S \quad (4.13)$$

$$h_{h,t} \leq h_{h,t-1} + \delta_h \cdot k_h \quad \forall t \in T, \quad \forall h \in H \quad (4.14)$$

Here, $e_{s,t-1}$ is the generated output of the previous hour and $\delta_s \cdot k_s$ is how much the generated output is allowed to increase within one hour. The ramp down constraint for the plants is presented below

$$e_{s,t} \geq e_{s,t-1} - \theta_s \cdot k_s \quad \forall t \in T, \quad \forall s \in S \quad (4.15)$$

$$h_{h,t} \geq h_{h,t-1} - \theta_h \cdot k_h \quad \forall t \in T, \quad \forall h \in H \quad (4.16)$$

Here, $e_{s,t-1}$ is the generated output of the previous hour and $\theta_s \cdot k_s$ is how much the generated output is allowed to decrease within one hour.

4.2 Supply and demand

The purpose of the energy system is to meet the demand of the processing. This section describes how the heat and electricity demands are met by the supplying technologies.

4.2.1 Energy balance - Electricity

The energy balance has to make sure that the amount of supplied electricity is larger than or equal to the demanded electricity at all hours of the year.

$$D_t^e \leq S_t^e \quad \forall t \in T \quad (4.17)$$

S_t^e is the electricity supply at all hours and D_t^e is the electricity demand at all hours. All electricity suppliers that S_t^e consists of are shown in the equation below

$$S_t^e = \sum_{s \in S} e_{s,t} + grid_{bought,t} + bat_{disch,t} \quad \forall t \in T \quad (4.18)$$

Here, $\sum_{s \in S} e_{s,t}$ contains the electricity generated by the solar panels and the diesel generator at each hour. $bat_{disch,t}$ contains the electricity discharged by the battery each hour. Finally, the variable $grid_{bought,t}$ contains the electricity bought from the grid.

The following equation describes the hourly electricity demand D_t^e

$$D_t^e = \sum_{h \in H} h_{h,t} \cdot \gamma_h + bat_{charge,t} + grid_{sold,t} + dp_{e,t} \quad \forall t \in T \quad (4.19)$$

Here $dp_{e,t}$ is the vector containing the electricity demand of the macadamia processing for each hour, $bat_{charge,t}$ is a variable containing the charging of the battery, $e_{sold,t}$ the electricity sold to the grid. $\sum_{h \in H} h_{h,t} \cdot \gamma_h$ depends on the generated heat

for each of the heating technologies and their corresponding electricity demand for generating the heat.

$$\gamma_{HP} = \frac{1}{COP} \quad (4.20)$$

$$\gamma_{EB} = \frac{1}{\eta_{EB}} \quad (4.21)$$

$$\gamma_b = d_{bio} \quad b \in B \quad (4.22)$$

COP is the coefficient of performance for the heat pump, η_{EB} is the efficiency of the electric boiler and d_{bio} is a conversion factor to convert the produced heat into an electricity demand for the pyrolysis and biomass boiler.

4.2.2 Energy balance - Heat

The energy balance has to make sure that the amount of supplied heat is larger than or equal to the demanded heat at all hours of the year.

$$D_t^h \leq S_t^h \quad \forall t \in T \quad (4.23)$$

S_t^h is the heat supply at all hours and D_t^h is the heat demand at all hours.

$$S_t^h = \sum_{h \in H} h_{h,t} \quad \forall t \in T \quad (4.24)$$

$$D_t^h = dp_t^h \quad \forall t \in T \quad (4.25)$$

S_t^h is the heat supplied by all heat generating plants and D_t^h is equal to the process heating demand.

4.3 Economic considerations

The purpose of the model is to build the energy system with the lowest total annual cost. The constraints and equations in this section make sure that all costs and revenues of the system are taken into account.

4.3.1 Investing

The model is free to invest in the technologies listed in section 2.2. The capital expenditures associated with investing in the technologies are calculated as in equation 4.26

$$C_I = \sum_{i \in I} ic_i \cdot k_i \cdot a_i \quad (4.26)$$

where ic_i is the investment cost per installed capacity of each investment, k_i is the installed capacity and a_i is the annuity factor. The annuity factor is calculated below

$$a_i = \frac{r}{1 - (1 + r)^{-l_i}} \quad \forall i \in I \quad (4.27)$$

the interest rate is denoted as r and the lifetime of the specific investment as l_i

4.3.2 Expenditures and revenues

The expenditures and revenues covered in this subsection are associated with maintaining and running the plants that is a part of the energy system.

4.3.2.1 O&M costs

The biomass boiler and the pyrolysis utilize biomass as their energy source. The energy in the macadamia nutshells E_{MNS} can be used as a source of biomass but if they run out, the model will have to buy extra fuel. Equation 4.28 below is a constraint that determines how much biofuel has to be bought.

$$\sum_{p \in BIO} \sum_{t \in T} \frac{H_{p,t}}{\eta_p} \leq E_{biofuel} + E_{MNS} \quad (4.28)$$

Here $\sum_{p \in BIO} \sum_{t \in T} \frac{H_{p,t}}{\eta_p}$ determines how much biofuel is consumed (in kWh), E_{MNS} is the energy available in the macadamia nutshells and $E_{biofuel}$ is a variable that will determine the amount of biofuel that has to be bought.

The total fuel cost of the system has to take both biofuel and fossil fuels into account and is calculated below

$$C_{fuel} = c_{biomass} \cdot E_{biofuel} + c_{diesel} \cdot \sum_{t \in T} \frac{e_{diesel,t}}{\eta_{diesel}} \quad (4.29)$$

The cost of biomass $c_{biomass}$ and diesel c_{diesel} is provided in EUR/kWh. $\sum_{t \in T} \frac{e_{diesel,t}}{\eta_{diesel}}$ is the energy consumption of the diesel generator for one year. The following equation was used to account for the fixed operation and maintenance costs of all plants C_{FOM} .

$$C_{FOM} = \sum_{p \in P} k_p \cdot fc_p \quad (4.30)$$

k_p is the installed capacity of the plant and fc_p the fixed cost per installed capacity. The variable operation and maintenance cost is dependent on the energy generation of the plants.

C_{VOM} is the combined variable operation and maintenance cost of all plants.

$$C_{VOM} = \sum_{t \in T} \left(\sum_{s \in S} (e_{s,t} \cdot vc_s) + \sum_{h \in H} (h_{h,t} \cdot vc_h) \right) \quad (4.31)$$

vc is the variable cost of the electricity supplier or heat generator, and $e_{s,t}$ and $h_{h,t}$ are the generated electricity or heat respectively. The cost C_{VOM} is a summation over the whole year.

The total annual operation and maintenance cost $C_{O\&M}$ includes the cost of the electricity bought from the grid $\sum_{t \in T} (c_{el} \cdot grid_{bought,t})$.

$$C_{O\&M} = C_{fuel} + C_{FOM} + C_{VOM} + \sum_{t \in T} (c_{el} \cdot grid_{bought,t}) \quad (4.32)$$

4.3.2.2 Revenues

The energy system can earn revenue either by selling electricity or biochar. The amount of biochar produced each hour is assumed to be proportional to the heat generated from the pyrolysis process as shown below

$$m_{biochar,t} = \alpha \cdot \frac{h_{pyro,t} \cdot HHV_{MNS}}{\eta_{pyro}} \quad (4.33)$$

Where $\frac{h_{pyro,t} \cdot HHV_{MNS}}{\eta_{pyro}}$ is the amount of fuel used by the pyrolysis plant each hour in kg and α the conversion factor from biofuel to biochar. This is used to calculate the revenue of the system, which also includes the sold electricity $c_{el} \cdot grid_{sell,t}$

$$C_{REV} = \sum_{t \in T} (c_{el} \cdot grid_{sell,t} + c_{biochar} \cdot m_{biochar,t}) \quad (4.34)$$

where c_{el} is the selling price of electricity and $c_{biochar}$ the selling price of biochar. The equation is summarized over the whole year to get C_{REV} .

4.3.3 The objective function

Finally, to create the energy system with the lowest total annual cost, the following function was minimized

$$C_{OBJ} = C_I + C_{O\&M} - C_{REV} \quad (4.35)$$

5

Results and analysis

The results from the model are presented and analyzed in this chapter. Firstly, all the cases with their respective technologies, economic data and weekly operation are shown. A summary of all cases can be seen in the appendix A.5. Lastly, the effects of outages and solar variation are shown for selected cases.

5.1 Cases without grid connection (Off-grid)

The following results correspond to the cases A-1 to A-5 which are all off-grid. Table 5.1 gives an overview of the cases and shows what technologies they had available to supply the demands of the processing plant.

Table 5.1: Overview of the off-grid cases that have been analyzed and what technologies were allowed to be used in the respective cases. BT is the base technologies that were defined as solar PV, heat pump, electric boiler and batteries.

Case	Technologies
A-1	BT
A-2	BT + Diesel generator
A-3	BT + Pyrolys
A-4	BT + Pyrolys + biomass boiler
A-5	BT + biomass boiler

5.1.1 Case A-1

Table 5.2 shows the most suitable technology size for case A-1. The system relies on solar PV to supply electricity and a heat pump together with a small electric boiler to supply heat. The total installed capacity of the solar PVs is over 2 MW, which is higher than the peak demand from NML's factory of 480 kW, and generates roughly 3600 MWh of electricity annually. The total installed heat generation capacity is 290 kW where the heat pump is big enough to supply the heat demand of 280 kW by itself although the electric boiler is used to save costs. Additionally, a battery with a charge capacity of 344kW and a storage size of 1486 kWh is used, giving it a C-rate of roughly 0.34.

Table 5.2: The installed capacity and annual generation of the technologies used in the off-grid case A-1.

Case A-1 (Off-grid)		Electricity		Heat	
		PV	Battery	HP	EB
Inst. cap.	[kW]	2140	344 (1486) ¹	280	10
Ann. gen.	[MWh]	3601	405	1776	65

¹Installed size of the battery (kWh)

Figure 5.1 below, show how the technologies for this case operate during the first week of production. During the day, the solar PVs generate enough electricity to supply the current demand of the process but also to charge the battery which is discharged during the night to ensure the demand can be supplied. During most days, the generation from the solar PVs are higher than the demand of the process and the charge capacity of the battery, and thus any excess electricity generated during these hours is curtailed. Curtailment is especially common during the week-ends when the demand from the process is lower. The heat demand of 280 kW is constant during the entire week and 270 kW is supplied by the heat pump and 10 kW by the electric boiler.

Table 5.3 contains the economic properties of case A-1 and shows that a large installed capacity of solar PVs and battery gives a high total investment cost of 2038 kEUR. The total annual cost is 157 kEUR, where the major part of the total annual cost is related to the annual investment cost of 137 kEUR. The operation and maintenance costs are comparatively small at 20.1 kEUR.

Table 5.3: The economic properties for the off-grid case A-1.

Economic property [kEUR]	
Total investment cost	2038
Annual investment cost	137
Annual O&M cost	20.12
Annual revenue	0
Total annual cost	157.0

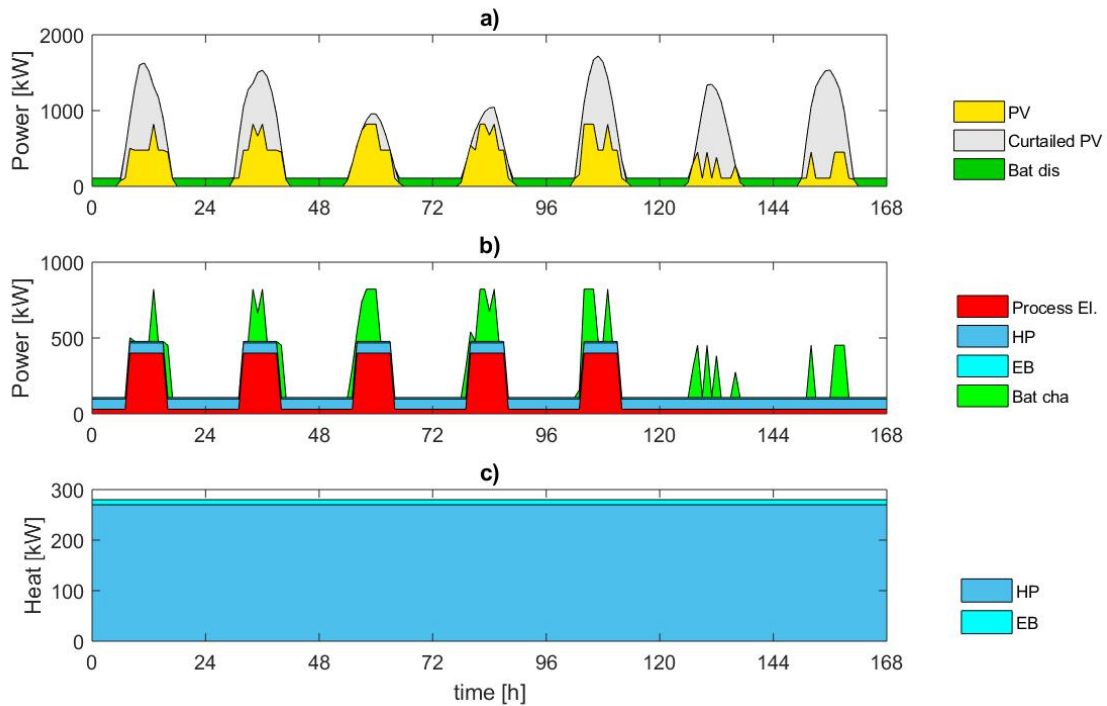


Figure 5.1: The energy system of case A-1 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case A-1 supplies its demand with solar PV during the day and by using its battery during the night. There is a lot of curtailment during most days but especially during the weekend. Subplot b) shows the energy demand of case A-1. It can be seen that most of the energy is needed for the processing, however, there is a large demand from the battery during the days when it charges to store energy from the solar PVs. There is also a constant electricity demand from the heat pump and the electric boiler. Subplot c) shows the heat supply of the process, it consists of a heat pump in combination with a comparatively small electric boiler.

5.1.2 Case A-2

Case A-2 is allowed to invest in the base technologies and a diesel generator, giving case A-2 two options to generate electricity, solar PV and a diesel generator. The solar PVs have an installed capacity of 1527 kW and the diesel generator of 48 kW, making the total installed capacity 1575 kW, as seen in Table 5.4. All the heat is supplied by a heat pump with a capacity of 280 kW. The battery used in this case has a storage size of 1383 kWh and a charge capacity of 222 kW, which gives it a C-rate of roughly 0.16.

Table 5.4: The installed capacity and annual generation of the technologies used in the off-grid case A-2.

