Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

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Assessment and development of microgrid with monitoring platform for educational purposes

Bachelor's thesis in Electrical Engineering
Supervisor: Basanta Raj Pokhrel
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Title page Bachelor thesis BIELEKTRO

Thesis title (English and Norwegian):		
Assessment and development of microgrid with monitoring platform for educational purposes Vurdering og utvikling av mikronettverk med overvåkingsplattform for utdanningsbruk		
Authors: David García Roca Ole Marcus Hovlid Johan Olav Nordahl Pablo Marqués Carrasco Per Ansgar Svee	**Project number:** E2233 **Delivery date:** 19.05.2022 **Grading:** [x] open [ ] closed	
Study:	Electrical engineering - BIELEKTRO	
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Client **Contact person:**	Skjetlein High School, Trondheim Stefan Preisig	

Abstract (English and Norwegian):

The purpose of the project was to use the micro hydro, solar and wind resource facilities at Skjetlein High School and combine them into a micro-grid platform, where the power production data is monitored so that it can be used for educational purposes through a graphical platform.

After assessing the status of the components on site, the system was designed and subsequently evaluated for what was required for it to be functional. Based on that the client was given a shopping list of needed components, of which there was some ambiguity on the formalities on public purchases. The project was delivered as a set of schematics for the production facilities and the microgrid, an assessment of the potential energy production and working software code for collecting and showcasing data on a GUI.

Formålet med prosjektet var å bruke vannkraft-, solkraft- og vindkraftfasilitetene på Skjetlein videregående skole og kombinere dem sammen til en mikronettverkplattform, hvor kraftproduksjonsdata blir overvåket slik at det kan bruke til pedagogiske formål gjennom en grafisk plattform.

Etter en vurdering av tilstanden på komponentene på stedet, ble systemet designet og deretter evaluert for å finne ut hva som krevdes for at det skulle være funksjonelt. Basert på dette ble klienten gitt en handleliste med de nødvendige komponentene, hvor det ble litt uklarhet rundt formalitetene ved offentlige innkjøp. Prosjektets ble levert som en samling av skjema for produksjonsfasilitene og mikronettverket, en vurdering av den potensielle energiproduksjonen og fungerende programvarekode for å samle og fremvise data på et grafisk brukergrensesnitt.

Key words English:	**Key words Norwegian:**
Microgrid, renewable energy, programming, solar energy, wind energy, hydro energy, educational	Mikronettverk, fornybar energi, programmering, solkraft, vindkraft, vannkraft, pedagogisk

Abstract

This bachelor was carried out in co-operation with Skjetlein VGS. Their title of the project pitch was: "Control system and Energy management for (solar/wind/hydro)". Skjetlein has micro hydro, solar and wind resource facilities. Their wish was to combine the 3 sources of renewable energy into a micro-grid platform, where the power production is monitored so that the data can be used for educational purposes through a graphical platform. The center of the micro-grid is the Energy Hut, where the students can see the electronics used, how everything is wired together, and a GUI that shows power production from sources and battery voltage level.

The first step was to assess the status of the components on-site, and consider what components were missing for the system to be functional. It was decided that the solar part of the project was closest to working condition, the panels were old but had been in use previously. For the wind they only had the turbine, everything else needed, except the mast, the group would have to procure. Finally, the hydro had a water turbine that was not connected but had already been used to produce electricity previously, and a working waterwheel that was not connected to anything. Afterwards, an evaluation was made for each source (solar/wind/hydro) as to how best utilize the available locations, such as where to place the wind turbine. As well as considerations for a missing components list, E.g. what generator would be needed to fit the size and RPM of the water wheel.

After identifying the status of each energy source, the focus was on the development of the operation platform. Including a control board with switches for the electrical system, a circuit board for the electronics, and a software for collecting and displaying data on a GUI.

Hence, finally at the bachelor's conclusion the group handed over finished schematics for the microgrid, working software code that suited the requirements, and the electronic components the grid needed to operate.

Sammendrag

Denne bacheloroppgaven ble skrevet i samarbeid med Skjetlein VGS. Tittelen på oppgaven var "Styringssystem og energimanagment (vind/sol/vann)". Skjetlein har mikro hydro, sol, og vind energi fasiliteter. De ønsket å kombinere de 3 formene for fornybar energi til en egen mikronettverk, hvor energi produksjons data ble logført og vist frem grafisk for undervisning. Mikronettverket var sentralisert i Energi Hytta, hvor studenter ved skolen kan se de elektroniske komponentene brukt, hvordan alt er koblet sammen, og en GUI som viser produksjon og batterinivå.

Det første steget var å vurdere statusen til alle komponentene de hadde, og å vurdere hvilke komponenter som manglet. En oversikt gruppen gjorde viste at sol-delen var nærmest å bli ferdig, solcelle panelene var gamle men har verdt i brukt tidligere. Vind-delen hadde kun en turbin, alt annet måtte anskaffes. Til slutt, vann-delen hadde en vannturbin som allerede produserte strøm og et fungerende vannhjul som ikke var koblet opp mot noe. Etterpå ble det en evaluering for hver energi kilde (vind/sol/vann) angående hvordan best å benytte seg av tilgjengelig lokalitet og utstyr. Eksempelvis hvor man kunne plassere vindturbinen og hva slags generator passer til størrelsen og RPM av vannhjulet.

Etter en gjennomgang av hver energi kilde, gikk fokuset til utvikling av operasjonsplatformen. Inkludert et kontrollbord for det elektriske systemet, og software for insamling og visualisering av data via GUI.

Ved bachelorens slutt overrakte gruppen plantegninger for hele mikronettverk systemet, fungerende software kode som oppfylte kravende, og elektroniske komponenter som trengtes for å drive mikronetverk.

Preface

This Bachelor thesis is the finishing project of the course of study for three students of the Department of Electrical power engineering and two students of the Department of Electronic Systems at NTNU. The initiator of the project was Stefan Preisig of the Skjetlein High Scool.

The purpose of the project was to utilize the hydro, solar and wind resource facilities at Skjetlein High school to combine them into a micro-grid platform. Subsequently, the energy production data is monitored so that it can be used for educational purposes through a graphical platform.

As the group was of a rather heterogeneous character with two foreign exchange students from Spain and three local students from different departments and studies, none of which having the working language as native, it has been a challenging yet rewarding process to work on this project. After some initial challenges the group gradually became what you might refer to as a well oiled machine. The task that we were challenged with was a relatively open ended one, giving lots of room to find creative solutions to the problem at hand.

The fact that the world is on a turning point when it comes to how to get enough clean energy, this project was highly relevant and interesting to us. Hopefully this could be a small increment on the way to a carbon neutral world, especially considering that this could potentially inspire future agricultural workers and technicians to consider alternative means of energy for their farms and facilities.

The entirety of the project has been done by all of the students in community, and we all want to direct our sincere gratitude to Stefan Preisig (Skjetlein high school) and Basanta Raj Pokhrel (supervisor from NTNU) for constructive comments, encouragement, guidance and support throughout the project.

Trondheim, 18.05.2022

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Acronyms and Definitions

GUI - Graphical User Interface

AC - Alternating Current

DC - Direct Current

MPPT - Maximum Power Point Tracker

PMSG - Permanent Magnet Synchronous Generator

VAWT - Vertical Axis Wind Turbine

HAWT - Horisontal Axis Wind Turbine

MC - Micro-Controller

SBC - Single-Board Computer

RPI - Raspberry PI

ADC - Analog-to-Digital Converter

GPIO - General-Purpose Input/Output

PCB - Printed Circuit Board

WLAN - Wireless Local Area Network

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1 Introduction

In today's world it's evident that we're experiencing cataclysmic changes in both climatic and security matters. On the course we are heading now it all points towards an era of resource scarcity and increased level of conflict. In this environment it is critical to look at alternatives to the ways of running our societies. The most important resource after the bare necessities like water and food is energy.

It is impossible to include all the settlements of the world in to centralized energy grids, so there is a need to find new solutions to remote sites beyond the ineffective and expensive fossil power plants of the past. A solution that could and should be explored is localized renewable energy production, storing and distribution, so called micro grids. These grids could include single entities like cabins or houses, but there is also potential to have somewhat larger grids to power small communities like villages or even islands. In order to achieve this, one needs to assess the potentials of the different sites and produce renewable according to the strengths of each individual site.

We are exploring in to such a system in this report. We have been given a set of equipment and our task is to tie it all together into a functional micro grid. We will assess the properties of the site and the equipment so that we can give advice, and so that we will be able to visualize the results of the completed system. This can in turn educate and entice the future agricultural workers and technicians of Skjetlein High School on the properties of different energy sources and the means of tying them together, as well as the benefits of a micro grid.

1.1 Background

Why is there a need for solar/hydro/wind?

- Generally: the need for more and more renewable energy. In today's world there is an ever-growing need for energy, as humanity continues to grow, more and more people obtain a higher standard of living. At the same time: the world's resources are already strained and is insufficient for tomorrow's problems. Clean, renewable energy is an important step towards a better life for all, so much so, that it is one of UN's "Sustainable Development Goals". 7: "Affordable and clean energy". [1]
- For the client specifically: The world needs more renewable energy, and it needs new innovations in the field. Therefore, it is important that the children of today learn about renewable energy: how it works, what it can be used for, and hopefully: create a spark of interest in them.

This project is about the setting up of simple hybrid (Solar/hydro/Wind) operational platform for high school students near Trondheim. Skjetlein high school wanted to rearrange the infrastructure they have and develop teaching learning platform to demonstrate the utilization of renewable energy resources. To that end, they wanted to utilize hydro, solar and wind sources they have, and develop the platform to visualize/monitor production and utilization of electrical energy through a GUI. One part of the hydro plant was already connected to a battery, and the solar panels had been in the past, but there is still some possibility to expand using existing resources to use it as an "Energy Hut" and develop it as the prototype of renewable energy operation system that can be helpful to educate school students.

The project then became a set of some small individual parts with the end goal of having a functioning "Energy Hut", that was self-sustained with the solar and wind energy it produced. In this hut you should be able to look at the screen and see a chart of the energy being produced (and possibly utilized) by the different sources and load (battery, charging station etc.). This info should also be available online. Similarly, the hydro should have probably its own GUI that show the energy produced, as well as the opportunity to transport the energy to the "Energy Hut" in a battery. Then the energy can be utilized out of the hut via a regular load as well as additional load for example an e-bike charging station.

1.2 The thesis text

Development of operational hybrid (PV/Hydro/Wind) power production platform with GUI and monitoring software at Skjetlein high school.

1.3 Problem statement

On the outset we have a hut with solar panel attached and with the components and batteries to produce and store the energy from it. We have a waterspout generator, with the necessary components, including a battery that can be moved physically to the school premises, and a windmill and battery, lacking the controller and the inverter. We also have a large wooden water wheel, that could be used to produce hydro power.

Until now the waterspout has been used to collect power, that subsequently has been utilized for charging cell phones, among other things. The water wheel has been used as a proof of concept, but not utilized for any kind of practical use.

The client wishes to be able to use some of the systems they already have to produce energy, and from that showcase the different concepts for the students at the high school. However, there is currently only one proven system (waterspout) and that do not produce any kind of useful data. The solar and wind system has been in use before but are disassembled and has been unused for a period, and there has not been any collection of data before. The water wheel system is except for the water wheel itself only a theoretical concept.

To fulfill the clients wishes, we must test the different systems, replace, or acquire the necessary components, collect relevant data, process them, and create a system for presenting them in a form that is understandable, engaging, and educational for high school level students. To sum it up, we will design and create a diversified power system for educational purposes, based on wind, solar and hydro energy production.

1.4 Project goals

- Develop a complete operational lay out and schematic diagram for the individual power system.
- Develop high level electrical circuit diagram (in reference to existing system) to show complete component set up and their rating.
- Create a system to manage different sources of power production.
- Implement hardware to measure weather data and power production data at the different sources.
- Implement proper software to present power production from different sources over time and compare to weather data.
- Propose power electronic components to transform and utilize the power from the wind generator.
- List and evaluate the equipment available.
- List and calculate the equipment needed.
- Propose a generator to utilize the water wheel for power production.
- Create a sun tracking system for the solar array.
- Design the energy hut for education and charging purposes.
- Implement all the equipment on the electrical circuit to have a complete set up (PV/Hydro/wind/battery charging system/GUI system) running.

1.5 Methodology

The first step was to assess the status of the entire micro-grid system as it was, then to consider what components were missing for the system to be elevated to a functional state. In this context, functional would mean for at least one power unit to produce energy with a functioning data monitoring system.

After this initial assessment, an evaluation was made for each energy source (solar/wind/hydro) as to how best utilize the available locations available and equipment on hand, such as calculating where to place the wind turbine and determining which generator would be needed to fit the size and RPM of the water wheel.

Once these evaluations were complete, a list of missing components was generated so that these could be acquired and the necessary installations made. While this was happening, the data collecting platform was being created in parallel as this was done through deploying micro-controllers and a small single-board computer as the main unit.

1.6 The structure of the report

This report has been split into different independent sections:

- First a little introduction about what the project is going to be about.
- Then, the Energy Hut. Which can be written in Chapter 2. The energy hut is the main place where all the connections and everything is connected, so it can be defined as one of the most important parts in our project.
- Afterwards it's written the different renewable sources which Skjetlein has available at its place, ordered from importance to the energy hut and power output. Beginning by the solar, which supplies the maximum power to the energy hut. Which is furthermore explained in Chapter 3.
- Then, it's written about how the wind produces energy which will be connected afterwards into the battery.This part is better explained in the introduction in Chapter 4.
- To finalize with the renewable sources, it's written about the hydro. And it's main production and realization of connections and blueprints. Which is written in Chapter 5.
- Before the conclusions, it's needed to define the electronics. And with it, what has been realized for the development of the firmware and software. Within the electronic components used for this realization. More information is written in the Chapter 6.
- Before the realizations of the conclusions, it has been added a chapter of the field work (Chapter 7). Which is mainly all the tasks that have been realized at Skjetlein and what elements are at the placement with some suggestions.
- To conclude the project, it has realized a few conclusions of what has been learned on the project, and the future goals within this project. Which is furthermore written in the last chapter of our project, Chapter 8

2 Energy Hut

The purpose of this chapter is to introduce the concept of the Energy Hut and the micro-grid and explain the design of the complete systems and that conform the Energy Hut and micro-grid.

2.1 Introduction

Our main goal in the Energy Hut, is to create a system designed to teach students about the production of energy from different renewable energy sources, and how this can be implemented to create a micro-grid.

The Energy Hut is a small building that will be used as the center of information for the monitoring of the energy sources data collected. The school's intention is to use this place as the main teaching place for the renewable energy topic.

The different energy sources that will have a data-logging system in the Energy Hut will be: hydro, wind and solar energy generating systems. Each of this energy sources will be used to charge three independent batteries which will be generating stations to power the Energy Hut and the Hydro Hut. The information will be displayed via a GUI and there will be a dedicated computer for the processing and analysis of data collected from the sources.

2.2 Micro-grid

A micro-grid is an electrical system that has all the elements needed to form an electrical grid, but it is isolated from the main electrical grid. Unlike common electrical grids, a micro-grid needs to have an energy storage system to store the energy produced but not consumed.

The different systems needed to form a micro-grid are the following:

- Energy generation: All electrical grids need to have energy generation systems to produce the power consumed by the loads connected. In a micro-grid, the energy generation systems are usually renewable energy systems that inject power in different parts of the grid. In our micro-grid, the energy generation comes from the solar and wind systems.
- Energy distribution: The energy that flows in the micro-grid needs to be transported to different points of the system, and the energy distribution system is in charge of this task. The system is composed of distribution lines and related accessories, that connect all the active elements of the system: generation, load and storage.
- Energy storage: As the energy generation systems are renewable sources, the energy production can not be controlled so it will not match the timing of the energy demand from the load. To solve this problem, an energy storage system has to be connected to the grid, in order to store the surplus energy from the generation and injected to the grid when it is needed. In our case, the storage system is a static battery.
- Energy consumption: The main purpose of an electrical grid is to provide power to a determined electric load, that can be anything that takes electric energy as its energy source. The loads connected to the grid can only absorb the energy injected to the grid by the generation system and the battery, in case the demand exceeds the production. In our micro-grid, the loads are the electronic systems in the Energy Hut and the electrical devices connected to the electrical circuits of the Energy Hut.

The advantages in respect to classical electrical grids are that want to be achieved with micro-grid systems are a higher implementation of the renewable energy sources, more efficient use of the energy distribution system and a more efficient use of cheaper energy sources, reducing cost for the client.

In our micro-grid, the goal is to proof that the concept works and can be implemented in a small scale system. It also wants to show that school students can learn this concepts, promote the development of this systems in the future.

This next figure 1, is a drawn schematic of how is conceptually made a micro-grid. This image illustrates a general concept of all the elements that can form a micro-grid, although it is not necessary to have all the elements present in figure 1 to have a functioning micro-grid.

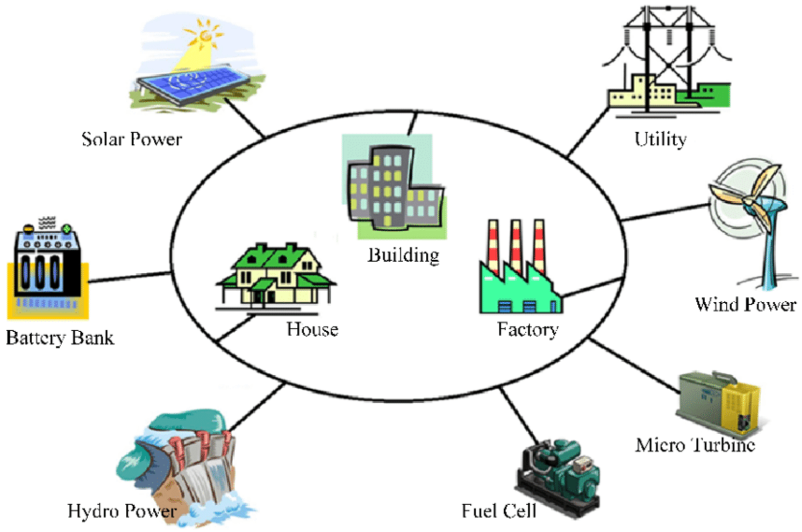

Figure 1: Example of micro-grid [2]

Our system creates a micro-grid that has two generating energy elements, solar and wind systems, one storage element, the battery, and one load element that is fed through the inverter. The common DC bus is the energy distribution element between the sources of energy, the battery and the inverter. In the following figure 2 can be seen the schematic connection of the different elements of our system that creates the micro-grid.

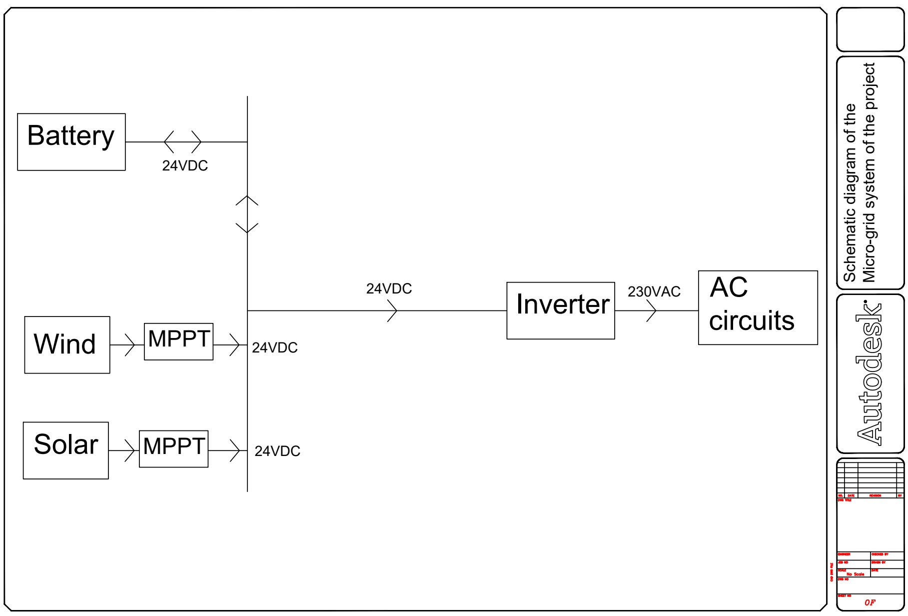

Figure 2: Schematic design of our micro-grid system

2.3 Layout of the Energy Hut

In this case the energy hut is used as a centralized building in which all the data will be controlled by different elements. Besides the hut is connected within the solar source the wind plant and the hydro. Even the hydro is not used as a main source to power the energy hut.

Before explaining which physical elements are located inside the energy hut, is needed a previous design to comprehend the location, and afterwards it will be explained the utility of each element.

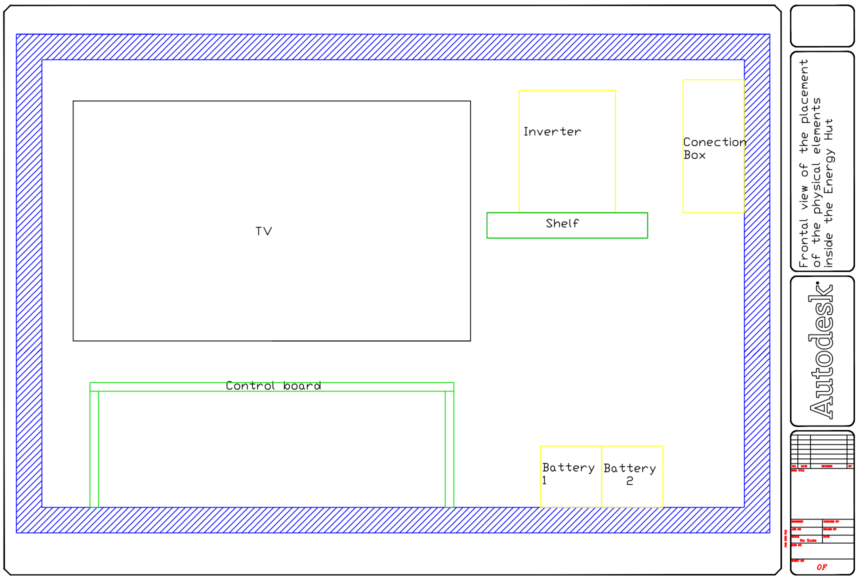

Figure 3: Energy Hut Layout Front view

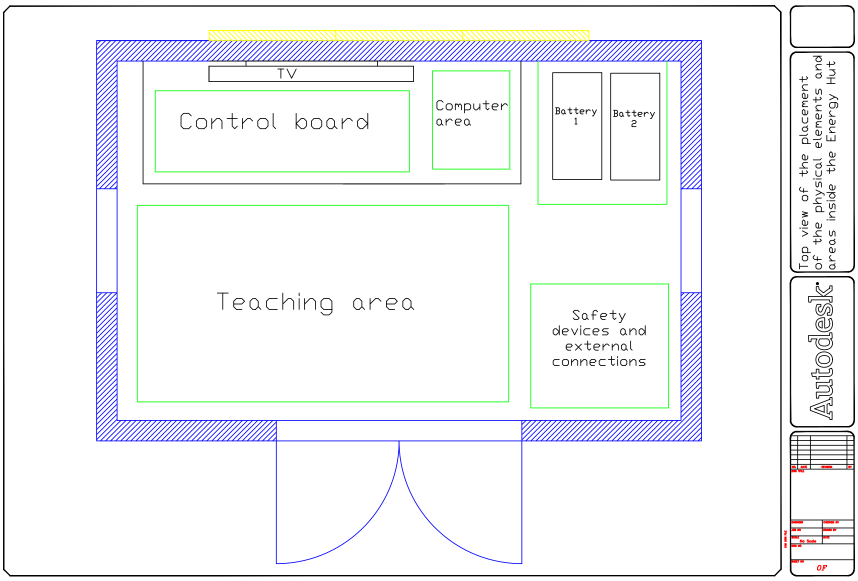

Figure 4: Energy Hut Layout top view

The energy hut as it can be observed in the representations made above of 3 and the 4 is split in to different main areas which are explained by the following:

- Teaching area: Whereas the students can observe the visual of how the energy flows from the different sources.
- Control board: the area used for the installation and the control of the electric and electronic system inside the hut.
- Computer Area, used for the unique use of the computer which runs the electronic program.
- Battery Area, used for the location of the batteries and the electric and electronic protection of the system

2.3.1 System topology

As the energy hut is isolated from the grid it is powered by two main sources, the solar and the wind system. The solar system is producing a maximum of 420 W and the wind 200 W. The output power is connected to a battery by a DC common bus of 24 V. Therefore, the bus is connected to an inverter that feeds all the AC connections at 230 V.

