Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Institutionen för energi och teknik

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– The possibility for Gotland and Åland to become self-sufficient with renewable electricity and energy storage in form of hydrogen

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Abstract

The objective of the project was to evaluate the possibilities for Gotland and Åland to become self-sufficient in electricity with the help of renewable electricity and storage in form of hydrogen. The outcome of the project will act as a feasibility study for a possible master's degree project. To do this project three questions of issue were set. What are the possibilities for Gotland and Åland to become self-sufficient in electricity with the help of renewable electricity and storage in form of hydrogen? How many hydrogen storages are required on each island for each scenario? Which scenario is the best? The boundaries that were made were to only use solar and wind power as renewable power sources. Four scenarios was set to get evaluated. This were, Scenario 1: How the year 2020 looked like. Scenario 2: Renewable electricity must constitute at least 60% of the total annual electricity consumption. Scenario 3: The amount of locally produced renewable electricity must correspond to the annual electricity consumption. Scenario 4: The amount of locally produced renewable electricity was set to 130 % of the electricity consumption. The results were presented based on own calculations and the solar production was calculated with the help of a model called PVGIS. The conclusion that was drawn was that the possibilities for Gotland and Åland to become self- sufficient in electricity with the help of renewable electricity and storage in hydrogen is low for scenario 1, 2 and 4 with this economical indicative, based on required full load hours for the electolyzer as an economic indicator. But it is achievable, and the possibilities are best for scenario 3 for both islands.

Sammanfattning

Syftet med detta projekt var att utvärdera möjligheterna för Gotland och Åland att bli självförsörjande på elektricitet med hjälp av förnybar el och lagring i form av vätgas. Projektets resultat kommer att verka som en förstudie för ett eventuellt examensarbete. För att göra detta projekt var tre frågeställningar skapade. Vad är möjligheterna för Gotland och Åland att bli självförsörjande på elektricitet med hjälp av förnybar energi och lagring i form av vätgas? Hur många vätgaslager krävs på varje ö för varje scenario? Vilket scenario är det bästa? Avgränsningarna som gjordes var att endast använda sol- och vindkraft som förnybara energikällor. Fyra olika scenarier utvärderas. Dessa var, Scenario 1: Hur 2020 såg ut. Scenario 2: Förnybar el måste utgöra minst 60% av den totala årliga elförbrukningen. Scenario 3: Mängden lokalt producerad förnybar el måste motsvara den årliga elförbrukningen. Scenario 4: Mängden lokalt producerad förnybar el sattes till 130% av elförbrukningen. Resultaten presenterades baserat på egna beräkningar och solproduktionen beräknades med hjälp av en modell som heter PVGIS. Slutsatsen som drogs var att möjligheterna för Gotland och Åland att bli självförsörjande på elektricitet med hjälp av förnybar el och lagring i vätgas är låga för scenario 1, 2 och 4 med denna ekonomiska indikativ, som är baserad på nödvändiga fullastningstimmar för elektrolysatorn som en ekonomisk indikator. Men det är uppnåeligt, och möjligheterna är bäst för scenario 3 för båda öarna.

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1. Introduction

For an island to be completely self-sufficient in electrical energy all year round, it is important to have a storage device, so that electricity can be accessed during periods when variable renewable sources are not available. Nowadays, the development of hydrogen use is increasing in many sectors, for instance, in electricity production, the industrial and vehicle fleet, and in particular as a range extender for the battery in electric vehicles. In addition, the discussion over the complications with the hydrogen battery is increasing.

Hydrogen is able to store a large amount of electrical energy for a long time, the disadvantages of hydrogen are that conversion and compression of electricity-hydrogen-electricity results in loss of conversion. Thus, the two forms complement each other to meet the need for regulation in the electricity grid. Hydrogen farm AB has a container solution for hydrogen storage that would be suitable for islands that do not need a large central source of electrical energy. The idea is small-scale storage on a large scale, which is advantageous from an energy-security standpoint. Because of the islands can be self-sufficient and are not dependent on the few cable connections which can be critical for reliable power supply on the islands. These could be destroyed during war, other extreme situations, or weather. This study is crucial to assess the number of storage units that are needed on the island in order for it to be self-sufficient.

1.1 Background

In 2015, the UN General Assembly adopted a resolution with 17 global goals for one better world: Agenda 2030 for sustainable development. Finland, followed by Sweden, are the leaders of the Sustainable Development Goals (SDG) index today, which is an assessment of each country's overall performance on the 17 SDGs, giving equal weight to each goal.

The most relevant goals for this project of agenda 2030 is:

- Goal nr 7: Affordable and clean energy
- Goal nr 11: Sustainable cities and communities
- Goal nr: 12: Responsible consumption and production
- Goal nr 13: Climate action

(Cambridge, 2021)

A year later, entered the global Paris climate agreement into force. Both Agenda 2030 and the Paris Agreement are important factors for Sweden's national energy and climate policy goals. Some of the important goals for Sweden are:

- By 2045, Sweden will have no additional greenhouse gas emissions to the atmosphere, to then achieve negative emissions.

- By 2040, Sweden will have 100 percent renewable electricity production.

- By 2030, Sweden will have 50 percent more efficient energy use compared with 2005, expressed in terms of added energy in relation to the gross domestic product (GDP).

- Emissions from domestic transport, excluding domestic flights, shall be reduced by at least 70 percent by 2030 compared to 2010.

(Energimyndigheten, 2019)

Some of the important goals for Åland are:

- Åland energy sector's greenhouse gas emissions to be reduced by 60% between the years 2005 and 2030.

- Renewable energy must constitute at least 60% of the total annual energy consumption on Åland by 2030.

- The amount of locally produced renewable electricity must correspond to the annual electricity consumption on Åland by 2030.

(Smart Energy Åland, 2021)

With that being said, there is already a well-established market for hydrogen worldwide, and its use in the industry, mainly in ammonia production and the oil industry which has more than tripled since 1975. Depending on how the hydrogen is produced, it produces different CO_2 footprints. To date, most of the hydrogen has been produced with fossil fuels, natural gas and coal at a cost below 2.5 USD / kg, where the fuel cost is 45–75% of the total cost (Energimyndigheten, 2021).

1.2 The islands

Gotland and Åland are islands in the Baltic Sea. The islands are popular destinations during the summer months with many summer residents and large tourism industry. With increased population comes increased energy use. Both islands are part of a network called the Baltic Islands Network or commonly known as B7. During 20 years of collaboration, B7 has carried out energy projects, exchanging useful experiences on mainland communications. During a conference on Gotland in the autumn of 1989, the foundation was laid for a collaboration between the seven large islands in the Baltic Sea (Monzón Preis, 2009).

Figure 1: File:Finland Sweden Locator.png (Pudeo~commonswiki 2008) (CC BY-SA 3.0).

Table 1: Consumption, production and installed capacity power for Gotland and Åland.

Islands	Gotland	Åland
Consumption [GWh/year]	944.1	298.7
Solar production [GWh/year]	13.2	2.5
Wind production [GWh/year]	521.7	57.2
Renewable electricity production [GWh/year]	535.6	59.7
Installed Wind power [MW]	179	21
Installed Solar power [MW]	11.9	2.6
Installed capacity renewable power [MW]	190.9	23.6

Figure 2 shows the consumption on each island hourly for the year 2020. Gotland's total yearly consumption is more than 3 times Åland's total yearly consumption.