Case A-1 (Off-grid)		Electricity			Heat HP
		PV	DG	Battery	
Inst. cap.	[kW]	1527	48	222 (1383) ¹	280
Ann. gen.	[MWh]	2570	20	370	1841

¹Installed size of the battery (kWh)

As for case A-1, the solar PVs generates enough electricity to fulfill demand during the day and to charge the battery, as shown in Figure 5.2. Most days, the generation from solar PV is more than both the demand from the process and the charge capacity of the battery, causing curtailment. There are however days with less generation from the solar PV, as can be seen between hours 48 and 72 in Figure 5.2, where there is no curtailment. Additionally, on the nights before and after days with less generation, the diesel generator operates to ensure supply can be met. Otherwise, it is normally the battery that is discharged to supply demand during the night. The constant heat demand of 280 kW is supplied by the heat pump at all times.

Table 5.5 contains the economic properties of case A-2 and shows a high total upfront investment cost of 1653 kEUR. The total annual cost is 136 kEUR, where the major part of the total annual cost is related to the annual investment cost of 112 kEUR. The operation and maintenance costs are comparatively small at 23.8 kEUR.

Table 5.5: The economic properties for the off-grid case A-2.

Economic property [kEUR]	
Total investment cost	1653
Annual investment cost	112
Annual O&M cost	23.8
Annual revenue	0
Total annual cost	136

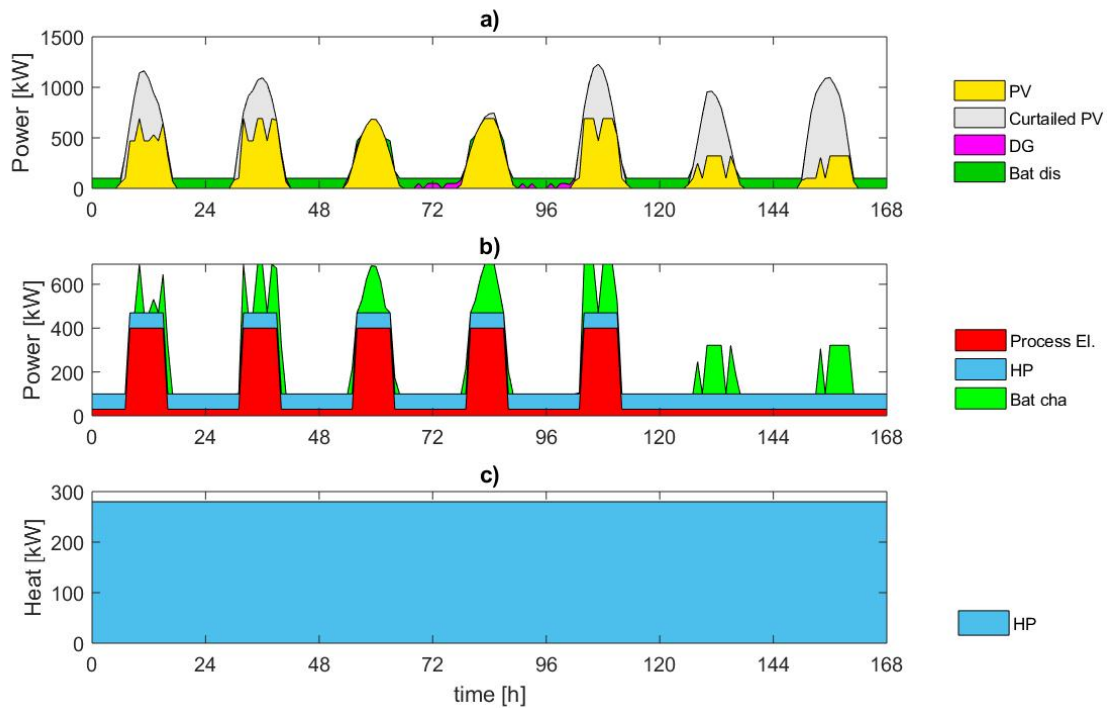


Figure 5.2: The energy system of case A-2 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case A-2 supplies its demand with solar PV during the day and by using its battery in combination with the diesel generator during the night. There is a lot of curtailment during most days but especially during the weekend. Subplot b) shows the energy demand of case A-2. It can be seen that most of the energy is needed for the processing, however, there is a large demand from the battery during the days when it charges to store energy from the solar PVs. There is also a constant electricity demand from the heat pump. Subplot c) shows the heat supply of the process, it consists of heat pump running at a constant load.

5.1.3 Case A-3

If the model can invest in a pyrolysis and the base technologies, the energy system in Table 5.6 will have the lowest total annual cost. The system found for case A-3 consisted of solar PVs with an installed capacity of roughly 1500 kW, as the only source of electricity, and a pyrolysis of 280 kW as the only utilized heat source. Additionally, it uses a battery with a storage size of 660 kWh and a charge capacity of 178 kW, giving it a C-rate of 0.27.

Table 5.6: The installed capacity and annual generation of the technologies used in the off-grid case A-3.

Case A-3 (Off-grid)	Electricity		Heat
	PV	Battery	HP
Inst. cap. [kW]	1496	178 (660) ¹	280
Ann. gen. [MWh]	2218	142	2453

¹Installed size of the battery (kWh)

As the only electricity generating technology, the solar PV supplied the electricity demand of the process, pyrolysis and charged the battery all days of the week. Any surplus electricity thereafter was curtailed, as can be seen in Figure 5.3. The low electricity demand during the night is supplied by the battery. It is clearly visible from Figure 5.3 that there is a lot of excess generation and curtailment, especially during weekends but also for most days during peak generation hours.

All of the heat demand is supplied by the 280 kW pyrolysis which operates at constant load, as can be seen in the bottom of Figure 5.3. The pyrolysis operates even during off-season, when there is no processing demand in place, but excess electricity is available. This is due to the value of biochar being high enough to warrant the added running costs and fuel consumption.

The total investment cost for the energy system in case A-3 is 1494 kEUR which gives an annual investment cost of roughly 104 kEUR, as can be seen in Table 5.7. The operation and maintenance costs is 60.8 kEUR but the energy system also provides a revenue of 80.7 kEUR due to selling the biochar generated by the pyrolysis. The total annual cost is 84 kEUR.

Table 5.7: The economic properties for the off-grid case A-3.

Economic property [kEUR]	
Total investment cost	1494
Annual investment cost	103.8
Annual O&M cost	60.8
Annual revenue	80.7
Total annual cost	83.9

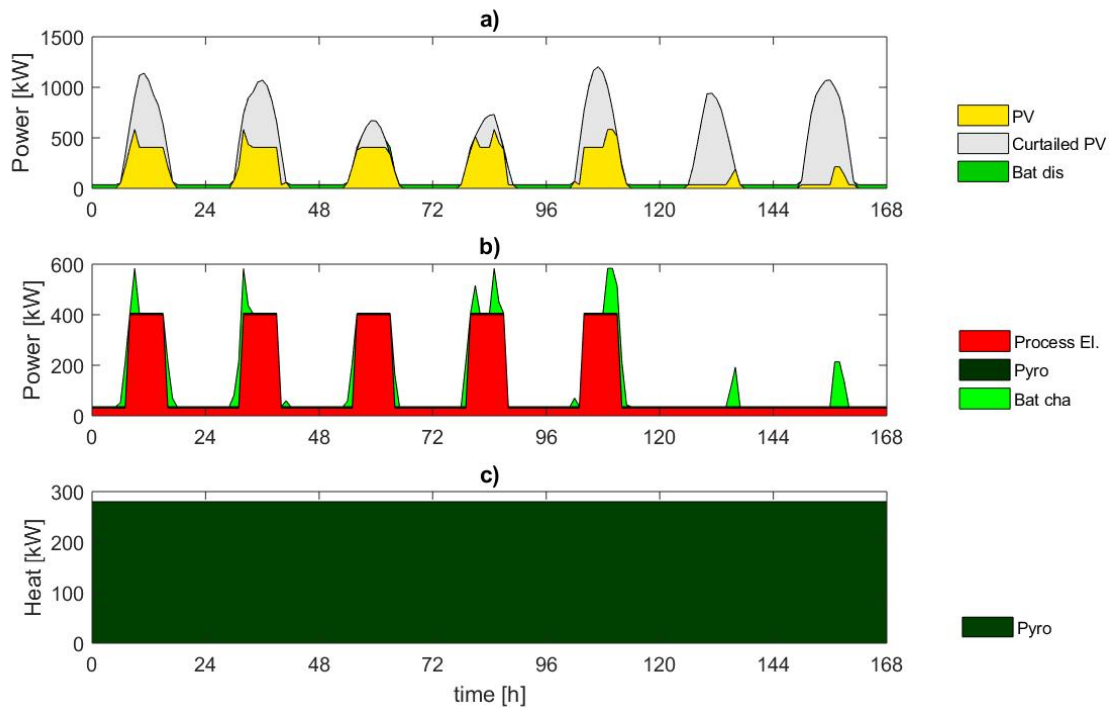


Figure 5.3: The energy system of case A-3 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case A-3 supplies its demand with solar PV during the day and by using its battery during the night. There is a lot of curtailment during most days but especially during the weekend. Subplot b) shows the energy demand of case A-3. It can be seen that most of the energy is needed for the processing, however, there is a demand from the battery during the days when it charges to store energy from the solar PVs. There is also a constant electricity demand from the pyrolysis although it is comparatively small and almost not visible. Subplot c) shows the heat supply of the process, it consists of a pyrolysis running at a constant load.

5.1.4 Case A-4

If the model can invest in the pyrolysis, biomass boiler, and the base technologies, the energy system presented in Table 5.8 will have the lowest total annual cost. All generated electricity comes from solar PVs with an installed capacity of 1496 kW. A battery with a storage size of 660 kWh and a charge capacity of 178 kW is used, which gives it a C-rate of 0.27. As for heat generation, three units were installed; an electric boiler of 169 kW, a biomass boiler of the same size (169 kW) and a pyrolysis of 111 kW. The total installed heat generation capacity was 449 kW, roughly 60% more than the peak heat demand of 280 kW.

Table 5.8: The installed capacity and annual generation of the technologies used in the off-grid case A-4.

Case A-4 (Off-grid)		Electricity		Heat		
		PV	Battery	EB	HOB	Pyro
Inst. cap.	[kW]	1496	178 (660) ¹	169	169	111
Ann. gen.	[MWh]	2518	187	486	627	970

¹Installed size of the battery (kWh)

The pyrolysis is run at maximum load constantly during the year, even when the processing plant has no heat demand. To meet the heat demand during processing, the model has to use at least one of the other heat generating technologies. Figure 5.4 shows what technologies are used to meet the electricity and heating demand during the first week of production.

It is clear from Figure 5.4 that when the generated electricity is high, the model prefers to use the electric boiler over the biomass boiler. It can also be seen that the model charges the battery during the day to supply the electricity demand of the processing during the night. The battery can be used to power the electric boiler during the night, which is especially clear on the first day and on the last two days. It is possible that the model is more likely to use the battery as an energy source when it knows that the curtailment will be high. The amount of curtailed energy is especially high during the weekend when the need for electricity is low.

The operation of the biomass boiler is irregular during the mornings and evenings, while the pyrolysis is run at maximum capacity during the whole week. There is an electricity demand from the pyrolysis and biomass boiler although it is too small to be visible in the figure.

The energy system will earn revenue as the biochar produced by the pyrolysis can be sold for profit and roughly 32 kEUR is generated annually. Other than that, the upfront investment cost is 1361 kEUR, which corresponds to an annual investment cost of 92.1 kEUR. The operation and maintenance is 21.8 kEUR and the total annual cost is 81.9 kEUR. Economic properties are shown in Table 5.9.

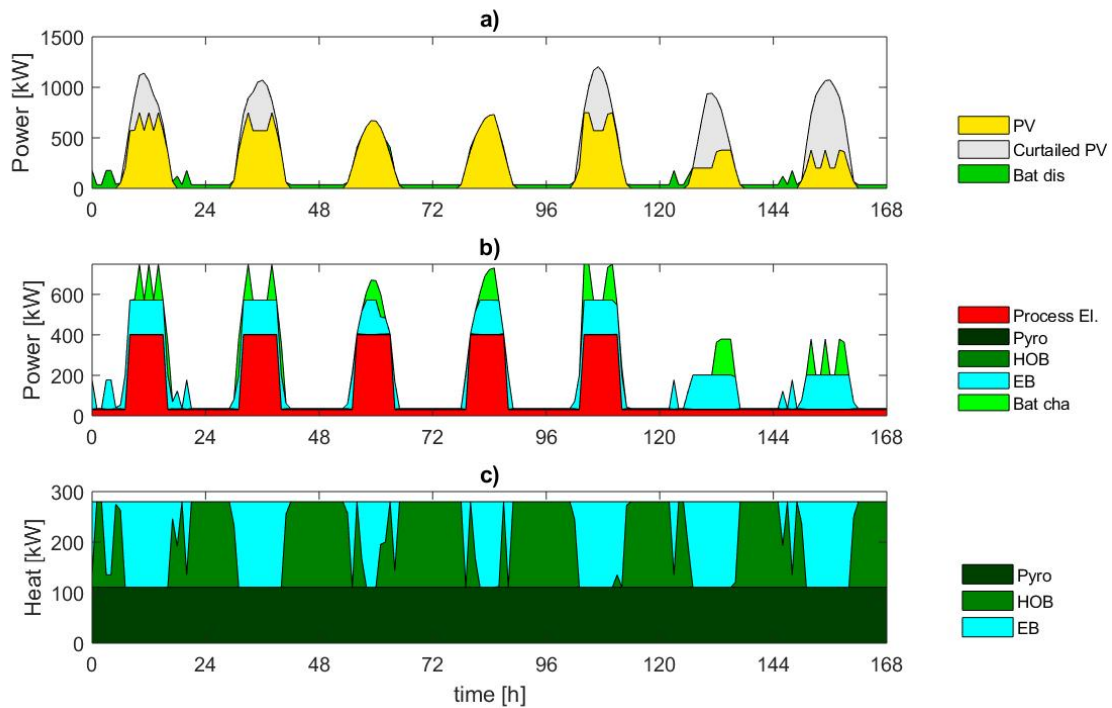


Figure 5.4: The energy system of case A-4 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case A-4 supplies its demand with solar PV during the day and by using its battery during the night. There is a lot of curtailment during most days but especially during the weekend. Subplot b) shows the energy demand of case A-4. It can be seen that most of the energy is needed for the processing, however, there is a demand from the battery during the days when it charges to store energy from the solar PVs and from the electric boiler as it is used to supply heat during the day. There is also a constant electricity demand from the pyrolysis and biomass boiler although they are comparatively small and almost not visible. Subplot c) shows the heat supply of the process, it is supplied in a combination of the pyrolysis, electric boiler and biomass boiler. The pyrolysis is constantly operated but the usage of the electric boiler and biomass boiler changes depending on the availability of excess electricity.