The battery has the following characteristics [3]:

Name	Voltage	Capacity	Weigh	Size(mm)	Storage technology
RITAR GEL Deep Cycle Battery	12VDC	100AH	30kg	328x169x222	Gel

Figure 5: RITAR GEL Deep Cycle Battery [3]

2.4 Power systems in the Energy Hut

The Energy Hut is isolated from the electrical grid. This creates the need of alternative power sources. In this project the Energy Hut is powered by the solar photovoltaic system and the wind power system. These two systems produce electrical energy that is stored in the batteries that are inside the Energy Hut. The energy produced in the Energy Hut is used to power all the electric and electronic systems in the Hut.

This configuration makes the operation of the Energy Hut independent from the electrical grid. This characteristic has a few advantages:

- Protection against grid power outages.
- Virtually zero cost operation, as all the energy is obtained for free from solar and wind systems.
- Extremely reduced carbon footprint of the Energy Hut, as it is totally powered from renewable sources.
- Not fixed to a determined location, as it is not tied to wires from the grid.

Having this configuration has also a few disadvantages that need to be taken into account:

- Limited amount of energy available for use in the Hut.
- Initial high economic cost, as the purchase of costly components, like the batteries, is needed.
- Possibility of running out of energy in the Hut and interrupting the Hut operation.

The energy consumption of the Energy Hut will be discussed in section 2.7.

2.5 Control board

One of the key elements of the Energy Hut is the control board. This is a table-like surface that has switches, relays and electronic devices to control the electric systems of the Energy Hut.

The control board has an electronic central element that is the Raspberry Pi 4(RPI)[4]. This device is a small size computer that can perform any task as a common computer, but with a reduced power consumption. In chapter 6 will dive deeper into the workings of the RPI. This electronic device is the central compute unit of the system. It is in charge of collecting the information from the data-logging external devices and then processing all of the information to display it appropriately and take actions in case it is necessary.

The Raspberry Pi 4 uses the WIFI communication protocol[5] to get the data from the external devices. This protocol is a wireless communication protocol that allows to send and receive information to the Raspberry Pi 4 through a local network. The devices communicating in the system are ESP32[6] devices explained in chapter 6.

The Raspberry Pi 4 actuates over three low power relays that are used to carry different actions over the system.In section 6.3.2 these devices are explained in detail.

The control board has two physical buttons that have different purposes. The first button is a push style button that it is used to connect or disconnect the battery from the rest of the electrical system. When the battery is connected to the system, pushing the button will disconnect the battery from the system. In the opposite case, if the system is powered on and the battery is disconnected, pushing the button will connect the battery to the system. The complete layout of the control board is in figure 6.

The second physical button is the emergency stop button. This button is a mushroom style emergency stop button that has the function of shutting down the complete system when pushed. The action of pushing this button will cut the power supply to two high power relays that will disconnect the inverter from the 24VDC common bus. This will turn off all the AC circuits, which will turn of the Raspberry Pi 4 and the low power relays will disengage and the battery will be disconnected from the rest of the system. These actions will isolate the different elements of the electrical system.

2.5.1 Board switches

The control board hosts all the control switches that are used to actuate on the electrical system. The control board has two kind of switches: electric and mechanical.

The electric switches are relays that are controlled by the Raspberry Pi 4.The high power relay can be actuated in person through the control board, or through WIFI, as the small power relay.

The switches controlled directly by the Raspberry Pi 4 are three independent low power relays that have different purposes. These relays are low voltage relays that are activated with 5V DC power. This power is provided directly by the Raspberry Pi 4. Two of these relays are used to turn on the LED lights on the control board that indicate if the wind or the solar systems are producing power.

The third relay is used to control the connection or disconnection of the battery from the rest of the system. This low voltage relay is used to activate a high power relay that is activated by 24V DC power. This high power relay is designed to handle the high currents that can be outputted the batteries. In parallel to the activation of the high power relay of the battery, an LED light is activated on the control board when the battery is connected to the system.

The control board also has two manual switches that are used to connect or disconnect the solar and the wind systems to the rest of the electrical system. These manual switches are also used as the way to power on the Hut, as it is necessary to initially have energy from the sources flowing to activate the rest of the system.

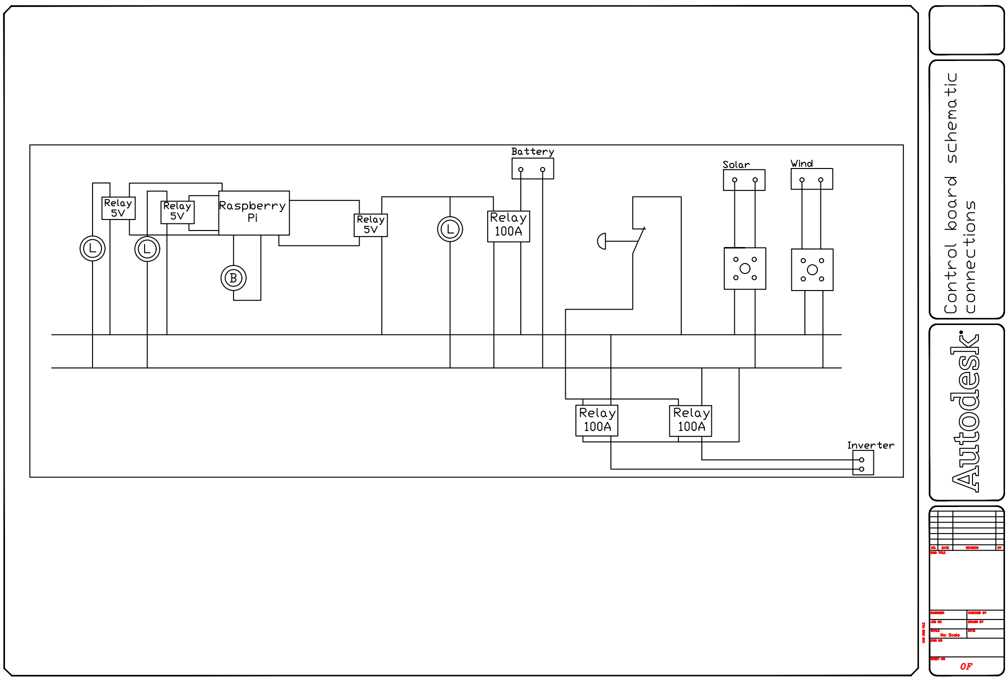

Figure 6: Control board schematic connections

2.6 Electric Sketch of the Energy Hut

Designs and blue prints of the electric systems in the hut. Also how the different circuits work.

Once all the areas and the elements in each area are define is needed to realize the electric connection and the distribution of where the different plugs are located.

This building will be only powered by the batteries charged by the three energy sources. In the building there will be a low voltage installation, working between 12V and 24V in DC, and there will also be a higher voltage installation, working at 230V AC.

Both circuits will be used to power all the devices in the building. There will be also outlets available for external use, such as an electric bike parking. But this installation has to be measured if it could be realized, because as it will be explained afterwards, maybe will be necessary more

In figure 7 a 2D sketch of the suggested distribution and wiring of the aforementioned elements in the Energy Hut:

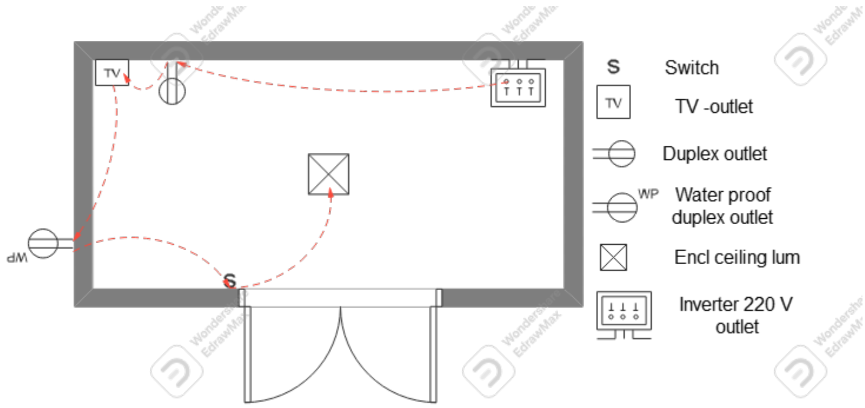

Figure 7: AC 2D-wiring diagram for Energy Hut

In the following diagram (figure 8), it can be observed the presence of the raspberry pi which will be controlling the switches via wifi. The raspberry pi will be able to control the current flowing through the TV, LED's and the possible Bike Charger.

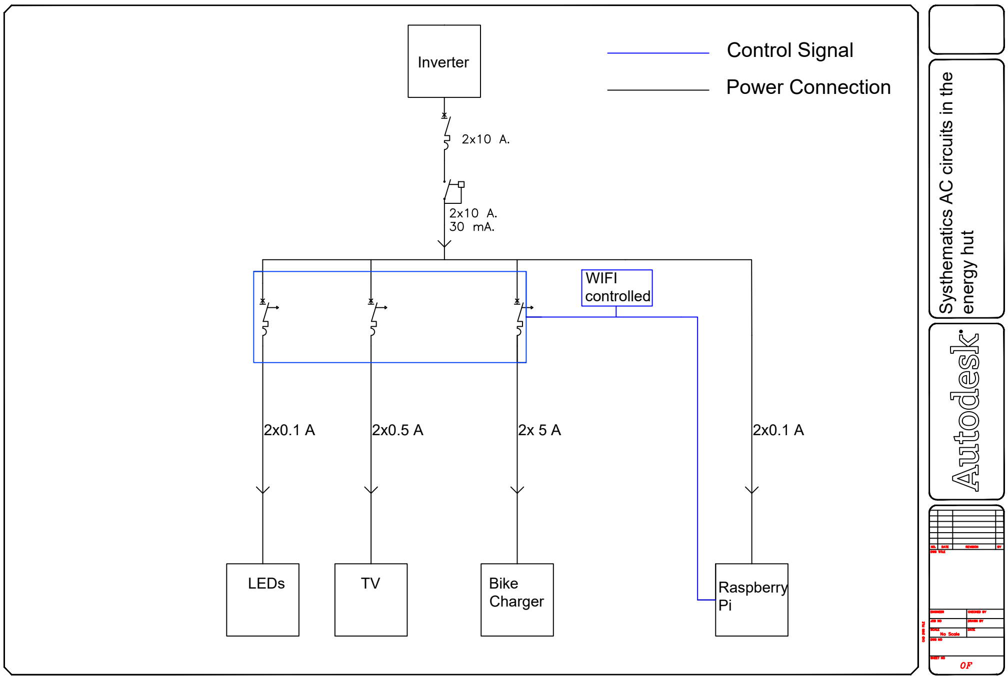

Figure 8: AC diagram for Energy Hut

Nowadays the bike charger hasn't been that advanced yet, and hasn't been chosen anything at all. Then the consumption the bike charger is going to have on our system is not available, but for the electric design, it has been decided 1000 W as a consumption. The energy hut might have some power left to power the bike charger.

2.7 Energy management of the Energy Hut

In this topic is going to be written mainly about the energy in the Energy Hut. Mainly about how the energy produced from the sources is stored, the energy balance between the consumption and the production and the generation of the sources that feed the energy hut.

The Energy Hut is isolated from the electrical grid, so all the electrical systems need to be powered by the energy generation systems or the battery. This limitation on energy availability has to be taken into account to know what loads can be powered from the Hut and for what duration. The topic of energy management refers to all the considerations related to powering the Energy Hut with the characteristics and constraints that the system has.

The main point of the energy management is the energy balance. This refers to the work done in to ensure that the Energy Hut system has enough energy to operate under most circumstances and there is awareness of the system limitations.

The energy balance in the Energy Hut has three factors. These factors will determine the amount of energy available in the Hut at any moment. The factors are:

- The energy generation from the solar and wind systems.
- The energy stored in the battery.
- The energy consumed by the different loads in the Energy Hut

The first factor is the energy generation by both sources. The solar and wind systems are independent and their energy production is not related. Each source has different factors that determine the amount of energy produced. On the solar system, the solar radiation is only available when the sun is shining and the intensity of the radiation is affected by atmospheric and seasonal factors. The wind system is dependant on the prevailing winds on the area and the effect that orographical elements have on wind currents.

For each source, an energy production estimation can be done in order to know an approximate amount of energy that will be generated. This prediction can be done on a yearly and monthly basis. If the time scale is smaller, the precision is greatly decreased and the information can not be used for the energy production estimation. The produced energy will be split between the electrical loads, like the television screen, and the battery, that will store the surplus energy from the energy sources.

The second factor to take into account is the energy stored in the battery. The battery can store a limited amount of energy. It is not expected to have excess energy over the maximum size of the battery, as the energy sources have a smaller scale than the battery. The purpose of the battery is to store or provide the energy offset between the energy produced and the energy consumed in the Energy Hut.

The third factor is the energy consumption of the Energy Hut. The electrical installation of the Energy Hut is designed to provide power to various devices. Some of these devices are known, like the television screen, the Raspberry Pi 4 or the interior lighting, but other electrical loads are not expected but can be connected to the electrical system from the electrical plugs. To estimate the loads of the system, there has been only taken into account the known loads, being the main one the television screen.

In order for the Energy Hut to be able to operate, the energy balance between the energy production and the energy consumption can not be negative. In case the balance turns out to be negative, the energy demand in the Energy Hut would be greater than what can be produced. This situation would lead to the shut down of the Energy Hut, as there would not be enough energy produced or in the battery to operate the electrical and electronic systems. To avoid this situation, the load would have to be reduced to an equal or lower level that the energy generation. This would mean actions like disconnecting the television screen, or reducing the interior lighting.

2.7.1 Energy availability calculation

The three factors that define energy calculation in the Energy Hut have to be factored in to measure the availability of the energy system. All three factors are important to calculate the energy availability, but the factors of generation and consumption have a higher importance than the energy storage factor. This is because the main focus of the energy balance is to have a non negative result in first place. Then, depending on the balance result, the energy storage factor will be taken into account.

The energy production calculation will depend on the predictions made on each energy source. For the solar system, there are two cases for the energy production forecast. This two cases will be explained on more detail on the solar chapter 3. In both cases, the energy production forecast on a monthly basis is clearly influenced by the year season and other atmospheric factors. For the wind system, the prediction is made on a yearly basis, having a similar average production for each month.

Detailed energy production of the solar system is explained in chapter 3. Detailed energy production of the wind system is explained in chapter 4.

In the case of the wind system, the wind energy production value has been calculated as an average monthly production. This assumption has been made because for the reach and scale of the wind system, there is not a practical way of doing a more precise calculation without exceeding the main reach of the project. Another reason for using this way of calculating the approximate wind energy production is the scale of the wind system compared to the solar system. The maximum power output of the solar system is over twice of the wind system, so the importance of the solar energy generation is much higher than the wind system. For the monthly wind energy calculation, the next formula(1) is applied:

$$\text{Monthly production(kWh)} = \frac{\text{Yearly production(kWh)}}{\text{12(months)}} \quad (1)$$

All the calculations are in the excel spreadsheet: energy balance.xls

The total monthly energy production for the system is the result of adding the monthly energy production of the wind and the solar systems. From this calculation there are two results, depending on the position of the solar panels. The results for the energy production can be seen in the following figures 9 and 10.

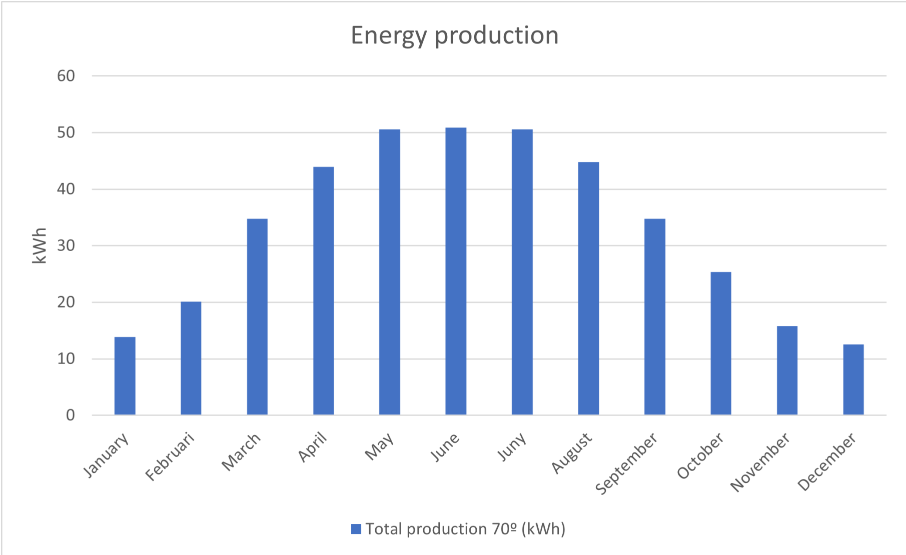

Figure 9: Energy production forecast in the opened position

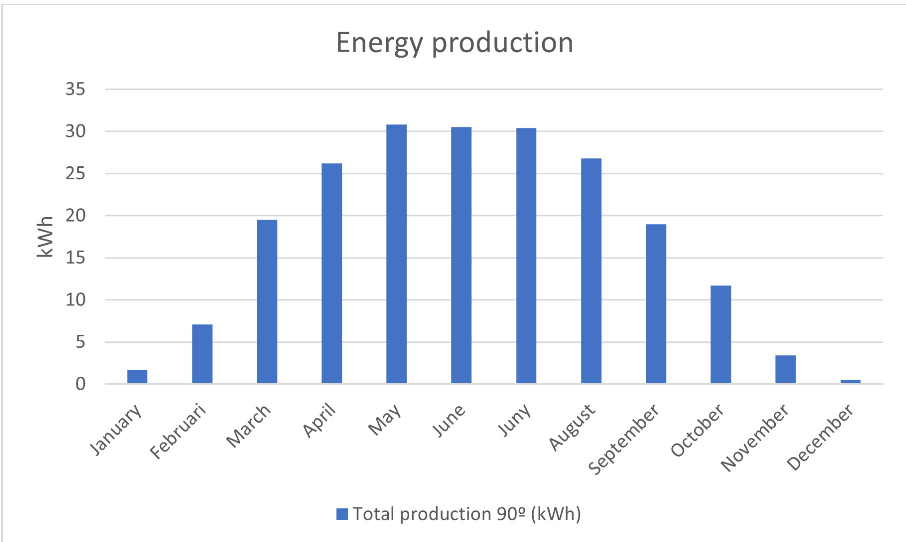

Figure 10: Energy production forecast in the closed position

The energy consumption has been calculated in the basis that the consumption occurs during daylight time, and during 6 hours per day. This value is a realistic balance between the time that the Energy Hut will be closed and unused, and the time that the school will use it for teaching purpose.

The electrical loads that have been predicted to work at the same time during the 6 hours each day, for 5 days per week. These are the amount of school days in a normal week. We are counting 4 weeks per month to calculate the monthly electrical consumption. The electrical consumption of each load has been measured with these values:

Electrical load	Power consumption
Television(TV) screen	103W
Electronic system	10W
Interior lighting	9W

The calculation steps to get the resultant value of the energy consumption monthly are the following:

1. Obtain the power consumption values of the different loads of the system from the table above.
2. Obtain the energy consumption for each device for the 6 hours per day that the devices will be working. This is the example calculation for the television screen.

$$\text{Daily energy consumption TV screen(kWh)} = \frac{103(\text{Power consumption(W)}) \cdot 6(\text{hours daily(h)})}{1000} \tag{2}$$

3. Add all the daily power consumption for all the loads connected to the electrical system.
4. Multiply the total daily energy consumption by 30 to account for a full month. This way we will obtain the monthly energy demand predicted for the Energy Hut.

$$\text{Monthly energy consumption(kWh)} = \text{Total daily energy consumption(kWh)} \cdot 30(\text{days}) \tag{3}$$

The resultant energy consumption calculated with this method is an approximately constant value of 14.64kWh per month.

To calculate the energy balance result in the Energy Hut, the total monthly energy consumption, calculated in equation 3, has to be subtracted to the total monthly energy production, that can be shown in figures 9 and 10.

2.7.2 Results of energy balance

With the data about the energy production and energy consumption in the Energy Hut, and calculation methods explained in section 2.7.1, it can be calculated the amount of spare energy that is in the Energy Hut. There is a visible difference in the results of the spare energy in the system for the different positions of the solar panels. The energy balance result of the scenario of the closed position of the solar system is seen in figure 11:

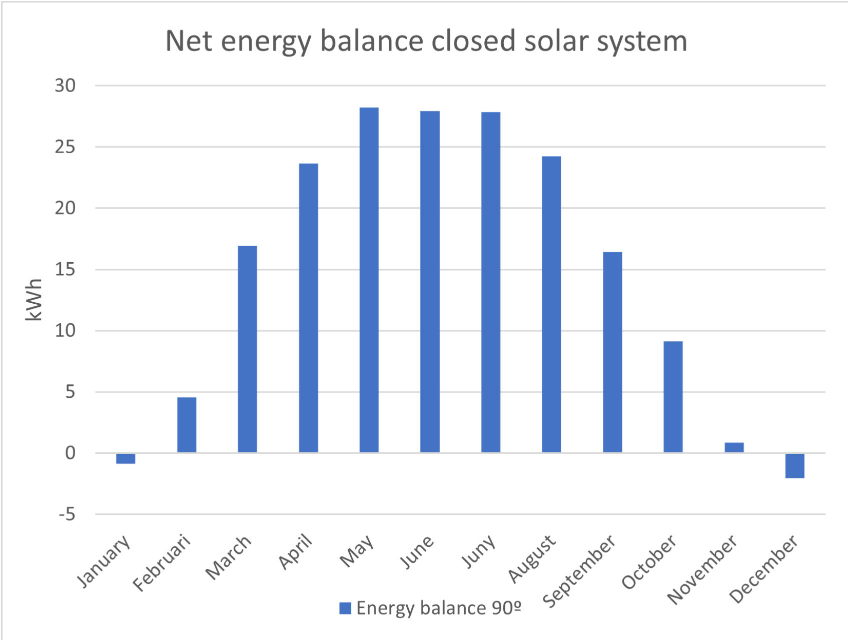

Figure 11: Energy balance forecast in the closed position

The energy balance result of the scenario of the opened position of the solar system is seen in figure 12:

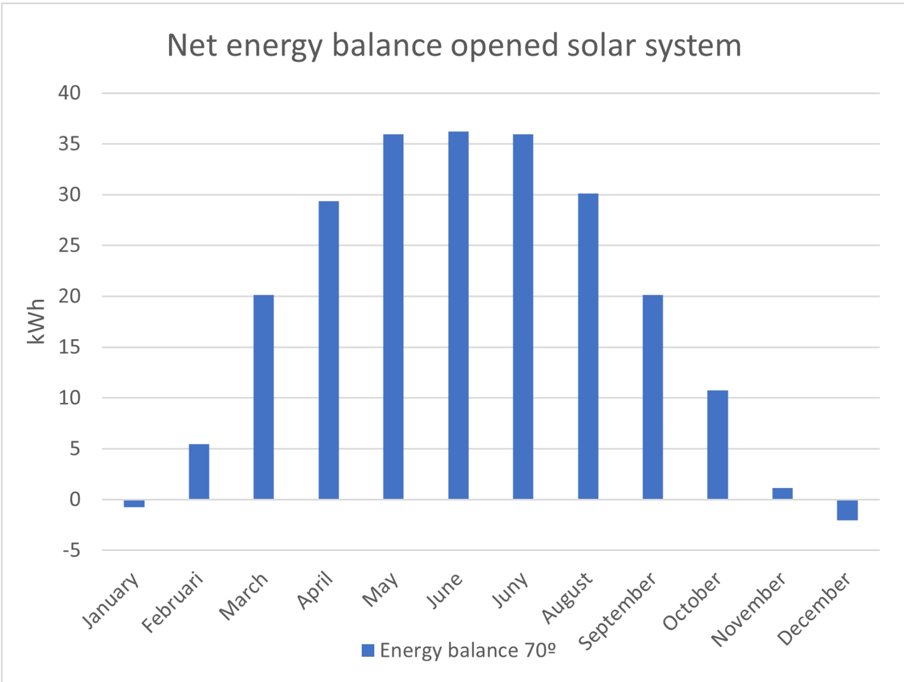

Figure 12: Energy balance forecast in the opened position

From the calculations results, can be seen that it is extremely probable to have spare energy most of the months, so the battery will have to store that energy to be used in later moments. In case there is more energy surplus from the generation than what can be stored by the battery, there are two possible solutions for this problem. The first solution is to increase the energy consumption from the AC system until the energy surplus is reduced to a correct level. Other solution would be to reduce the energy production, in order to reduce the spare energy. From a hole system point of view, it is advisable to give a higher priority to the use of the first solution, as the implementation can be slightly easier from a technical point of view.