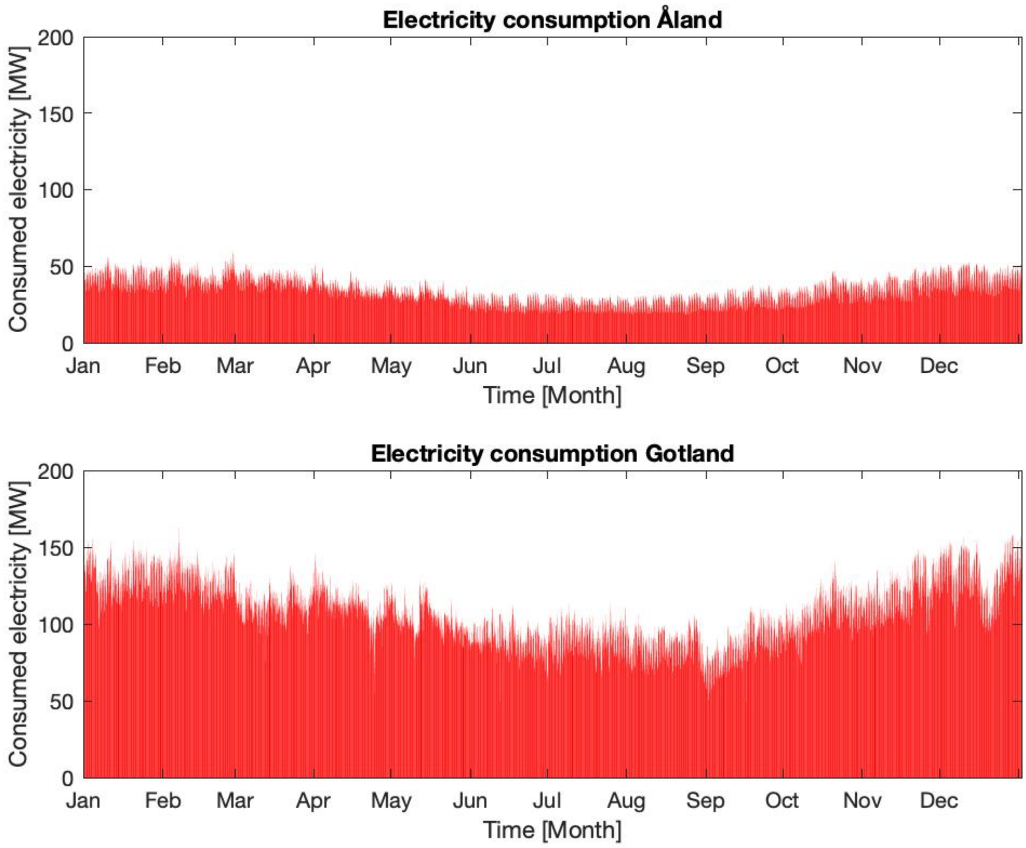


Figure 2a: Electricity consumption on Åland for year 2020 (Mörn, J., 2020).
Figure 2b: Electricity consumption on Gotland for year 2020 (Karlsson L., 2020).

1.2.1 Gotland

Gotland had 60,124 all year residents in the year 2020 (SCB, 2020). The size of the island is 3,135 km^2, which means that Gotland has 19.2 inhabitants per km^2 (Region Gotland, 2017). The Swedish Energy Agency has been commissioned by the government to work for Gotland to be a pilot area that precedes the transition to a sustainable energy system (Energimyndigheten, 2019). Gotland has the greatest solar irradiation in all of Sweden. A large part of the energy is used in industry, but also transport and households are large consumers. In 2016, 2,200,000 passengers travelled to and from Gotland by plane and ferry. Gotland's most greenhouse gas emitters are the limestone and cement industry, which accounts for about 75% of the island's climate impact (Region Gotland, 2017). Wind power is Gotland's largest local source of electricity. Gotland's consumption was 944.1 GWh the year 2020 which can be observed in table 1. The island has today a lack of capacity in the electricity grid but still want to build more electricity production from wind and solar. For this to be realistic there would be adequate to have solutions for storage (Energimarknadsinspektionen, 2020).

1.2.2 Åland

Åland is an autonomous, demilitarized and Swedish-speaking territory with Finnish state affiliation. Åland consists of 6,757 islands in 2020, 30,000 people were living there all year round (ÅSUB, 2021a). The size of Åland is 1,581 km² (Nordic CO-operation, n.d.). Åland's total electricity consumption in 2020 was 298.7 GWh/year which can be observed in table 1 (Kraftnät Åland, n.d.). More than 9,000 ships arrived at Åland ports in 2018. Åland consists of 16 municipalities, of which 6 are in the archipelago (ÅSUB, 2021b).

1.3 Project description and purpose

The objective of the project was to evaluate the possibilities for Gotland and Åland to become self-sufficient in electricity with the help of renewable electricity and storage in hydrogen. The renewable electricity sources in this project are wind power and solar power. The goal is to find out how many hydrogen storages are required on each island. The project also evaluates three different scenarios that are based on national energy and climate policy goals. Furthermore, the outcome of the project will act as a feasibility study for a possible master's degree project.

1.3.1 Research question

- What are the possibilities for Gotland and Åland to become self-sufficient in electricity with the help of renewable electricity and storage in hydrogen?

- How many hydrogen storages are required on each island for each scenario?

- Which scenario is the best?

1.4 Boundaries and method

The boundaries that were made were to only use solar and wind power as renewable power sources. This is because the hydropower on these islands is nearly negligible. The production from biofuel is mainly used to heat housing, real estate and fuel vehicles. The global radiation that was used in the model for calculation was from the year 2016 this since it was the latest year the model provided data from. The consumption was used from year 2020 and was not changed in any of the scenarios due to uncertainties in the projections for future consumption.

1.5 The different scenarios

The different scenarios that are going to investigate are based on the national energy and climate policy goals on each island. First is the result of how the year 2020 looks like.

Scenario 1:
- How the year 2020 looked like.

This scenario was chosen to get an overview of what consumption and production look like today.

Scenario 2:

- Renewable electricity must constitute at least 60% of the total annual electricity consumption.

This is based on Åland's goal that renewable energy must constitute at least 60% of the total annual energy consumption on Åland by 2030.

Scenario 3:

- The amount of locally produced renewable electricity must correspond to the annual electricity consumption.

Scenario 2 is based on the goal that the amount of locally produced renewable electricity must correspond to the annual electricity consumption on Åland by 2030 and the goal that by 2040, Sweden will have 100 percent renewable electricity production.

Scenario 4:

- The amount of locally produced renewable electricity was set to 130 % of the electricity consumption.

This was to see how the 30 % surplus electricity would affect the result.

2. Theory

Hydrogen is an energy carrier just like electricity. This means that hydrogen is not a primary energy source, but can be used to store, transport, and provide energy. The flexibility is great because hydrogen can be produced from all types of energy sources (Vätgas Sverige, n.d. a).

Hydrogen can be produced in many ways; therefore, hydrogen is divided into 3 different colours. Green hydrogen: produced by electrolysis. All that is needed is clean water and electricity. In the electrolysis plant, the water is split into hydrogen and oxygen by means of renewable electricity. Blue hydrogen gas: Most of all hydrogen is currently produced by steam reforming of natural gas. Carbon dioxide from this process can be collected and stored in depleted gas fields or aquifers or used for other chemical processes. The blue hydrogen gas can therefore be carbon neutral. Gray hydrogen: The carbon dioxide from hydrogen production through steam reforming of natural gas and is released into the air. This is the most common method today (Vattenfall, 2019).

2.1 Hydrogen storage

Hydrogen can act as a power equalizer and storage for accessible energy. In the future, for the renewable significance in the energy system, methods for intermediate storage are very important. This would make energy systems, for example, wind power more flexible and expedite the expansion of renewable energy. Storing energy in hydrogen provides the opportunity to store larger amounts of energy than in, for example, batteries (Vätgas Sverige, n.d. b). In this process, the most critical aspects in the system are the electrolysis and the fuel cell. An electrolyser is a device that produces hydrogen and oxygen using electricity and water. An electrolyser is the opposite of a fuel cell, it is where oxygen and hydrogen react to form energy and water.

2.1.1 Electrolysis

The hydrogen is produced through an electrolysis process. Water molecules are broken down into hydrogen and oxygen by using electricity. The environmental impact of this process depends on how the electricity is produced. About 30% - 40% of the energy is lost through electrolysis (My fuel cell, 2015). Electrolysis starts and drives chemical reactions with electricity. For electrolysis, there are two rods that conduct electricity (metal or carbon rods) and an ion solution. The rods are called electrodes, and the ionic solution - electrolyte. A power source with a direct current is needed. When a voltage is applied, in this case, the left electrode will be a negative pole (cathode) and the right electrode a positive pole (anode), the positive ions are attracted to the cathode and the negative ions to the anode (Ugglans kemi, n.d.). Hydrogen is formed on the cathode electrode and oxygen on the anode electrode.

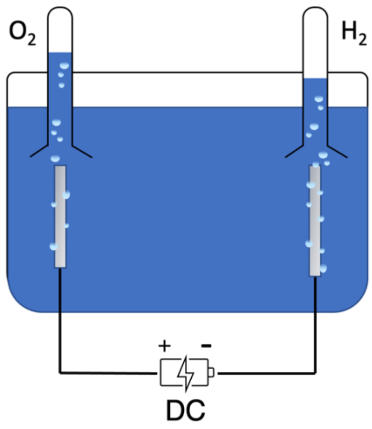


Figure 3: Explanatory figure of an electrolysis (Ugglans kemi, n.d.).

The chemical formula for electrolysis:

- Anode reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
- Cathode reaction: $4H^+ + 4e^- \rightarrow 2H_2$

(LRF, 2020)

The electrode's dimensions are correlated to how much water can be split and how much hydrogen can be produced. Since the electrodes are not varied in size from the supplier, hydrogen production is adjusted by using several electrode pairs until the need is covered (Blomstrand, 2019).

2.1.2 Storage

Hydrogen is the most common and lightest element in the universe. At room temperature and normal pressure, hydrogen is gaseous. The energy density is high per unit mass, but low per unit volume. Because of the low density per volume, it is challenging to store and transport hydrogen. The most common ways to store hydrogen are either in compressed format at 200-700 bar or in liquid form, which it assumes at -253 °C (Vätgas Sverige. n.d. a). Hydrogen gas is usually stored in gaseous form in tanks under high pressure. The hydrogen gas can be stored in properly designed tanks for almost any length of time. To run a normal-sized, modern villa for an entire winter, about three cubic meters of hydrogen with a pressure of 300 bar are needed. Three cubic meters are about the same size as the oil tanks previously existed in many houses (Göteborg Energi, n.d.).