Table 5.9: The economic properties for the off-grid case A-4.

Economic property [kEUR]	
Total investment cost	1361
Annual investment cost	92.1
Annual O&M cost	21.8
Annual revenue	31.9
Total annual cost	81.9

5.1.5 Case A-5

If the model can invest in the biomass boiler and the base technologies, the energy system in Table 5.10 will have the lowest total annual cost. For electricity generation, solar PVs of 1496 kW were installed with a complementing battery with a storage size of 660 kWh and a charge capacity of 178 kW, giving it a C-rate of 0.27. As for heat generation, only a biomass boiler of 280 kW was utilized.

Table 5.10: The installed capacity and annual generation of the technologies used in the off-grid case A-5.

Case A-5 (Off-grid)		Electricity		Heat
		PV	Battery	HOB
Inst. cap.	[kW]	1496	178 (660) ¹	280
Ann. gen.	[MWh]	2518	187	1841

¹Installed size of the battery (kWh)

Figure 5.5 below show how the demand varies over the first week of production and what technologies are used to supply the demand. It can be seen that, during the day, all electricity is supplied by the solar PV and it is enough to supply the demand of the process, the electricity demand from the biomass boiler and to charge the battery. There is more than enough electricity generated and thus curtailment occurs most days, especially during weekends. During the night, the battery is discharged to supply the demand. The constant heat demand is supplied by the biomass boiler that operates at rated power throughout the entire season.

The total investment cost of case A-5 was calculated to 1026 kEUR which corresponds to an annual investment cost of 81 kEUR. Operation and maintenance costs were calculated to be 21.6 kEUR and no revenue was generated. The total annual cost was calculated to 102.6 kEUR and all data can be seen in Table 5.11.

Table 5.11: The economic properties for the off-grid case A-5.

Economic property [kEUR]	
Total investment cost	1026
Annual investment cost	81.0
Annual O&M cost	21.6
Annual revenue	0
Total annual cost	102.6

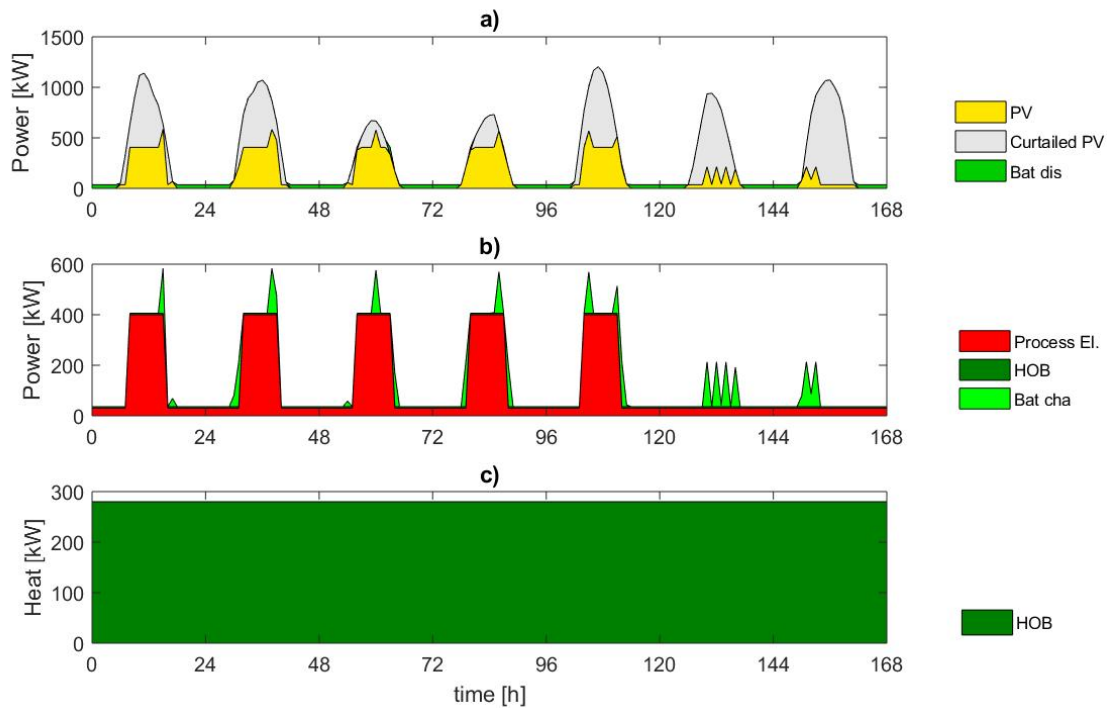


Figure 5.5: The energy system of case A-5 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case A-5 supplies its demand with solar PV during the day and by using its battery during the night. There is a lot of curtailment during most days but especially during the weekend. Subplot b) shows the energy demand of case A-5. It can be seen that most of the energy is needed for the processing, however, there is a demand from the battery during the days when it charges to store energy from the solar PVs. There is also a constant electricity demand from the biomass boiler although is comparatively small and almost not visible. Subplot c) shows the heat supply of the process, it consists of a biomass boiler running at a constant load.

5.2 Grid connected cases with the ability to purchase and sell electricity

The following results correspond to the cases B-1 to B-4 which are all on-grid and can both sell and purchase electricity for the price of 0.07 EUR/kWh. Table 5.12 gives an overview of the cases and shows what technologies they had available to fill the demand of the processing plant. Case B-2 did not utilize the diesel generator and because of this, its results are the same as case B-1. The same thing can be said about cases B-3 and B-4 as case B-4 did not utilize the biomass boiler.

Table 5.12: Overview of the grid connected cases which can both purchase and sell electricity that have been analyzed and what technologies were allowed to be used in the respective cases. BT is the base technologies that were defined as solar PV, heat pump, electric boiler and batteries.

Case	Technologies
B-1	BT
B-2	BT + Diesel generator
B-3	BT + Pyrolysis
B-4	BT + Pyrolysis + biomass boiler

5.2.1 Case B-1 and B-2

Case B-1 is allowed to invest in the base technologies but is now grid connected with a transmission capacity of 480 kW where electricity can be both bought or sold at a fixed price of 0.07 EUR/kWh. All electricity is generated by solar PVs with an installed capacity of 1617 kW while all heat is supplied from a heat pump with an installed capacity of 280 kW. There is no energy storage but instead electricity can be purchased from the grid to supply the demand. Additionally, it can be seen that throughout the year, almost half of the total generated electricity is sold to the grid while less than 30% of the same amount is bought from the grid. Thus the system becomes a net-producer rather than a consumer on the grid. The data is summarized in Table 5.13 below.

Table 5.13: The installed capacity and annual generation of the technologies used in the grid connected case B-1.

Case B-1 (On-grid)		Electricity		Heat HP
		PV	Grid	
Inst. cap.	[kW]	1617	480	280
Ann. gen.	[MWh]	2721	367 (1345) ¹	1841

¹ Electricity sold to the grid (kWh)

During the day, all electricity is generated by the solar PVs which generate enough to supply the process and the heat pump, while also generating a great amount that

can be sold. As can be seen in Figure 5.6, there are many hours where electricity is sold to the grid but there are also hours where excess generation is more than the grid can handle and curtailment is required. There is no energy storage in the system but the grid can be used to supply electricity during the night and for hours when generation from the solar PVs is not enough. The constant heat demand is supplied by the heat pump which operates at rated capacity throughout the entire season.

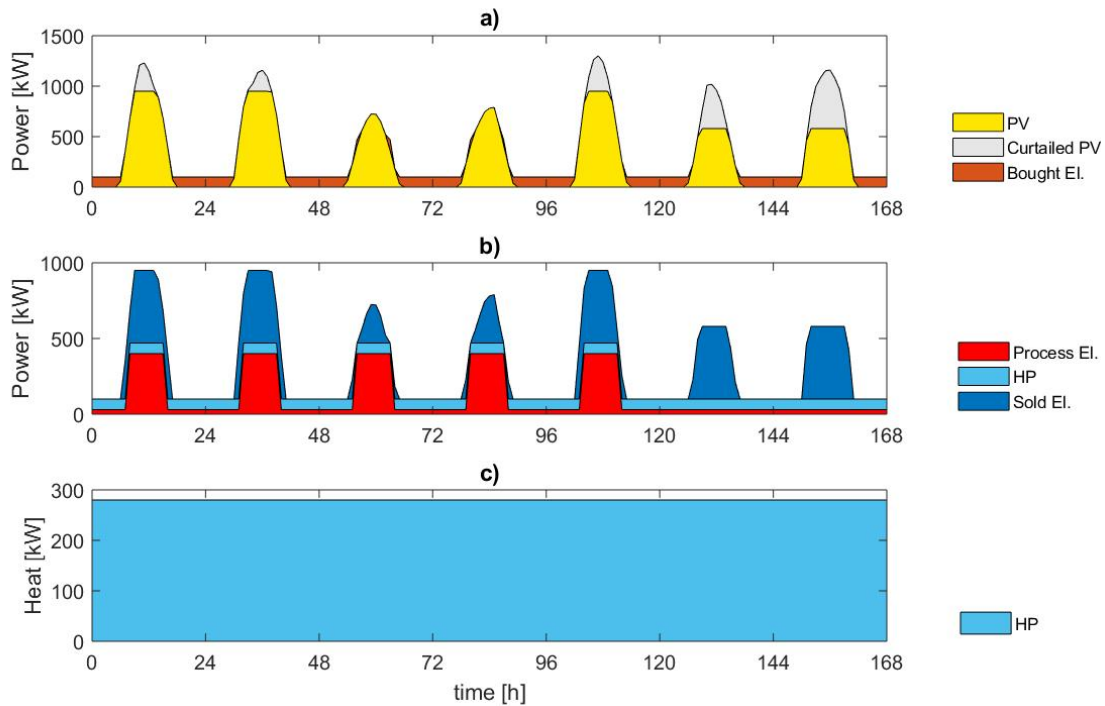


Figure 5.6: The energy system of case B-1 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case B-1 supplies its demand with solar PV during the day and by purchasing electricity during the night. As the system has no batteries it is reliant on the grid to fulfill the electricity demand. There are relatively small amounts of curtailment as the system is allowed to sell excess electricity. During the third and fourth days, all electricity is being utilized. Subplot b) shows the energy demand of case B-1. It can be seen that a large part of the electricity is needed for the processing and the constant electricity demand from the heat pump. A similarly large amount of electricity is being sold each day which adds an additional revenue for the energy system. Subplot c) shows the heat supply of the process, it consists of a heat pump running at a constant load.

The total investment cost for case B-1 is 1525 kEUR which gives an annual investment cost of 96.5 kEUR. By having the ability to purchase electricity, the operation and maintenance cost increased and was calculated to 48.7 kEUR while the revenue for selling electricity was calculated to 92.8 kEUR. The total annual cost is

46.1 kEUR, as can be seen in Table 5.14.

Table 5.14: The economic properties for the grid-connected case B-1.

Economic property [kEUR]	
Total investment cost	1525
Annual investment cost	96.5
Annual O&M cost	48.7
Annual revenue	92.8
Total annual cost	46.1

5.2.2 Case B-3 and B-4

Case B-3 is a grid connected version of case A-3. It can purchase and sell electricity to the grid at a fixed rate of 0.07 EUR/kWh. The energy system with the lowest total annual cost is presented in Table 5.15. All generated electricity comes from solar PVs with an installed capacity of 1503 kW where heat is generated by the pyrolysis with an installed capacity of 280 kW. The system is connected to a grid with a transmission capacity of 480 kW, and over the year, more than half of the generated electricity is sold (1382 MWh out of 2530 MWh), while less than 10% of that amount (129 MWh) is purchased. Thus the system becomes a net producer rather than a consumer on the grid.

Table 5.15: The installed capacity and annual generation of the technologies used in the grid connected case B-3.

Case B-3 (On-grid)		Electricity		Heat
		PV	Grid	Pyro
Inst. cap.	[kW]	1503	480	280
Ann. gen.	[MWh]	2530	129 (1382) ¹	1992

¹ Electricity sold to the grid (kWh)

The model utilizes the pyrolysis as the only source of heat supply and it is run at maximum load when the processing plant has a heat demand. As the energy system has no other way to supply electricity than with solar PVs, it has to buy electricity from the grid during the night although during the day, enough is generated by the solar PVs to supply demand and to sell a significant amount to the grid. Even though it is possible to sell electricity, there are days when the electricity generation is large enough that the transmission capacity of the grid is met and excess generation has to be curtailed. Curtailment is especially common during weekends but also during the middle of some days. Figure 5.7 shows what technologies are used to meet the electricity and heating demand.

It can be seen that the energy system is able to sell significant amounts of electricity to the grid during the daytime although it has to purchase during the night and on days with low solar radiation, such as the third day. The system is selling electricity to the grid at maximum capacity several days of the week and the overall curtailment is relatively low, even though the weekends experience quite a heavy curtailment.

As can be seen in Figure 5.8, the energy system will sell electricity during off-season, when no processing is happening. This significantly reduces the amount of total curtailed energy over the whole year and will earn additional revenue. Further, it's visible that the pyrolysis will be operated during the days even if there is no heat demand while the cable capacity is maxed out. This is done as the system prefers to use electricity to produce biochar over curtailment.