As can be seen in the resultant data, the energy balance prediction calculated in section 2.7.1, is positive in most of the months of the year, excepting the winter months when the daylight time is the lowest. This energy deficit would be covered by the battery supplying the surplus energy from the other months of the year. The energy deficit is predicted to be small enough to avoid the shut down of the Energy Hut systems, although it is advisable to reduce the energy consumption for those months to increase safety working margins.

2.8 Operation procedures

The operation procedures for the Energy Hut are the needed operations to shutdown and startup all the electrical and electronic systems. These procedures can occur automatically or be manually triggered, as explained in section 2.5.

The shutdown procedure can be manually triggered or can occur automatically. This procedure can be triggered manually in case of a system malfunction or because the electronic or electrical systems need to be accessed and manipulated due to maintenance or other reasons.

To initiate the shutdown procedure in a non emergency case in the system shown in figure 6, the following steps need to be followed:

1. Select the OFF position in both switches that disconnect the solar and wind systems.
2. Push the blue button on the control board panel to disconnect the battery, in case it was connected to the system.

As long as the battery is not connected to the system, and the solar and wind systems are also disconnected, the Energy Hut has all systems not powered.

In case of a system malfunction or other emergency, the system needs to be shutdown immediately through the emergency shutdown procedure.

To initiate the emergency shutdown procedure, the following steps need to be followed:

1. Press the emergency button on the control board.
2. Select the OFF position in both switches that disconnect the solar and wind systems, to avoid unexpected restarts.

The startup procedure for the Energy Hut is an automatic procedure that will occur after the system is shutdown for any reason. This procedure will reactivate the electronic and electrical systems of the Energy Hut. This procedure must be automatic, as the installation is designed to keep working without supervision in case it runs out of power and there is not a malfunction.

The necessary conditions to have an automatic restart of the system are the following:

- Have not pushed the emergency stop button.
- Select the ON position in both switches that connect the solar and wind systems.

If these two conditions are fulfilled, the Energy Hut systems will startup when one of the energy sources begins generating power. The flow electrical power in the circuit for the restart has the following steps:

1. The initial necessary conditions are fulfilled.
2. The solar or wind systems begin producing power and injecting it to the DC common bus.

3. The inverter generates AC power from the energy injected in the DC common bus.
4. The Raspberry Pi 4 is turned on from its own AC power line from the inverter.
5. The electronic systems are initialized. The battery is connected to the system and is available to inject power to the DC common bus.

These steps will be followed in case that there is not any electronic malfunction. This process can be interrupted in case the energy generation from solar and wind systems is interrupted before the electronic system connects the battery to the electrical system. In case the battery is not connected to the system, because there is not enough energy stored or any other reason, the system will shutdown if the energy generation is not sufficient to keep the system running.

3 Solar

This chapter is about the solar photovoltaic energy system that is installed in the Energy Hut. All features about the system are described and analysed, giving a full explanation of the system, its design choices and its purpose in the micro-grid.

3.1 Introduction

One of the three power sources of the system is the solar photovoltaic system. This system is used to generate electricity from the solar radiation. A solar photovoltaic system is generally constituted by three elements: solar panels, maximum power point tracker(MPPT) and an inverter.

3.2 Theory

The theoretical basis of any solar photovoltaic system is transforming solar radiation into electrical energy. For this purpose, the photoelectric effect in semiconductor materials, specially silicon, is applied. Silicon cells create the solar panels, which are the point of generation of electrical energy.

One of the key aspects of a solar system is to know the amount of energy that it will produce[7]. To calculate the energy produced, there are a few system characteristics that are needed to know:

- Area of the solar panels.
- Efficiency of the solar panels.
- Solar radiation on the panel's surface.

With this information, there is the following formula that can give us an estimation of the energy production[7].

$$E = A \cdot r \cdot H \cdot PR \tag{4}$$

- E = energy produced in kWh
- A = area of the solar panels in m^2
- r = panel yield or efficiency in %
- H = the solar radiation on the solar panel surface taking into account to surface angle, in W/m^2
- PR = performance of the complete solar system in %. Usually between 0.6 and 0.9.

Our system has the following technical characteristics, obtained from the manufacturer information[8].

A (m^2)	r (%)	PR (%)
3	14	5

To obtain the missing parameter H, we can access to an online database from the European Union with publicly available information about the solar radiation from the last decade. This information is divided into monthly periods.

This theoretical basis allows us to design and calculate the characteristics and results expected from our solar installation. All the power calculations methods used in the project are explained in detail in section3.4.

3.3 Elements of the system

The solar panels are arrays of silicon cells connected in series and parallel. Each solar panel produces electrical power when the silicon cells are irradiated by the sun. The output of a solar panel is a DC voltage and current. The solar panels are connected in series or parallel to obtain different output voltages and currents for the system.

Our system is formed by 3 solar panels with this specification provided by the company GETEK Energy[8].

Name	V_{oc}	Short-circuit current	Weight	Size(mm)
SOLARTEK PVP14012	17,2V	8,14A	11kg	1480x680x34

Figure 13: SOLARTEK solar panels

This solar panels are connected in series to form one string.

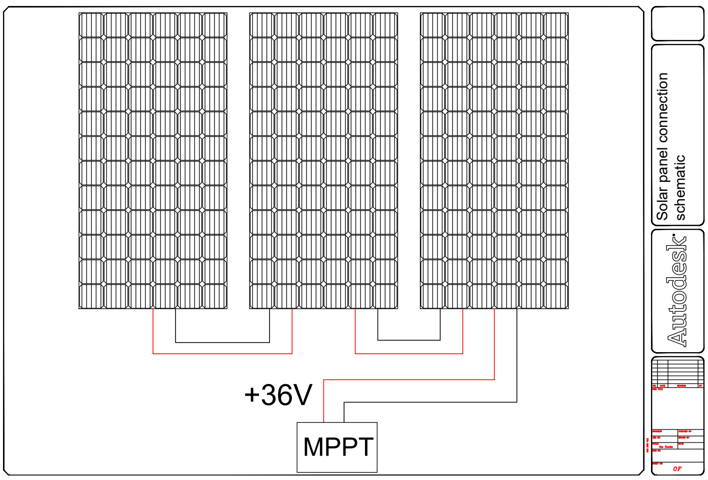

Figure 14: Solar panel schematic connections

The output power of the system changes depending on the amount of solar radiation that the solar panels receive. This power produced is a function of the voltage and the current produced by the panel. To maximize the power produced we need to optimize the current and voltage outputs based of the curve of power production of a solar module. This is an example of graph.

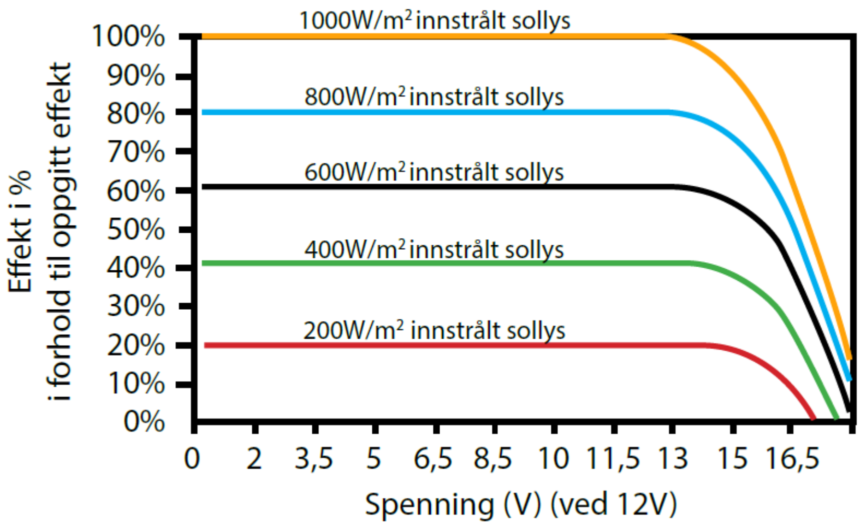

Figure 15: Voltage-power curve for the solar panels [9]

The electronic device that maximizes the power output of the solar panels is the maximum power point tracker or “MPPT”[10]. This device has implemented an algorithm that measures the power output of the solar panels and changes the voltage output of the system to obtain the maximum power. To obtain the maximum power, this device maximizes the voltage output of the system while following the power curve of figure 15.

Our system has one MPPT that it is connected to the output of the string. The nominal voltage output of the string is 36V and the MPPT steps down this voltage to match the 24V needed. The specifications, provided by GETEK Energy[8] of the MPPT are the following:

Name	Voltage	Maximum current	Weight	Size(mm)
Optimizer	12/24VDC	15A	0,6kg	169x64x73

Figure 16: Optimizer [8]

Once the DC power is produced, it must be transformed to AC to be suitable for use in the common electrical circuits. The device with this purpose is the inverter. This device has as the input the

DC power from the MPPT, and outputs AC power. The AC power outputted by the inverter matches the characteristics of the AC power in the grid, with a frequency of 50Hz and an effective voltage of 230V.

Our system has one inverter that is used by more than one energy source, what will be explained in the system topology chapter. The inverter initially used can be seen in figure 17. The inverter has the following specifications[8]:

Name	Voltage	Maximum Power(30 min)	Output current	Weight	Size(mm)
XTM 3500	24VDC	3500W	0-90A	21,2kg	133x322x466

Figure 17: GETEK XTM 3500 inverter [8]

The solar system installed in the Energy hut is consists of one string of three solar panels, an MPPT device and an inverter that is shared with the rest of the energy sources and storage systems. The MPPT injects the energy produced by the solar panels to the common DC-bus. This energy is distributed to the inverter or to the battery, depending on the demands of the system.

3.4 Energy calculation

One of the key factors for the solar system is the energy production. It is necessary to know the average energy production to compute the energy available for the Energy hut. The solar system is one of the two energy sources.

The energy production of the solar system depends on the radiation received by the solar panels and the angle of their surface to the incoming sun light. Considering these factors, can be determined that the energy production will change depending on weather factors and the season of the year. The angle of the surface of the solar panels will also determine the efficiency of the system, as a closer angle to perpendicularity will reduce the reflection of the radiation on the surface before reaching the silicon cells, therefore increasing the power production.

With the theoretical information used for this project, there are online computer programs that apply the same methodology to calculate the energy production forecast, implementing forecasting technologies to the solar radiation information. These technologies help to improve the production forecast, but require applying mathematical methods that are outside the scope of the project. To solve this problem we have have used public available online programs to make the energy estimations.

To estimate the energy production, we have used online software that uses solar radiation data and the geographical placement of the installation to make the power calculation estimation. The software is an open-source tool made by European Commission called "Photovoltaic Geographical Information System"[11].

This program uses databases of satellite obtained information to calculate the solar radiation of a specified location. Then the program considers other parameters like the installed peak power of the solar installation, the slope of the solar panels mounting system, the azimuth angle in respect to the south and general system loses.

With all the parameters of the solar system, the program makes an estimation of the monthly and early photovoltaic energy production. With this data we know of the amount of energy we dispose for usage in the Energy Hut. The parameters used for our system The parameters obtained from

Figure 18: Coordinates and orientation of the solar system

the physical location of the solar system can be seen in figure 18. All this parameters are based on the solar system design and placement. From this placement, the information fed to the calculation program[11] is the following:

- Location coordinates: 63.341, 10.302
- Photovoltaic Power: 0.42kW
- System loss: 5%
- Slope: 90º - 70º
- Azimuth (South 0º): 65º

3.4.1 Energy calculations results

For the calculation of the results we have analyzed two cases. The difference between the cases is the inclination of the solar panels. This factor has been changed because the option of the solar panels to change the inclination angle into two different positions.

The predicted monthly energy output for the solar system is calculated by the computer program[11], and it is based of the information of solar radiation between the years 2005 and 2020. The forecast done by the program it is not specified for a concrete period of time. It is a general prediction of the energy production in any year with average climatic conditions.

The first position, "closed position", it is when the panels are flat with the surface of the Energy hut. In this case the inclination of the panels in respect to the horizontal surface is 90º. In this situation the panels are completely vertical. This placement is not optimal for receiving the sun radiation, as the incidence angle of the radiation on the panels' surface is too acute, reducing the energy production of the system. The result in figure 19, shows how the energy production is higher for the summer months.

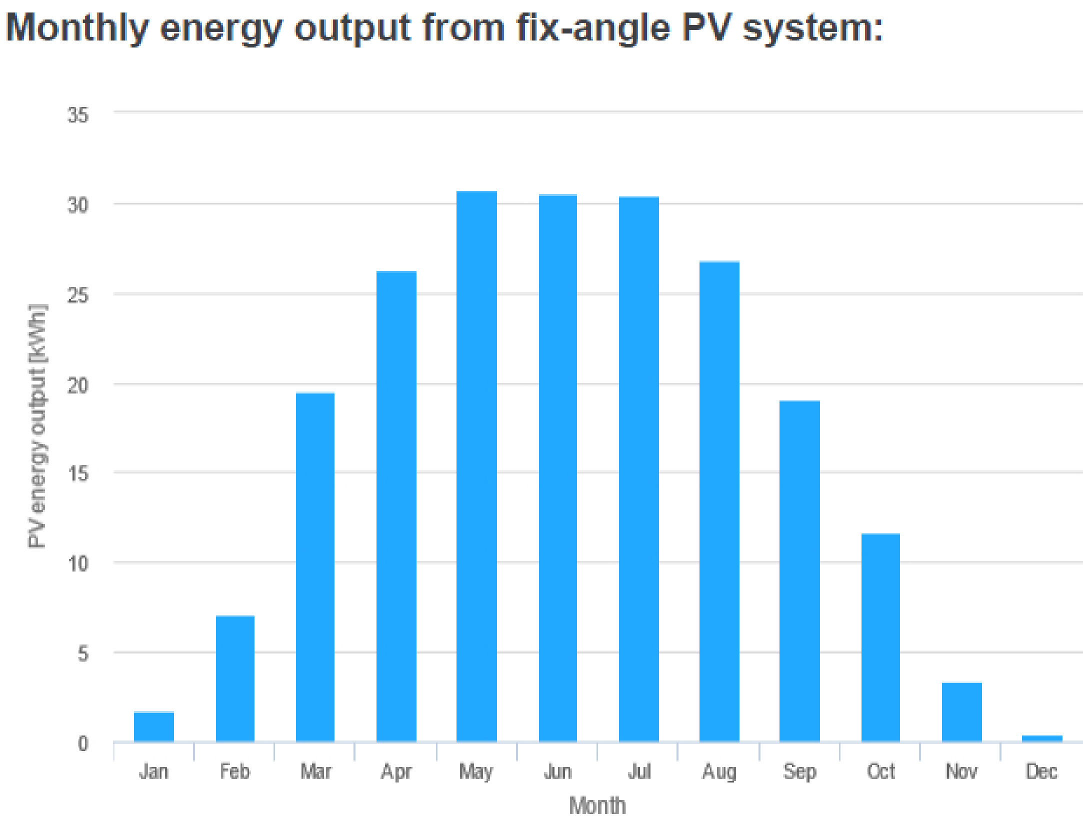

Figure 19: Energy production forecast in the closed position

The second position, "opened position", it is when the panels are angled with the surface of the Energy hut. In this case the inclination of the panels in respect to the horizontal surface is 70º. In this situation the panels are separated 50cm from the energy hut wall on their bottom. This separation on the bottom gives the panels the 20º angle of opening on the top part. This placement is better for the incidence of the sun radiation, as the incidence angle of the radiation on the panels' surface is closer to the ideal perpendicularity to the sun radiation, improving the energy production of the system in respect to the closed position of the panels. The result in figure 20, shows how the energy production when the system is in the "opened position" is higher than in the "closed position", shown in figure 19.

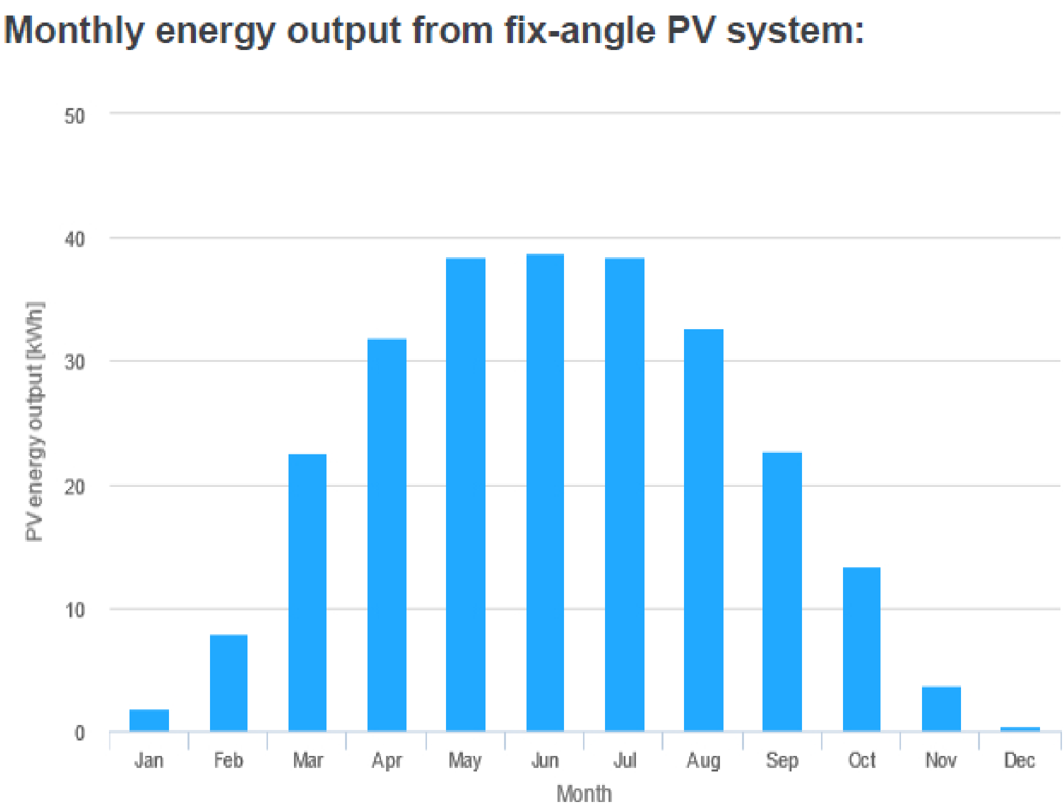

Figure 20: Energy production forecast in the opened position

As can be seen from the results, the energy generation is increased, for equal solar radiation, when the panels are in the opened position. As the solar panels are moved manually, there is not a specified reason to think that the panels will remain in the open position. On top of that, the open position has a few drawbacks, like exposing more the surface of the solar panels to weather factors like rain, hail or flying debris. These factors can get the surface of the panels dirty quickly or damage the glass surface and reduce the power production of the solar system.

All these factors need to be considered and will mean that the panels will alternate between the opened and closed positions. This variance needs to be considered in the energy production forecast, as the real production will be between both cases.

Taking into account these factors, the yearly energy production can be considered about is 215kWh. This value is inside the range of values for the possible solar energy production that the program results show, as can be seen in appendix A.

This energy production will not be distributed equally for the twelve months of the year. The energy production will change following the year seasons. As can be seen on the monthly energy production graphics, the energy production will increase to its maximum the summer months, and will decrease to the minimum the winter months. This changing energy contribution of the solar system will combine with the wind system, that it is not so heavily affected by the seasonal effects, to have enough energy for the operation of the Energy Hut.

3.5 System topology

The photovoltaic system is designed to work in conjunction with the wind system to provide power to the hut. This creates some requirements so they can both generate energy simultaneously. The requirements are that the output voltage of the system must be 24V and it must be DC power. This requirements are established in order to have a common electrical characteristics to all the devices that connect to the common DC bus in the Energy Hut. This also allows the transfer of electrical energy between all the components of the micro-grid in figure 2.

The photovoltaic modules will generate electricity that will go to the MPPT. The MPPT will adapt the voltage to 24V and will regulate the current to maximize the power output. Then the energy is injected into the common DC-bus.

The configuration of our system is designed so the inverter is connected to the common DC-bus, so the DC energy can come from different energy sources, like the wind turbine or the battery storage system. This configuration has some advantages:

- Using one inverter for all system which reduces system cost and complexity.
- More efficient use of the inverter hardware, as there is a higher use of the specified power rating.
- Simpler design of the DC and AC circuits in the Energy hut.

Having this configuration has also a few disadvantages:

- Less protection against hardware failure, as there is only one inverter, that in case of failure there is not energy production.
- There is limited expansion capacity, as the inverter limits the amount of AC power that the system can deliver.

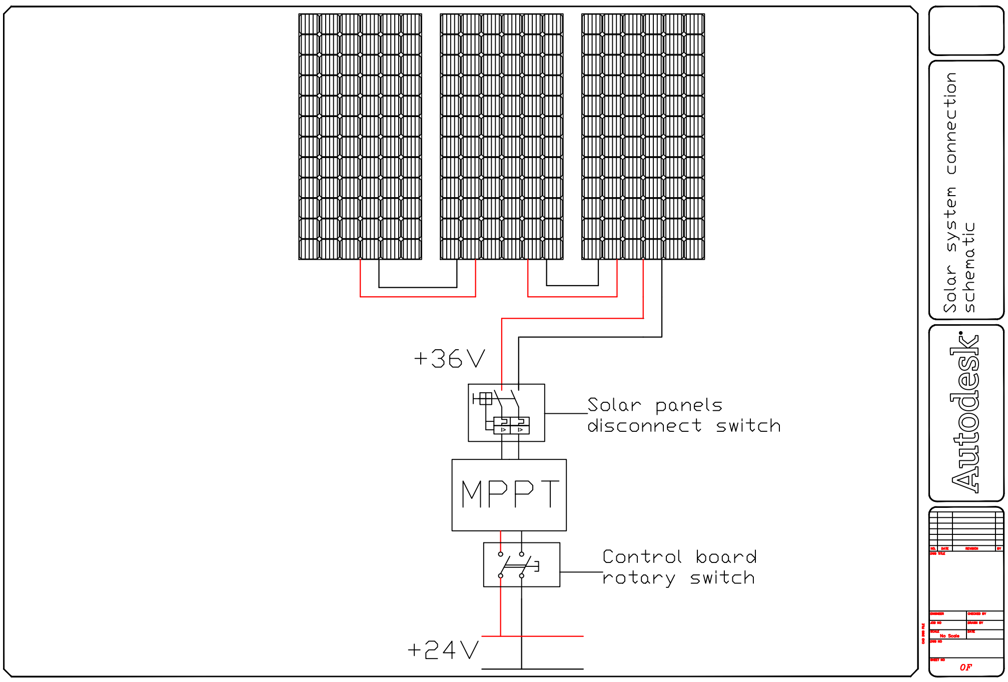

Figure 21: Solar system schematic connections

3.6 Practical case and final configuration

In the final configuration of the system the system is configured with 1 string of 3 solar panels. These panels are connected in series. The output of the string is connected to a safety switch that then connects to the MPPT. This device scales down the voltage to the 24VDC. Then the output of the MPPT is connected to the DC common bus. In that point, the energy mixes with the energy coming from the rest of the system.