It takes about 50 kWh to produce one kilo of hydrogen. 1 kg of hydrogen provides 33 kWh of energy, which is enough, for example, to drive 100 km with a fuel cell car (Vätgas Sverige, n.d. c). This means that the storage needs to contain 303.3 kg hydrogen.

2.1.3 Fuel cell

A fuel cell is an energy converter. The fuel cell can be used efficiently to convert the chemical energy of hydrogen into electricity. The reactions in a fuel cell are the opposite of those of an electrolyser. The remnants that are produced are pure water and heat. The water is drinkable, and the residual heat can be taken care of. Because of the high efficiency, the fuel cell can often compensate for the energy loss that occurs when hydrogen gas is produced.

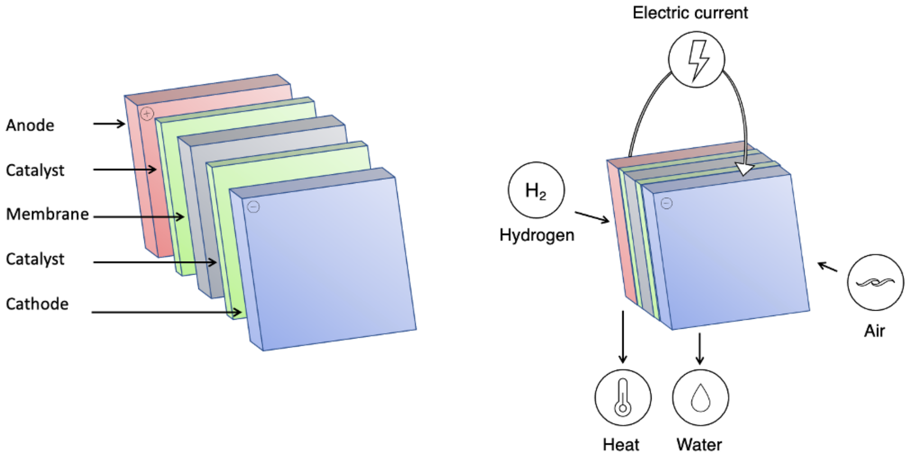


Figure 4: Explanatory figure of a fuel cell (Vätgas Sverige, n.d. d).

A fuel cell has an anode “+” side and a cathode “-“ side which is separated by a membrane. The membrane only allows protons to pass. On the anode side, a catalyst divides the hydrogen atoms into protons and electrons. The electrons cannot pass the membrane but are led to an external circuit where they generate electricity. The protons pass through the membrane. On the cathode side, the electrons and protons combine and connect to oxygen (O_2) from the air. The reaction gives water (H_2O). A fuel cell produces about 0.7 volts. To get a higher voltage, many separate fuel cells are combined in one "stack". The total chemical reaction in a fuel cell is written:

The chemical formula for a fuel cell:
$2H_2 + O_2 \rightarrow 2\ H_2O$

(Vätgas Sverige, n.d. d)

2.1.4 Container solution Hydrogen farm AB

Hydrogen Farm AB is located on Gotland and is planning to create one container solution, to begin with, and then expand. The argument for this is, that the need to store energy increases when there are more renewable and intermittent energy sources (electricity that comes unevenly over time, from wind and solar). Wind power productions on Gotland correspond on an annual basis to 50% of the electricity consumption on the island. Occasionally there is a surplus of electricity on the Gotland electricity grid, where it can be exported from Gotland, but there is also an agreement between GEAB Elnät and the island's wind turbine producers that enables disconnection of wind turbines. To instead be able to produce as much as possible when it is windy, and then be able to sell electricity when there is demand in the local grid, storage in hydrogen can be a possibility (LRF, 2020).

The components in the container solution that hydrogen farm AB is planning to have is a 100-kW electrolyser. A compressor that will compress the hydrogen gas from ca 30 to 300 bar. The storage tank is going to store up to 10 000 kWh in hydrogen. The fuel cell is going to be a 100-kW fuel cell. The battery is going to have a capacity of 100 kW at discharging and 50 at charging (Karlsson P., 2020).

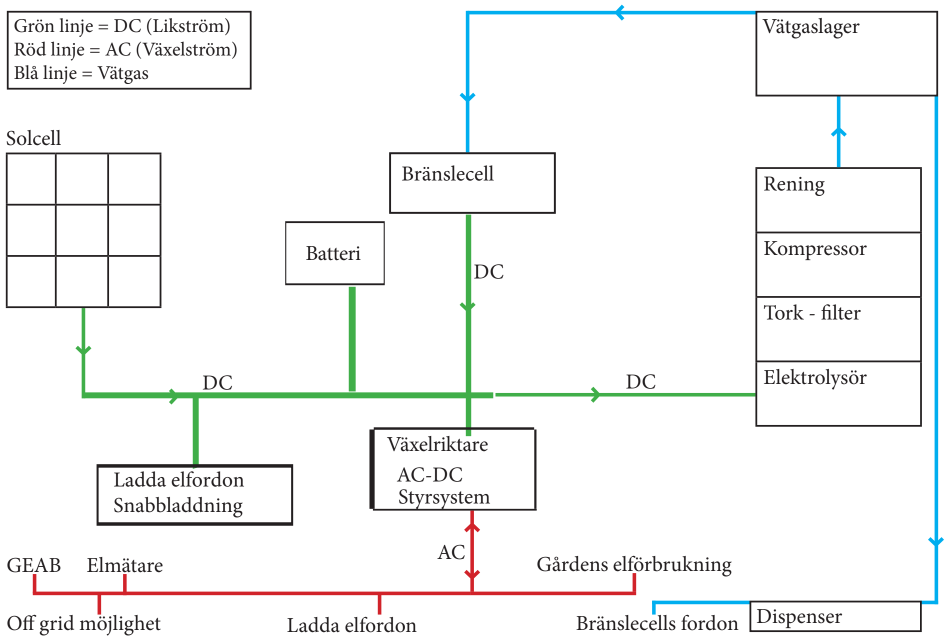


Figure 5: System sketch of the hydrogen storage (Karlsson, P., 2020).

In the current study, the system is simplified for assessment, corresponding to there is no charging of eclectic vehicles or refuel of fuel cell vehicles. The input is both PV's and wind power and the consumption are the total consumption of the Islands.

2.2 Wind speed

The wind is an increasingly important source of renewable electricity, which is also infinite. No fuel is used when producing electricity from wind power, which contributes to no CO_2 once they have been installed. In addition, carbon dioxide emissions during the construction phase are compensated by the renewable electricity the wind farm produces within six months after it is put into operation. Advances in wind turbine technology, with larger rotors and taller turbines, have increased power capacity. Today's wind turbines are more powerful and more efficient. (Fortum, n.d.).

Usually, a wind turbine has three blades, together they are called a rotor. The rotor is mounted on a shaft that is connected to a generator. This converts the spinning motion into an electric current. Since the rotor rotates rather slowly, a gearbox is often placed between the shaft and the generator, in order to achieve an even speed that suits the generator. Modern wind turbines often have generators that are connected directly to the rotor shaft. They are then able to generate power even at low speeds. The wind turbines are connected to the electricity grid and supply electricity as long as they spin. A wind turbine cannot capture all the wind energy, the theoretical limit is 59 percent. The efficiency (how much of the supplied energy can be utilized) in modern wind turbines is close to this limit (between 40-50 percent efficiency). The larger the wind turbines, the higher the efficiency can be. The energy yield in weak winds is low but increases rapidly when the wind picks up. If the wind speed doubles, the energy yield increases by eight times. The wind turbines are built to be most efficient in a normal wind (rated wind), often around 12-14 meters per second. When a storm blows, the wind turbine shuts down to protect it from excessive stress (Naturskyddsforeningen, 2021).

In 2020, Gotland had 130 active wind power plants which gives an installed capacity of 179 MW and produced 522 GWh annually (Energimyndigheten, 2020a). Wind power has grown strongly in recent years and supplies about 20 percent of the electricity use in Sweden. It is also planned for further expansion since production costs have fallen so that wind power today is competitive without subsidies. Wind power gives no emissions to nature during normal operation and leaves no environmentally hazardous waste behind. The ground can also be easily restored. Wind power's environmental issues are more about effects on the landscape and other natural values, for example birdlife, and the choice of location is therefore important. When a site is chosen to build wind power, the impact on both natural values and experience values for outdoor life must be weighed in, as well as, of course, the impact on surrounding homes (Lejestrand, 2021).