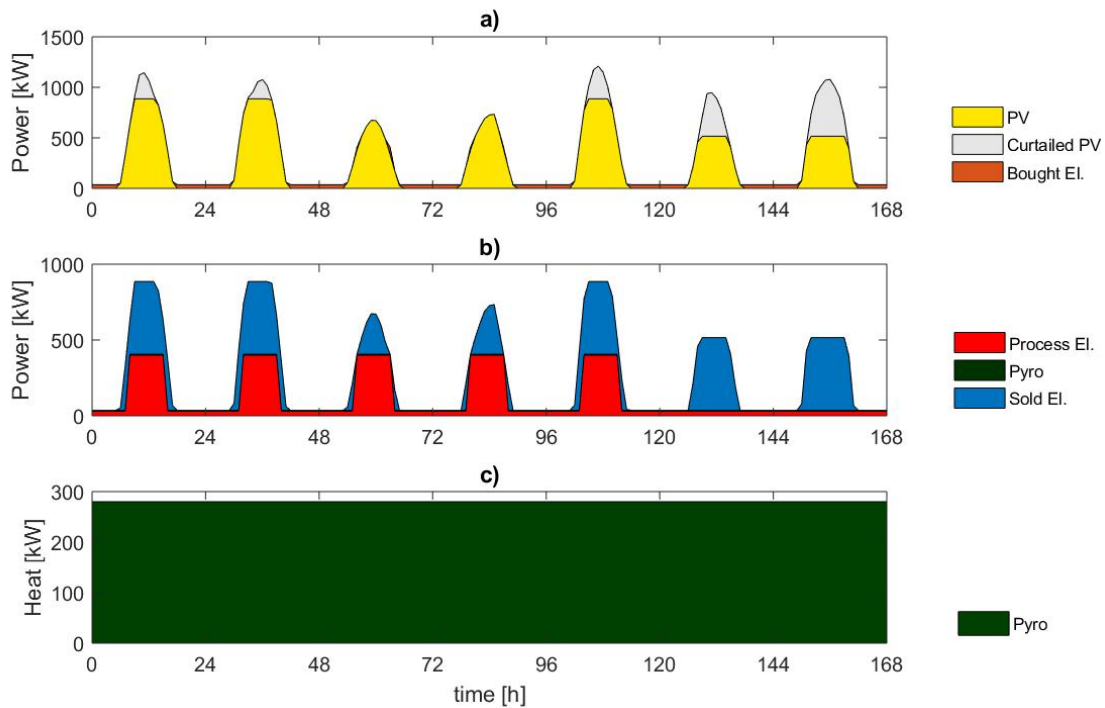


Figure 5.7: The energy system of case B-3 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case B-3 supplies its demand with solar PV during the day and by purchasing electricity during the night. As the system has no batteries it is reliant on the grid to fulfill the electricity demand. There are relatively small amounts of curtailment as the system is allowed to sell excess electricity. During the third and fourth days, all electricity is being utilized. Subplot b) shows the energy demand of case B-3. It can be seen that a large part of the electricity is needed for the processing although a small amount is needed to supply the pyrolysis. A large amount of electricity is being sold each day which adds an additional revenue for the energy system. Subplot c) shows the heat supply of the process, it consists of a pyrolysis running at a constant load.

The total investment cost of case B-3 is 1516 kEUR, which corresponds to an annual investment cost of 101 kEUR. Operation and maintenance costs were calculated to 55 kEUR while revenue from selling electricity and biochar reached amounts of 161 kEUR, which is more than the annual investment cost and operation and maintenance cost together. Thus the total annual cost of this system is negative 5.3 kEUR, which means the system would generate a net income each year while supplying the process demand for free. For the energy system to generate a net income each year means that the energy system will payoff itself, without including the value it adds to the processing of macadamia nuts.

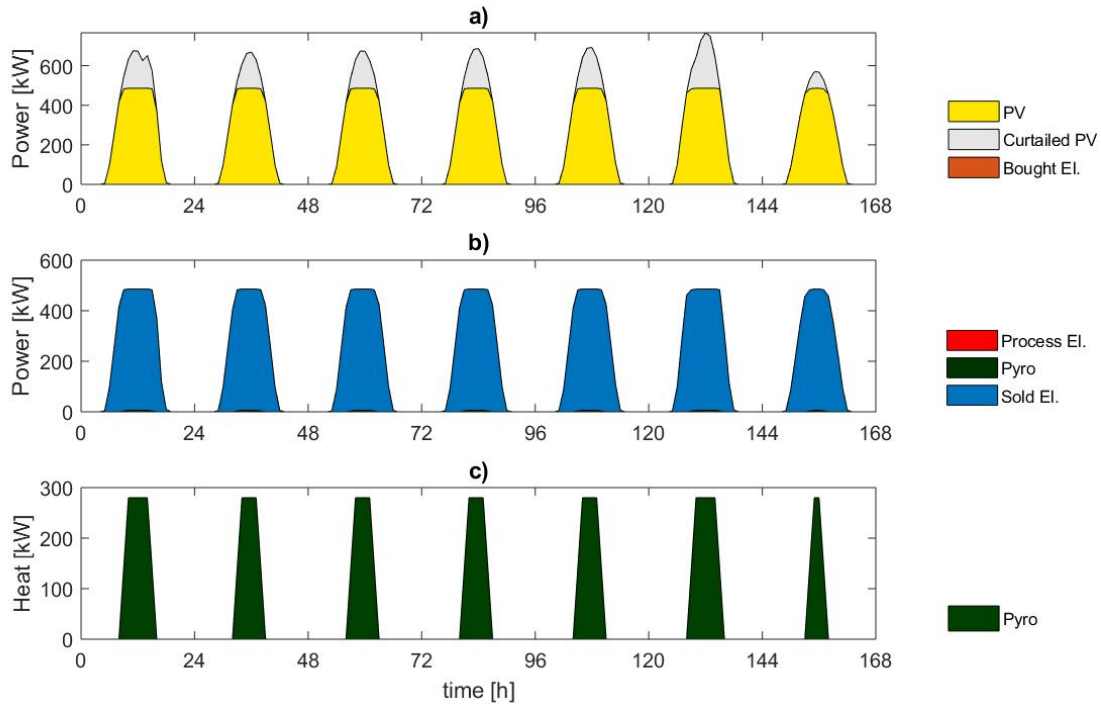


Figure 5.8: The energy system of case B-3 during a week with no operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case B-3 supplies its demand that almost completely consists of selling electricity using solar PV. As there is no process demand during this week, no electricity is purchased. There are relatively small amounts of curtailment as the system sells most of the excess electricity. Subplot b) shows the energy demand of case B-3. It can be seen that most of the demand can be attributed to selling electricity, which adds additional revenue to the system, although a small amount is needed to supply the pyrolysis during the day. Subplot c) shows the heat supply of the process. As no processing is carried out this week, there is no heat demand although the pyrolysis still runs if the cable capacity is maxed out. This is done as the system prefers to use electricity to produce biochar over curtailing.

Table 5.16: The economic properties for the grid-connected case B-3. The negative total annual cost implies that the energy system will earn money for NML.

Economic property [kEUR]	
Total investment cost	1516
Annual investment cost	100.7
Annual O&M cost	55.0
Annual revenue	160.9
Total annual cost	-5.3

5.3 Grid connected cases with the ability to purchase but not sell electricity

The following results correspond to the cases C-1 to C-4 which are all on-grid but can only purchase electricity. Table 5.17 gives an overview of the cases and shows what technologies they had available to fill the demand of the processing plant. Case C-2 did not utilize the diesel generator and because of this, its results are the same as case C-1. The same thing can be said about case C-3 and C-4 as case C-4 did not utilize the biomass boiler.

Table 5.17: Overview of the grid connected cases which can only purchase electricity that have been analyzed and what technologies were allowed to be used in the respective cases. BT is the base technologies that were defined as solar PV, heat pump, electric boiler and batteries.

Case	Technologies
C-1	BT
C-2	BT + Diesel generator
C-3	BT + Pyrolysis
C-4	BT + Pyrolysis + biomass boiler

5.3.1 Case C-1 and C-2

Case C-1 is a grid connected version of case A-1 with the ability to purchase but not sell electricity. To generate electricity, the solution relies on solar PVs with an installed capacity of 680 kW and for the heat supply, a heat pump is used with an installed capacity of 280 kW, as seen in Table 5.18. The grid has a transmission capacity of 480 kW where electricity can be purchased at a fixed cost of 0.07 EUR/kWh. Over the duration of the year, the grid supplies an amount equal to roughly a third of the annual electricity generated by the solar PVs.

Table 5.18: The installed capacity and annual generation of the technologies used in the grid connected case C-1.

Case C-1 (On-grid, buy only)		Electricity		Heat
		PV	Grid	HP
Inst. cap.	[kW]	680	480	280
Ann. gen.	[MWh]	1144	367 (-) ¹	1841

¹ Electricity sold to the grid (kWh)

In Figure 5.9 it can be seen how the generation from the solar PV is very rarely enough to supply the demand for the process and heat pump. For most days, it is necessary to purchase electricity from the grid to ensure supply is met. For days three and four in Figure 5.9, the generation from the solar PV contributes with just over half of the demand during peak generation and most of the demand is supplied by the grid instead. However, curtailment still occurs during some days, especially during weekends.

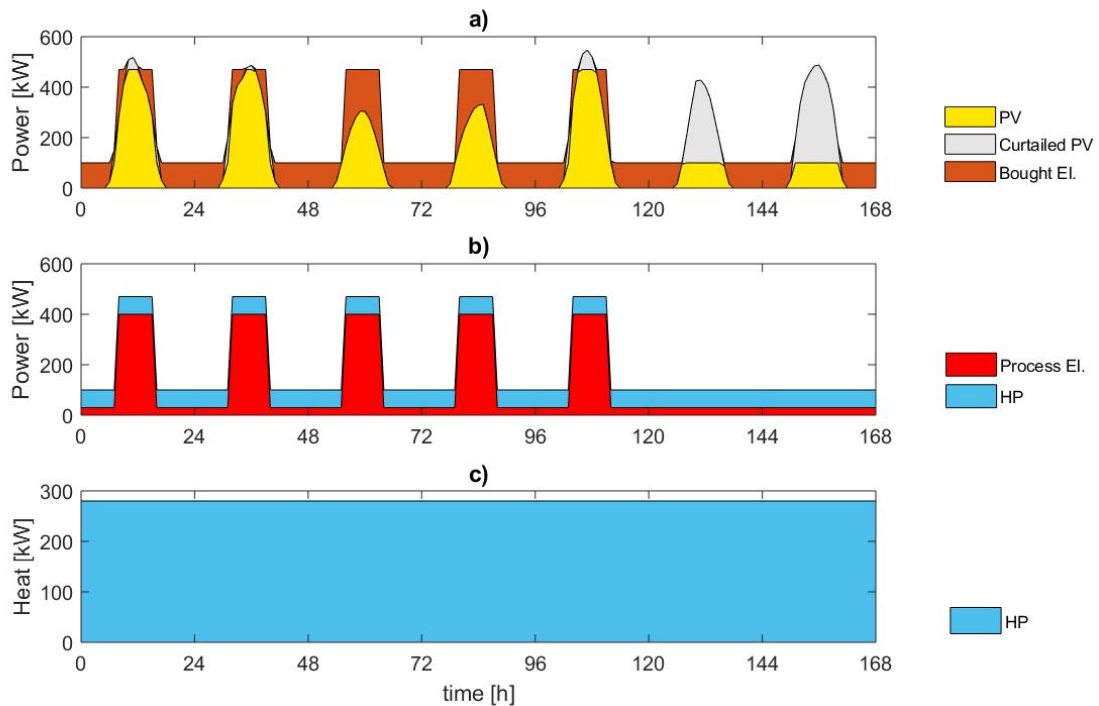


Figure 5.9: The energy system of case C-1 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case C-1 supplies its demand using a combination of purchasing electricity from the grid and generating electricity using solar PV. During weekends the curtailment is significant. The energy system is almost completely reliant on the grid and can only supply the demand using on-site generation for a few hours of the week. There are insignificant amounts of curtailment during the weekdays as the system has a relatively small amount of installed solar PV capacity. Subplot b) shows the energy demand of case C-1. All of the demand can be contributed to the processing demand and the constant load of the heat pump. Subplot c) shows the heat supply of the process, it consists of a heat pump running at a constant load.

The total investment cost of case C-1 is 1000 kEUR which gives an annual investment cost of 64.4 kEUR. The operation and maintenance cost which includes the purchasing of electricity is calculated to 48.7 kEUR. No additional revenues were made and the total annual cost was calculated to 113 kEUR, as can be seen in Table 5.19.

Table 5.19: The economic properties for the grid-connected case C-1.

Economic property [kEUR]	
Total investment cost	1000
Annual investment cost	64.4
Annual O&M cost	48.7
Annual revenue	0
Total annual cost	113

5.3.2 Case C-3 and C-4

Case C-3 is a grid connected version of case A-3 with the ability to purchase but not sell electricity. The energy mix consists of solar PVs with an installed capacity of 582 kW as the only electricity generation unit and a pyrolysis of 280 kW as the only heat source. A small battery with the size of 11 kWh and charge capacity of 10 kW and a C-rate of 0.9 is installed and the grid has a transmission capacity of 480 kW where the system can purchase electricity. Over the duration of the year, the grid supplies an amount equal to slightly less than a third of the annual electricity generated by the solar PVs. All energy system data is presented in Table 5.20.

Table 5.20: The installed capacity and annual generation of the technologies used in case C-3.

Case C-3 (On-grid, buy only)		Electricity			Heat
		PV	Bat	Grid	Pyro
Inst. cap.	[kW]	582	10 (11) ¹	480	280
Ann. gen.	[MWh]	979	9	279 (-) ²	2205

¹ Installed size of the battery (kWh)

² Electricity sold to the grid (kWh)

As the only electricity generating technology, the solar PVs supply the demand with electricity and if enough is not generated, electricity is bought from the grid to ensure supply can be met, as can be seen in Figure 5.10. During most days, it is necessary to purchase electricity from the grid, and especially during the night. During the weekends there is a very low process demand but a normal generation from the solar farm and which causes high curtailment to occur. In general, the system purchases a significant amount of electricity from the grid over the year while curtailment is relatively low.

Figure 5.11 show the demand and supply for a week before the production season start and how the pyrolysis operates during the day when the solar PVs generate electricity. As no processing is carried out this week there is no heat demand although the pyrolysis will still run to utilize any excess electricity. This is done as the system prefers to use electricity to produce biochar instead of curtailing. The operation of the pyrolysis is irregular during the night as can be seen in Figure 5.11 below.

Table 5.21 shows the economic properties of case C-3. The total annual investment cost is 1005 kEUR which gives an annual investment cost of 69.6 kEUR. The operation and maintenance cost, including the purchase of electricity, was calculated to 66.0 kEUR while the generated revenue from selling biochar and electricity was evaluated to 72.6 kEUR. The total annual cost was calculated as 63.0 kEUR.