Figure 22: Solar panels in the opened position

As is stated in 3.3, all of the hardware elements of the solar system have been provided by the school, from an existing system. This system has been out of service for the last 7 years. The system was in operating condition when it was last used. The original solar system was formed by the solar panels, the MPPT and the inverter. These three components have been stored since the system was put out of service.

The first step to implement the design of the new solar system into the Energy Hut is testing all the existing hardware to ensure that it is in correct working order. This procedure was carried out with all the devices forming the solar system.

The results from the solar panels showed that they were in correct working order. The MPPT and the inverter were tested, as can be seen in figure 23, and the results were not satisfactory. The MPPT and the inverter where tested with the assistance of the battery of the Energy Hut. The test was carried out this way because the battery is a brand new device that was tested individually and it is working properly. The testing on the MPPT has shown some unknown problem on the electronic control circuits that display an error message in the user interface. The testing on the inverter is showing problems in the device electronic control systems. These problems are not allowing to startup the inverter.

Figure 23: Testing of the MPPT and inverter

These problems on the hardware of the solar system have lead to changes in the hardware of the solar system. The design of the system remains conceptually the same. The modification done to the system is the use of a new inverter. This new inverter has already implemented an MPPT. This allows to take out of the system the original MPPT that was causing problems. The new inverter and MPPT are enclosed in the same device, what reduces complexity of the system.

The new inverter has the following characteristics [12]:

Name	Voltage	Max AC Power	DC Output current	Weight	Size(mm)
SKANBATT Hybrid inverter	24VDC	2000VA	0-40A	7,4kg	272x355x128

The new inverter matches the needed characteristics to connect to the rest of the system. The main one is the 24VDC as the stated voltage for the DC connections. The changes in the hardware mean that there is less maximum power available for the AC circuits in the Energy Hut. This power limitation is compliant with the power demand of the Energy Hut system.

The MPPT embedded in the inverter has the following characteristics [12]:

Name	Input voltage	Maximum current	Maximum solar power
MPPT	30-66	40A	600W

The new MPPT can handle the characteristics of our solar installation, as the nominal voltage of the string of the solar panels is 36VDC as in diagram 14. The new inverter and MPPT for the system can be seen in figure 24.

Figure 24: SKANBATT Hybrid inverter 24V [12]

The new hardware does not modify the design of any system in the solar or in any other part of the project.

With the new hardware for the inverter and the MPPT, the system is completed and has all the hardware in complete working order. The solar system is designed to provide twice the amount of power to the Energy Hut, compared to the wind system. This high importance for the energy generation creates the need for having a reliable system. This is why all the hardware has been tested, in order to ensure the final system is fit for the task.

As the system is designed, there is not an important margin for improvement on the electrical side of the system. This is because the main improvement that can be done on the electrical side is to increase the size of the solar panel arrangement in order to produce more energy. On the construction side of the system, one way of improving the system could be to automate the movement of the solar panels, automating the opening and closing of the solar panel array. This would orient the solar panels in a more efficient angle in respect to the solar radiation. The solar energy production would benefit and increase.

On the monitoring and electronics of the system, the solar system is monitored from the Energy Hut electronic systems, so the school will be able to know the power that is being produced in the solar system. An improvement that can be carried out in this part of the system is monitoring the power production of each solar panel individually. This would give a more detailed description of the power production of the solar system and could help in the maintenance of the system.

4 Wind

The purpose of this section is to investigate different aspects of wind energy, with focus on considerations needed for the project at Skjetlein high school.

4.1 Introduction

The second power source of the system is the wind turbine. The client had procured a used wind system containing a wind turbine, a generator and a battery prior to the start of the project. The wish of the client is that by the use of the preexisting components a comprehensive wind production system should be created.

In order to achieve that the wind potential of the location need to be accessed, the equipment need to be tested, faulty equipment need to be replaced and missing equipment need to be procured. And finally to figure out how to integrate the wind system in to the Energy Hut micro grid (section 2) and generate data for the electronics system. Details on this matter can be found in Section 6.

4.2 Theory

Wind energy are these days usually synonymous with the generation of electricity using wind turbines. Historically wind energy has been harvested through sails, windmills and wind pumps. It is a sustainable, renewable and arguably popular source of energy. It has gained a lot of importance in the later years, as it has been installed in large wind parks all over the world. The installed global wind power capacity as of 2021 is 743 GW, of which 93 GW was installed during 2021. It produced about 1800 TWh of energy, providing about 6% of the global electricity production, and 2% of the total world energy [13].

4.2.1 Energy in wind

The potential energy of wind is given by the kinetic energy of the air particles that are in motion. The kinetic energy of air in motion is expressed by [14]:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(Avt\rho)v^2 = \frac{1}{2}At\rho v^3 \tag{5}$$

where Avt is the volume of air passing through A, ρ is the density of air and v is the wind speed.

Power, which is energy per time unit, is given by [14]:

$$P_0 = \frac{E}{t} = \frac{1}{2}A\rho v^3 \tag{6}$$

As we can see by the expressions above the power of the wind is proportional to the third power of the wind speed. In other words, if the wind speeds doubles, the potential power increases by eight.

However, it is impossible to harness the full potential energy of the wind, as the wind need to pass through the turbine to do work on the blades of the turbine. If the full potential energy was harnessed, that would mean the air particles would simply stop after the turbine, consequently the particles would pile up, eventually blocking any more particles from passing the turbine. To keep wind going through the turbine it's impediment that there is some movement of air behind the turbine, thereby having some kinetic energy. The theoretical maximum amount of power any turbine can capture is $\frac{16}{27}$ or 59,3% of the kinetic energy of the wind. This limit was discovered by the German physicist Albert Getz in 1919. This limit is therefore called the Betz's coefficient, the

Betz limit or the Betz law. The most efficient modern wind turbines achieves a power extraction of about 80% of the Betz limit, or about 50% of the total energy of the wind [15][16].

Proof of Betz limit:

Assumptions:

1. Air is a incompressible liquid, $\rho = const.$
2. There is no drag on the rotor blades.
3. There is no turbulence.
4. The flow of air is one dimensional and axial into and out of the rotor.
5. The rotor is a actuator disc (infinite rotor blades).
6. No hub nor tower, uniform air flow.

The change in the airflow is illustrated by Betz' tube (figure 25). Assuming that the average wind speed, v, through the rotor area, A, is the average of the wind speed before the wind turbine, v_1, and the wind speed after passing through, v_2 [16][18]:

$$\overline{v} = \frac{v_1 + v_2}{2} \tag{7}$$

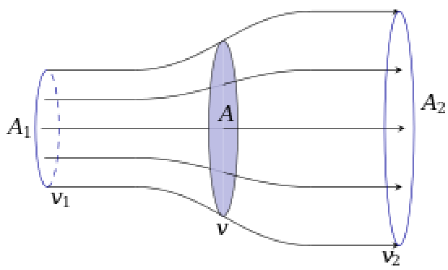

Figure 25: Betz' tube [17]

The mass flow of the wind is given by:

$$\dot{m} = \frac{\rho A(v_1 + v_2)}{2} \tag{8}$$

Where $\dot{m}$ is mass per second, ρ is the density of air.

Using equation 6 and the wind average from equation 7, then:

$$P = \frac{1}{2}\dot{m}\left(v_1^2 - v_2^2\right) \tag{9}$$

Substituting the expression for $\dot{m}$ from equation 8 in to equation 9 provides an expression for the extracted power from the wind:

$$P = \frac{\rho}{4}\left(v_1^2 - v_2^2\right)(v_1 + v_2)A \tag{10}$$

Now using the power of undisturbed wind from equation 6 to find the ratio between extracted power, P, and undisturbed power, P_0:

$$C_P = \frac{P}{P_0} = \frac{1}{2}\left(1 - \left(\frac{v_2}{v_1}\right)^2\right)\left(1 + \frac{v_2}{v_1}\right) = \frac{1}{2}\left(1 - a^2\right)(1 + a) \tag{11}$$

Where C_P is the power coefficient. $\frac{v_2}{v_1}$ is substituted by the interference factor a.

Plotting the expression for C_P (figure 26) from equation 11 where the horizontal axis represents the interference factor $a = \frac{v_2}{v_1}$ and the vertical axis represent C_P.

The expression from equation 11 is differentiated and set it equal to zero to find the maximum mathematically.

$$\begin{gathered}\frac{dC_p}{da} = \frac{1}{2}\left(-2a + 1 - 3a^2\right) = \\ \frac{1}{2}(1-3a)(1+a) = 0 \\ (a = -1) \\ \text{not physically possible (negative power).} \\ a = \frac{1}{3} \\ \frac{v_2}{v_1} = \frac{1}{3}\end{gathered} \tag{12}$$

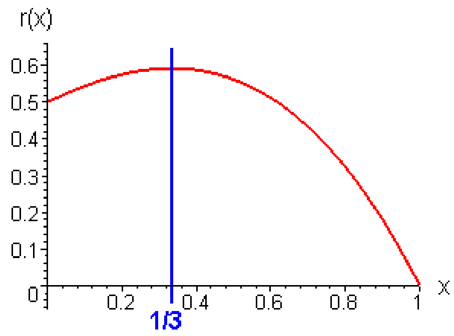

Figure 26: C_P Plot [17]

This tells us that when the wind going out of the turbine is one third of the wind coming in, we get the maximum power extracted from the wind. We can the substitute for a in equation 11 and get [16][18]:

$$C_p = \frac{1}{2}\left(1 - \left(\frac{1}{3}\right)^2\right)\left(1 + \frac{1}{3}\right) = \frac{16}{27} \approx 59,26\% \tag{13}$$

4.2.2 Types of wind turbines

There are two main types of wind turbines, one rotates on an horizontal axis while the other rotates along an vertical axis. Their characteristics are significantly different, and their use is thereby for different environments and conditions.

Horizontal axis

Horizontal axis wind turbines (HAWT) are by far the most efficient type of wind turbine, as they can use all their rotors to generate energy at the same time, however, they demand a lot more adjustments and monitoring than the vertical axis turbines to function optimally. In order to produce the optimal amount of energy, the turbine need to face the wind perpendicular to the rotor plane, to do that a yawing system need to be implemented.

On smaller turbines it's sufficient with a more passive system where the nacelle is mounted on a bearing and a wind vane is used to point it in to the wind. On larger turbines it's much more complex, where it's needed to evaluate wind measurements to activate a electric or hydraulic yawing system to turn the nacelle and the rotor. By the nature of such a system, there will be a delay in the system as the yaw mechanism both need to evaluate and engage the yaw system before it's rotated in to position, of that reason there will be a significant loss off efficiency, especially when wind conditions are turbulent or gusty.

Adding to the complexity is the fact that the rotational hub is high up, meaning that much of the heavy equipment, like gearing mechanism and the generator, is forced to be high up in the nacelle on top of the wind generator tower, requiring a substantial construction to withstand the forces of both gravity and wind.

On the most recent offshore wind generator designs, the height of the tower will be at about 150 m, for reference that is close to the height of the Washington Monument and the combined height of tower and rotor will be about 260 m, 40 meters shy of the Eiffel tower. These behemoths are expected to produce up to 14 MW. (Figure 27) [19]

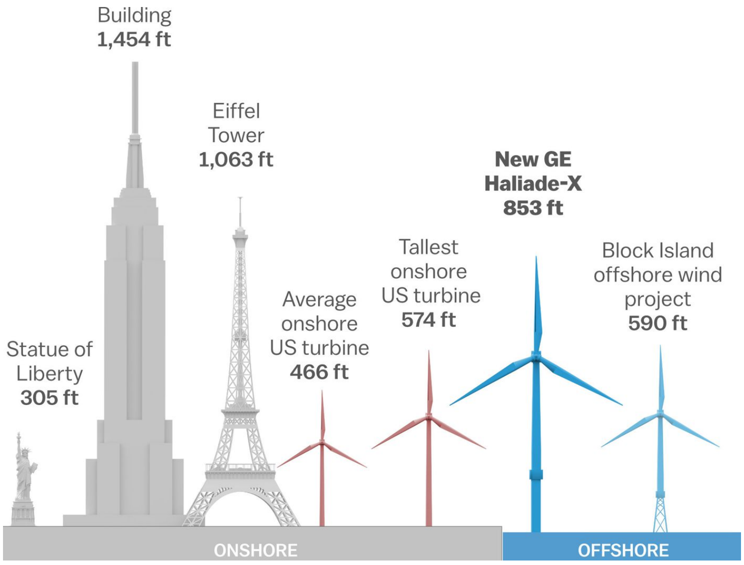

Figure 27: Comparisons of height [19]

Furthermore HAWTs need to adjust the pitch of the blades of the rotor to regulate the speed of the rotor and to protect the rotors in higher wind conditions, in additions to brakes on the generator shaft. If that is not done, the blades might develop so much lift that they start to bend, in the worst cases the blades have been bent all the way back in to the tower itself, causing a catastrophic failure of the whole construction.

Vertical axis

Vertical axis wind turbines (VAWT) have generally a much simpler construction, the fact that the turbine rotates around a vertical axis means that all the heavy equipment (generator and gears) can be placed at ground level, eliminating the need to support a big mass high up, as well as making it more accessible for maintenance. VAWT doesn't require yawing or pitching to catch wind, as it can exploit wind from any direction.

There are two main types of VAWT, the Savonius and the Darrieus type. The Savonius is characterized by it's scoop design, as it's traps or scoops up the air in order to rotate as seen in figure 28, they are also referred to as drag type turbines. The Savonius wind turbine gets its name from the Finnish engineer Sigurd Johannes Savonius who invented it in 1922.

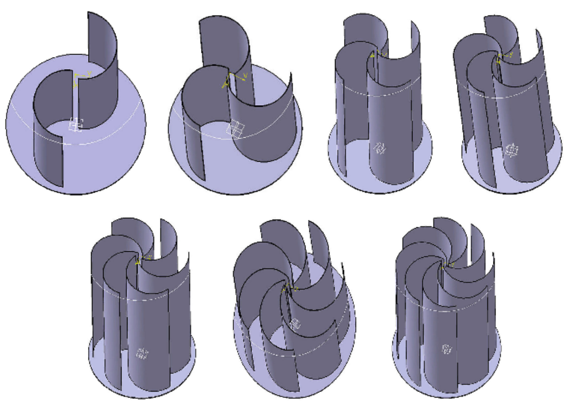
Figure 28: Examples of Savonius turbine designs [20]

Due to the curvature of the scoops it creates less drag when they are moving against the wind, and maximizes drag when moving with the wind. This type of turbines have the ability to harvest wind energy from much lower wind speeds, they are very mechanical robust, they create substantially less noice and are independent of wind direction. They do however have significantly less efficiency especially compared to HAWT, but even Darrieus designs are more effective in harvesting energy. These types of wind turbines are typically used when cost, noice or reliability trumps efficiency [21].

The Darrieus design is a more prolific type of VAWT and use airfoils in stead of scoops to catch the wind energy. It was patented in 1926 by the French aeronautical engineer Georges Jean Marie

Darrieus.

In its original form it was constructed with two curved airfoils on opposite sides of a rotating shaft. As the turbine rotates the airfoils will be moving forward in a circular path, generating a variable positive angle of attack, however there is only one place on the circuit that have a optimal angle of attack, so the force generated by any given point on the airfoils varies constantly. This is one of the main reasons why the Darreius turbine is less efficient than the HAWT [23].

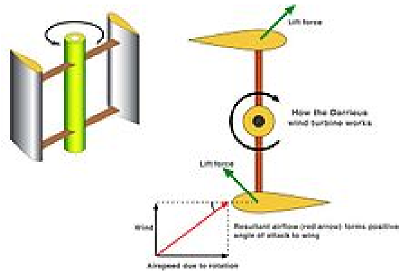

Figure 29: How the Darrieus turbine work [22]

In addition the constantly varying forces cause a lot of ripple effects, both to energy production of the generator and to the construction of the wind turbine. This can be mitigated by many techniques, one is to increase the number of blades in order to make sure that there more often is a blade that are in an optimal angle, thereby diminishing the ripple. Another technique is to curve the blades horizontally, making a helical design. In this configuration all the points of the curve are occupied by an airfoil at any time, smoothing out the ripple effect.

The history of the VAWT can be divided in to two main periods, the first period was the early experimental period after the invention and in to the post war era. A lot was learned, but the limited knowledge of material fatigue and the rather limited construction methods and material availability of the period reached it's limit. Most projects failed after a relatively short period due to material failure and technical difficulties with especially with the material and the rippling effects.

The second period is more recent, in the late 80s and early 90s, as the realization of the environmental problems of the more conventional sources of energy became more and more prevalent, the interest in all kinds of means of generating renewable energy came much more in to attention. Since the last period the knowledge of materials and the discovery of new materials and construction methods made the VAWT a much more viable option. And the qualities of the VAWT gave it a new lease of life. Since then the development and research on the topic has been increasing exponentially and there is even suggestions that the energy produced in a specific area could potentially be greater with VAWTs than HAWTs as they can be grouped much closer together exemplified in figure 30 [24]:

Figure 30: Illustration of a VAWT park [24]

4.3 The wind turbine

The main component of the system is the wind turbine. The wind turbine that were procured by the client is the Hoyi 200 as seen in figure 31 below:

Figure 31: The HOYI 200 wind turbine [25]

It is as one can observe a helical Darrieus vertical axis turbine (VAWT). Its key characteristics is at follows:

Name	Effect	Rated wind speed	Weight	Swept Area
HOYI 200	200 W	12 m/s	41kg	0,84 m^2

Further characteristics of the wind turbine is found in figure 71 in section B of the appendix.

4.4 Location

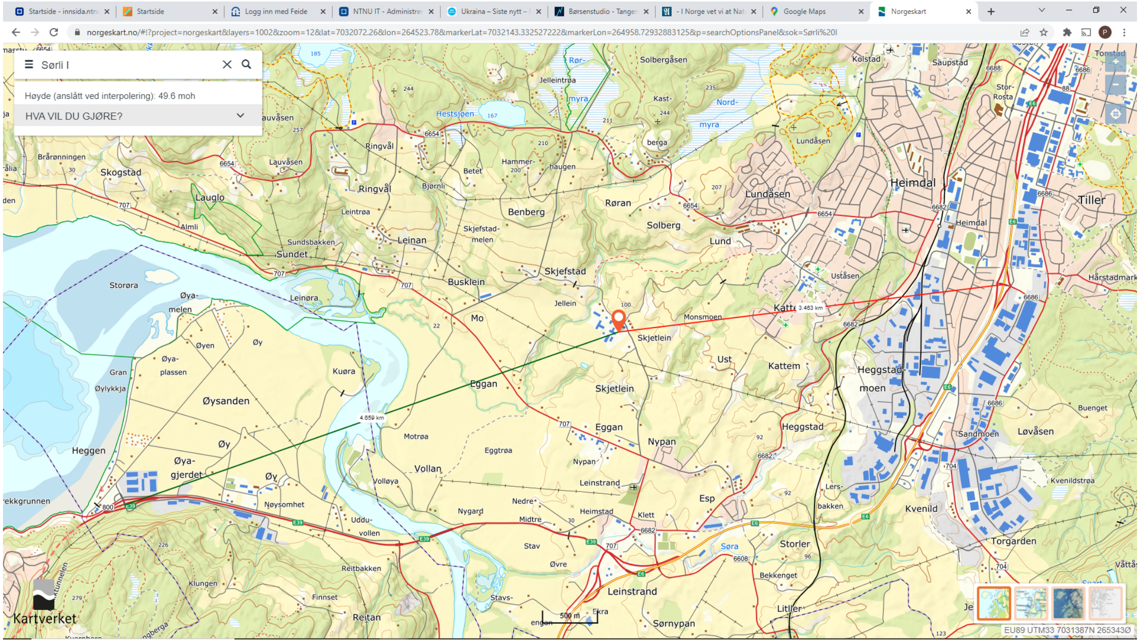

Figure 32: Location of Skjetlein [26]

Skjetlein high school is in Trondheim municipality of Trøndelag county. The high school is situated to the east of the Gaula estuary. The site has open fields to the south and west, sloping gently in a south westward direction, while towards north and east, the incline of the landscape increase significantly towards the plateau of Heimdal and Tiller (figure 46).

4.5 Wind data

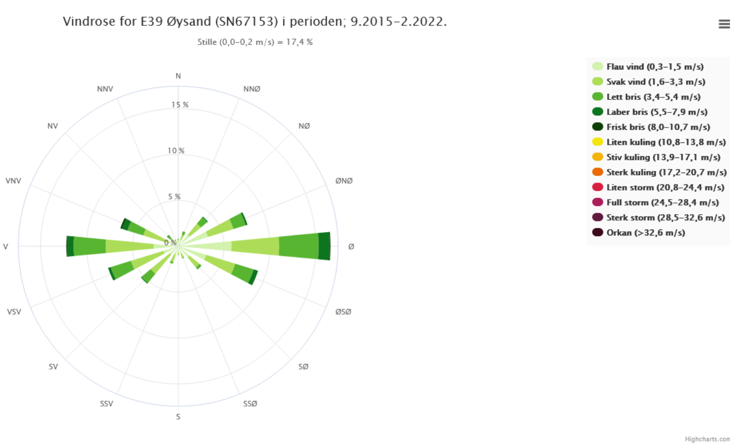

Figure 33: Wind rose at E39 Øysand measurement point [27]

As it happens the high school has an active weather station on site, however, though it has some measurements of winds, the data was not found to be consistent or useful enough for the considerations on potential power production. The most accurate and useful wind data that could be found, was acquired from the web page of the Norwegian institute of Meteorology, specifically the weather stations Heimdal E6 (figure 34) and Øysand E39 (figure 33), 3,5 km and 4,6 km distance from the site respectively (figure 46). It's clear that the topographical features in the area plays a significant role on the wind conditions, seen especially on the data at the Øysand measuring point, were there is a substantial hill to the south, impacting the wind conditions.

The measurements at the Heimdal plateau gives a good indication of the general winds of the region, as there are few direct obstacles around that measuring point. Although the wind measurements in Øysand is significantly skewed, it still indicates that there might be funneling effects around the estuary and the valley of Gaula, that runs in a south-easterly direction from the locations of Skjetlein and Øysand. The measurements at Heimdal indicates that the prevailing wind in the area is primarily south-western and generally there are more southern winds than northern. The site of Skjetlein is therefore in a relatively good position when it comes to catching the winds of the area. It probably shielded from most of the northern winds, so those can likely be ignored. The funneling effect might however enhance the prevailing winds, to an extent that probably exceeds the lost winds from the north.

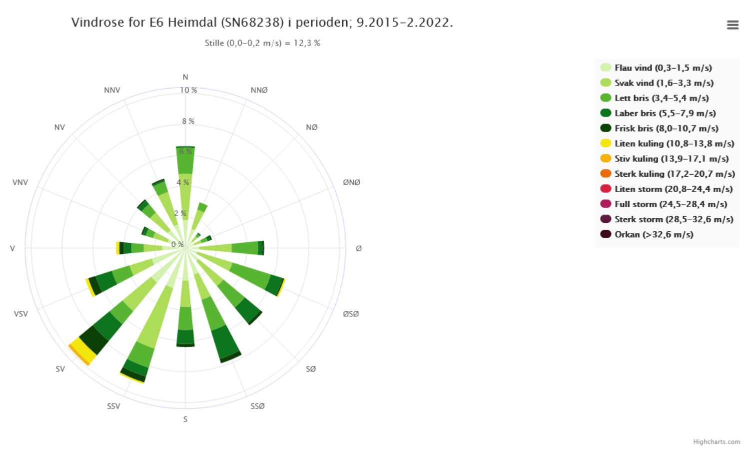

Figure 34: Wind rose at E6 Heimdal measurement point [27]

4.6 Wind turbine placement

The proposed placement of the energy hut gives an insight in how the client envisions the integration of the hut in the campus. The proposal clearly put weight on the convenience part, but little regard to the potential energy production on site. That being said, the horizontal axis turbine that we have, as opposed to the more commonly used vertical axis turbine, is better suited to catch the energy in the wind despite the turbulence caused by the buildings.