Åland had 21 MW installed capacity in wind turbines. This resulted in a production of 57.2 GWh the year 2020 (Smart Energy Åland, n.d.). One possibility is to build offshore wind turbines, where it blows more often, the wind is stronger and fewer people are disturbed. However, it is so far significantly more expensive to build and maintain wind power at sea than on land. The costs for both onshore and offshore wind power are falling quite fast, mostly for offshore but from a higher level. The technology for wind turbines has developed rapidly, with taller towers and larger, more efficient turbines. By making the wind turbines larger, they can produce significantly more electricity even though the blades rotate more slowly than on small plants (Lejestrand, 2021).

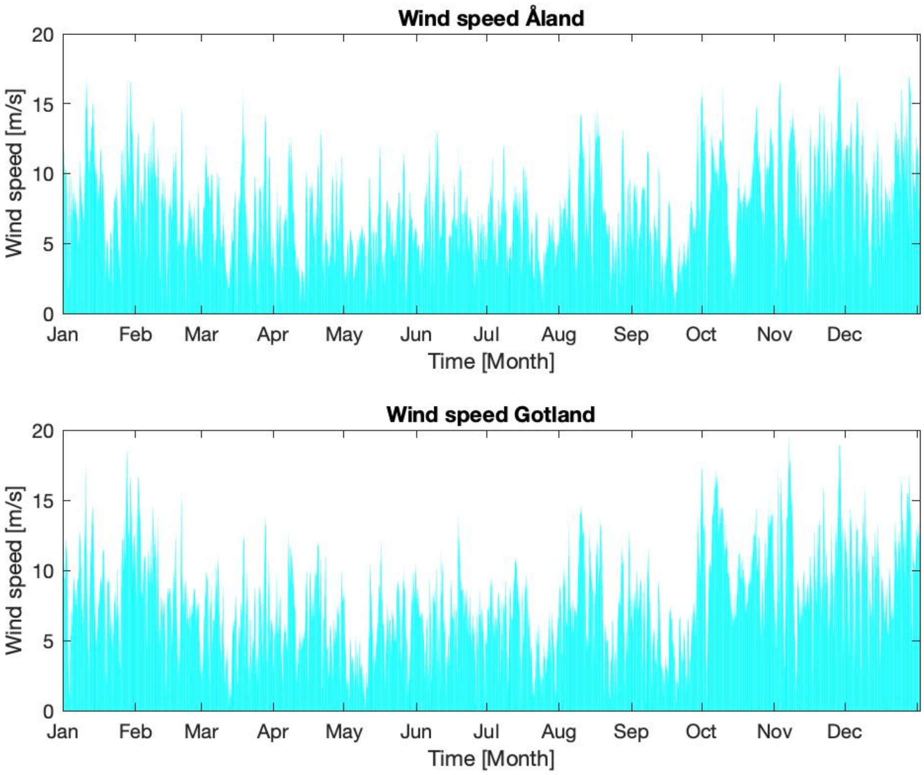


Figure 6a: Wind speed on Åland for year 2016 (hourly data) (European Commission, 2019).
Figure 6b: Wind speed on Gotland for year 2016 (hourly data) (European Commission, 2019).

In figure 6 shows the wind speed on Gotland and Åland in m/s. The average wind speed on Åland was 7.45 m/s and the average wind speed on Gotland was 7.74 m/s the year 2016 (European Commission, 2019). This shows that they have similar potentials, but Gotland have slightly higher.

2.3 Solar irradiation

The global solar radiation decides how big the radiated energy is and controls the size of the solar production. Global radiation can be measured in a photovoltaic system with a reference solar cell or a pyranometer mounted in the modular plane. Since the middle of 1980s and until 2006, annual global radiation has increased by almost 8% in Sweden. Recent years have seen some further increase. A similar trend is seen in large parts of Europe. High-pressure blockages over Scandinavia gave very sunny weather, especially in May and July 2018, which led to top records of global radiation over Sweden. The total amount of solar irradiation that hits a horizontal surface is called global radiation. The global radiation thus consists of the sum of the irradiation directly from the sun and the diffuse irradiation from the rest of the sky, i.e. solar radiation that is scattered by the molecules and particles of the atmosphere or reflected by clouds. The two most important factors that affect global radiation are the height of the sun and cloudiness (SMHI, 2021).

Solar cells are connected in larger solar panels that are mounted on the roof of the property or the facade. When the sun's rays hit the solar cells, electrical voltage arises between the front and back of the cell. By connecting a wire between the front and back of the cell, a current is formed in the form of direct current. In order for the electricity to be used on the property, a so-called inverter is used which converts a direct current to alternating current. In the summer is when the PVs (photovoltaics) provide most energy, but they do not stop producing electricity just because it is cloudy or because there is snow on the roof. So, it does not have to be sunny, just bright. On a clear summer day, most electricity is produced. Between March and October, production is at its highest. Solar cells convert about 10-15% of the incoming solar energy into electricity (Vattenfall, u.å.).

Crystalline silicon PV's can be divided into two different kinds of crystalline silicon solar cells. These are monocrystalline solar cells and polycrystalline solar cells. Monocrystalline solar cells are based on silicon. The solar cells used in these modules are not completely rectangular but have rounded edges. Usually, the solar cells have a black colour. The efficiency of the modules is around 15–22%. The cost per module is higher than for polycrystalline solar cells. Polycrystalline PV's are based on silicon and contain rectangular solar cells. The colour is usually shimmery bluish, but it is also available in other colours, which can, however, affect the efficiency negatively. The efficiency of the modules is around 15–17% (Energimyndigheten, 2019).

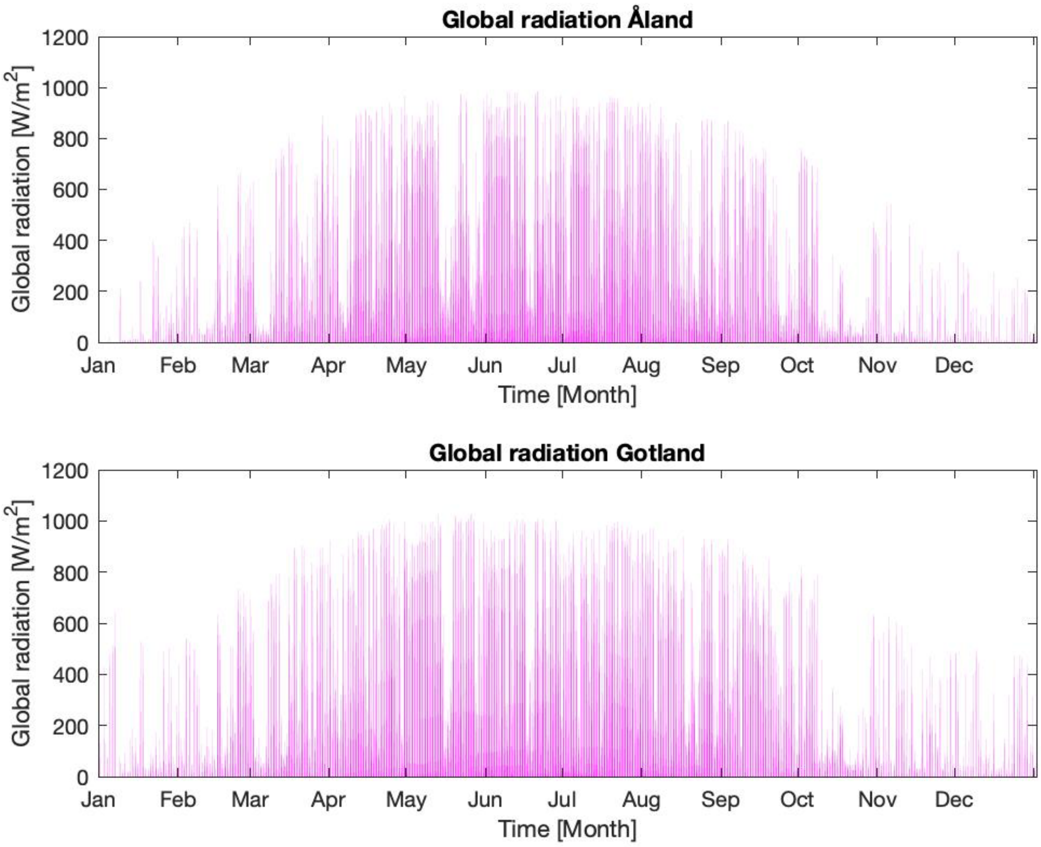


Figure 7a: Global radiation on Åland for year 2016 (hourly data) (European Commission, 2019).
Figure 7b: Global radiation on Gotland for year 2016 (hourly data) (European Commission, 2019).

In figure 7 shows the global radiation on Gotland and Åland in W/m^2. The average global radiation on Åland was 132.2 W/m^2 and the average global radiation on Gotland was 155.4 W/m^2 year 2016 (European Commission, 2019). Gotland has 17 % greater global radiation than Åland.