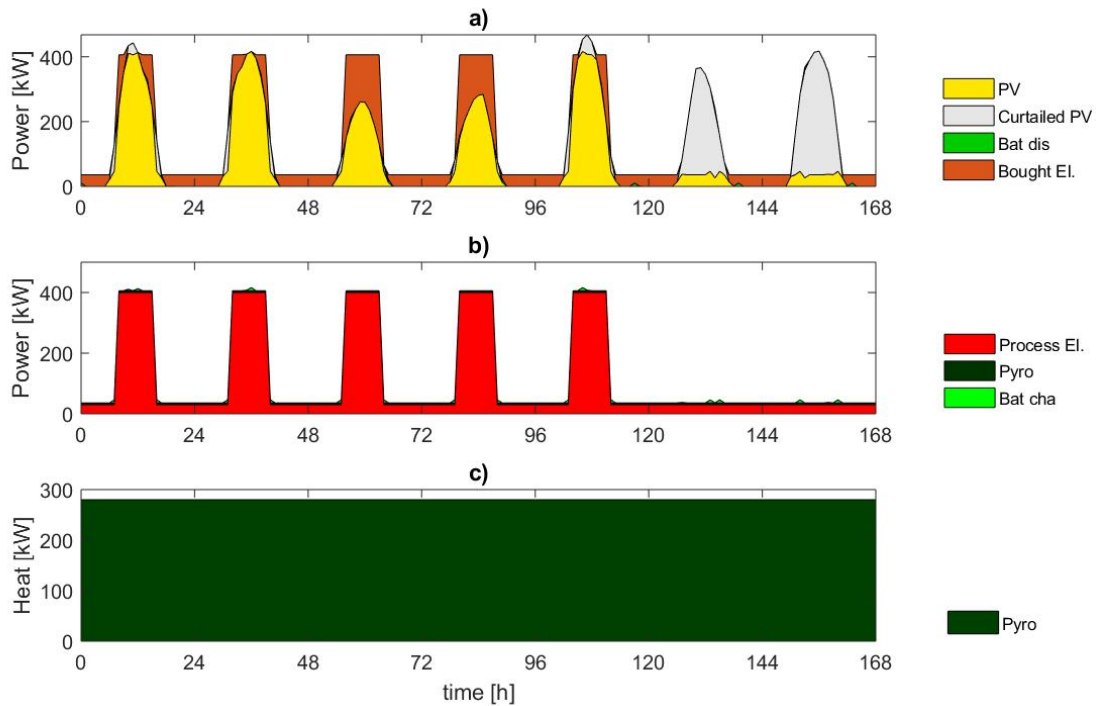


Figure 5.10: The energy system of case C-3 in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case C-3 supplies its demand using a combination of purchasing electricity from the grid and generating electricity using solar PV. The energy system is almost completely reliant on the grid and can only supply the demand using on-site generation for a few hours of the week. There are insignificant amounts of curtailment during the weekdays as the system has a relatively small amount of installed solar PV capacity. During weekends the curtailment is significant. Additionally, a small battery is used to avoid purchasing electricity during some hours. Subplot b) shows the energy demand of case B-3. Almost all of the demand can be contributed to the processing demand and the constant load of the pyrolysis, although a very small amount is being used to charge the battery. Subplot c) shows the heat supply of the process, it consists of a pyrolysis running at a constant load.

Table 5.21: The economic properties for the grid-connected case C-3.

Economic property [kEUR]	
Total investment cost	1005
Annual investment cost	69.6
Annual O&M cost	66.0
Annual revenue	72.6
Total annual cost	63.0

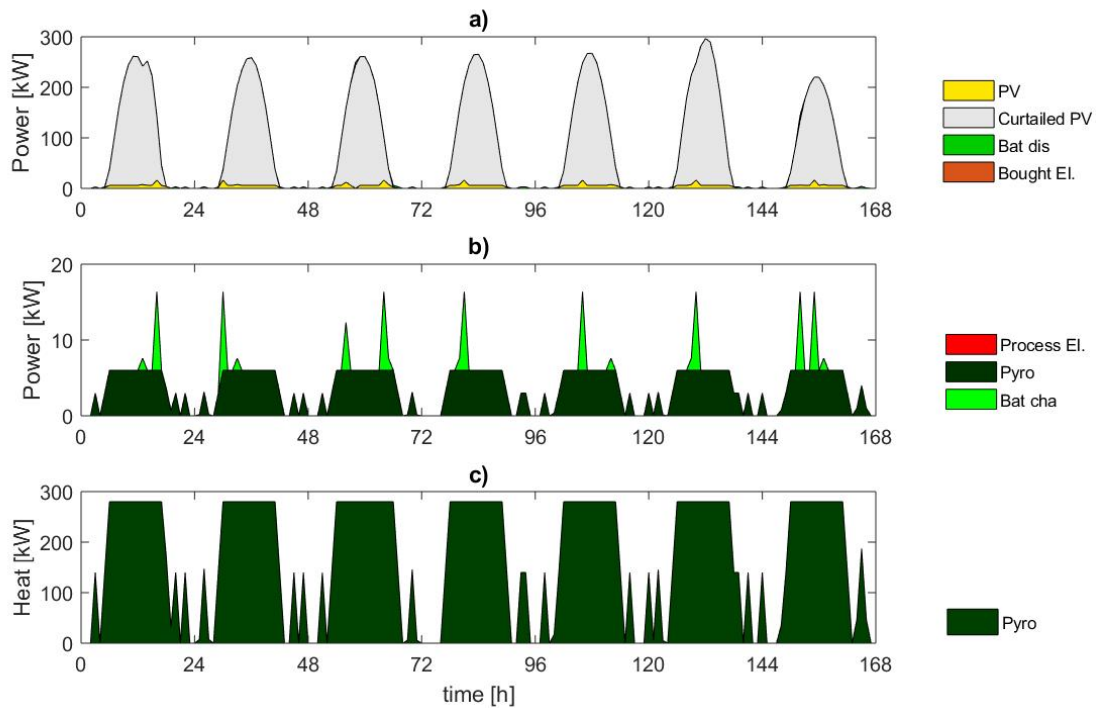


Figure 5.11: The energy system of case C-3 during a week with no operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case C-3 supplies electricity using solar PVs although the demand is small and can be attributed to the pyrolysis and the battery. As there are no processing demands during this week, no electricity is purchased during the night. There are large amounts of curtailment as the system can not utilize any excess electricity. Subplot b) shows the energy demand of case C-3. It can be seen that most of the demand can be contributed to supplying the pyrolysis during the day although the battery is charged during the day, to supply the pyrolysis during the night. Subplot c) shows the heat supply of the process. As no processing is carried out this week there is no heat demand although the pyrolysis will still run to utilize any excess electricity. This is done as the system prefers to use electricity to produce biochar instead of curtailing. The operation of the pyrolysis is irregular during the night.

5.4 The effect of outages on the energy systems

From Table 5.14 and 5.16 it was shown that grid connected systems yield solutions with lower costs, however, the systems become dependent on the grid and their ability to purchase electricity. The following chapter shows the size and capacity of batteries required for the grid connected cases B-1 and B-3 to mitigate a system failure during outages and how economy related parameters are affected. Additionally, the effects of outages on a grid connected system that can only purchase electricity, case C-3, have been investigated in terms of how the installed capacity of solar PVs, batteries and its economic properties will be impacted.

5.4.1 Effect of outages on case B-1

Table 5.22 shows the effect of outages on the energy system of case B-1. To withstand a year with 100 hours of outage, the required battery size and capacity vary depending on when the outage occurs. Out of the ten simulations, a battery with a size of 431 kWh and charge capacity of 135 kW, would be able to handle all the simulations with 100 hours of outage. The smallest battery, which only handles one of the simulations, has a size of 348 kWh and a charge capacity of 100 kW. For the studied simulations with 1000 hours of outage, the required battery size and capacity to handle all outages was 608 kWh and 223 kW, while the smallest battery was 392 kWh and 100 kW.

It can be seen that the battery size and capacity are in a more narrow range for the simulations with 100 hours of outage, compared to those with 1000 hours of outage. However, an interesting finding is that the largest battery retrieved from a year with 100 hours of outages is bigger than the smallest battery from a year with 1000 hours of outages. Thus the time of the day when the outage occurs and its duration is the deciding factor when determining the battery size and capacity. The smallest battery for 100 hours of outage is roughly the same as the smallest battery for a year with 1000 hours of outage.

When investigating the economic properties, it can be seen that the battery required to handle outages increases the total investment cost significantly, but it can also be seen that the expenditure goes down, compared to the original case with no outages. The expenditures decrease as the system can utilize the battery during the night, causing it to purchase less electricity. It can also be seen that simulations with 100 hours of outage have a higher revenue than the original case with no outages as they can charge the battery to sell electricity at a later time when the cable transmission is not at maximum capacity. Even though the revenue increase and the expenditure decrease, the total annual cost is higher when outages are included due to the increased investment cost.

Neither the simulations with 100- nor 1000 hours of outages experienced any significant differences between their respective minimum and maximum value of the recorded economic properties. The parameters that did change the most were the

expenditures, as shown in Table 5.22. It is also clear that the systems with more frequent outages (1000 hours) yield higher total annual cost than the simulation with 100 hours of outage, where the major difference is the revenue, which experiences a clear decrease for the simulation with more frequent outages. This can be attributed to the case not being able to sell electricity during the outages, at 1000 hours the increased selling flexibility of having a battery is negated by the loss of opportunities to sell.

For grids with outages, batteries are required to make sure the demand can be supplied during hours when generation is not enough and it is not possible to purchase electricity. As can be seen in Figure 5.12, there are hours during the night when there is an electricity demand but no generation. Most often this demand is supplied by electricity bought from the grid but when outages occur the battery is needed to provide electricity for the system. Additionally, outages during the day remove the possibility to sell electricity and increase curtailment, both during weekends and weekdays.

Table 5.22: The effect of outages on economic properties and energy system of case B-1, for different frequencies of outages. Recorded minimum and maximum storage size and charge capacity of the batteries required to ensure that demand can be met during outages are presented along with the range of which economic properties vary for the different outage simulations.

Case: B-1 Number of outage hours:	0 h	100 h		1000 h	
		Min	Max	Min	Max
Total annual cost [kEUR]	46.1	48.4	49.3	57.0	59.6
Investment cost [kEUR]	95.6	105	107	105	113
Expenditure [kEUR]	25.7	19.5	20.7	16.3	19.6
Revenue [kEUR]	92.8	93.8	94.4	84.1	86.9
Bat. Size [kWh]	0	348	431	392	608
Bat. Cap. [kW]	0	100	135	100	223

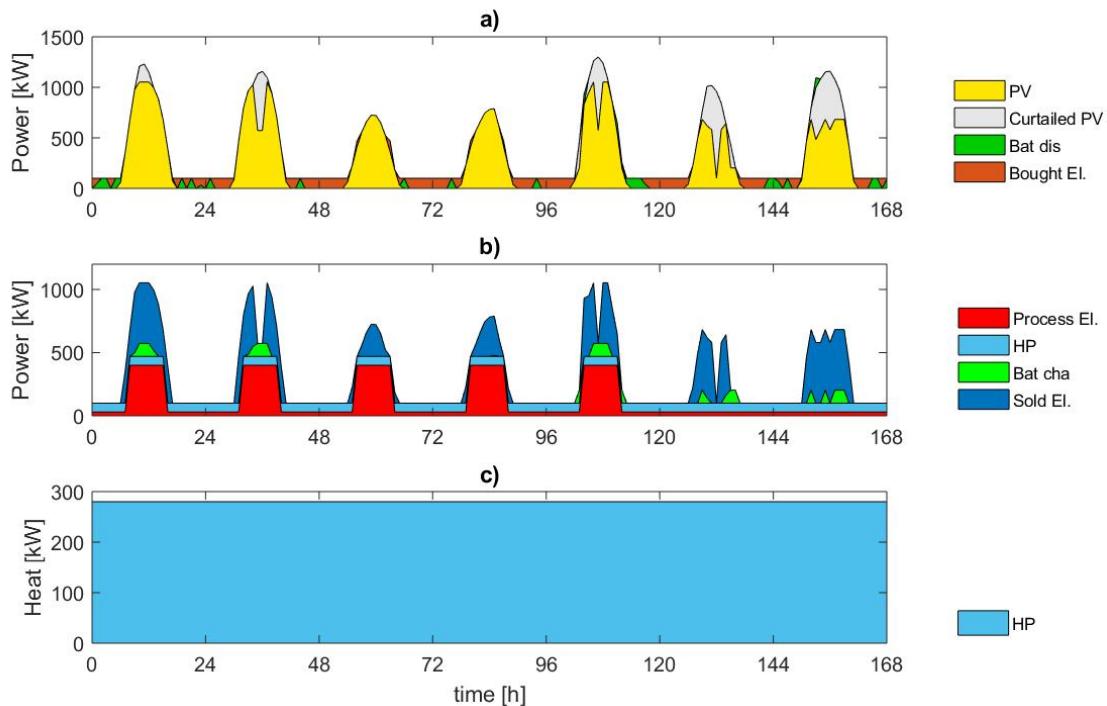


Figure 5.12: The energy system of case B-1 with 1000 annual hours of outage in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case B-1 supplies its demand with solar PV during the day and by purchasing electricity during the night although a battery is sometimes used. The battery makes the energy system more reliant to outages as it could supply itself if outages were to occur during the night. An alternative use of the battery is to simply avoid purchasing electricity to save on costs even though there are no outages. There are relatively small amounts of curtailment as the system is allowed to sell excess electricity although it can be seen that more electricity is curtailed during certain hours of the day when an outage is occurring. Subplot b) shows the energy demand of case B-1. It can be seen that a large part of the electricity is needed for the processing and the constant electricity demand from the heat pump. A similarly large amount of electricity is being sold each day, although it is sometimes interrupted by outages. A small amount of electricity is used to charge the battery. Subplot c) shows the heat supply of the process, it consists of a heat pump running at a constant load.

5.4.2 Effect of outages on case B-3

While subjecting case B-3 to outages it could be seen that the required battery size and capacity varied depending on when the outage occurred. Out of the studied outage simulations, a battery with a size of 329 kWh and charge capacity of 95 kWh, would be able to handle all the ten studied simulations with 100 hours of outage while the smallest, which only handles one of the simulations, has a battery size of 137 kWh and charge capacity of 36 kW. For the studied simulations with 1000 hours of outage, the required battery size and capacity to handle all outage simulations is 527 kWh and 147 kW respectively, while the smallest battery is 166 kWh and 44 kW.

It can be seen in Table 5.23 that the battery size and capacity are in a more narrow range for the simulations with 100 hours of outage, compared to 1000 hours of outage. However, once again, the largest battery retrieved from a year with 100 hours of outages is bigger than the smallest battery from a year with 1000 hours of outages, thus the time for when an outage occurs and its duration is the most important when dimensioning the battery.

Table 5.23: The effect of outages on economic properties and energy system of case B-3, for different frequencies of outages. The minimum and maximum storage size and charge capacity of the batteries required to ensure that demand can be met during outages are presented along with the range of which economic properties vary for the different outage simulations.

Case: B-3 Number of outage hours:	0 h	100 h		1000 h	
		Min	Max	Min	Max
Total annual cost [kEUR]	-5.3	-4.03	-2.75	5.44	7.45
Investment cost [kEUR]	101	104	109	105	114
Expenditure [kEUR]	33	28,4	31,2	25,9	30.9
Revenue [kEUR]	161	161	162	152	155
Bat. Size [kWh]	0	137	329	166	527
Bat. Cap. [kW]	0	36	95	44	147

When investigating the economic properties presented in Table 5.23, it can be seen that the increased investment cost of batteries is significant but it can also be seen that the expenditure decrease when batteries are in place. The expenditures decrease as the system can utilize the battery during the night, causing it to purchase less electricity. All simulations with outages on case B-3, decreased expenditures and the ones with 100 hours of outage experienced increased revenue, compared to the original case without outages. The revenue is increased as they can utilize the battery to sell electricity at a later time if the cable transmission is at maximum capacity when the system has excess energy to sell. However, the overall impact of outages is negative as the increased investment cost due to the battery increases the total annual costs.