Based on the wind data, the advice on relative placement to buildings (figure 35) and within reasonable distance from the energy hut, the best location for the wind turbine would be in the southern end of the campus, marked as a yellow square on the map (figure 36), and to minimize friction losses in the wires, while maintaining a reasonable location on the campus, it's recommended to move the energy hut from the planned site, marked with the orange pointer, to the area marked in purple on the map (figure 36).

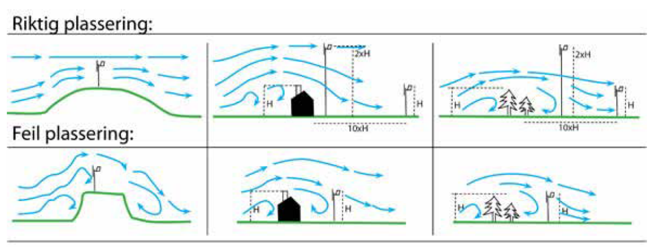

Figure 35: General advice on wind turbine placement [8]

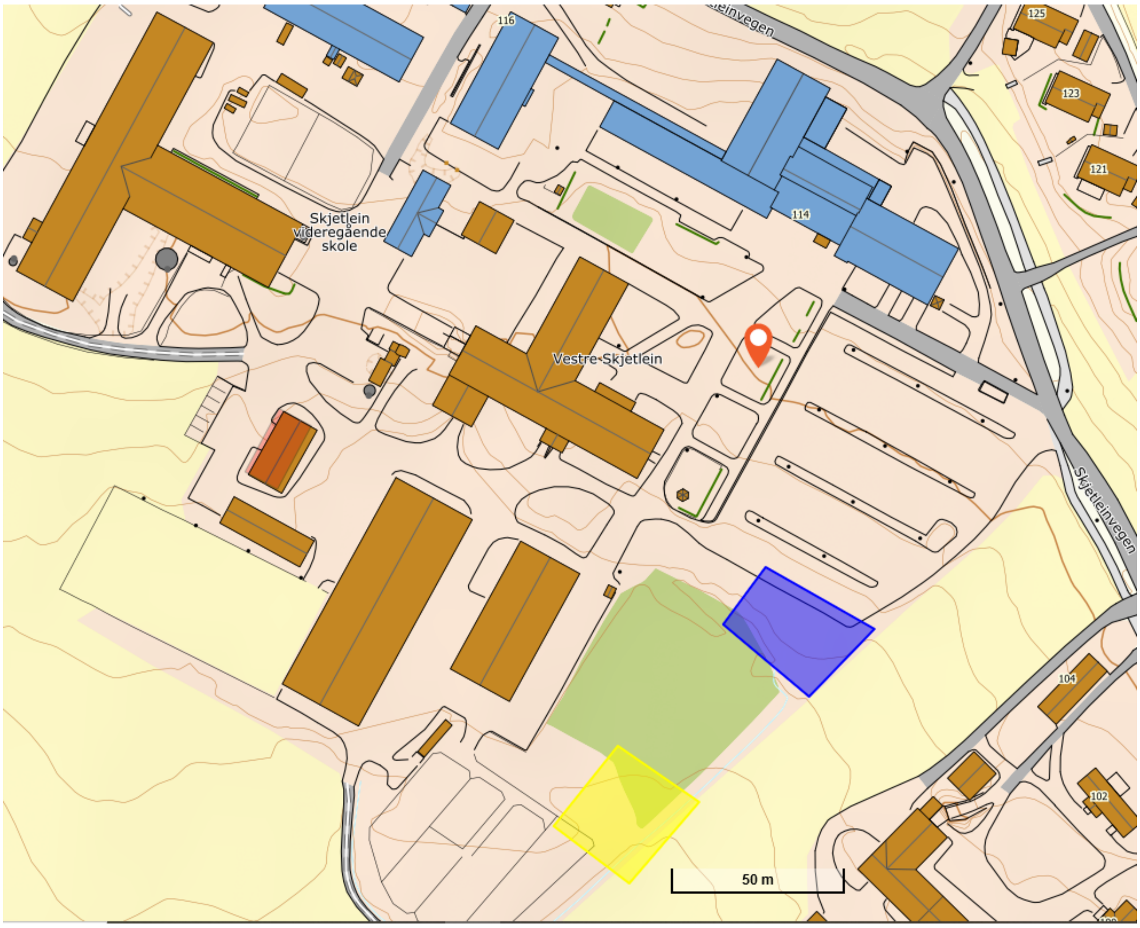

Figure 36: Suggested area for The Energy Hut (purple) and wind turbine (yellow) [26]

4.7 Potential energy production

If the turbine is placed at an optimal site, utilizing the wind potential there is, then it's possible to estimate how much energy might be produced, based on the characteristics of the wind generator. Using the data of the generator it's possible to evaluate the efficiency of the wind turbine at peak performance. First we calculate the power of the wind at 12 m/s, using equation 6:

$$P_0 = \frac{E}{t} = \frac{1}{2}A\rho v^3 = \frac{1}{2} \cdot 0,84m^2 \cdot 1.225kg/m^3 \cdot (12m/s)^3 = 885,43W \tag{14}$$

Where swept area, A, is found in figure 71 to be $0,84m^2$ and ρ at sea level is $1,225kg/m^3$. [18]

Taking the rated power of the turbine, using the ratio from equation 11 and inserting the result from equation 14:

$$\frac{P}{P_0} = \frac{200W}{885,43W} \approx 22,6\% \tag{15}$$

As seen in the characteristics and the power curve, figure 37, the turbine needs a minimum wind speed of 2 m/s to produce energy. Based on the wind statistics at Heimdal E6 (Table 2), 37,1% of all wind speeds are under 1,5 m/s, a further 29% are in the region 1,6-3,3 m/s where the energy production would be negligible, as the output at 3,3 m/s would be about 10 W, indicating that there will be no (substantial) production in about 2/3 (66,1%) of the time.

It will run at rated production when the winds are near or above 12 m/s, which is 1,8% of the time. With 8765,8 hours in a year, it will run at capacity for about 157,8 hours per year, generating 31,5 kWh, in the area 3,4 – 5,4 m/s the generator will produce about 20 W, giving a yearly production of 32,8 kWh, In the area 5,5 – 7,9 m/s the generator produces approximately 50 W, giving 43,4 kWh in a year. In the area 8 – 10,7 m/s an approximation of the average production would be 120 W, giving 37,9 kWh. The calculations that were performed in this section is represented in table 1:

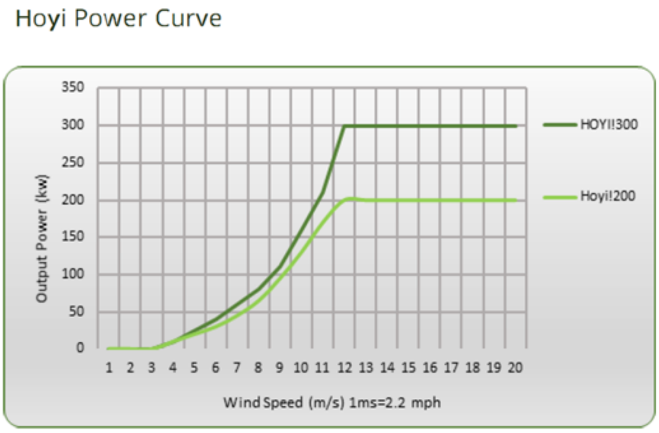

Figure 37: Power to wind curve of Hoyi wind generators [25]

Wind speed (m/s)	0 - 3,3	3,4 - 5,4	5,5 - 7,9	8 - 10,7	10,8 <
Generated power (W)	0	20	50	120	200
Relative amount (%)	66,1	18,7	9,9	3,6	1,8
Yearly production (kWh)	0	32,8	43,4	37,9	31,5

Table 1: Calculations on average annual wind energy production

All in all with optimal placement, no downtime and assuming funneling effects canceling the loss of northern winds, it's possible to assume that the potential annual energy production will be in the region of 145 kWh. Which translates to about 500 Ah per month at 24V. The planned placement of the wind turbine, however, in the midst of buildings and downwind from the closest building, one have to assume at least a halving of the output to approximately 250 Ah at 24 V. If it was a HAWT turbine a even greater loss would have been expected.

4.8 System topology

As mentioned in the introduction (section 4.1) the wind turbine and the generator was already procured by the client. In addition there where a battery that belonged to the original system. The system that was procured by the client were second-hand and had not been in use for several years, the condition of the components were unknown from the start of the project. The crucial wind/charge controller was missing from the original system. Doing an evaluation of the components that were present, the conclusion was drawn that the original battery had been depleted to a point that made it unfit for further use, the wind turbine and the generator could not be tested, as it was not in a proper location for testing. After this evaluation the decision was made that a new charge controller was needed and a new storage solution.

As seen in figure 38 there are four main components of this system:

- The wind turbine
- The generator
- The wind charge controller
- The battery system
- The inverter

As to the battery system and inverter it was decided to use it in tandem with the solar system (section 3) as the energy produced by both systems are small enough to have a centralized power bank in a more comprehensive micro grid (section 2). To complete the wind system from a components part of view, the charge controller was the only component missing. After some considerations, a MPPT-controller was found to be the most optimal for this system. The requirements were 12V AC to 24 V DC minimum 200 W MPPT charge controller and based on those a "Wind Charge Controller,12V/24V 300W/600W Waterproof Wind Turbine Generator Charge Controller Regulator" (figure 39) was recommended.

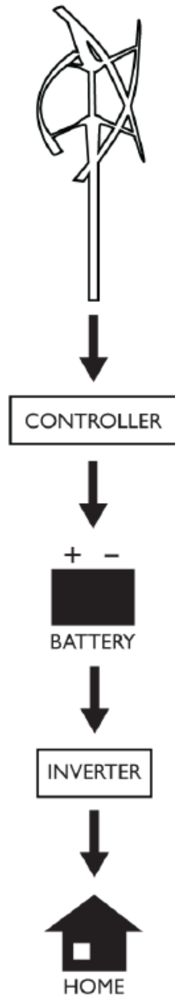

Figure 38: Wind system topology [25]

Figure 39: Wind charge controller [28]

As the turbine and the generator still remain to be tested, there still are some uncertainty on the condition of the components and thereby the potential for energy production. The testing can only be done when the turbine and generator is mounted on to a fixed point where the turbine can rotate freely.

4.9 Conclusion

After assessing the wind conditions of the area it's clear that it's impossible to recommend using wind power as a reliable or economical energy source in the inner parts of Trøndelag, the winds are simply to weak and unreliable. This clearly shows why all of the major wind projects of the region are generally placed near the coast and in higher elevations. However, as the client views this project to be a mainly educational showcasing of different power sources and how they are affected by local conditions and weather, it should be possible to get some useful production and data from the wind energy system.

The amount of energy from the wind system by itself however, are not sufficient to power the planned system in the hut, let alone provide any meaningful energy to charge bikes with, especially with regards to where the client plans to put the wind turbine (section 4.6). It's estimated that the potential production is reduced by at least 50% compared to the potential of the suggested position (figure 36), the only factor that work in favour of production is the fact that the VAWT have a decent potential of harvesting energy from turbulent wind conditions.

For the execution of the physical part of the project, progress were hampered by administrative and technical difficulties. The main component of the Energy Hut micro grid, the inverter, turned out to be out of order. This could not be confirmed until the new batteries was procured and the system could be tested. In addition, the wind system is more dependant on external resources, like the construction of the wind tower and the final placing of the Energy Hut.

Nevertheless, there is a clear perception that the request of the client has been fulfilled, as the plans of the system and how to integrate the wind energy system to the microgrid (section 2) and the integration with the electronics part (section 6) has been completed.

5 Hydro

This chapter is about the hydro power generation system and the description of all its features and design choices done in the system.

5.1 Introduction

In this part of the project, it's going to be written everything necessary to obtain energy from two hydro sources, a water wheel and the Turgo turbine.

5.2 Theory

In this part it's going to be written about how the hydraulic energy hydro energy, it's needed a brief explanation of how this energy is produced.

The hydro as a main source of energy is one of the oldest sources of energy for producing mechanical and afterwards as a electrical energy. First, the production started with the invention of the hydro wheel, mainly in those times around, III a.C , used to perform mechanical jobs, such as grinding wheat and other cereals. But as the time was passing by, it was realized that by transmitting this movement to spin a generator, they were able to produce electricity. And this was the discover of the hydro as a source of energy production. Afterwards, within the passing of the years, and the enhancement of the science, in 1898, James B. Francis created the most known and used turbine nowadays, the Francis turbine. This invention was followed with some more inventions of different types of turbine, such as, the Pelton in 1879 and the Kaplan in the 1913.

Nowadays, in Norway the hydro power is being the mainstay of the Norwegian electricity system. Providing approximately the 90% of the energy production in a year.

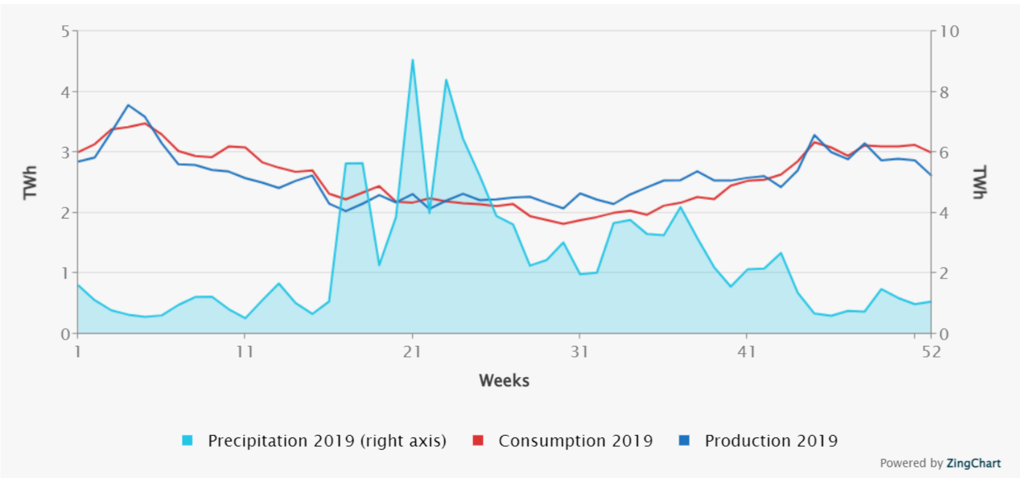

Figure 40: Energy Hydro Production in Norway [29]

5.3 Power Calculations

In this subsection it's going to be explained all the calculations related to the extraction of the power output of the different hydro sources.

In this project it has been used data from previous students, which worked in the same project before.[30]. From them it's obtained the following table:

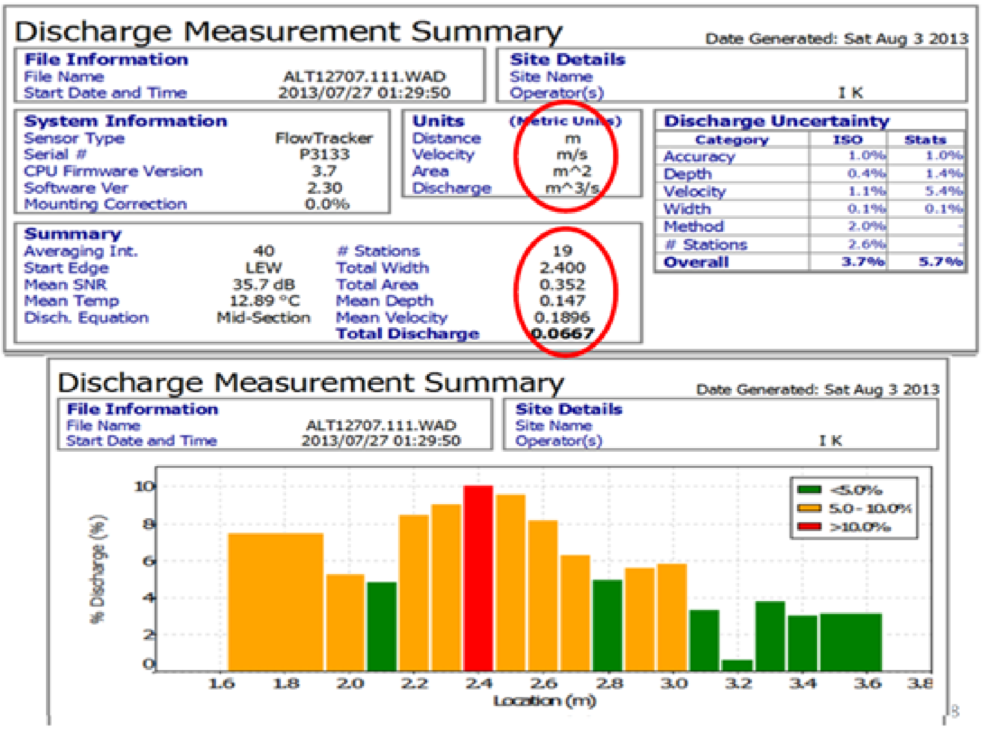

Figure 41: Data Production [30]

Once the data is collected from [30], is time to obtain the speed of the water flowing:

$$Q_{H_2O} = A \cdot v = 0.352 \cdot 0.1896 = 0.0667 = 66,7\frac{l}{s} \tag{16}$$

[31]

Now that all the data necessary is already collected, it can be proceeded to obtain the basic values to proceed with the calculations. Firstly it's going to be proceeded with the calculations for the water turbine:

5.3.1 Water Turbine

For the obtaining of the power of the turbine it's used the following formula:

$$P_{turbine} = \frac{1}{2} \cdot d \cdot A \cdot c \cdot v^3 \cdot 0.9 = \frac{1}{2} \cdot 1000 \cdot \pi \cdot 5^2 \cdot 0.1896^3 \cdot 0.9 = 240W \tag{17}$$

[32]

Whereas:

- A = Flowing area of the turbine.
- v = speed of the water flow.
- 0.9 = efficiency of our turbine.
- d = density of the water.

Once the power of the turbine is obtained, it can be decided which turbine to choose. But in our hut, currently a turbine is already installed. Concretely a Turgo Turbine, which is mainly a Pelton.

The reason of why it has been chosen a Pelton is mainly because as it's observed in [33] and because of the installation is held in a place whereas there are low discharges and the water pressure is not that high, the best option for our installation is choosing a Pelton.

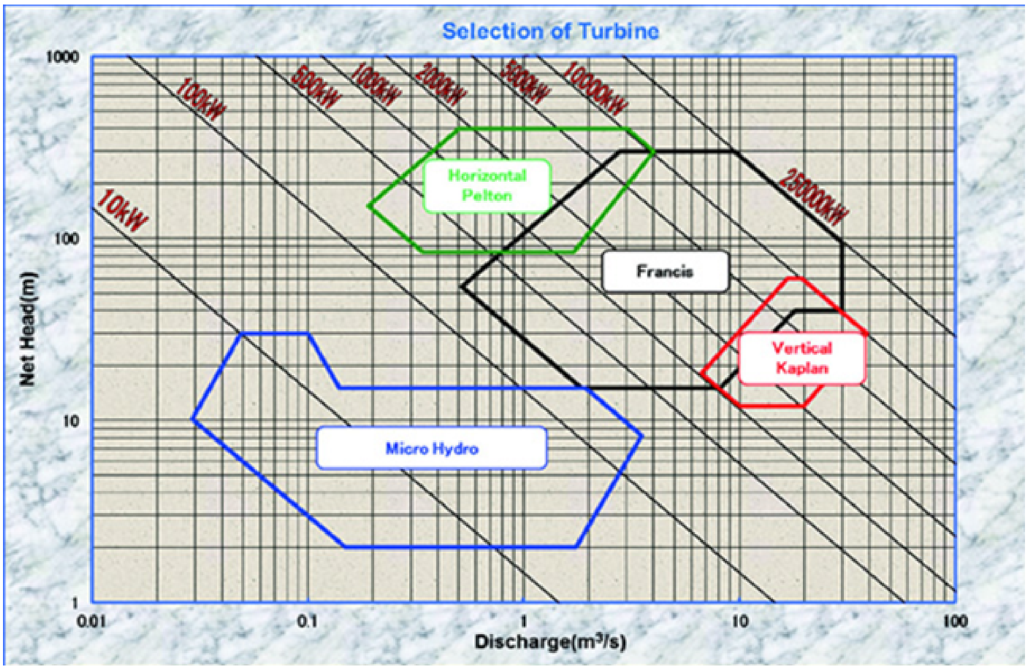

Figure 42: Types of turbines [33]

Now that the calculations, and every important fact related to the turbine is already considered, it's time to move on with the calculations for the water wheel.

5.3.2 Types of Turbines

The Turbines mainly can be divided in two types, the impulse turbines and the reaction turbine.

The reaction turbines generate power mainly by using the force of moving water and the pressure. Those turbines are mainly placed directly in the water stream, which allows the water to flow over the blades rather than striking each one individually. This type is commonly used for lower head and higher flows.

For the reaction turbines the most commonly types used are usually Propeller(including Kaplan) and Francis.

This type of turbine involves:

- Propeller, has from 3-6 blades. And for the generation of power, water contacts the blades constantly.
- Francis, the first modern hydropower turbine. Usually has 6-9 blades. Water goes above the runner which causes the blades to spin.
- Kinetic, generate electricty from the energy present in flowing water rather than the potencial energy from the head.

As it was mentioned before, there is another type of turbines. The impulse ones. Which generally uses the speed of the water to move the runner and discharges at atmospheric pressure.

This type of turbine involves:

- Pelton, this ones are used for high heads and low flows.
- Cross-Flow Turbine, this one uses an elongated, rectangular section against the one with a cylindrically shaped runner. This one allows the water to flow through the blades twice.

5.3.3 Water wheel

Mainly in our project it has been realized different calculations, one for the water wheel and the other ones related to the turbine. For the calculations related with the water wheel 64, it's explained that this element is not commonly used to obtain power from it, mainly because there is produced a lot of loses due to the water. This water wheels are more commonly used to realize mechanical efforts rather than a main source to realize electrical efforts.

Then from this part, is not expected to produce as much power as the Turgo Turbine can produce.

Figure 43: The water wheel [34]

Once a few things have been explained, it's proceeded with the power calculations:

But first, it might be obtained the normal rotating speed of the wheel. In our case, the rotational speed our water wheel can produce is π rad/s. Then by using the radius of the wheel, it can be obtained the tangential speed:

$$v_t = r \cdot w = 1.2 \cdot \pi = 3.76 m/s \tag{18}$$

[35]

Whereas:

- v_t = speed
- r = radius
- w = angular speed

Now it can be finally proceeded to obtain the maximum power output of our wheel:

$$P_{waterwheel} = C_t \cdot Q \cdot H \cdot \eta = 0.1134 \cdot 2.355 \cdot 1 \cdot 0.7 = 0.187HP \cdot 765 = 143W \tag{19}$$

[36]

Whereas:

- H = distance from the fall of the water to the wheel.
- Q = water flow in ft^3 per second.
- C_t = constant = water weight lbs/lbs · s
- η = efficiency = 0.7(constant obtained from 72)

As it was mentioned previously, the main problem of using wood as the main material for the wheel is that this material easily rots and holds water unevenly. These unbalances make the water wheel suitable for the use of grinding grain and not for obtaining power. So probably these unbalances will make this water wheel not produce as much power as it was expected.

5.4 Energy Production

For the generation of energy in the hydro spot, it will be needed to develop or obtain a generator to produce electricity coming from the water wheel.

5.4.1 Generation

Mainly because, in the case of the Turgo turbine, the turbine has already installed in it an inverter and an MPPT (Maximum Power Point Tracker) so mainly we can obtain the energy from it, and the only thing remaining is a battery to store.
In our case, all our systems of charging are working within 24 V of dc, so the output will be limited to 24 V dc.

Now that the turbine generation is solved, it's necessary to have a generator to obtain the energy from the hydro wheel. For the decision of which generator should be chosen, a few questions must be answered first. Such as, which is our purpose and which generator should be chosen for fulfilling it. In this case, the generation of the water wheel is not that high, so by using a PMSG, might be the best option, mainly because it's able to generate power with low power inputs. As well as with the turgo turbine our purpose is being able to charge a battery of 24 V at the output. So, once it's been decided to use a PMSG, that will output AC power it will be needed a rectifier to transform the AC into DC.