2.4 Methodology

The calculations were done in MATLAB where the electricity production from wind and solar were plotted and added. Then the consumption was subtracted from the total production to get the relationship between the consumption and the production in equation 1.

$$Tot = P_{sun} + P_{wind} - P_{\text{con}} \tag{1}$$

P_{sun} = Production from PV modules simulated in PVGIS [kW]
P_{wind} = Production from wind [kW]
P_{con} = The Islands consumption [kW]

To get the electricity deficit and surplus the negative and positive values were split into two vectors and then plotted.

To calculate how many storages is needed to cover the electricity deficit is calculated with equation 4.

$$P_{fuel\_cell} = P_{fc} \cdot \eta_{fc} \; [kW] \tag{2}$$

$$P_{battery\_discharge} = P_{bd} \cdot \eta_B \; [kW] \tag{3}$$

$$N_{storage\_needed} = \frac{P_{deficit}}{P_{fuel\_cell} + P_{battery\_discharge}} \; [kW] \tag{4}$$

P_{fc} = Theoretical power fuel cell: 100 kW (Karlsson P., 2020
η_{fc} = efficiency fuel cell: 60 % (Lokar et.al., 2020).
P_{bd} = Theoretical power battery at discharge: 100 kW (Karlsson P., 2020
η_b = efficiency battery: 90 % (Own assumption).

P_{fuel_cell} = Power fuel cell [kW]
$N_{storage}$ = Number of storages [st]
$P_{deficit}$ = Deficit electrical power [kW]
$P_{battery\_discharge}$ = Power battery at discharge [kW]

The compressor consumes 2.2 kWh/kg (Linde, n.d.) and the energy value of hydrogen is 39.44 kWh/kg. This results in 5.4% losses during compression. The electrolyser gives loss in 25 % (Lokar et.al., 2020). This gives a total efficiency in this step of 69.4 %.

$$P_{\text{electrolyser}} = P_e \cdot \eta_e \; [kW] \tag{5}$$

$$P_{battery\_charge} = P_{bc} \cdot \eta_B \; [kW] \tag{6}$$

To calculate how many storages can be loaded with the help of the surplus electricity is calculated with equation 7.

$$N_{storage\_loaded} = \frac{P_{surplus}}{P_{elecrolyzer} + P_{battery\_charge}} \; [kW] \tag{7}$$

P_e = Theoretical power elecrolyzer: 100 kW (Karlsson P., 2020
η_{fc} = efficiency elecrolyzer: 69.4 %
P_{bc} = Theoretical power battery at charging: 50 kW (Karlsson P., 2020

$P_{elecrolyzer}$ = Power electrolyzer [kW]
$N_{storage}$ = Number of storages [st]
$P_{surplus}$ = Surplus electrical power [kW]
$P_{battery\_charge}$ = Power battery at charge [kW]

To calculate the FLH (Full Load Hours) for the hydrogen storages equation 8 and 9 was used.

$$FLH_{storage\_needed} = P_{deficit} \geq (P_{fuel\_cell} + P_{battery\_discharge}) \cdot N_{storage\_needed} \text{ [h]} \quad (8)$$

$$FLH_{storag\_loaded} = P_{surplus} \geq (P_{elecrolyzer} + P_{battery\_charge}) \cdot N_{storage\_loaded} \text{ [h]} \quad (9)$$

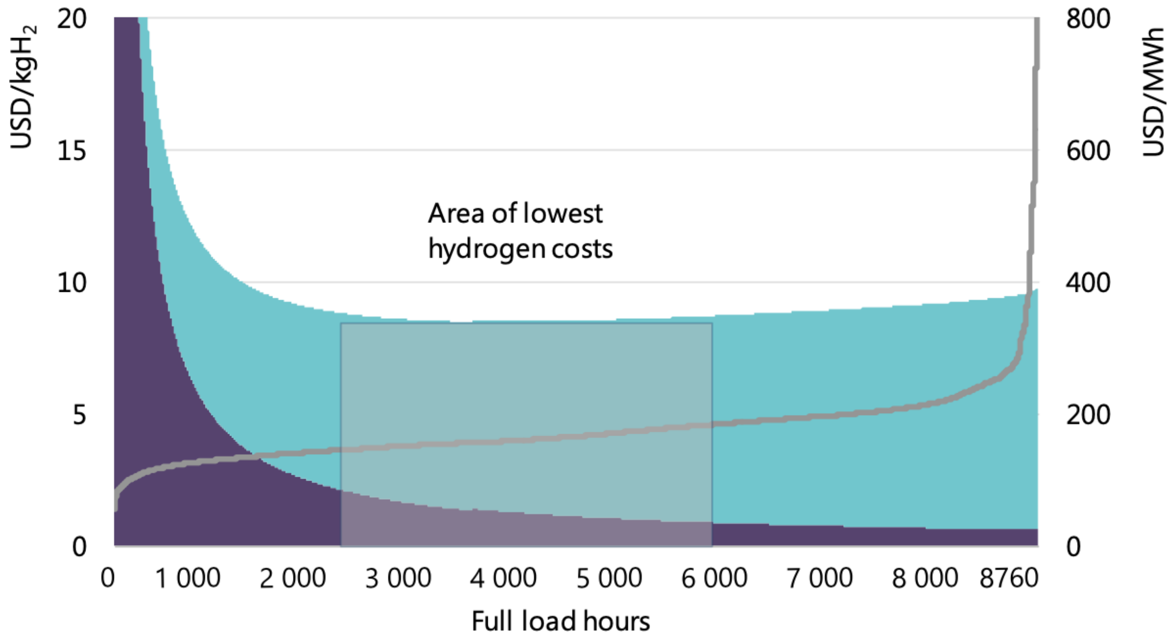


Figure 8: Descriptive figure of full load hours and area of lowest cost (IEA, 2019).

Full load hours represent the number of hours within a year the system would run at its design capacity, in other words full load, to achieve a certain annual output. Very low-cost electricity is generally available only for a very few hours within a year. If surplus electricity is only available on an occasional basis it is unlikely to make sense to rely on it to keep costs down. Running the electrolyser at high full load hours and paying for the additional electricity can be cheaper than just relying on surplus electricity with low full load hours. A indicative for this is that if the hydrogen storage has 2,500 to 6,000 FLH, the storages is used enough to be economically sufficient. That is, the marked interval in figure 8. Otherwise does higher electricity prices during peak hours lead to an increase in hydrogen unit production costs. Full load hours are an indicator of the annual utilisation of hydrogen storages (IEA, 2019).

2.4.1 PVGIS

Photovoltaic Geographical Information System (PVGIS) is a web application that enables the user to obtain data on solar irradiation and solar cell system electricity production in most parts of the world. It is free to use, without restrictions on how the results can be used and is without registration requirements. PVGIS makes it possible to estimate the average electricity production per hour, month and year. The calculation considers solar irradiation, temperature, wind speed and type of solar module. The user can choose the slope and orientation of the solar modules or let PVGIS calculate optimized slope and orientation that maximizes the annual solar production (Energimyndigheten, 2017).

In the program assumptions were made. The roof slope is assumed to be 30°. To get as much effect from a solar cell as possible, the solar cell must have an inclination of between 30° and 50°. A deviation of 10° gives a reduction in annual production of 1-2%, in other words, the slope is usually not so important (Solcellskollen, 2021). To get a realistic result as possible, the angle was not set to the most optimal one and therefore 30°. The direction is assumed to be facing south. Therefore, was the azimuth angle set to 0° in PVGIS. The global radiation is an hourly value for the chosen area. The solar panel that was chosen was crystalline silicon, which is the most common one in the world and accounts for about 95 percent of the world market (Solkompaniet, n.d.). The system loss was set to 14 % which is a standard value that PVGIS uses. That loss includes loss in cables, inverter losses and over the years reduces the efficiency of the system. Effects that are not considered in PVGIS are snow, dust and dirt and partial shading (European Commission, 2019).

PVGIS uses mainly geostationary satellites. Satellite data used to estimate solar irradiation comes from the METEOSAT satellites covering Europe, Africa, and most of Asia. In PVGIS the power is assumed to depend on the global radiance G and the module temperature T_m like in equation X (European Commission, 2020).

$$P = \frac{G}{1000} \cdot A \cdot \eta(G, T_m) = \frac{G}{1000} \cdot A \cdot \eta_{STC} \cdot \eta_{rel} \quad [W] \tag{10}$$

To find η_{rel} equation 2 is needed

$$\eta_{rel}(G', T'_m) = 1 + k_1 ln(G') + k_2 ln(G')^2 + k_3 T'_m + k_4 T'_m ln(G') + k_5 T'_m ln(G')^2 + k_6 {T'_m}^2 \tag{11}$$

And G' and T'_m gets from equation 3 and 4

$$G' = \frac{G}{G_{STC}} \text{ [W/m2]} \tag{12}$$

$$T'_m = T_m - T_{STC} \text{ [°C]} \tag{13}$$

Where

- η_{rel}: Relative efficiency (compared to the efficiency at STC) for crystalline silicon (c-Si), taking into account all the effects (reflectivity, spectral effects, temperature and low irradiance)
- η = modular efficiency
- η_{STC} = modular efficiency at STC

- $k_1,\ldots,k_6$ is coefficients of the module power model. They are determined for each solar cell technology by adapting to measured data. The coefficients used in PVGIS are based on measurements performed at the European Solar Test Installation (ESTI)

(European Commission, 2020).