Most economic properties for simulations with outages have minimum and maximum values relatively close, but looking at the difference in percentage, the total annual cost shows large differences, as can be seen in Table 5.23. An interesting difference between the two frequencies of outages is that the simulation with fewer outages yields a negative total annual cost, thus generating money each year and thereby supplying the nut processing plant with energy for free, while the one with more outages yields a positive total annual cost. Thus the system with 100 hours of outage will still yield an annual net income while a higher frequency of outages causes the system to become a net cost.

When there are outages on the grid it is not possible to sell nor buy any electricity thus there can be increased curtailment or extra need to discharge the battery to supply demand. Figure 5.13 shows generation and demand of a week with full production for a simulation with 1000 hours of outage. The main effect of the outages for these simulations is the loss of ability to sell electricity during outages, as can be seen in the figures, and how the curtailment increase during these hours.

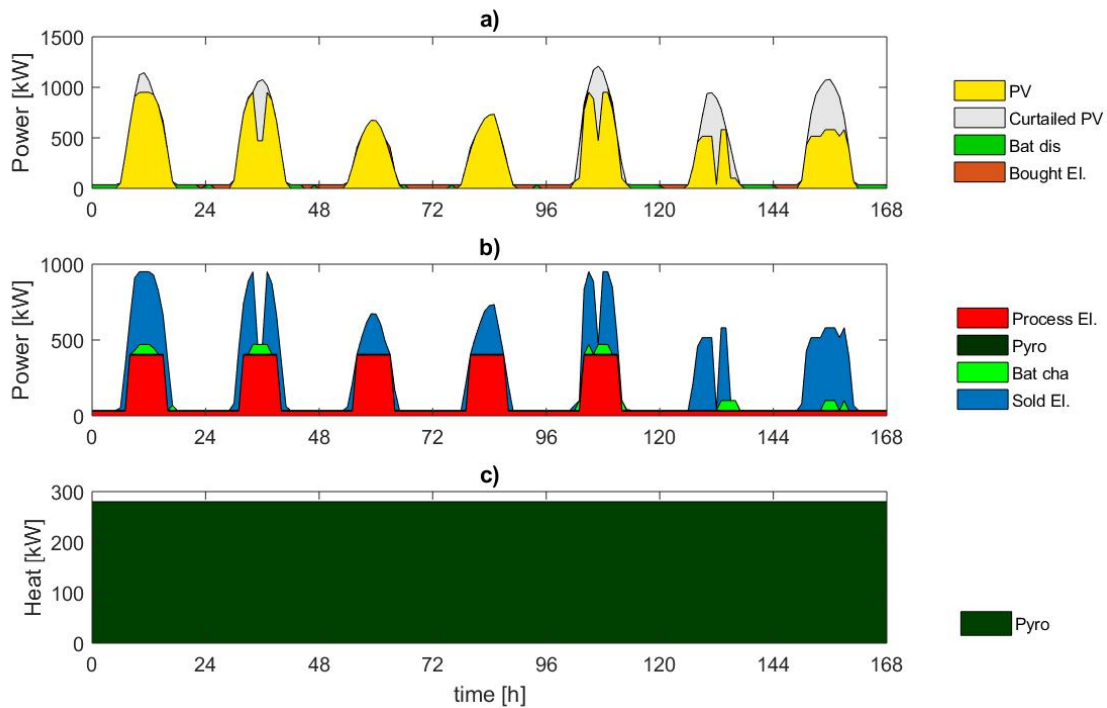


Figure 5.13: The energy system of case B-3 with 1000 annual hours of outage in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case B-3 supplies its demand with solar PV during the day and by purchasing electricity the night although a battery is sometimes used. The battery makes the energy system more reliant to outages as it could supply itself if outages were to occur during the night. An alternative use of the battery is to simply avoid purchasing electricity to save on costs even though there are no outages. There are relatively small amounts of curtailment as the system is allowed to sell excess electricity although it can be seen that more electricity is curtailed during certain hours of the day when an outage is occurring. Subplot b) shows the energy demand of case B-3. It can be seen that a large part of the electricity is needed for the processing although a small amount is needed to supply the pyrolysis and charge the battery. A large amount of electricity is being sold each day, although it is sometimes interrupted by outages. Subplot c) shows the heat supply of the process, it consists of a pyrolysis running at a constant load.

5.4.3 Effect of outages on case C-3

As for all systems that utilized the grid for supply during some hours, the battery of case C-3 had to increase in both size and capacity to ensure supply could be met during outages. During the simulations with 100 hours of outages, the largest battery required a size of 266 kWh and a charge capacity of 266 kW, while the smallest was of 162 kWh and 162 kW.

When subject to 1000 hours of outage each year, the biggest installed battery size was 484 kWh while the smallest was 302 kWh, likewise, the battery capacity varied from 234 kW up to 302 kW. However, the battery with the highest storage size did not have the highest charge capacity, instead, the battery with the smallest storage size of 302 kWh had the highest charge capacity of 302 kW. This implies that the most demanding outage had a duration of only one hour during this simulation, yielding a battery with a C-rate of 1.

Other than larger batteries, the installed capacity of the solar PVs increased with outages. For the simulations with 100 hours of outage, the installed capacity of the solar PVs varied in a narrow range from 674-677 kW. On average, the installed capacity of the solar PVs for a year with 100 hours of outage increased by 16% compared to the original case with no outages. The simulations with a higher frequency of outages recorded even larger installed capacity of the solar PVs where the capacity varied in a wider range from 680-756 kW, corresponding to an increased installed capacity of the solar PVs from 17% to 30%, compared to the original case without any outages.

Table 5.24: The effect of outages on economic properties and energy system of case C-3, for different frequencies of outages. Recorded minimum and maximum storage size and charge capacity of the batteries required to ensure that demand can be met during outages are presented, along with the installed capacity of the solar PVs. Additionally, the range in which economic properties vary for the different outage simulations.

Case: C-3	Number of outage hours:	0 h		100 h		1000 h	
				Min	Max	Min	Max
Total annual cost [kEUR]		63.0		65.8	68.6	63.9	70.4
Investment cost [kEUR]		70.0		78.9	83.1	84.7	89.2
Expenditure [kEUR]		50.3		49.4	50.7	44.3	48.9
Revenue [kEUR]		72.6		80.7	80.7	80.7	80.7
Installed solar PV [kW]		582		674	677	680	756
Bat. Size [kWh]		11		162	266	302	484
Bat. Cap. [kW]		10		162	266	234	302

Looking at the economic properties presented in Table 5.24, the major effects from outages are the additional investments required, both in batteries and solar PV. The annual investment cost increased by 13-19% for simulations with 100 hours of

outage and 21-27% for those with 1000 hours of outage. Another parameter affected when outages are included is the revenue, which increases by 11% when outages are included and remains the same for all simulations, independent of the frequency of the outages. This increase in revenue is because more biochar is produced by the pyrolysis which operates more hours when the battery is available and can store energy from the day.

Another property affected was the expenditure, which could be both higher or lower for a simulation of 100 hours of outage compared to the original case with no outages. The simulations with 1000 hours of outages do however lead to lower expenditures for all simulations, which is because the larger batteries can be used to shift more of the load from the nighttime to daytime, discharging energy from the solar PVs during the night instead of purchasing electricity from the grid.

It was shown earlier that, systems that can purchase electricity from the grid but not sell, utilized the grid to a high extent and were completely reliant on purchasing electricity most days. If the energy systems are modified to be able to handle outages, this dependency decreases as is shown in Figure 5.14. It can be seen that the battery is used to provide most of the electricity even though the grid is needed between the third and fourth day as the production from the solar PVs is low.

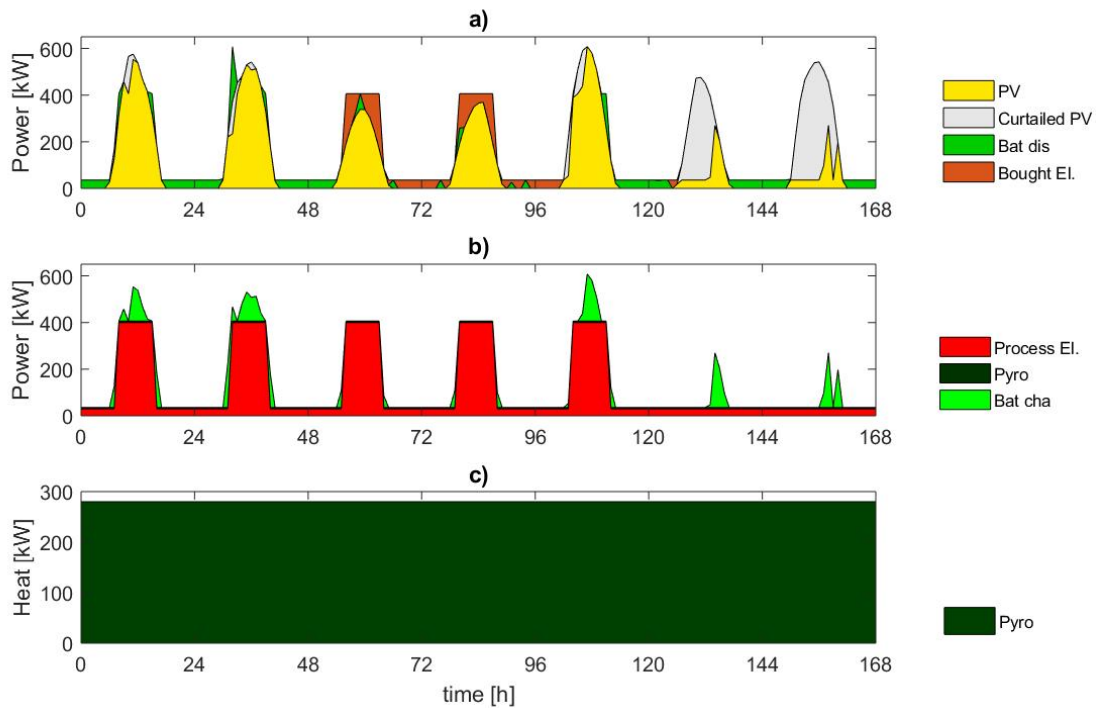


Figure 5.14: The energy system of case C-3 with 1000 annual hours of outage in operation. Subplot a) shows how energy is being supplied to the system and if any curtailment is taking place. It can be seen that case C-3 supplies its demand using a combination of purchasing electricity from the grid, generating electricity using solar PV and utilizing a battery. The battery is relatively large and as such it can cover the demands of most nights even though electricity has to be bought if the battery could not recharge during the day. The battery makes the energy system more reliant to outages as it could supply itself if outages were to occur. An alternative use of the battery is to simply avoid purchasing electricity to save on costs even though there are no outages. There are insignificant amounts of curtailment during the weekdays as the system has a relatively small amount of installed solar PV capacity. During weekends the curtailment is significant. Subplot b) shows the energy demand of case C-3. The demand can be attributed to the processing demand, the charging of the battery and the small but constant load of the pyrolysis. Subplot c) shows the heat supply of the process, it consists of a pyrolysis running at a constant load.

5.5 The effect of small changes in solar radiation

Generation from solar PVs is dependent on solar radiation, which fluctuates from year to year, thus its effect on the solution was investigated and presented below in Tables 5.25 to 5.28.

Table 5.25 shows how the battery size and capacity and total annual cost change for the off-grid solutions if the solar radiation change. As expected, the battery would become larger and the objective function increase if the solar radiation would increase and the other way around for a year with less solar radiation. The battery capacity, on the other hand, does not follow the same trend and becomes smaller than the original in all observed instances. Additionally, changes of more than 10% can be observed, even though the input parameter is only changed with 2%.

Table 5.25: The affect of small changes in solar radiations on the energy system and economic properties for the off-grid case A-1. The percentile change on installed battery storage size and charge capacity along with total annual cost is presented for small increases and decreases in solar radiation.

Solar radiation [%]	Bat. Size [%]	Bat. Capacity [%]	total annual cost [%]
+ 2	-0.7	-11.3	-0.6
+ 1	-0.3	-5.8	-0.3
0	0	0	0
- 1	+3.8	-2.6	+0.6
- 2	+7.6	-4.9	+1.1

A grid-connected solution is also affected by years with increased/decreased solar radiation as can be seen in Table 5.26. With increased solar radiation the revenue increased, while both expenditure and objective function decreased, which was expected. The same trends, but reversed, could be seen for the cases with decreased solar radiation, which yield more expensive solutions with decreased revenue and increased expenditure. However, the change in the results is within the same order of magnitude as the change in input data, unlike the results of the off-grid solution.

Table 5.26: The affect of small changes in solar radiations on the economic properties for the on-grid case B-1. The percentile change on revenue, fuel and el. cost and total annual cost is presented for small increases and decreases in solar radiation.

Solar radiation [%]	Revenue [%]	Fuel & el. cost [%]	total annual cost [%]
+2	+ 1.3	-0.3	-2.8
+1	+ 0.7	- 0.1	- 1.4
0	0	0	0
-1	- 0.7	+0.2	+1.5
-2	-1.4	+0.3	+3.0

Table 5.27 shows that with increased solar radiation, the battery becomes smaller

and the system cheaper for the off-grid biomass case, while the opposite can be observed for decreased radiation. The battery capacity and objective function slightly follow the radiation increase in the order of magnitude while the battery storage size is greatly affected. Changes of a few percent in solar radiation resulted in an increased battery size of over 10%.

Table 5.27: The effect of small changes in solar radiations on the energy system and economic properties for the off-grid case A-3. The percentile change in installed battery storage size and charge capacity along with total annual cost is presented for small increases- and decreases in solar radiation.

Solar radiation [%]	Bat. Size [%]	Bat. Capacity [%]	total annual cost [%]
+ 2	-2.1	-2.8	-0.4
+ 1	-1.1	-1.7	-0.2
0	0	0	0
- 1	+6.7	+1.1	+1.0
- 2	+13.3	+2.2	+2.1

The same test was done for the grid connected biomass system B-3, as shown in 5.28. If solar radiation were to increase, the grid connected biomass system would have slightly increased revenue while the expenditure remains close to the same. The total annual cost experience a larger percentage change with rather small changes in radiation, however, in actual numbers, the total annual cost showed small changes.