Now that the decision of which generator could fit the best to our project, it must be proceeded to check which generator may be chosen. To realize this, it has been trying to look through Norwegian websites, but nothing was found, so it was decided to look through amazon, and the best option was the following one:

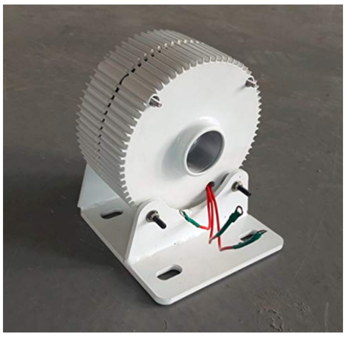

Figure 44: Proposed Generator [37]

Name	Voltage	Power Output	Weight
AC Synchronous Generator G-400 M	24 V	400 W	4,5 kg

[37]

The decision of why this generator has been chosen, is mainly because this generator acts in a larger range of voltages. Also, our batteries are charged at a fixed voltage of 24 V, and the power of the first generator is higher. So it's required more power than needed and it will be more difficult to find a rectifier for those power range. Once the generator has been decided, the gear ratio must be calculated. Because it's necessary to obtain the maximum power, the calculations will be proceeded with the maximum rotational speed of the generator, which is 650 rpm, and it will be compared within the maximum rotational speed of the water wheel, which is 30 rpm. So, the gear ratio will be realized by the following:

$$i_{ratio} = \frac{w_{generator}}{w_{wheel}} = \frac{650}{30} = 21.6 \tag{20}$$

[38]

Once the gear ratio is calculated it's necessary to obtain or to create a gear, but Skjetlein has already people there available which could create a gear able to modify and control the speed of the generator and the water wheel.

Before obtaining the calculations for the gear, previously is needed to define which diameter to choose, mainly because the number of the teeth is already defined with the diameter. As the determination of the gear is already defined as 21.6, it has been decided for the realization 20, so far. Then by knowing that the diameter of the water wheel where the gear will be installed corresponds approximately to 35 mm and the one corresponding to the generator is 24mm. It has been proceeded to realize a gear diameter of 600mm corresponding to the water wheel and 30mm for the one corresponding to the generator. By clarifying the values corresponding to the different gears. It's obtained the following diagram for the transmission line:

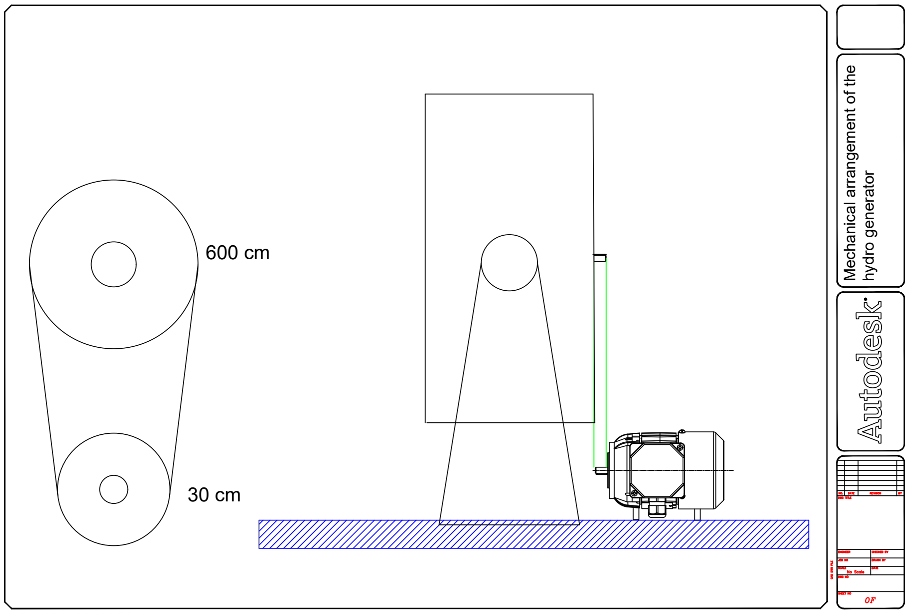

Figure 45: Hydro Gear

Now that all the transmission is calculated, it's time to proceed with the decision of which rectifier to use. In our case, by the data required the rectifier that suits the best our system is the following:

Name	Voltage	Power Output
Wind/Hydro Charge Controller	24 V	600 W

[28]

Once everything is decided, it's the time to move on with the calculations for the wires and for the protections.

5.4.2 Electricity Distribution Grid

In this part it's going to be proceeded with all the calculations related to the extraction of the currents flowing through the generator and the inverter. And will be decided which width of cable should be used in the installation.

The first current that's going to be calculated is the one flowing through the generator. For the extraction of this value it's going to be used the maximum output power formula 22. Which will be obtained by dividing the maximum power that our generator can produce, by the battery voltage:

$$I_{maxgenerator} = \frac{P_{max}}{V} = \frac{420}{24} = 17.5A \tag{21}$$

[36]

This current will be the maximum value that could be flowing from the generator to the rectifier. Now it will be followed with the calculations for the extraction of the current flowing from the rectifier to the battery.

$$I_{maxrectifier} = \frac{P_{maxr}}{V} = \frac{600}{24} = 25A. \tag{22}$$

[36]

As it's observed there is more current flowing through the rectifier rather than in the generator. This is obviously produced because there is produced much more power in the rectifier rather than in the generator.

Once, every current is calculated is the time to obtain the width of the cables. In this case, mainly because approximately is the same current in both cases, it's going to be used the same cable for the two of them. And by looking at the table of the normalized width for the different cables for the transmission line, it was decided a $4mm^2$.

But once the width of the cable is chosen, it has to be obtained which is the length of the cable from the wheel to the hydro hut, whereas the battery will be stored. By checking in Skjetlein it has been approximately measured that the length of the cable should be 17m.

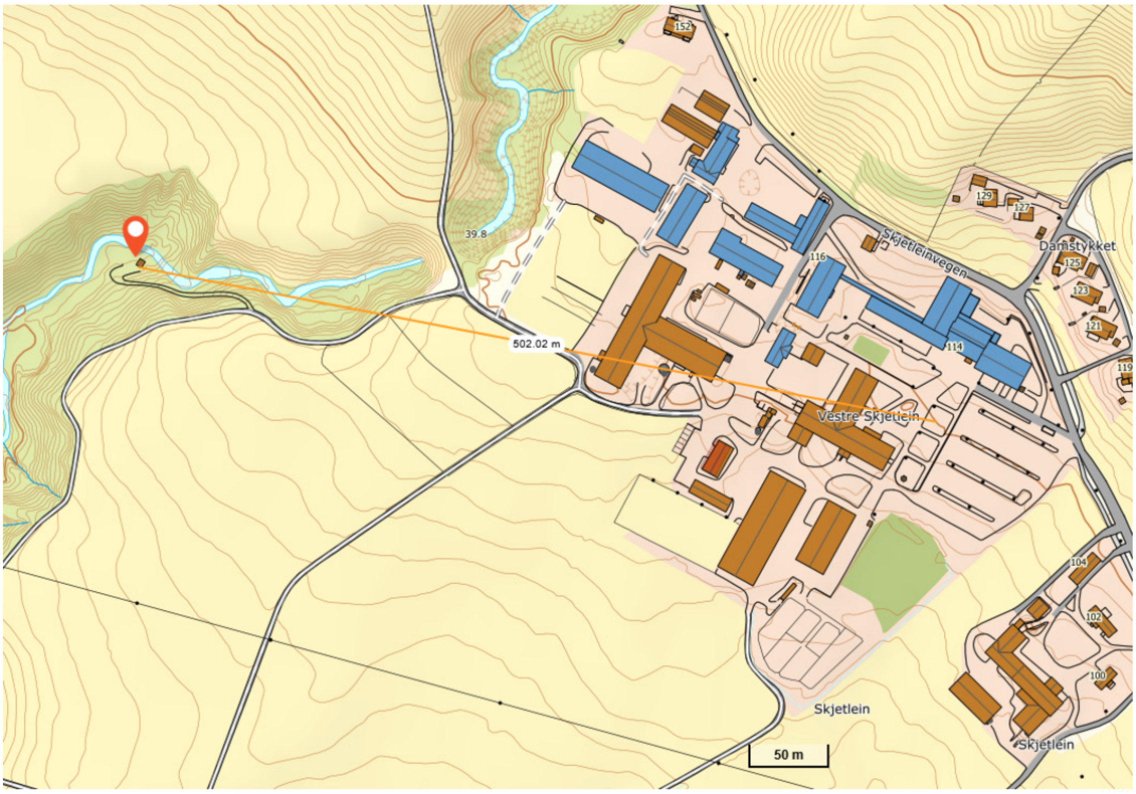

Figure 46: Skjetlein Hydro Location [26]

Once the map is observed it was took a decision for not connecting the hydro hut with the energy hut by a connection cable. Mainly, because the length of the cable and the installation it will harm a lot of elements that are on the middle of the connections. So, the best choice is to have the hydro hut in its placement.

Once it's decided how to send the energy from the hydro to the energy hut, it's the time to realize the connection sketch of the elements at the hut. For this realization, it will be necessary to decide which batteries to use. And as it was mentioned previously, the batteries were required to be 24 V. So, by the currents obtained previously, the battery that suits the best this characteristics, is the same as in the energy hut:

Name	Voltage	Capacity	Weigh	Size(mm)	Storage technology
RITAR GEL Deep Cycle Battery	12VDC	100AH	30kg	328x169x222	Gel

[3]

Once everything is decided, now it can be proceeded with the connection sketch. Which will be the following:

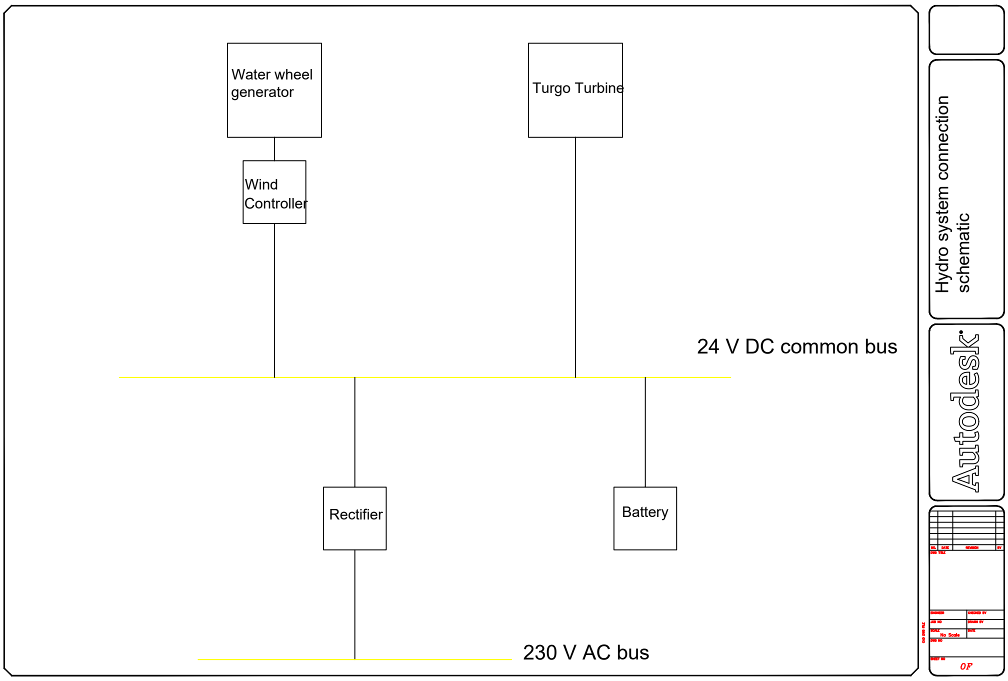

Figure 47: Hydro Electric Sketch

5.4.3 Hydro Hut

Inside the hydro hut it's just placed the following elements:

- rectifier
- hydro charge controller(MPPT)
- battery
- ESP42
- modem 4G
- 24 V dc output

In this placement for the DC part it's just necessary to make the connection between the battery and the 24 V dc bus. And also at this bus, it will be connected the rectifier used in the energy hut, which will output 230 V. This rectifier will be useful to connect there the electronic elements such as the Modem 4g and the ESP42.

The other element which remains to be explained is the wind charge controller. This element has an input connected into the generator of the water wheel and the output will be also connected to the 24 V dc bus which powers the previous elements explained. everything within 230 V.

For the rectifier the one used is going to be the one located at the energy hut which was previously used for the solar. Currently this rectifier is not able to use, mainly because it has been 8 years or more without being used. But still remains to be either repaired by the NTNU officers or buy a new one.

Now for the connection of this system into the energy hut it will be used a few more elements such as an ESP32 and a modem 4G which are also represented afterwards. This part is furthermore explained in section 6.

Figure 48: Inside of the Hydro Hut

5.5 Conclusion

The energy produced is enough to power all the elements that have been mentioned in the electricity distribution grid. But the main problem in our installation is facing the climate. Mainly Skjetlein has 5 months a year temperatures below zero, which means that the main source for producing power, which is the river, is frozen. Even the weather conditions are not favorable, the other months without temperatures below zero, the river flows water, and the hydro is the renewable energy that produces the most energy, but with the actual configuration of the energy hut, is not able to use that energy to power up the elements there.

Even not being able to realize that much physical looks at the hydro hut, because of the weather conditions. It is concluded that the group is pleased with the solutions and the problems that have been overcome in this part. Even the connections are not already done at the placement, everything necessary to realize all the electric connections is already presented on the project. As well as all the elements necessary to realize the connections.

6 Electronics

This chapter intends to introduce the concept of the electronics used in this project, as well as delving in to some of the finer details of the electronic parts and plans. There will be an explanation of the software used, the sensors needed and the design of a PCB.

6.1 Introduction

The electronics part of the project consists of micro-controllers (MC) and a single-board computer (SBC). The SBC chosen was a Raspberry Pi 4 model B (RPI), and the reasoning behind this was that it is a readily available SBC that can be acquired easily, and the RPI platform has been in use for almost a decade [39]. This makes it a solid choice as the group has no prior experience with SBCs, making the RPI a safe option as it is a well-documented SBC.

As for the choice of MC; the group has experience with the ESP32 (model "DevkitC" v4) [40] MC and combined with its low cost it became a natural choice. Several projects have been completed by some of the group members using the ESP32 the past two years, so its functionality is familiar and it was proven to be a great supplement to the RPI for covering the areas the RPI would not be able to handle. Primarily this is done by using the ESP32 at the two locations necessary as seen in figure 49 below. The two sites detailed will be elaborated upon further on in this chapter.

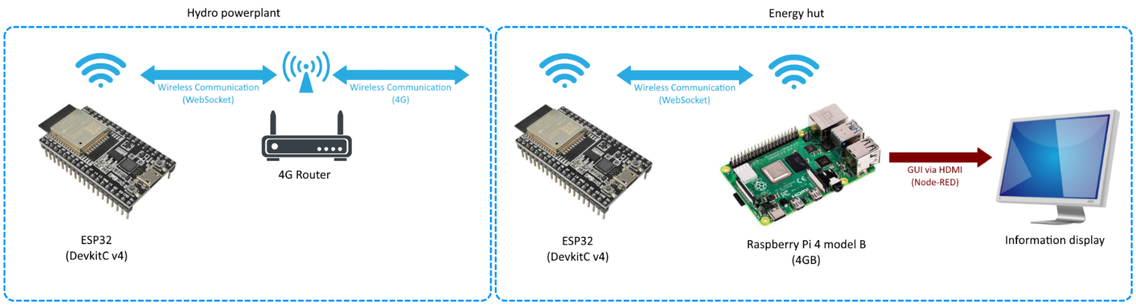

Figure 49: General overview of the electronic setup

The main idea is for the RPI to act as the head communication unit, collecting all necessary data from other units and performing the final calculations and manipulations needed. A brief research venture was done to investigate as to whether the RPI had available software that would cover the needs expressed by the client, and when this was quickly confirmed the choice became solidified. The software chosen and how the group utilized it will be described later in this chapter. The RPI's main purpose is to receive information from the ESP32 units via WebSocket [41], a full-duplex TCP/IP communication protocol. The ESP32 units are present to provide the ability to read sensor data from sensor inputs, as the RPI inherently lacks this functionality out-of-the-box. Given that the ESP32 of choice has a built-in WiFi module it was quickly decided to deploy the ESP32 units for this purpose.

6.2 Theory

The electronics part of the project can be separated into two parts: electronics and data processing. The first part is the operation of the ESP32 and its associated hardware components as well as some parts of the RPI, whereas the second part best describes the Node-RED running on the RPI.

6.2.1 Analog to Digital and resolution

The ESP32 has a specific limitation that must be taken into account; its Analog-to-Digital Converter (ADC) only allows for a maximum input of 3.3 VDC. This becomes relevant as the sensors utilized in this project give out a 0 to 5 VDC signal, and what this means is that the measurement done must be scaled down to match this 3.3 VDC input. This will affect the resolution of the measured signal, and the resolution for a current sensor that can sense from 0 to 20 Ampere with a 0 to 5 VDC output signal will be calculated accordingly:

$$\text{Resolution} = \frac{5V}{20A} = 0.25\frac{V}{A} \tag{23}$$

which means that we can see a change of 250 mV in the output signal from the sensor being equal to a measured change of 1 Ampere. This resolution will once again become relevant as we have to voltage divide this 0 to 5 VDC sensor signal down to a maximum 3.3 VDC signal. To continue with the example above, we will then receive a different resolution:

$$\text{Resolution} = \frac{3.3V}{20A} = 0.165\frac{V}{A} \tag{24}$$

which now gives us a change of 165 mV per Ampere. We can also look at how this will be from the side of the ADC, which has a total of 12 bits per ADC channel. This means we have a total range in the software equal to:

$$2^{12} - 1 = 4095 \tag{25}$$

which means that when given a maximum input voltage signal of 3.3 VDC the result in the software will be equal to a numeric value of 4095. This gives us a following resolution when comparing the maximum input voltage to the available bits in the ADC:

$$\text{Resolution} = \frac{4095}{3.3V} \approx 1240.9 \tag{26}$$

meaning that inside the ESP32 software we will see, while reading from the ADC, a change of ca. 1241 in the analog value per Volt from the current sensor. This becomes highly relevant once we wish to design the behavior of the system given that we wish for this analog value to perhaps showcase the current flow in the system or maybe to program a set behavior that follows different levels of Ampere currently in the system.

This is the primary use of the ESP32 in this system, given that this functionality does not exist in the RPI. Its secondary use is its integrated WiFi module which allows us to transmit the aforementioned analog values via WebSocket which is, as mentioned in Chapter 6.1, a wireless communication protocol. The recipient of this is the host unit; the RPI. The details surrounding this protocol as well as how it functions is more towards the IT side of things, as it is not deemed important to delve into the finer points and workings of precisely how the information is sent between these two main units.

The last type of operation that will be described here is the General-purpose input/output (GPIO) of the RPI. As mentioned in Chapter 2.5 the RPI is used to control some low power relays. This is simply done by having the RPI actuate a digital output pin via the Node-RED software, which raises its voltage level to a point where the receiving module recognizes this change in potential and therefore continues with its own actuation. In this case, we will use it to close or open a circuit using a relay that will be described better in a following chapter further on in this text. The operation of actuating the digital output pin happens via the Graphical User Interface (GUI) of the RPI, which is a website with a backend consisting of JavaScript and Node-RED. This will be detailed further in Chapter 6.4.1.

6.2.2 Data processing

The second part of the electronics part is best described as data processing. This means when the data transmitted from the ESP32's ADC is received by the RPI we will need some way to process what we receive. The finer details of this is described later on, touching on how the data is packaged as a JSON object as well as how the software in use, Node-RED, handles and manipulates this data. This is primarily done using basic electrical formulas and equations such as

Ohms law to calculate the power production of the system and the charge status of the batteries. The most important part done here is to ensure that the data received is stored in such a manner that it can later on be fetched on demand, something that will be required as the RPI also has the responsibility of showcasing a graphical interface where the data is presented. Said interface will also allow for operation of parts of the system, namely the relays connected to the RPI.

6.3 Hardware

The hardware used in this project consists of the units mentioned above (ESP32 & RPI) being used as main processing units in a host/client relationship, together with sensors, relays and some basic voltage dividers.

6.3.1 Current Sensor

The current sensor used is a "HO 40-NP-0100" [42], which is a open loop Hall effect current sensing module that can measure up to 100 A, giving out a 0-5 V signal which will be voltage divided down to 0-3.3 V for input to the ESP32. The sensor can be configured and has therefore been given the range of 0-20 A in this system, which gives us a resolution of 165 mV/A on the ESP32, which is sufficient for its 12 bit ADC.

6.3.2 5V NO/NC Relays

As seen and mentioned earlier in Chapter 2.5, there are three small relays being used in the control board operation. The relays are all "Parallax 27115" [43] which are mounted mechanically to the PCB, and then wired to the RPI via headers on the PCB itself. The relays feature an Normally Open (NO) and Normally Closed (NC) connection each, as well as a separate connection used to close the circuit. In Chapter 6.4.1 the software operation detailing how the relays are actuated will be described more in detail.

6.3.3 Resistive voltage dividers

A resistive voltage divider [44] is, at the most basic level, two resistors in series that follow Ohm's law. The full details surrounding how the voltage dividers are used, as well as how they work, will be detailed later on in Chapter 6.3.4.

6.3.4 Printed Circuit Boards

Printed Circuit Boards (PCB) are typically copper sheets with etched conducting pathways, lamented between insulating material. These boards are used to mechanically support and electrically connect electronic components mounted on them. The layout of each PCB is made to fit the electronics for used in the individual product, giving each component a designated space on the board and wiring them together as needed. Nowadays this process has been automated: simply send in the design or have someone design it for you, and a machine will print it, hence the name, and you receive your custom PCB. It's a cheap and effective way to handle the wiring and placement of electronic components, depending on the parts they may also be soldered directly to the board. [45]

The original plan for the project did not include a PCB, but rather a much more simplistic wiring on breadboard. This was later scrapped for the PCB, as the better mounting and less loose components will give more stable readings, as well as a need arising to properly mount several components that were added as the project grew in size. For this Bachelor, the PCB was designed by the group after deciding which components should be moved to the board. An example is the voltage sensor. Originally a separate module was to be used as a voltage sensor, however these components were delayed by shipment and the rising need to design a PCB gave way to simply creating our own solution with other parts. The completed PCB design can be seen in Figure 50.

Instead two resistors were mounted in series on the PCB to form a resistive voltage divider, which works by measuring the connection point between the two resistors. This gives us a new voltage, based on this formula:

$$\frac{V_{in} \cdot R_2}{R_1 + R_2} = V_{out} \tag{27}$$

Where V_{in} is the input voltage that is measured, R_1 is the resistor above the measure point, R_2 is the resistor below the measure point, and V_{out} is the new output voltage that is lower then V_{in} by the fraction $\frac{R_2}{R_1+R_2}$. The reason this is done, is because of the ESP32's max input voltage is 3.3V, so not only can it not register anything above this voltage, it can also damage the ESP32. The new voltage is then fed onto one of the ESP32's analog pins to use the Analog-to-Digital Converter (ADC). As the name suggests it takes analog signals, witch are continuous signals such as sound or voltage, and converts them into digital signals, time discrete signals with quantified amplitudes. These digital signals are made up of 1's and 0's and can then be handled by computers such as the RPI. The ADC of the ESP32 has a max resolution of 12bit, witch is 0-4095 (it can be lowered down to 9bit should you need to). This means for 3.3V the resolution is:

$$\frac{3.3V}{4096 - 1} = 0.805mV \tag{28}$$

In this project the batteries used, both in the energy hut and the hydro power plant, are 24 VDC, and to measure them on the ADC, a voltage divider is needed.

$$\frac{3.3V}{24V} = 0.1375 \tag{29}$$

which is the minimum division needed to make sure the ADC is not overloaded. On the PCB two voltage dividers in series are used. One with $R_1 = 30k$ and $R = 7.5k$, the other with $R_1 = 2k$ and $R_2 = 1K$. This gives a conversion of:

$$V_{in} \cdot \left(\frac{7.5k}{37.5k}\right) \cdot \left(\frac{2k}{3k}\right) = 0.1333 \tag{30}$$

So even if 24V is being measured, only 3.2V is transferred to the analog pin. The details of the wiring can be seen in the PCB wiring schematic below in figure 50. The PCB itself can be viewed below as well, one figure down at figure 51.