The module temperature T_m can be calculated according to equation X.

$$T_m = T_a + \frac{G}{U_0 + U_1 W} \tag{14}$$

- T_a: The air temperature [°C]
- W: Wind speed [m/s]
- U_0: Coefficient describing the effect of the radiation on the module temperature in the Faiman model [W/°C m²].
- U_1: Coefficient describing the cooling by the wind in the Faiman model [Ws/°C m³].

(Koehl et al., 2011)

STC: Stands for standard test conditions
- Solar radiance - 1000 W / m²
- Module temperature - 25 °C
- Air mass – 1.5

(Coule energy, 2020).

2.4.2 Data

The data on consumption on Åland was obtained from a contact person on Kraftnät Åland AB. The data for the electricity consumption was received from a contact person on Gotland Energi AB and the data obtained was at a measuring point where import end export from and to Gotland was measured and then was the electricity production from wind added to get the total consumption. In this, the solar production was not included but it's such a small amount that it is not considered to affect the final results. The number that was calculated was 944.1 GWh/year and a reliable source says that the quantity should be at 1,002 GWh the year 2019 (Regionfakta, 2020). The data for the wind speed and global radiation was received from PVGIS for both islands and was measured 2016. The electricity produced from solar on both islands was then calculated in the PVGIS model with the help of what the installed solar power was in 2020. The electricity produced from wind turbines was received in the same way that the consumptions on both islands were.

3. Results

3.1 Electrical energy production

3.1.1 Solar power

The electricity production produced from PVs was calculated in the PVGIS model. From those calculation was figure 9 received. Gotland produced 13.2 GWh the year 2020 from 1 040 st PV module systems which was calculated from the total installed effect on 11.99 MW (Energimyndigheten, 2020b). Åland had 2.637 MW installed power that produced 2.5 GWh/year electric energy (Toivonen, J., 2020). This result declare that Gotland produced 5 times more electricity than Åland produces yearly. However, was also the installed power roughly 5 times more.

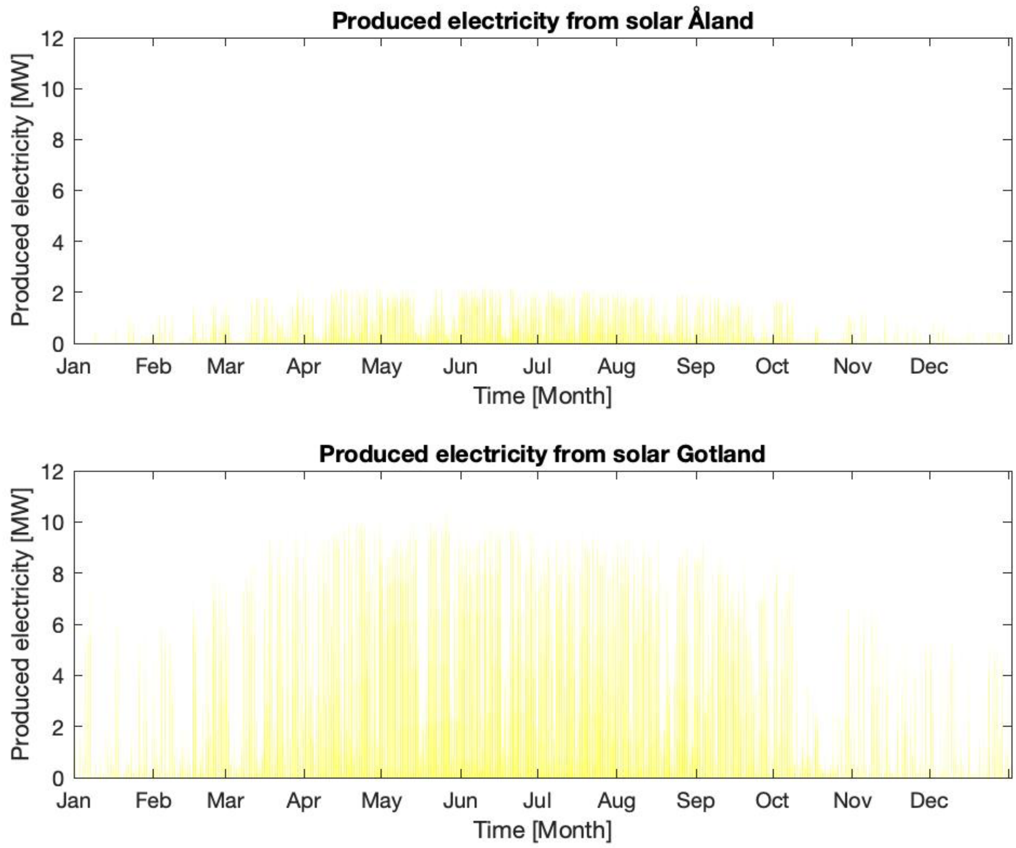
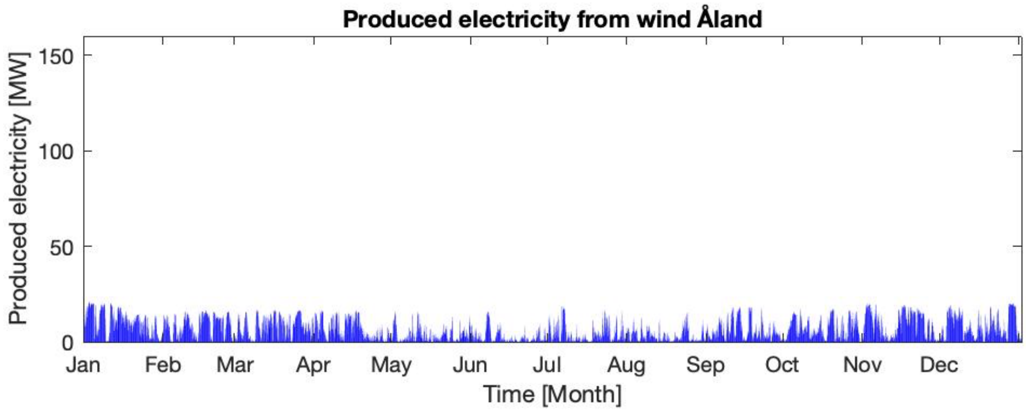


Figure 9a: Calculated produced electricity from solar power on Åland year 2020 (hourly data).
Figure 9b: Calculated produced electricity from solar power on Gotland year 2020 (hourly data).

3.1.2 Wind power

In figure 10 is the total production shown hourly. From the 21 MWp installed wind power, the production was the year 2020 57 GWh on Åland. On Gotland 2020 was the total wind production 522 GWh/year from the installed wind power of 179 MWp. The data was received from the local energy companies on the islands. This results in that Gotland produces produced more than 9 times more electricity from wind energy than Åland produces yearly.



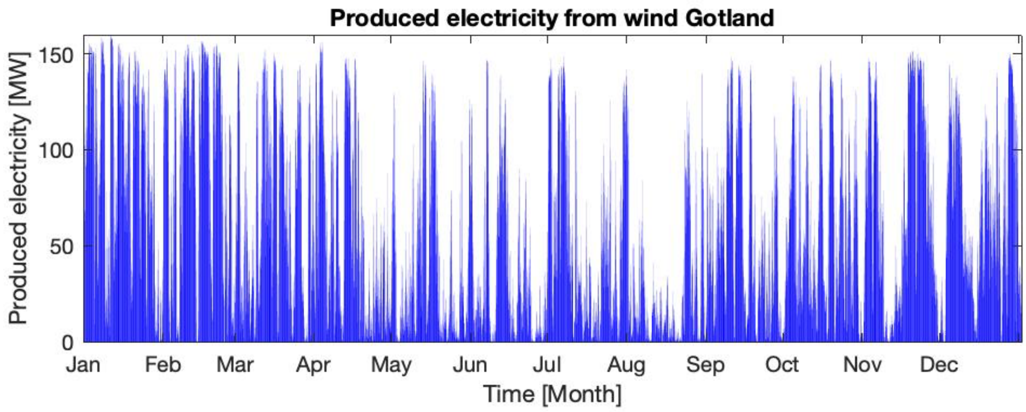


Figure 10a: Measured produced electricity from wind power on Åland year 2020 (hourly data) (Björkqvist, P., 2020).
Figure 10b: Measured produced electricity from wind power on Gotland year 2020 (hourly data) (Karlsson L., 2020).