Table 5.28: The effect of small changes in solar radiations on the economic properties for the on-grid case B-3. The percentile change in revenue, fuel and electricity cost and total annual cost is presented for small increases- and decreases in solar radiation.

Solar radiation [%]	Revenue [%]	Fuel & el. cost [%]	total annual cost [%]
+2	+0.8	-0.0	-22.9
+1	+0.4	+0.0	-11.6
0	0	0	0
-1	-0.4	-0.0	+11.8
-2	-0.8	+0.0	+23.8

6

Discussion

In the following chapter, the results will be discussed. Firstly the cases from the results are discussed and evaluated in section 6.1. This is followed by a discussion regarding the effect of outages and solar variations in section 6.2 and 6.3 respectively. Thereafter, the value of having grid connection and potential of demand side management is discussed in section 6.4 and 6.5, followed by uncertainties presented in section 6.6. Finally, the societal aspects of the project are discussed in section 6.7.

6.1 Case evaluation

In this section, the different cases are analyzed and their results are discussed. Key differences, advantages and drawbacks from the different cases are brought up and compared with one another.

6.1.1 Cases without grid connection (Off-grid)

When the processing plant has no grid connection, the case with the lowest total annual cost will be case A-4. However, if investigating how the biomass boiler is run, it can be seen that the operation is irregular during mornings and evenings. This is probably due to the fact that the model does not have a start-up and shutdown cost for the technologies. If a biomass boiler was operated like this in practice, it likely would lead to increased wear on the equipment which is not reflected. Further, there might be a minimum load for the boiler to reach an efficient combustion and if it would be run in this way, fuel costs could increase. Another aspect is that it would be more complicated for the plant operator to run the plant, which also might increase the costs of labor or lead to mistakes that would negate the lower cost of such an operation.

This combined with the fact that the total annual cost of case A-4 is only 2 tEUR lower than case A-3 makes it seem less advantageous. Further, case A-3 only utilizes the pyrolysis as a heat source and runs it at a constant load which makes it less complicated to operate. It is also worth noting that the investment costs in the model are linear. Because of this, it would probably be more realistic if the investment cost per kW was higher for the pyrolysis in case A-4 compared to A-3 as its installed capacity is less than half the size of the pyrolysis in case A-3. Case A-4 is utilizing three different technologies to meet the heat demand and all of them

being of smaller capacities. This complicates the energy system further and would probably lead to higher investment costs in practice. Due to all of these considerations, case A-3 is likely the off-grid energy system with the lowest total annual cost in practice, even though it is not reflected in the model. Another positive factor in favor of case A-3 is that it produces more biochar which will lead to more negative emissions and likely increased plant growth if used as a fertilizer.

Out of all off-grid cases, case A-5 has the lowest investment cost although the total annual cost is higher than for cases A-4 and A-3. The low investment cost makes this case the least sensitive to increases in interest rates. Further, case A-5 would be the cheapest case if NML would not be able to use biochar from the pyrolysis in cases A-4 and A-3 to generate carbon credits. As the biomass boiler is the only heat generating technology used and due to its constant operation, it is deemed to be easy to operate.

Cases A-1 and A-2 have the highest investment costs and total annual costs out of the cases, in large part due to the increased battery capacity that is needed to run electric heaters such as the heat pump during the night. They should only be considered if the MNS can not be used as a biofuel and no other biofuel can be found. The operation of cases A-1 and A-2 seems to be realistic, although the diesel generator in case A-2 makes it slightly more complicated and flexible than A-1. A-2 needs a smaller installed capacity of solar PVs compared to A-1 which decreases the investment cost significantly. However, this comes at an environmental expense as it utilizes fossil fuels.

6.1.2 Grid connected cases with the ability to purchase and sell electricity

By connecting the energy system to the grid, all cases experienced lower total annual expenses which are expected. Especially for the cases where it is possible to sell electricity to the grid and generate income of otherwise curtailed energy. The possibility to sell electricity to the grid becomes even more attractive since the demand is zero during spring and weekends, which allows the systems to sell excess energy. In fact, the possible revenue of selling electricity is big enough to motivate investments in more generation than for cases without grid connection, even though the demand is the same. Thus the limiting factor is the grid capacity and a bigger cable would entail an even larger installed capacity of solar PV.

Another aspect where it is favorable with grid connection is the possibility to purchase electricity during events where not enough is generated on-site. This is primarily during the nights, when no energy is provided by the sun and as could be seen in Figure 5.6 for case B-1, all (more or less) electricity is purchased on the grid during the night. By being able to purchase electricity during the night, the system does not require any more generation than solar power nor is it needed to have energy storage. Energy storage is a large component of the investment cost, especially for the cases that do not utilize biomass as they otherwise would need a large battery during the night to operate power-to-heat technologies to meet the

heat demand.

The revenue increase for all cases which can sell electricity and for case B-4, where it is also possible to sell biochar, the total annual cost is even negative, and thus the system has a net income each year. This clearly shows the value of having a grid connection, where NML can generate income by selling excess energy while also supplying their own energy demand. Another positive aspect of having a grid connection is that more of the generated energy can be utilized and curtailment decreased, thus increasing the efficiency of the system. Overall, the observed cases recorded a lower investment cost when grid connected, compared to off-grid, which is primarily because batteries are no longer needed and investment in cable connection is cheaper. Additionally, a new source of revenue is introduced, which creates a value of otherwise curtailed energy.

Out of the two observed cases with grid connection (Case B-1 and B-3), Case B-3 with pyrolysis as a heat source is the most profitable option. However, if the possibility to sell biochar would be removed, it is uncertain which solution would be the best. This is because the investments in pyrolysis would no longer be justified and thus it would be more profitable with a biomass boiler, as mentioned in the previous subsection, but based on assumptions for this project, Case B-3 with pyrolysis is the best solution.

6.1.3 Grid connected cases with the ability to purchase but not sell electricity

As could be seen from the results, grid connected solutions are more economically favorable than off-grid solutions, however, if the possibility to sell electricity is removed, a big part of the revenue is removed and the excess generation becomes useless. The systems connected to the grid, which can only purchase (case C-1 and C-3), have the least installed solar capacity of the observed cases. This is because excess energy has no value and the most demanding hours, where solar radiation is low but demand high, can be covered by the grid rather than increased investments in solar capacity or energy storage. In other words, it is no longer profitable to install in overcapacity unless it can replace a significant amount of purchased electricity.

As could be seen from the figures showing the operation for the different cases with grid, where it is only possible to purchase electricity, there is not a lot of curtailment during the weekdays but instead much more common that electricity is bought, to fill the demand. This was not the case for the other grid-connected solutions which could sell electricity, as they instead had more than enough electricity every day.

When comparing the two different systems (C-1 and C-3), case C-1 has roughly 100kW more installed solar capacity while C-3 has a small battery. They both had a total investment cost of one million EUR, but C-3 recorded cheaper yearly expenses. This is primarily because of the ability to sell biochar and thus generate

an income, which is not possible when heat is supplied by a heat pump. However, operation and maintenance cost increase because of the need for fuel to operate the pyrolysis but overall, the pyrolysis solution is deemed more profitable. Once again the ability to sell biochar is crucial for the pyrolysis, but the utilization of waste biomass is likely more profitable. Additionally, such a small battery as in case C-3 is unlikely to be used in reality, especially since it seems to be used to power the pyrolysis during nighttime operation during the season when no harvesting occurs. The nighttime operation of the pyrolysis in case C-3 is irregular and probably unrealistic during this season. However, even if the plant would be turned off during the night, it would likely still be more profitable than case C-1.

6.2 The effect of outages on the energy system

As mentioned at the beginning of the report, the grid in Mozambique is not very stable and outages were proven to have big effects on the result. What could be noticed from the results when outages were included, is that the time- and duration of the outage was most important, looking at the battery. Outages that occur during the day entailed losses of revenue but were easily covered by on-site generation while outages during demanding hours, typically the first or last hour of the workday, required a battery or the demand could not be met. The capacity of the required battery was determined by the most challenging hour, and the battery size by the duration of the most demanding outage. However, the frequency of the outages was not limiting as batteries required to mitigate failure for scenarios with 100 hours of outage, could be bigger than a battery required for a scenario of 1000 hours of outage. Thus the time of the day and duration of an outage was more important than the frequency, looking at battery size.

Looking at the effects on systems B-1 and B-3, where electricity could be both sold and purchased, there is a clear difference in battery capacity. The average required battery capacity for a system with a heat pump was bigger than that for a system with a pyrolysis, which is expected since the heat pump requires more electricity to operate compared to the pyrolysis. However, an interesting discovery is that the C-rate is roughly the same for both systems, proving that the batteries serve the same purpose for both systems; to ensure long-time energy management.

Another finding is that the batteries required to ensure sufficient supply are not only used during outages but also used to store electricity from events where the cable is full, to events where the excess generation is not enough to fully utilize the cable. Excess electricity generated that is not utilized or sold, is temporarily stored in the battery to instead be sold when there is capacity left in the cable. This is however something that is unlikely to happen in reality since you would like to keep the battery charged and have it ready to help during outages, but the model used has a perfect forecast and knows exactly when an outage will occur and can thus plan thereafter. Instead, one could store energy during the night and discharge it when morning comes, right before new electricity will be generated, to ensure supply

security during the night, without losing too much efficiency.

It could be of interest to let the model change the size of the solar farm and not lock its capacity as was done for the B-cases in this project. This has however been done in another project [60] where it was shown that a system that can change both the battery and the solar farm would yield a slightly cheaper solution than a system that can only change the battery size and capacity. It was also seen that the systems that could change both the battery and capacity of the solar farm, would produce more excess electricity.

The system that had a grid connection but was only able to purchase electricity (case C-3), could invest in both a larger installed capacity of PVs and also a larger battery. This was done as this case was significantly impacted by outages in terms of costs by not being able to increase its installed solar PV capacity. From the results, it can be seen that the installed capacity of the solar PVs increases by 16% when there are 100 hours of outage annually on the grid and up to 30% for when there are 1000 hours of outage annually. Additionally the revenue increase for when installed generation and storage capacity increase because it is now beneficial to operate the pyrolysis more frequently as the battery can provide it with free electricity during the night.

Another interesting finding from the outage simulations of case C-3 is that many of the designed batteries had a C-rate of 1, which is rarely the case for batteries used in BESS. Batteries used in BESS typically have a lower C-rate to ensure long-term energy management but here it is clear that the batteries designed in the outage simulations are purely designed to withstand the most demanding outage.

6.3 The effect of small changes in solar radiation

Based on the results of investigating changes in solar radiation, it can be seen that there will be an impact. The off-grid cases will be more sensitive as they are not able to purchase electricity from the grid. This means that when the solar radiation decreases, they will have to compensate by investing in a larger battery, increasing costs. The grid connected cases will mostly be affected by not being able to sell as much energy, but no system changes will be necessary. Because of this, no special consideration regarding the design of the grid connected cases will have to be taken in regard to variations in solar radiation. The results further show that a decrease in solar radiation with 2 %, which could be expected over time, could change the battery size by 13.3 % for case A-3 and 7.6 % for case A-1. This concludes that the off-grid should be designed with this in mind and the battery size should be increased accordingly to be able to meet the processing demands with a margin of safety.

6.4 The value of having a grid connection

The results of the case study show that it is beneficial to be grid connected as all cases connected to the grid had lower total annual cost compared to using the same technologies off-grid, regardless of whether they were able to sell electricity or not. The main reason grid connection is valuable is that the systems rely on solar PVs, which have an intermittent generation that varies and can not be controlled to follow the demand.

During hours with full process demand but a low generation from the solar farm, such as during sunrise or sunset on cloudy days, a small load increase would require much more installed capacity. The investments required to ensure supply on the most demanding hours are difficult to justify because the extra generation is very rarely required and most of their generation is curtailed. Instead, it would be more profitable to invest in a grid connection and purchase electricity during demanding events. The same reasoning is applicable to replacing energy storage to ensure supply during the night.

With intermittent generation, grid connection is valuable both to purchase electricity to make sure demand can be met and also to sell excess generated electricity. The ability to sell electricity to the grid is highly valuable because during events of high generation from the solar farm, but low process demand, electricity can be sold rather than curtailed causing the energy efficiency of the system to increase.

Another aspect where the grid connection is attractive is to handle the expected decrease in solar radiation over time. From the results, it was proven that grid connected systems could handle the decrease in generation without major issues, while off-grid systems would need a battery to handle the decrease. The same results could be applied to conclude that the decrease in generation from solar panels as they age can be mitigated with grid connection, while off-grid systems would need to increase their installed capacity in solar PV or have storage.

6.5 Demand side management

Since most of the electricity will be generated by solar PVs and their generation will have daily variations, one can either invest in technologies such as a battery or diesel generator to have supply match demand or one could change the demand to match the supply, demand side management (DSM). Utilizing DSM could be a way to significantly lower the amount of investments needed in storage capacity while utilizing the storage it has more effectively. Managing the demand could potentially lower processing output but might save significant costs.

6.5.1 Different operating hours

The processing plant is likely to install a pasteurization machine further into the future. This machine will have an electricity demand almost as large as the entire processing that is currently modeled. Instead of doubling the installed capacity of the current energy system, it is probably more beneficial to run the pasteurization machine when the rest of the production is halted. This could for example be during the weekends when the plant is currently not running or during certain hours of each day. During the solar peak, a lot of energy is curtailed in the current energy systems, due to the large amount of installed solar energy. If the pasteurization machine would run during these hours curtailment could be lowered and no more installed capacity would be needed which would keep investment costs low.

6.5.2 Batteries vs altering the production

The energy demand of the nut processing is fixed and required to be met at all times in the model. A side effect of this is that to meet the demand, the model might decide to buy a battery that is only used one hour of the year. If the model could know the cost of lowering the production of this hour, it might decide that it is more beneficial to halt production instead of installing additional capacity.

Further, the most demanding hours often coincide with the first or last hour of the working day. These hours are probably the most flexible hours as the shift could be ended early if the amount of solar radiation is lower than usual. This would allow the battery to charge for one additional hour which might be useful the next morning if the solar production still is low.

6.6 Uncertainties affecting the result

There are many assumptions made in order to create the model and retrieve results. In this section, some of the assumptions made are addressed and their impact on their result is discussed.

6.6.1 The energy demand of the processing plant

The energy demand of the processing plant is modeled as described in the background. This is a simplified demand based on conservative assumptions as all specific equipment used in the processing is yet to be decided. It is probable that the load during processing will be lower as the daily load is based on the peak load. If the load of the completed processing plant is lower than assumed, the usage of batteries and their respective capacity can likely be lowered, which would save costs and allow the grid connected cases to sell more electricity.