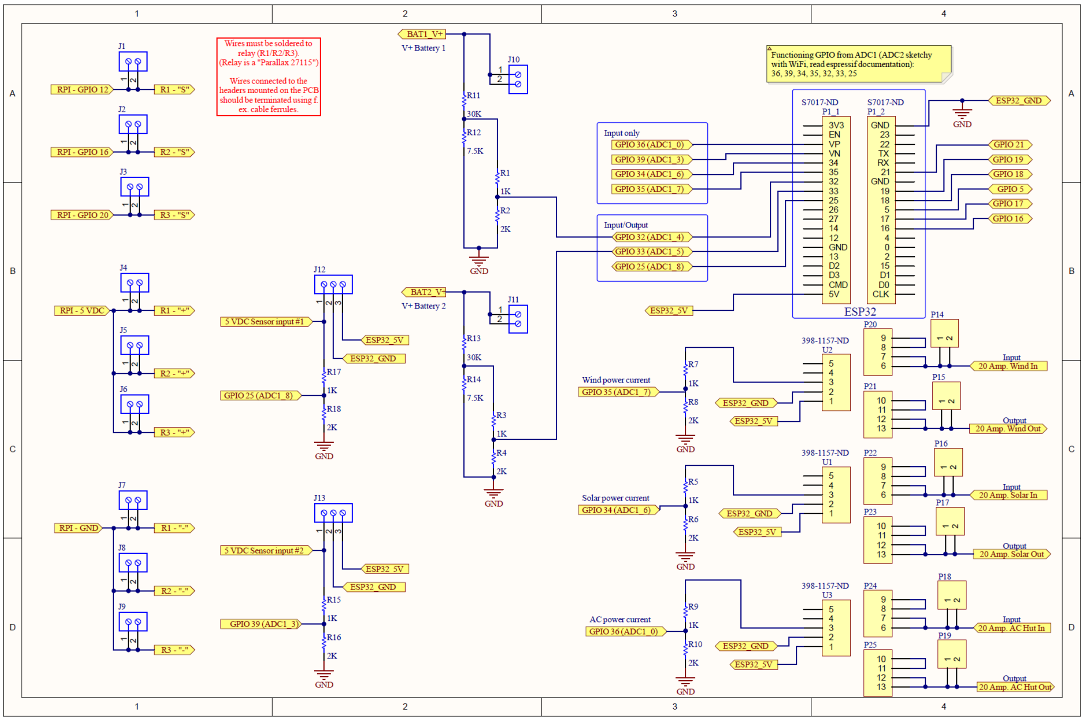

Figure 50: The groups design of the wiring schematic for the PCB

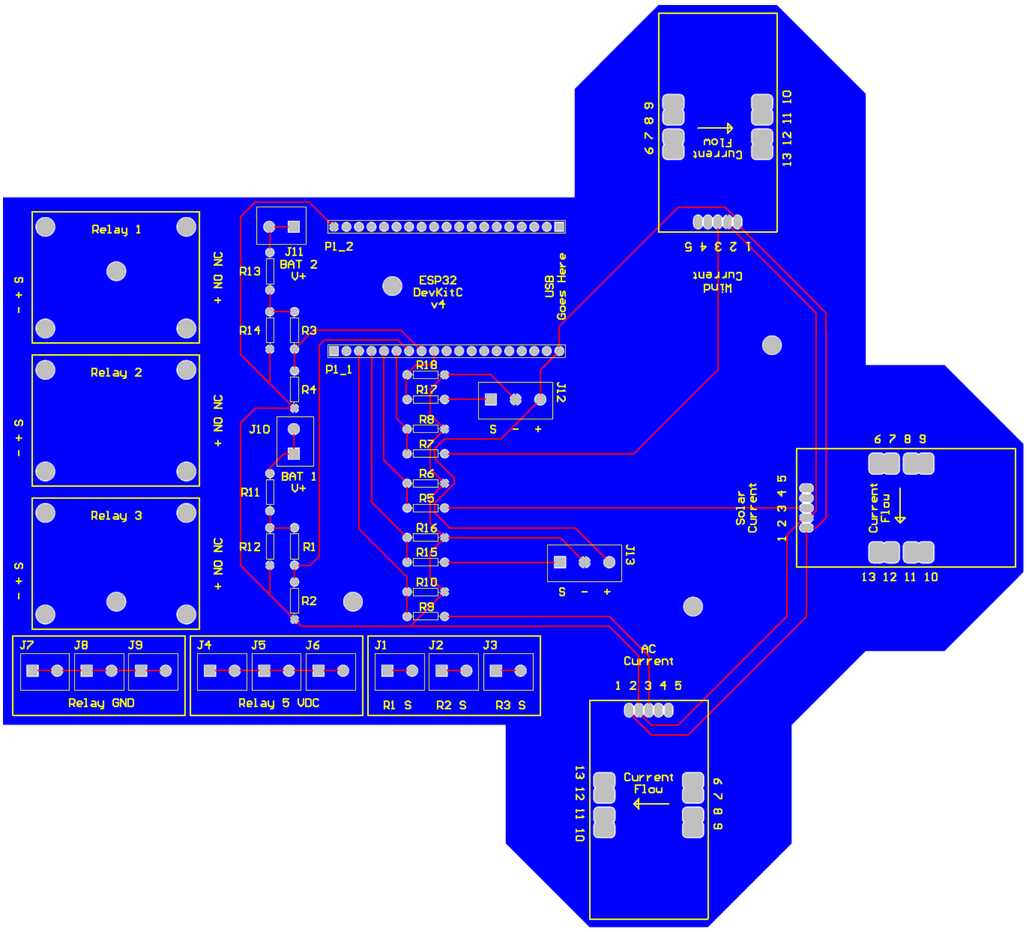

Figure 51: The groups design of the PCB itself

6.4 Software

This section will go over the different software used for the project: what they do, and how they were used. The actual software code is found in the appendix. Below you will see the flowcharts for the two units, the MC 52 and the RPI 54.

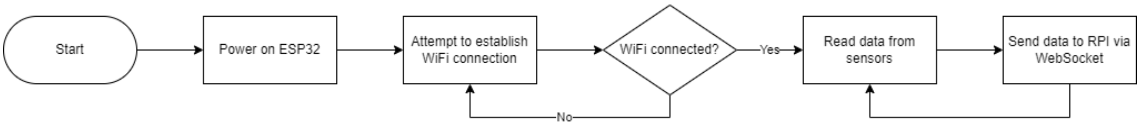

Figure 52: Flowchart for the ESP32

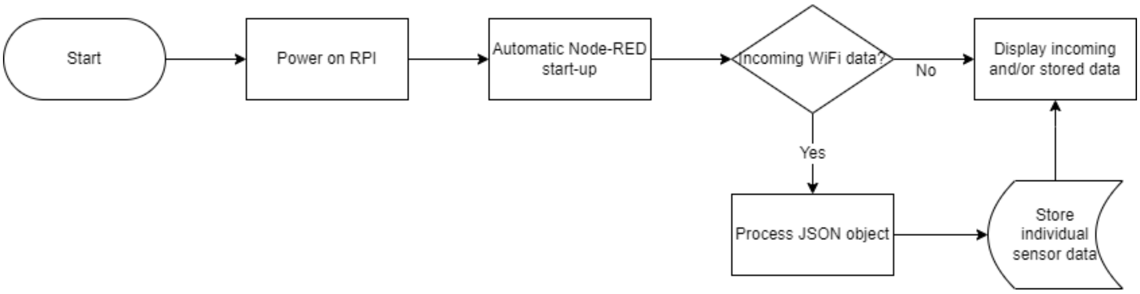

Figure 53: Flowchart for the RPI with Node-RED

6.4.1 RPI application: Node-RED

Node-RED is an open-source, flow-based programming tool, that uses coding blocks, called "nodes", to help visualize it. These nodes are wired together to form the flow of the program. This is shown in Figure 54, which shows the flow of data received from the ESP32. Notice how it has a similar structure to the flowchart for Node-RED in Figure 52.

It's a browser based editor that runs on JavaScript. JavaScript can also be used in the code to create a functionality not covered by the nodes. Specifically it runs on "Node.js", as a event-driven, non-blocking model. This also makes it ideal to run on low-cost hardware such as the Raspberry PI, and also on network edge, communicating over WiFi. [46]

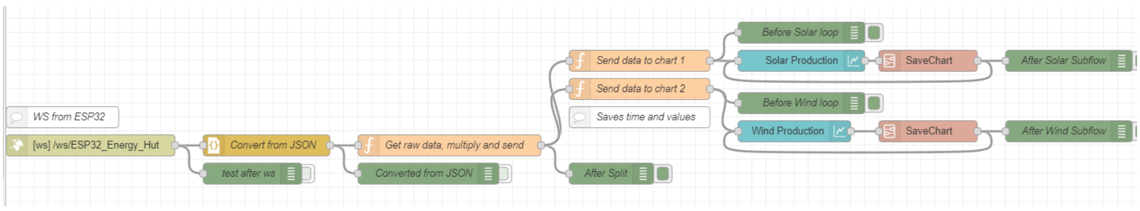

Figure 54: The flow of data in Node-RED

The reason why Node-RED was chosen, is because a goal of the bachelor is for the project to be used as a tool in the education of the students at Skjetlein. The flow-based code makes it very visual, and people not experienced in code can still see the functionality. With the "dashboard" module, a simple user interface can be created. I can both show data in graphs like the measured Watt, and take user input like virtual buttons connected to the code. Another flow-based programming tool that was considered is LabVIEW. The group already had experience with it, and it comes with a built in user interface. The main problem with LabVIEW for the project is that it's not open-source, it runs on a yearly licence. The group only had the licence as part of a different course. Being unsure about the legal side of using a licensed software for the bachelor, and the inability to update the code without a license, led the group to search for alternatives, and quickly found Node-RED, which fit the requirements from the client.

The Node-RED code receives the sensor data from the ESP32, the data is sent over WebSocket, a full-duplex TCP/IP communication protocol. The data is sent as a JSON object, an open-standard for data interchanging, used by many programming languages. The data is stored in text format that is readable for people, as well as machines. Once in Node-RED the data is decoded from JSON, then the data is read and handled in a function. Using the same names for variables between code, makes this process much simpler, as retrieving stored data is done simply by name. In the case of the batteries, the data consists of readings of each batteries current and voltage values. These are multiplied together to get the power, after this formula derived from Ohm's Law:

$$U \cdot I = P \tag{31}$$

Where U is the voltage measured in Volt [V], I is current measured in Ampere [A], and P is the power measured in Watt [W]. Afterwards the data gets split and sent to a text file to save it, and a graph to visualize it on the user interface. A handy, premade sub-flow lets the graph plot previous data, even after a re-boot. The GUI can be edited to suit the need of the project. It can have displays of different kinds such as graphs, as well as buttons, sliders and text input from the user. For this project the GUI shows the calculated Watt as mentioned, in addition to having virtual buttons to control the pins on the RPI, as seen in the example UI in Figure 55.

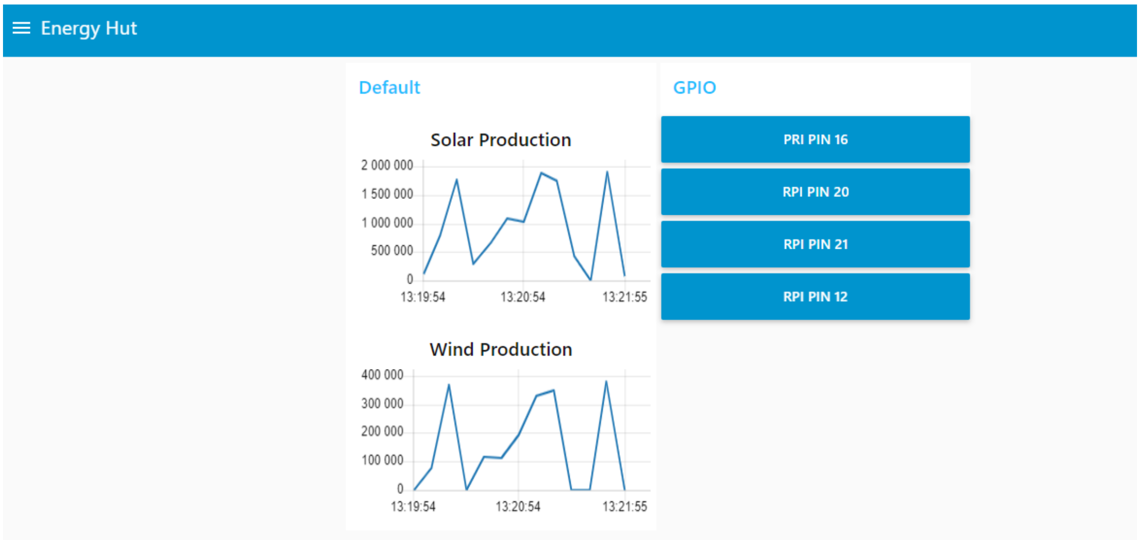

Figure 55: Example UI for the project. Made in Node-RED.

6.4.2 ESP32 code: C++

The code for the ESP32, was written in the language C++. C++ is a procedural programming language, initially developed to write operating systems. It has become a popular language all-around language for a wide array of uses. Featuring: a clean style with simple keywords and low-level access to memory.

The code itself was originally written in Visual Studio, an IDE from Microsoft for C/C++ and .NET developing. However to flash the code to the ESP32, a different IDE was used: Arduino IDE. It's a simple open-source software made by the manufacturer (Arduino) for writing and uploading code to Arduino boards, and additional MCs can be added. This proved to be simpler, partially because of the groups previous experience of using this IDE for the MC. The "WiFi" and "WebSocket" libraries gave all the additional functionality needed to send data to the RPI. The Arduino IDE was also downloaded to the RPI, so that any future updates could be flashed on site.

6.5 Electronics: Energy hut

The energy hut, as mentioned previously in this text, has two power production units (solar/wind) and two batteries. The core idea is for the ESP32 to connect to the current and voltage sensors and send the data live to the RPI via WebSocket. The RPI will then, via the flow-based development tool Node-RED, collect the data and display the necessary information through a graphical user interface on a nearby information screen via an HDMI cable. Said interface can also be accessed via the internet (or LAN) by any other computer on the same network as the RPI. As mentioned in the introduction, the interface running on the RPI will be used to display the relevant voltage/ampere/watt of the system as well as directly controlling a small amount of relays that will be used for safety.

The need to display this data was expressed by the client so that they are able to use this project as a teaching platform for green energy production and use.

Furthermore, the RPI has functionality for generic digital I/O control and thus it will be used to control some of the system in the energy hut via relays. The choice to let the RPI handle this was simple as the aforementioned Node-RED supports operating the GPIO of the RPI via its website application.

6.6 Electronics: Hydro power plant

The hydro power plant consists of, as mentioned previously in this text, a waterwheel and a turbine. For the electronics side of things these are both considered the same as the solar/eolic units, as the method of sensor data gathering will be identical as in the energy hut. Current and voltage will be measured by the ESP32, but in contrast to the energy hut the hydro power plant is not capable of being connected to any local WLAN due to its problematic geographic location. Several options were considered, and given that the ESP32 has built-in WiFi support the choice landed on simply procuring a 4G router that will handle the traffic between the energy hut and the hydro power plant. 2G was discussed briefly, but it was discovered that this communications network will close in 2025, and the group unanimously agreed that providing a solution that will be obsolete within 3 years was not acceptable. Given that the 3G network was phased out by November 2021 in Norway this was also obviously not a solution.

The operation is the same as in the energy hut; the ESP32 collects the necessary sensor data and sends it via WebSocket to the RPI in the energy hut.

6.7 Conclusion

This section is about conclusion to the chapter as well as discussing the solution the group came up with.

The electronics part of the system has the advantage of being something that can easily be tested compared to the rest, as this part only requires a computer with a functioning IDE, a USB cable, a WiFi connection, a handful of miscellaneous electronic components and sensors, and of course the RPI and ESP32. Having had all these things on hand for quite some time, it has allowed the group to work on this part and also run tests that normally may not be so easy compared to other parts in this project. Given how a fair bit of it was researching what software to use and what modules to deploy, there has been a typical preparation phase as well as a development phase and a testing phase. The end result is very close to what the client expressed needs for, with a functioning web GUI and measurements of the production of power so that the system can not only function as a renewable microgrid but also display the data of its production so that it has a more intuitive interface.

As for the technical decisions made, the group has experienced a rather straight-forward decision making pattern for this part of the project. There exists a plethora of components, sensors, microcontrollers and single-board computers, and for this project with the limitations and requirements we were given we still had a lot of freedom of choice. Therefore, it became our focus to use familiar items and solutions so that we could strive towards completing as much as possible rather than to try out new things for curiosity's sake.

The software development was done by two members of the group, this worked quite well. The tasks were ruffly split into code for the ESP32 and Node-RED. Each member was responsible for a part, and showed what they had been working on to the other during regular meetings and messages. Here they could also ask the other to review the code, help with what they struggled with, or just exchange ideas. A different set of eyes to look at the code and a different way of thinking about functionality solved some of the issues in the code. Also simpler things, such as different keywords to search for to find answers online proved helpful, as there was several parts of the codes functionality that was unfamiliar to the group before the start of the project. GitHub was used to store the code, and made it easy for both members to test each others code on their respective ESP32 and RPI.

Given what we have completed in terms of schematics and software, we are pleased with the solution offered and on the whole find the electronics part to fit the requirement and also fit what we as future engineers would consider an acceptable solution.

7 Field work

Work on site in the school.

The initial phase of the project included a site survey to check the Energy Hut building and where it is currently placed in the school.

Figure 56: Corridor from the school entrance to the Energy Hut

Figure 57: Corridor from the school building to the Energy Hut

As can be seen in figures 56 and 57, the Energy Hut is currently placed next to the school building.

After the design phase of the project, the next step was the testing of the equipment of the solar system, as this system is already mounted in the Energy Hut building. The testing of the system can be seen in figure 58.

Figure 58: Testing of the solar system

Other important phase of the project after the design process is the conceptualizing phase, as the design is brought to the real case with physical materials. As can be seen in figure 59, the control board schematic 6 is being tested to see how would the mounted system look like.

Figure 59: Testing of the control board concept

Also the Energy Hut layout explained in section 2.3 is being tested with the placement of the batteries and a mock-up of the placement of the inverter and connection box. This can be seen in figure 60.

Figure 60: Testing of the control board concept

The clients suggested site of the Energy Hut seen in figure 61:

Figure 61: Clients suggested site of the Energy Hut

The site suggested by the group seen in figure 62:

Figure 62: The suggested site by the group, looking south

Looking west from the group suggested site (yellow) toward the client suggestion (red arrow) seen in figure 63:

Figure 63: The suggested site by the group, looking west

The waterwheel is right now operating at his speed ratio, and it's just left to add the generator:

Figure 64: Water Wheel [34]

The Turgo Turbine is placed in the following placement:

Figure 65: Hydro Turbine Generator Placement

In the inside of the hydro hut it can be observed the following, whereas every connection will be made:

Figure 66: Inside of the Hydro Hut


6.5.2022, 13:56:21 node: dffd2f3764405ab6
msg.payload : string[74]
"{"voltData_1":"4095","voltData_2":"362","currData_1":"0","currData_2":"0"}"
6.5.2022, 13:56:26 node: dffd2f3764405ab6
msg.payload : string[74]
"{"voltData_1":"3770","voltData_2":"417","currData_1":"0","currData_2":"0"}"
6.5.2022, 13:56:31 node: dffd2f3764405ab6
msg.payload : string[74]
"{"voltData_1":"2931","voltData_2":"368","currData_1":"0","currData_2":"0"}"
6.5.2022, 13:56:36 node: dffd2f3764405ab6
msg.payload : string[74]
"{"voltData_1":"2320","voltData_2":"331","currData_1":"0","currData_2":"0"}"
6.5.2022, 13:56:41 node: dffd2f3764405ab6
msg.payload : string[74]
"{"voltData_1":"1799","voltData_2":"301","currData_1":"0","currData_2":"0"}"
6.5.2022, 13:56:46 node: dffd2f3764405ab6
msg.payload : string[74]
"{"voltData_1":"1085","voltData_2":"272","currData_1":"0","currData_2":"0"}"
6.5.2022, 13:56:51 node: dffd2f3764405ab6
msg.payload : string[73]
"{"voltData_1":"229","voltData_2":"240","currData_1":"0","currData_2":"0"}"
6.5.2022, 13:56:56 node: dffd2f3764405ab6
msg.payload : string[71]
"{"voltData_1":"0","voltData_2":"448","currData_1":"0","currData_2":"0"}"

Figure 67: Data transmission test with potentiometer, from full actuation down to no actuation. Change can be seen in "voltData_1" going from full 12 bits down to 0.

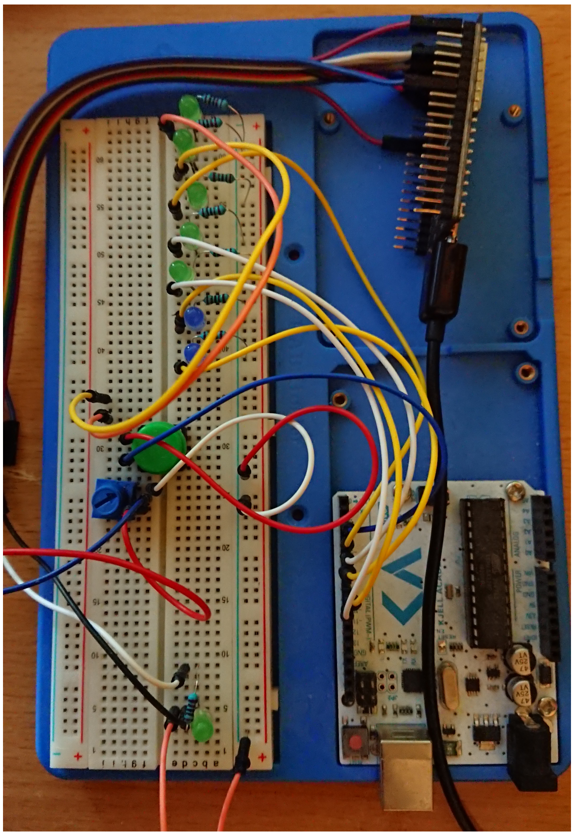

Figure 68: Picture of general electronics test bench, ESP32 in top right.

8 Project Conclusion

The world needs more renewable energy, in every sector. From goal #7 of the UN's 17 Sustainable Development Goals:
"Ensure access to affordable, reliable, sustainable and modern energy for all". [1]
Sketlein VGS wishes to teach their students, the future generations, about renewable energy. One of their initiatives is this bachelor, as a start towards a renewable microgrid on campus, with a GUI to visualize the data for educational purposes. The bachelor students were wanted for their expertise in the different skills needed to realize this goal. In the end the students served an advisory role, and per Skjetlein's request completed the groundwork and delivered the theoretical materials needed for the microgrid.

Delays and other unforeseen problems happen in most larger projects, they are in some cases unavoidable. This bachelor was no exception. The starting phase of the bachelor project had some confusing elements, as the group consists of a co-operation between two separate faculties. This led to some of the members checking for information through available channels, only to later discover it had not been released for their faculty. This happened, for instance, when attempting to locate the bachelor office as this proved to take some time to clarify. In addition, two of the students were exchange students from Spain, and a lot of the information was only available in Norwegian. Because of this, the group had to translate some of the available documents to English in order for everyone to read them. The group inquired about a visit to Skjetlein during the December month, but it was a busy time for the school, with their own exams, and invited the group to visit after the holidays.