3.2 Simulations

From the simulation 2 figures was formed for each island and each scenario. To profit better realization for the results the total number of hydrogen systems that was needed to cover the electricity deficit on the islands are called "storages needed". By needed means that the hydrogen system run the fuel cell to provide with electricity to the grid. The total hydrogen systems that can be loaded from the surplus electricity is called "storages loaded" or "storages that can be loaded". By loaded means that the hydrogen systems can run the electrolysis to fill the storage for later use.

3.2.1 Scenario 1

In this scenario was the electricity consumption and production received from 2020. Here is the production against the consumption on the islands being demonstrated. From that are the electricity surplus and deficit extracted. From the electricity surplus and deficit is the number of storages that is needed and can be loaded calculated. Finally, is the FLH (Full Load Hours) calculated and plotted.

Åland

For this scenario when data was received from 2020 on Åland was the electrical surplus strictly zero. This means that no hydrogen storage can be loaded, and it is, therefore, no reason to have hydrogen storages when the production is at this low level and there is no surplus electricity to store in this case. This can be observed in figure 11.

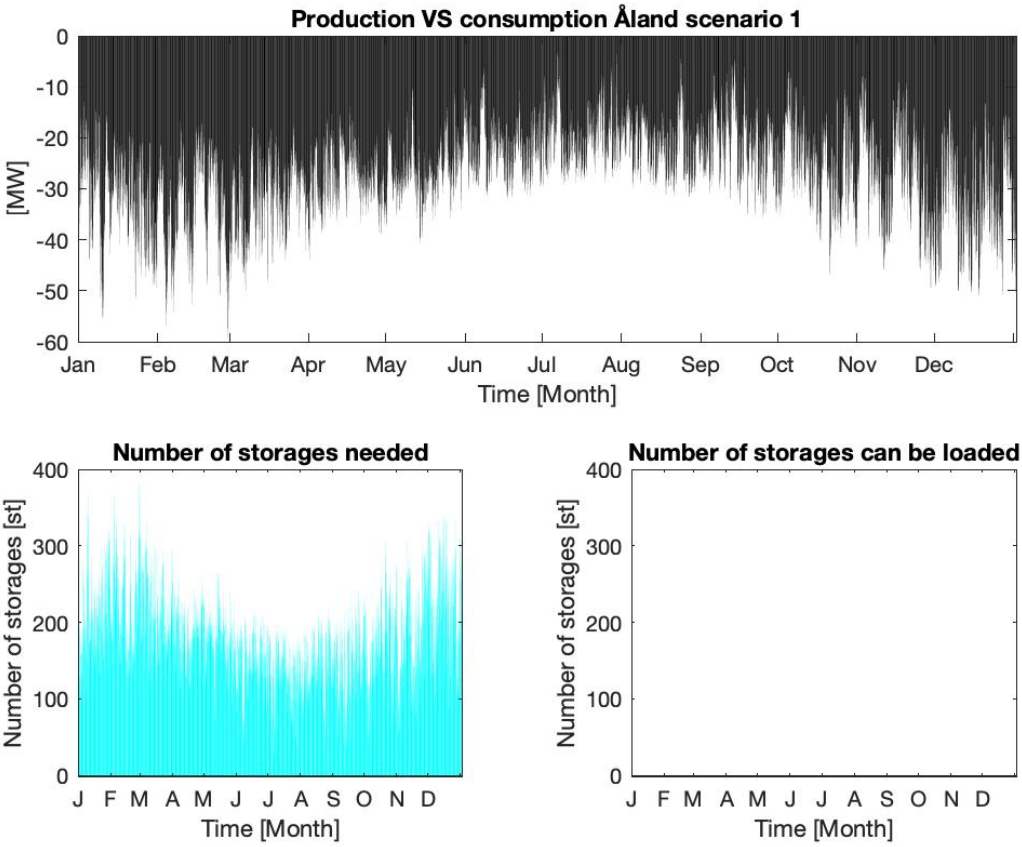


Figure 11: Calculated production VS consumption, number of storages needed and can be loaded year 2020 on Åland.

Gotland

This scenario is for year 2020's electricity consumption and production on Gotland and are observed in figure 12. The electrical surplus is considerably lower than the electricity deficit. This results in that the number of hydrogen storage that are needed is much more than the number that can be loaded with surplus electricity. The maximum number of storages that are needed to cover the electricity deficit is 1,084 storages. The largest number of storages that can be loaded yearly is 636.

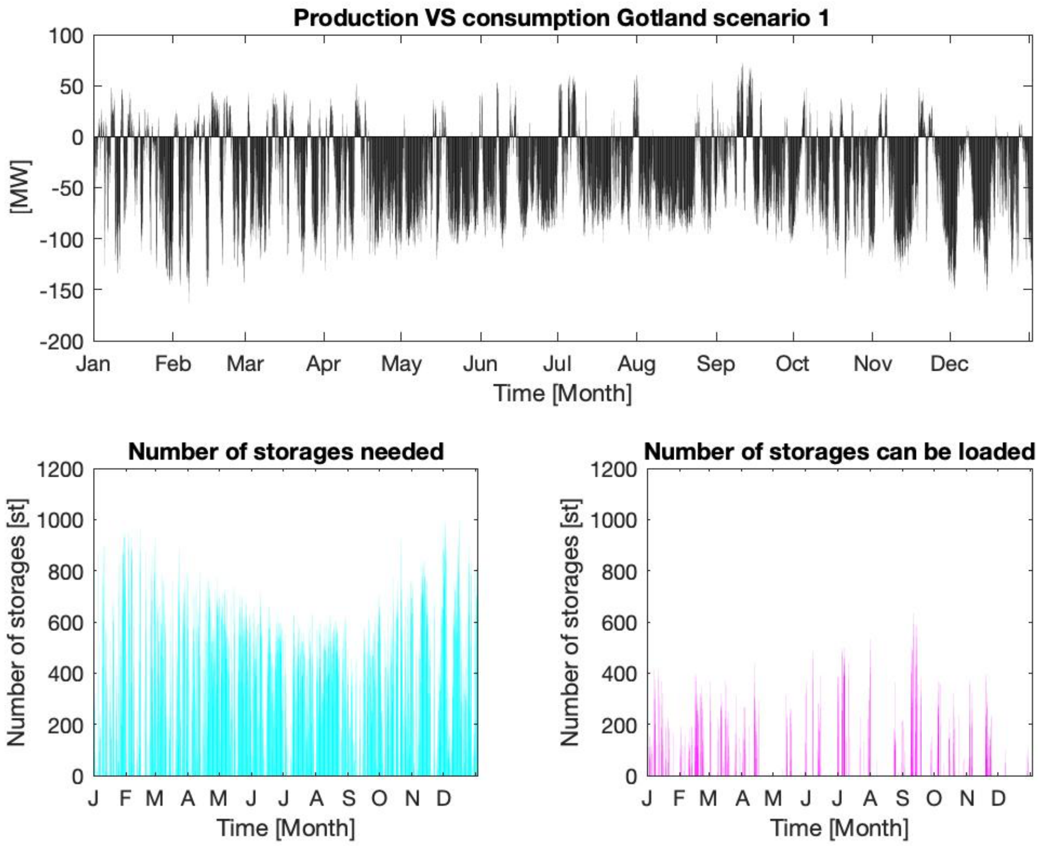


Figure 12: Calculated production VS consumption, number of storages needed and can be loaded year 2020 on Gotland.

The full load hours are low for the storage needed and are for this scenario not in the span of 2,500 to 6,000 FLH. In figure 13 it can be seen that the number of storages needed for the FLH to be over 2,500 is ca 400 and the number for the storage needed, the FLH never reach 2,500. This can be noticed in figure 13.