The current harvest assumptions assume that no harvesting is done during the first three months of the year. If one were to implement irrigation, however, there is potential to extend the harvesting season and get a process demand during this

period as well. If these months would have a process demand, the costs would be increased due to increased running costs, more purchased electricity and less sold electricity. However, the installed capacity will likely stay similar as the system is dimensioned based on the peak load.

6.6.2 The cost of buying and selling electricity

The size of the installed electricity generation will be dependent on the electricity price if the system is grid connected. The ability to sell produced electricity in Mozambique is still relatively recent and it is yet uncertain how it will work in practice. The same thing can be said about the purchasing price of electricity as it will depend on the buyer. Based upon interviews with industries close to the factory, and discussions with officials at the Swedish embassy, the price used in the model should be close to what can be expected although if the model should be used as a basis for a real investment, the actual price should first be negotiated.

6.6.3 Linear costs in the model

The costs in the energy model are based on the assumption that the investment cost of the technologies is scaled linearly. This assumption will especially impact smaller systems, as, in reality, the cost per installed kW tends to decrease as the size of the unit increases. The linear cost in the model is based on large capacities and as such smaller systems will be unrealistically cheap. This has to be acknowledged and depending on the decrease in total annual cost, systems with one large and one smaller technology might realistically be cheaper if the technology with the smaller installed capacity would be left out.

The linear cost approximation should be more reasonable for some technologies than for others. As an example, the modularity of solar panels makes the cost more linear than the cost of a biomass boiler that has to be built by more or less the exact specification.

6.6.4 Weather affecting plant growth

The energy demand of the processing plant is identical from week to week in the model and is based on a fixed amount of nuts being processed and dried each hour. In reality, the amount of nuts harvested could have a closer correlation with the weather. The correlation might be such that a higher amount of sun would yield more nuts, but it could also be more dependent on rain.

If the amount of harvested nuts is more dependent on the rain a cloudy year could lead to a higher energy demand from increased processing but also a lower electricity production due to the decrease in sunlight. This would make it harder to meet the demand of the processing for the off-grid cases. For the grid connected cases, the amount of purchased electricity would likely increase, also increasing the objective function as a result. If the harvest would increase during a year with more solar

radiation, the energy demand of the increased harvest will most likely not be a problem as the associated increase in energy demand would be met with the increase in energy availability.

The off-grid base case would be more sensitive to changes in weather affecting the harvest as it purely uses electricity as a heat source. The cases utilizing biomass as a fuel source will more easily follow the changes in demand as most of the needed energy is a waste product from the harvest itself. It is likely that if allowed, the use of the diesel generator would also increase.

6.7 Societal aspects

As Mozambique is one of the UN's least developed countries there are many areas in the society that has flaws and here there is great potential for Niassa Macadamia Limitada to have an impact. By generating green and sustainable energy it is possible to positively affect many of UN's Sustainable Development Goals (SDG) but primarily goals related to green energy for all, if they could sell excess energy to local villages. From the results it is clear that there is a significant amount of excess energy generated, primarily for off-grid solutions but also the grid connected solutions generate more than is required. Here there is big potential to sell excess electricity very cheaply, or even give it away for free, as there is no other way for the plant to make use of it anyway, thus working towards goal 7 *Affordable and clean energy*.

Another big part of the most promising systems is the generation of biochar, which generates negative emissions if buried, related to goal 13 *Climate action*. Currently, the plan is to sell the biochar to other big companies as an "Emission offset", however, these companies are not interested in the actual product but only have the right to emit more. Thus, it could be possible to give biochar to local farmers to use on their plantations to improve soil quality and increase growth. This would then favor sustainability goal 2 *Zero hunger*, as more food could be produced in a region that struggles with food. Another use of biochar could be to replace the firewood used as fuel in cooking, which could mitigate the serious problem of deforestation currently in place in Mozambique, working towards goal 15 *Life on Land*. However, if this would be the case, no emission permits would be granted.

To process the number of nuts planned for the factory, of which the energy system is designed, will require a big factory which will create job opportunities for local villagers. By employing more people from the village, the cash flow within the village will increase and the economy slowly rise, working towards goal 8 *Decent work and economic growth*. Additionally, there will be a demand for educated people such as engineers to operate and maintain equipment which will make it possible for educated people to live nearby which will also favor society.

There are however aspects that could be negatively impacted by the process such as land usage. The main source of food in Lichinga is vegetables, fruits and root crops

and by building a big plantation of trees or a big solar farm, the company could compete with local inhabitants about farmland, which could cause food deficit. Another aspect that could have negative effects if not done properly could be the biofuel bought to run the bio boiler and pyrolysis. The biomass bought could be the same biomass used in cooking and therefore increase the cost of firewood, which is crucial to local inhabitants for cooking in Lichinga and could cause a crisis as people would not afford to cook anymore.

Another area where NML have to take responsibility is their plan to utilize smallholder farming. Currently, deforestation is a big issue in Mozambique and one of the main contributors are smallholder farmers. Thus, if not monitored or given proper land, the smallholder farmers could contribute to deforestation, which can lead to loss of biodiversity, desertification and fuel shortage for those utilizing biomass to cook.

There is no doubt there are many aspects where the company can play a big role and have a positive effect on local-, regional- and global scale but there could also be negative effects if not performed correctly. There is a big responsibility for the company to have the well being of the local environment and people into consideration when planning and executing their processing facility and farm.

7

Conclusion

The findings of the study show that a suitable energy system for NML would consist of solar PV and a pyrolysis, no matter if the system is grid connected or not. To utilize the nutshell generated on-site is economically beneficial compared to commercial power-to-heat technology and this is the case even if the solutions were to be grid connected. The main reason is the generated income when selling biochar, which not only generates income for the company but also helps to reduce global carbon emissions. The pyrolysis is the most beneficial heat supplying technology, both from an economic point of view and also out of social and environmental aspects.

If the system were to be grid connected or not has big effects on the energy system and installed capacity. Grid connected systems have the ability to purchase electricity to replace peak generation and reduce shifting technology and thus reduce investment costs. Additionally, if it is possible to sell electricity to the grid, curtailment can be reduced and overall efficiency increased, as well as extra income for the company. Based on assumed electricity prices, a grid connected system would generate enough income to warrant an increase in installed solar capacity and has a large impact on the solution.

Energy storage was deemed interesting, and in many cases required, especially for the off-grid solutions but also for the on-grid solutions. The battery required to handle outages could have multiple usages and be used both as a backup supply to mitigate outages but also to decrease curtailment. By making use of excess energy during the day and selling electricity when there is capacity available in the grid transmission, the overall energy efficiency would increase.

Variance in solar radiation was deemed to have notable effects on the off-grid systems, where small changes in solar radiation greatly impacted the installed battery capacity, concluding that off-grid systems should invest in overcapacity of batteries. The grid connected cases were only slightly affected as they can supply the deficit by purchasing from the grid, which will only slightly increase the total annual cost.

Based on the observed cases and their results, the energy system with the lowest total annual cost is a grid connected system with solar PV for electricity generation and pyrolysis for heat generation. Unless the grid becomes more reliable or DMS can be utilized, a battery should be added to ensure processing during outages. For an off-grid solution, the same technologies would be used but the size of the battery should be increased.

7.1 Final recommendation

Based on the findings in this report, the final recommendation to Niassa Macadamia Limitada would be to base their energy system on case C-3 with outages of 100 hours taken into account. This utilizes a pyrolysis to supply heat and solar PVs together with the grid to supply electricity. The energy system is grid connected but can only purchase electricity, and to compensate for grid outages, a battery is included in the energy system.

This energy system takes a conservative approach as it assumes that no electricity can be sold to the national grid and has the lowest investment cost of all the grid connected cases. This is chosen as NML currently has no contract to sell electricity and the selling price still is uncertain. However, if NML gets a contract to sell electricity, the energy system can easily be adapted by installing more solar PVs until the system is similar to case B-3, which would increase its revenue. The installed size of the technologies in the proposed energy system and its economic properties are presented in Table 7.1 and Table 7.2 respectively.

Table 7.1: The installed capacity of the technologies in the energy system recommended to NML.

Case C-3 (On-grid, buy only)	Electricity			Heat
	PV	Bat	Grid	Pyro
Inst. cap. [kW]	677	266 (266) ¹	480	280

¹ Installed size of the battery (kWh)

Table 7.2: Economic properties of the final recommended energy system to NML.

Economic property [kEUR]	
Total investment cost	118.7
Annual investment cost	83.1
Annual O&M cost	66.1
Annual revenue	80.7
Total annual cost	68.6

8

Future work

The process demand is a rough estimate in the current model. When more details about the processing equipment are known, the demand can be updated to better reflect the actual load. When the demand is better understood, more focus could be put on demand side management which might decrease the need for capacity which would further lower total annual cost. If the value of processing nuts was added to the model, it could further be investigated if there might be beneficial to stop production during outages instead of investing in batteries.

Since the quantity of processed nuts will affect the energy demands of the system, it is suggested that future work should focus on incorporating a more realistic model of nut growth and harvesting. This could include the effects of weather and fertilizer. It would be beneficial to include how introducing biochar in the soil could affect plant growth as it could make the pyrolysis even more favorable and increase the revenue of the energy system. As the pyrolysis will produce different qualities and amounts of biochar depending on the fuel used, the MNS should be test fired in practice.

This report has mostly focused on ways to utilize the macadamia nut shell, however, there might be additional benefits from utilizing the macadamia husk. It could either be sold or used as a fertilizer, or as a fuel when dried. Due to the husks not containing any valuable products, the drying does not have the same need of control and it might be viable to dry them in the sun. Further studies regarding the husks would have to be made to know how they could most effectively be put to use.

To be able to construct the system in practice, it is necessary to further investigate system stability. This project has only focused on the size of generation technology to ensure enough is supplied to meet demand while if an energy system is to be designed, more components are required. Components such as capacitors and converters are not considered but are important to keep reactive power at stable levels and control frequency, to name a few. Therefore, more work on electric power engineering is required to design a complete system.

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A

Appendix 1

The appendix contains a description of the model input, the settings used in the PVWatts calculator and a summary of the case results.

A.1 Modeling sets, indices, variables, and parameters

This section contains a description of the sets, indices, variables, and parameters used in the model. Table A.1 contains a description of the sets, Table A.2 describes the different parameters and Table A.3 describes the variables.

Table A.1: The different sets and indices used by the energy system model

Set name	Notation	Indices	Elements
Investments	I	i	$\{PV, DG, EB, HP, Pyro, HOB, grid, store, power\}$
Plants	P	p	$\{PV, DG, EB, HP, Pyro, HOB\}$
Heat suppliers	H	h	$\{EB, HP, Pyro, HOB\}$
Biofuel users	B	b	$\{Pyro, HOB\}$
El Suppliers	S	s	$\{PV, DG\}$
Time	T	t	$\{1, \dots, 8760\}$

Table A.2: The different parameters used by the energy system model

Parameters	unit	description
sun_t		normalized solar supply
O_t		Grid outages
dp_t^e	kWh/h	process electricity demand
dp_t^h	kWh/h	process heat demand
a_i		annuity factor
vc_p	EUR/kWh	variable cost
fc_p	EUR/kW	fixed cost
ic_i	EUR/kW	investment cost
c_{el}	EUR/kWh	cost of electricity
$c_{biochar}$	EUR/kg	cost of biochar
K_i	kW	Max installed capacity
α		biofuel to biochar conversion
θ_i		ramp down
δ_i		ramp up
η_i		efficiency
γ_h	kWh_e/kWh_h	el. demand to gen. heat
E_{MNS}	kWh	Energy in macadamia nut shell
HHV_{carbon}	kWh/kg	HHV of carbon

Table A.3: The different variables used by the energy system model. The positive variables can not be less than zero

Positive variables	unit	description
D_t^e	kWh/h	total hourly el. demand
D_t^h	kWh/h	total hourly heat demand
S_t^e	kWh/h	total hourly el. supply
S_t^h	kWh/h	total hourly heat supply
$e_{s,t}$	kWh/h	supplied electricity
$h_{h,t}$	kWh/h	supplied heat
$grid_{sold,t}$	kWh/h	sold electricity
$grid_{bought,t}$	kWh/h	bought electricity
$bat_{charge,t}$	kWh/h	charged electricity
$bat_{disch,t}$	kWh/h	discharged electricity
SOC_t	kWh	battery state of charge
$E_{biofuel}$	kWh	bought biofuel
k_i	kW	installed capacity
C_I	EUR	annual investment costs
C_{fuel}	EUR	annual fuel costs
$C_{FO\&M}$	EUR	fixed O&M costs
$C_{VO\&M}$	EUR	variable O&M costs
$C_{O\&M}$	EUR	total O&M costs
C_{REV}	EUR	total annual revenue
Variables	unit	description
C_{OBJ}	EUR	total annual costs

A.2 PVWatts® Calculator settings

The settings in Table A.4 was used in the PVWatts® Calculator to calculate the normalized generation from the solar PVS.

Table A.4: Setting used in *PVWatts® Calculator* to generate the location specific solar generation

PVWatts Hourly PV Performance Data	
Requested Location	NIASSA, MOZAMBIQUE
Location	HARARE, ZIMBABWE
Latitude (DD)	-17.92
Longitude (DD)	31.13
Elevation (m)	1503
DC System Size (kW)	1
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt (deg)	20
Array Azimuth (deg)	0
System Losses (%)	14.08
DC to AC Size Ratio	1.2
Inverter Efficiency (%)	96

A.3 Case summary

This section summarizes all cases from section 5.1 to 5.3 and presents them in Table A.5.

Table A.5: Summarised table containing the energy systems from section 5.1 to 5.3

Case	El				Heat				tot
	PV	DG	Bat	Grid	EB	HOB	Pyro	HP	
A-1									
kW	2140		345 (1486) ¹		10			280	290
MWh	3601		405		66			1776	1842
A-2									
kW	1527	48	222 (1383) ¹					280	280
MWh	2570	20	370					1841	1841
A-3									
kW	1496		178 (660) ¹				280		280
MWh	2518		136				2453		2453
A-4									
kW	1496		178 (660) ¹		169	169	111		449
MWh	2518		187		486	627	970		2083
A-5									
kW	1496		178 (660) ¹			280			280
MWh	2518		136			1841			1841
B-1									
kW	1617			480				280	280
MWh	2721			367 (1345) ²				1841	1841
B-3									
kW	1503			480			280		280
MWh	2530			129 (1382) ²			1992		1992
C-1									
kW	680			480				280	280
MWh	1144			367 (0) ²				1841	1841
C-3									
kW	582		10 (11) ¹	480			280		280
MWh	979		9	279 (0) ²			2205		2205

¹ Size of battery

² Annual amount sold electricity

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