The information phase of the project started in December, but due to the holiday and exam season the group agreed to begin the work once the Christmas break was over. During startup there was the problem of not knowing who the supervisor was, as they were not listed on the paper where other supervisors were. This delayed the first visit to Skjetlein by the group as a supervisor present was required. Reaching out to Steve Völler, the NTNU contact responsible for the bachelor, on the 17th of January, the group was informed that the supervisors had not been set and would be decided on during that week. Due to some miscommunication on the side of the faculties, the group was not informed as to who their supervisor was. On the 24th the group sent a new mail, where they got name of the supervisor, and on the 25th of January, contact with the supervisor, Basanta Raj Pokhrel, was established.

Having already been in contact with Skjetlein, both parties tried to find a time everyone could visit and settled on Friday the 4th of February. The project had properly started but was severely delayed which meant the first deadline, the pre-project report, was right around the corner, due on the 15th of February. The group was told to finish as much as possible until the 15th, then they received a new deadline to complete it by, the 22nd.

Once the pre-project was completed, the main project began, including a survey of components needed to complete the microgrid. The group made a shopping list of components and gave it to Skjetlein. However, they were told Skjetlein as a public school should, when possible, buy from Norwegian companies. The group was then tasked to search for Norwegian suppliers for all the components, including more niche components such as a generator and an inverter for the wind turbine. Being inexperienced in these types of projects, the group tried to comply to the request and spend additional time. on trying to find fitting suppliers, some of which did not exist. On a meeting with the staff at NTNU, the students were told that this is not their job, and simply handing in a list of components they need is enough.

When the list of components was handed over to Skjetlein there was a waiting period as the parts were being delivered, so work on the thesis was coming together in the meantime. Some parts were delayed such as the voltage divider component the group originally planned to use; this, and other factors, led the group to move forwards with a design process for a PCB, making these voltage dividing components obsolete.

Another part of the project included what Skjetlein could do. They had plans to move the hut from its current location, and the group suggested a spot that would be well-suited for wind, but ultimately Skjetlein chose a spot in front of the parking lot. After being given a preferred height from the group, Skjetlein wished for their metallurgy students to weld the mast of the wind turbine. In addition, concrete foundations were needed for the wind turbine and the hydro generator.

When enough parts had arrived for testing a new problem appeared; the current inverter for the solar systems that had been used by Skjetlein previously was no longer working. This was first discovered the 6th of May, too close to the end of the bachelor on the 20th, to get a replacement, meaning the solar could not be installed in time.

This was a milestone the group had hoped to achieve, as the solar panels were a key part of a functioning proof of concept as they were the energy source closest to being complete. All the theoretical parts are done, and handed over to Skjetlein, so they can get electricians to install the system.

8.1 What has been delivered to Skjetlein

The Bachelor started off quite large and open, on the first visit Skjetlein put it as follows: "We have a lot of things that need to be done, so you may choose what to focus on". The group's supervisor was really helpful in this initial part, having much more experience with the requirements of a Bachelor and what is a reasonable scope. During the stages of the pre-project Skjetlein gave a priority list of what they wanted out of the Bachelor: The highest priority was to complete the schematics for all three energy harvesting systems (Solar/Wind/Hydro), a way to store the energy, and software for measuring, handling, saving and visualizing data, which could also send over WLAN. The reason this was considered highest priority is because Skjetlein lacks the expertise to do these parts themselves. They wanted the bachelor students' expertise on electrical engineering, electronics and software to create schematics for the individual parts of the micro-grid, so that the project they had started could move forward. Once all this is in place, and they have been handed the blueprints, their electricians can deploy the system.

8.2 Future project works

This section is for detailing the remaining steps needed for the system to be complete. Each part is described individually in sub-chapters so that it is more clear in each instance what is required.

8.2.1 Future works on the Energy Hut

The future work that needs to be carried out in the Energy Hut covers many different aspects that can be complementary to this project. The first step is to finalize the construction of the Energy Hut building on the exterior and the interior part. This work will cover from completing the door to the building, to building inside the shelves needed to mount all the hardware of the system.

The second part of the future work for the Energy Hut is the production and mounting of the control board. After that, the electronic and software systems need to be set up in conjunction with the electrical systems. The electrical AC system will also need to be mounted.

Future improvements to the Energy Hut can be done in various aspects. The first one is on the interior part. As the control board and the other hardware of the systems is placed inside the building, it is going to be spare space that the school can use for other educational purposes complementary to the Energy Hut use.

Other improvements to the Energy Hut can be done in the software aspect, as there is already a RPI installed, there is a wide variety of options that can be implemented and can be used to digitize the Energy Hut.

8.2.2 Future works on the solar system

The future work that needs to be carried out in the solar system is to complete the electrical connections to the inverter and to the control board. This has to be done in order to change the defective hardware that is currently in the system.

As is explained in section 3.6, the improvements to the solar system can come mainly in two ways. The first one is increasing the power output of the solar system by adding an automated system to control the opening and closing of the solar panels, to improve its efficiency. The second way would be to monitor the solar panels individually to have a more precise knowledge of the solar panels energy production.

8.2.3 Future works on the wind system

What is remaining in the wind project is to construct the wind turbine tower, move the Energy Hut itself and erect the wind turbine tower in the location the client choose.

Then what remains is placing the wind turbine, extending the wires from the generator in to the energy hut, connecting them to the wind MPPT controller and then finally connecting the controller to the batteries, thereby completing the system, as the batteries are connected to the micro-grid bus and the inverter.

8.2.4 Future works on the hydro system

What is remaining in the hydro project is the realization and construction of the gear box able to transmit the power from the water wheel into the energy hut, and afterwards into the battery.

Also it's still required to add and construct following the blueprints, all the connections between the elements inside the hut. Such as the inverter and the inside connections for a better electric distribution grid inside the hut.

8.2.5 Future work on the electronics system

The future work needed to finish the remaining work on the electronics side is to complete the design of the PCB, and then to order and solder it. Said PCB has been designed together with a wiring schematic, and will be supplied together with the necessary files for making a complete order. There will also be a need for a 4G router so that the hydro power plant can communicate together with the Energy hut. Once the PCB is in place the sensor equipment can be connected to the ESP32, and then the system can be initialized.

8.3 Recommendation to the school

The end result of the project delivery contains the necessary blueprints and schematics required for a system initialization. The immediate steps recommended for each part of the system has been explained in detail in Chapter 8.2. The next recommended step would be the assembly and installation of the micro-grid system.

Once the currently designed systems are in operation, these systems can be a useful foundation to implement new systems on each of the different elements that are in the current project. These will now be detailed separately down below.

For the electronics part, the current system layout allows for expanding the functionality through adding more micro-controllers. The communication type between the host and the clients is done via WebSocket, and the way this is handled in the host RPI means that new WebSocket connections can easily be made. This means that the expansion can be done in many ways as long as the

WebSocket protocol is maintained, and as this is a standardized WLAN protocol it is not a difficult task.

Further on the solar system, it can be recommended to increase the energy production to improve the energy availability the Energy Hut. This can be beneficial for the micro-grid, as a higher energy availability opens options to implement other electrical loads, like an electrical bike charger or a charging station for electronic devices, like smartphones or laptops.

On the Energy Hut side, the improvement recommendations can come in two main aspects. The first one is the electrical system, where the storage energy system can be increased in capacity, to absorb more surplus energy from the energy sources. In the electrical system can also be recommended to increase the power delivery capacity of the AC system, in order to be able to feed larger electrical loads that contribute to improve the functionality of the whole system.

The second aspect that can be improved in the Energy Hut are the electronics systems. It is recommended to look into automation procedures to implement in the electronic control system in order to improve the energy management in the Energy Hut. An increased automation of the Energy Hut can be used to provide more information for teaching purposes and better real-time energy generation system performance.

With regards to further development on the wind system, it is generally not recommended to go any further as the assessments in chapter 4 showed the site to be unsuited for any significant energy production. One aspect that could be explored is to showcase the difference in potential energy output of different systems, comparing VAWT vs. HAWT, for example, but that is viewed to be rather more expensive than the value of the output.

Lastly for the hydro it would be interesting for the future to be able to transport the energy from the hydro hut into the energy hut. If not, it would be really useful to install some more plugs or connections inside the hut. So more electric energy will be used rather than for charging the battery.

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Appendix

A Solar energy production forecast

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

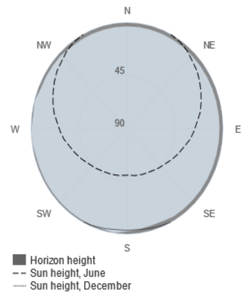
Provided inputs:

Latitude/Longitude:	63.341,10.302
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed:	0.42 kWp
System loss:	5 %

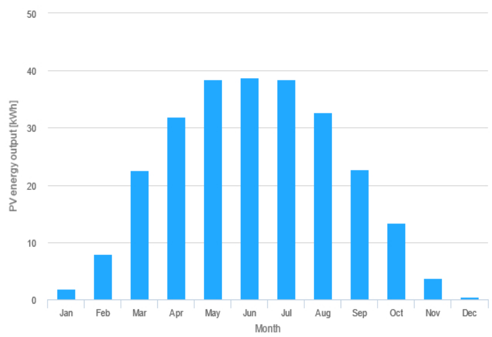
Simulation outputs

Slope angle:	70 °
Azimuth angle:	65 °
Yearly PV energy production:	253.04 kWh
Yearly in-plane irradiation:	719.68 kWh/m²
Year-to-year variability:	16.92 kWh
Changes in output due to:	
Angle of incidence:	-3.26 %
Spectral effects:	NaN %
Temperature and low irradiance:	-8.91 %
Total loss:	-16.29 %

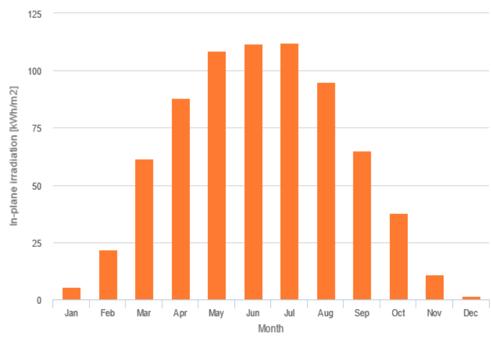
Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	E_m	H(i)_m	SD_m
January	1.8	5.4	0.9
February	8.0	22.0	1.7
March	22.7	61.4	6.0
April	31.9	88.0	6.9
May	38.5	108.8	5.3
June	38.8	111.6	5.6
July	38.5	112.2	5.3
August	32.7	94.8	3.5
September	22.7	65.2	3.9
October	13.3	37.8	3.9
November	3.7	10.8	1.2
December	0.5	1.6	0.2

E_m: Average monthly electricity production from the defined system [kWh].

H(i)_m: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SD_m: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Report generated on 2022/04/27

Figure 69: Program result for the solar energy forecast in the "opened position"

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

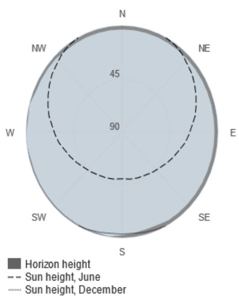
Provided inputs:

Latitude/Longitude:	63.341,10.302
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed:	0.42 kWp
System loss:	5 %

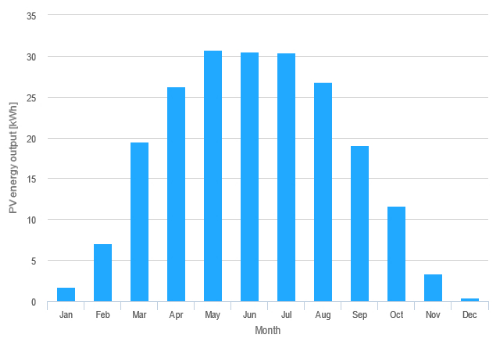
Simulation outputs

Slope angle:	90 °
Azimuth angle:	65 °
Yearly PV energy production:	207.8 kWh
Yearly in-plane irradiation:	597.19 kWh/m²
Year-to-year variability:	14.54 kWh
Changes in output due to:	
Angle of incidence:	-3.76 %
Spectral effects:	NaN %
Temperature and low irradiance:	-9.38 %
Total loss:	-17.15 %

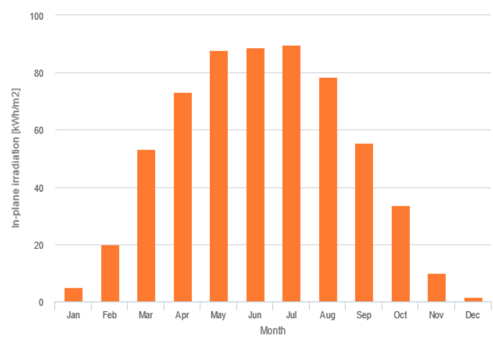
Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	E_m	H(i)_m	SD_m
January	1.7	5.1	0.9
February	7.1	19.8	1.6
March	19.5	53.4	5.4
April	26.2	73.3	6.1
May	30.8	87.8	4.6
June	30.5	88.8	4.5
July	30.4	89.7	4.5
August	26.8	78.7	3.0
September	19.0	55.4	3.5
October	11.7	33.5	3.6
November	3.4	10.0	1.1
December	0.5	1.6	0.2

E_m: Average monthly electricity production from the defined system [kWh].
H(i)_m: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].
SD_m: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Report generated on 2022/04/27

Figure 70: Program result for the solar energy forecast in the "closed position"

B Characteristics of Hoyi 200 wind generator

General	Hoyi 200
Axis	Vertical
Height	1.3m (4.3 ft)
Width	0.8m (2.8 ft)
Weight	41 kg (90.4 lb)
Swept Area	$0.84m^2$ ($9.0 ft^2$)
Blade Materials	Fiberglass

Performance	
Rated Power	200 W
Cut-in Wind Speed	2 m/s (5.6 mph)
Cut-out Wind Speed	30 m/s (66 mph)
Rated RPM	200 RPM
Survival Wind Speed	50 m/s (110 mph)
Rated Wind Speed	12m/s (26 mph)
Noise Level at 12m/s	40 dB

Electric Generation	
Generator Type	PMG
Rated Output	
Off-Grid	200W

Figure 71: Characteristics of Hoyi 200 wind generator [25]

C Average wind at E6 Heimdal

	Average wind and wind direction (from) for E6 Heimdal (SN68238) in the period 09.2015-02.2022. (%)															
Average wind (m/s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	SUM
0,0-0,2																	12,3
0,3-1,5	1,8	1,3	0,6	0,6	0,9	0,8	1,1	1,8	2,1	2,7	2,9	2,3	1,5	1,2	1,5	1,6	24,8
1,6-3,3	3	1,3	0,4	0,5	2,1	2,4	2,1	1,7	1,7	4,1	2,4	1,5	1,2	1	1,5	2,2	29
3,4-5,4	1,7	0,5	0,2	0,4	1,7	2,6	1,8	2,1	1,5	1,3	1,1	1,2	0,8	0,5	0,7	0,7	18,7
5,5-7,9	0,1	0	0,1	0,2	0,3	0,8	1,3	1,9	0,9	0,6	1,4	1,1	0,5	0,2	0,3	0,1	9,9
8,0-10,7	0	0	0	0,1	0,1	0,1	0,2	0,3	0,2	0,4	1,2	0,5	0,3	0,1	0,1	0,1	3,6
10,8-13,8	0	0	0	0	0	0,1	0	0	0	0,1	0,7	0,2	0,2	0	0	0	1,3
13,9-17,1	0	0	0	0	0	0	0	0	0	0	0,2	0	0	0	0	0	0,4
17,2-20,7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,1
20,8-24,4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24,5-28,4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28,5-32,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
>32,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM	6,6	3,1	1,3	1,8	5,1	6,7	6,5	7,9	6,4	9,3	9,8	6,8	4,4	3,1	4,2	4,7	100
	Data is valid as of 21.02.2022 (CC BY 4.0), Meteorologisk institutt (MET)																

Table 2: Table of average wind speeds at E6 Heimdal for the period 09.2015-02.2022 [27]

D Characteristics of Waterwheel efficiency

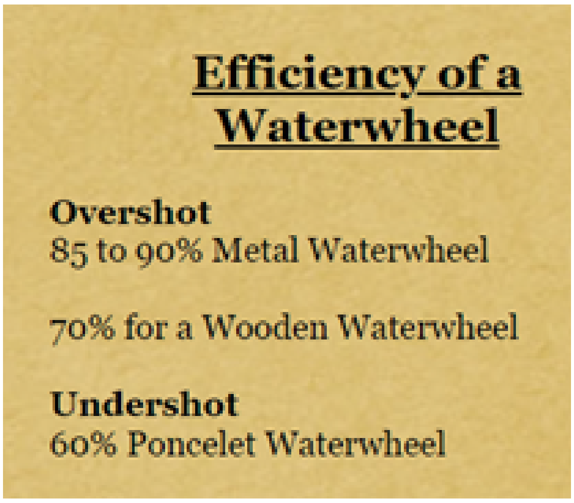


Figure 72: Efficiency of waterwheels [34]

E Article

The article starts on the next page, due to formatting.

Background/Introduction

Skjetlein videregående skole is an agricultural school educating, among others, the agricultural workers of the future. As such there is a need to actually showcase the advantages of renewable energy sources for these students.This can be done through combining several different sources of renewable energy into a microgrid platform, where the power production data is monitored so that it can be used for educational purposes through a graphical platform.

A microgrid is in essence a small-scale power production facility that is not connected to the main power grid. This means it must be self-sufficient and has to survive using only the renewable energy sources available. This also makes monitoring the power production relatively simple as there are few sources available.

Objective

The primary objectives of the project has been:

- Combining the power production of three solar panels and a wind turbine which connects to a small hut, named the “Energy Hut”.
- Combining the power production from a water wheel generator and a turgo water turbine located approx. 500m away from Energy Hut.
- Storage of power at both sites so that it can be used by students.
- Creating a platform to monitor the power production at both sites, sending the data to a main processing unit that will both store and display the data.

Methodology

The first step was to assess the current status of the components on-site, and consider what components were missing for the system to be functional. Afterwards, an evaluation was made for each source (solar/wind/hydro) as to how best utilize the available locations and equipment, such as where to place the wind turbine and what generator would be needed to fit the size and RPM of the water wheel.
After these evaluations a list of missing components was generated so that these could be acquired and the installations made. While this was ongoing, the data collecting platform was being created in parallel as this was done through deploying micro-controllers and a small single-board computer as the main unit.

Results

The result of the project is more advisory: A shopping list of all the needed components, finished blueprints for the systems of the individual energy sources including storage for the energy, a Printed Circuit Board for the electronic components, and a working software for measuring, handling, saving and visualizing data that could also be sent over Wi-Fi. All the primary objectives were fulfilled, which is in line with Sketlein's main request: They wanted the bachelor students' expertise on electrical engineering, electronics and software to create schematics for the individual parts of the microgrid, so that the project they had started could move forward.

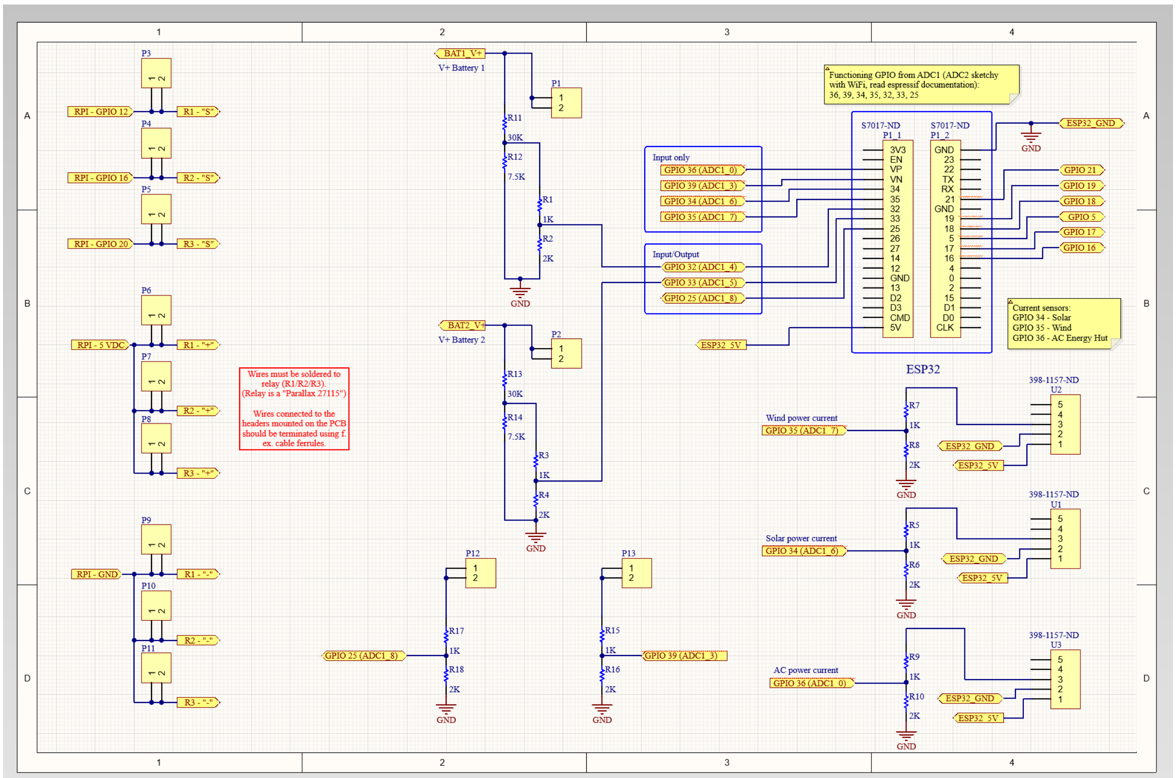


Fig 1: PCB designed for the Energy Hut.

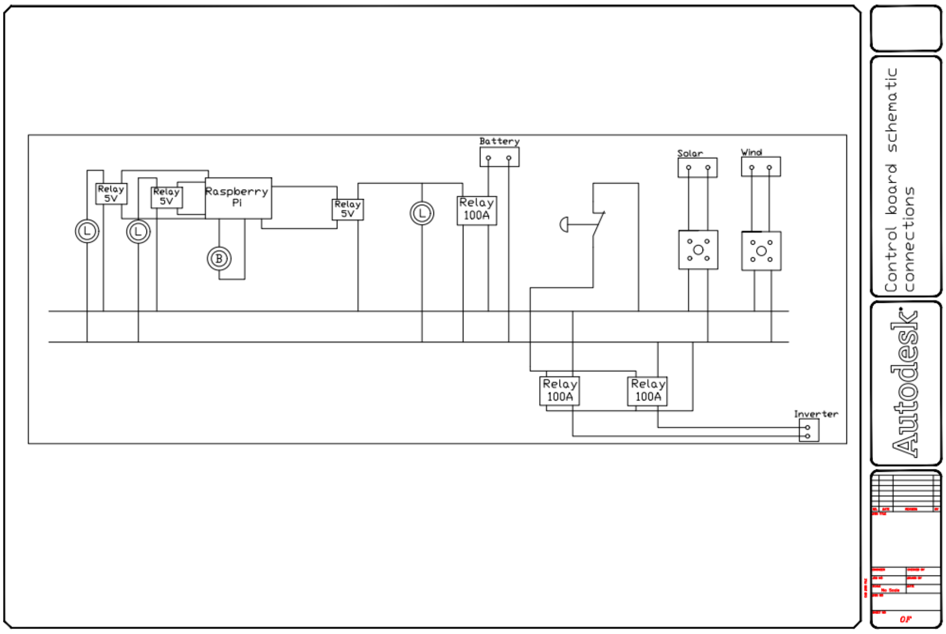


Fig 2: The Energy Hut's control board schematic.

Conclusion

The bachelor was a new experience for the entire group. It was an unusual type of work compared to previous projects we've had during our degree. There was no template or given means to complete the task, simply a number of problems and a goal. Being closer to an actual task we might receive as working engineers, it has been a useful experience. It started out as wide and a little unclear, where we needed to focus and define what should be done, and how it should work. The group itself consisted of 3 electrical engineering students, 2 of which were exchange students from Spain, and 2 electronics engineering students. We worked well together and the different skill sets were a good match for the project. The group did encounter some unexpected problems that slowed down the project, such as discovering the rectifier on the school was out of order. All in all, the final result is satisfying although not perfect, some parts could have been done better and the group's goal of deploying both the Solar and Wind systems was not reached.

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