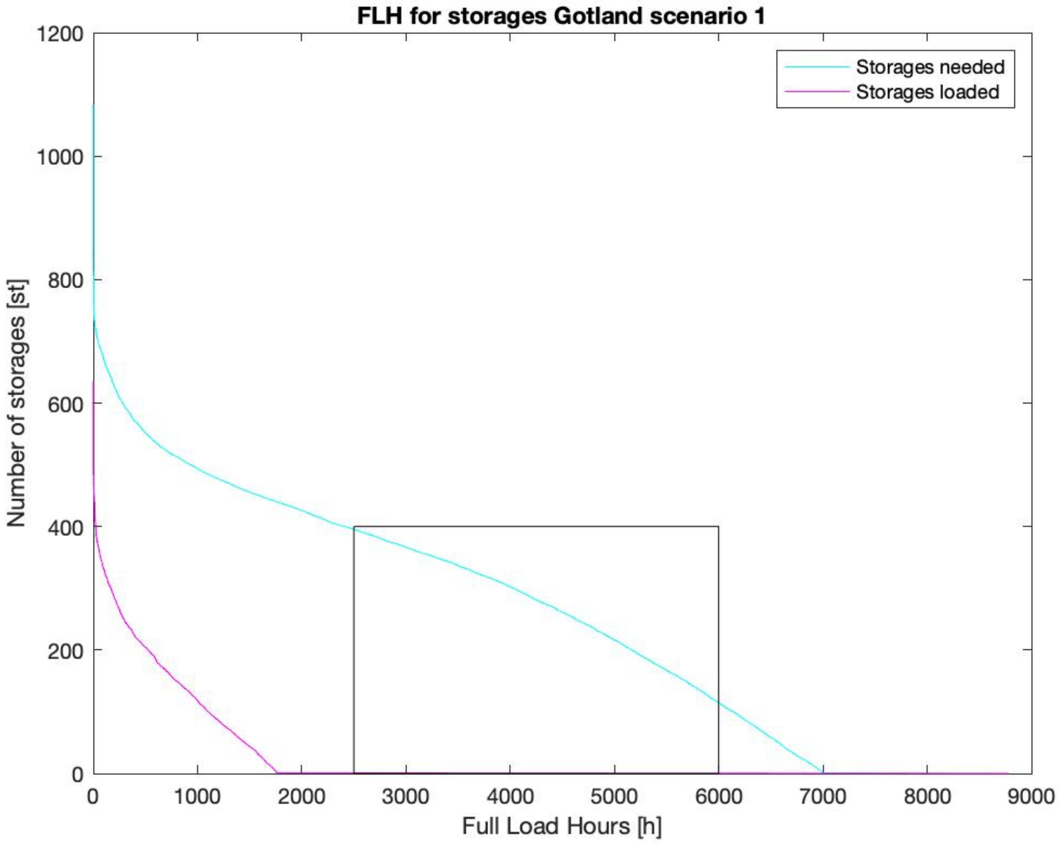


Figure 13: Full loading hours for storage needed and storage that can be loaded on Gotland year 2020.

3.2.2 Scenario 2

In this scenario, renewable electricity must constitute at least 60% of the total annual electricity consumption. Which is based on Åland's goal that renewable electricity must constitute at least 60% of the total annual electricity consumption by 2030.

Åland

For Åland to produce 60 % of the consumption from renewable sources the renewable production must have an increment from 59.7 GWh/year to 179.2 GWh yearly. This is presented in figure 14. This gives an increase of ca 3 times the daily renewable production. In this scenario for Åland, the electrical surplus is considerably lower than the electricity deficit. This scenario is a lot comparable to the one above for Gotland for the year 2020. The outcome was that the number of hydrogen storage that are needed is much more than the number storages that can be loaded with surplus electricity.

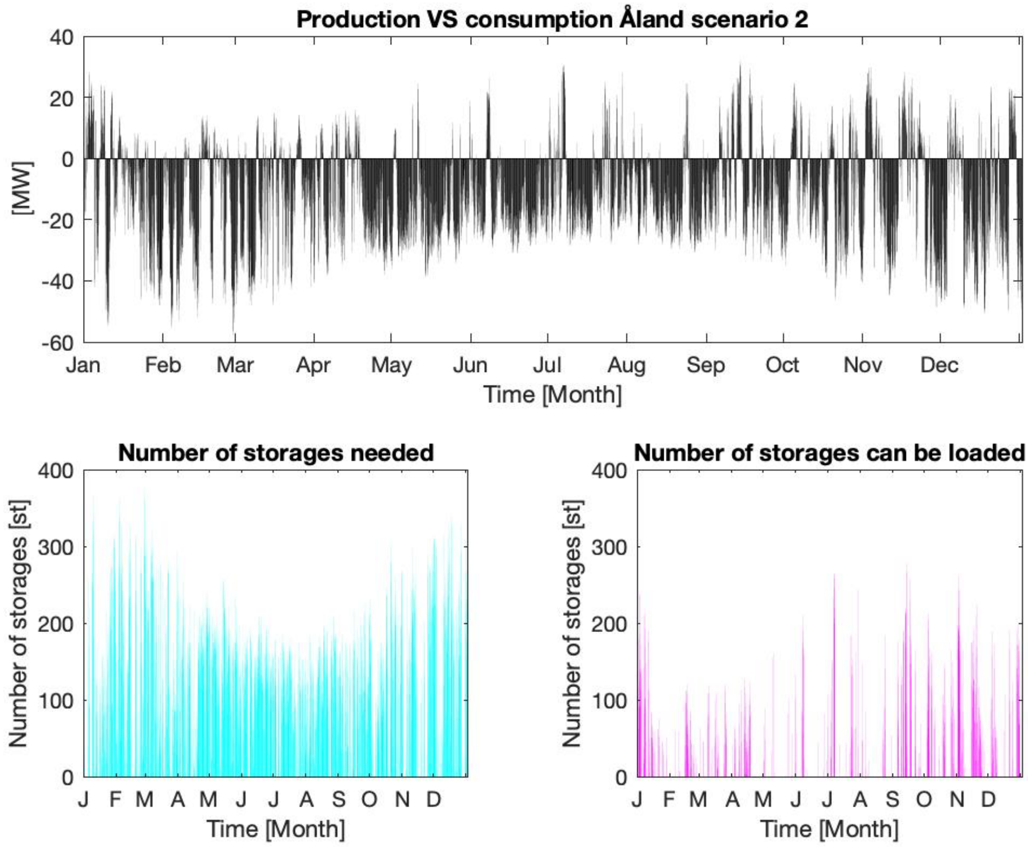


Figure 14: Calculated production VS consumption, number of storages needed and can be loaded scenario 2 on Åland.

The number of storages needed for the FLH to be over 2,500 is ca 125 and for the number of storages loaded never reach 2,500 FLH. This can be noticed in figure 15.

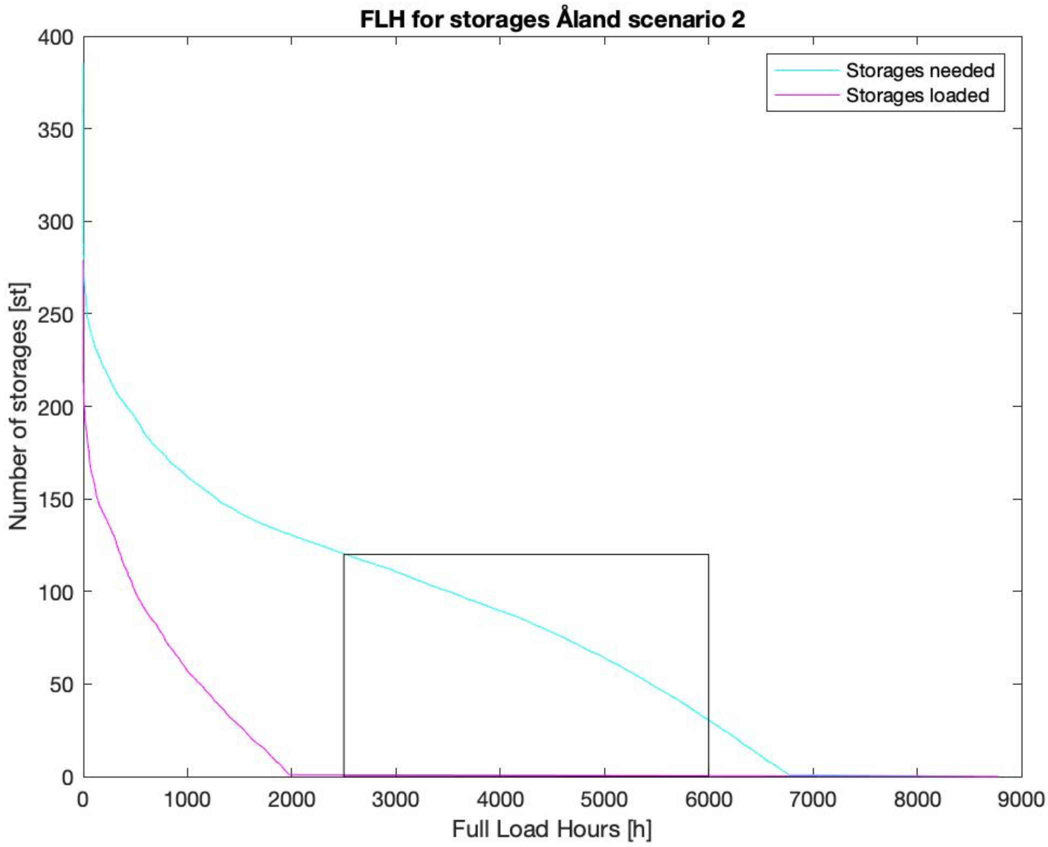


Figure 15: Full loading hours for storage needed and storage that can be loaded on Åland scenario 2.

Gotland

For Gotland to produce 60 % of the consumption from renewable sources the renewable production must increase from 535.6 GWh/year to 566.5 GWh yearly. This is presented in figure 16. That gives an increase of ca 1.06 times the daily renewable production. The difference between 535.6 GWh/year and 566.5 GWh/year is not that substantial, this result and what can be read from the figure has similarity to the two figures above that the number of hydrogen storage that are needed is greater than the number storages that can be loaded with surplus electricity.

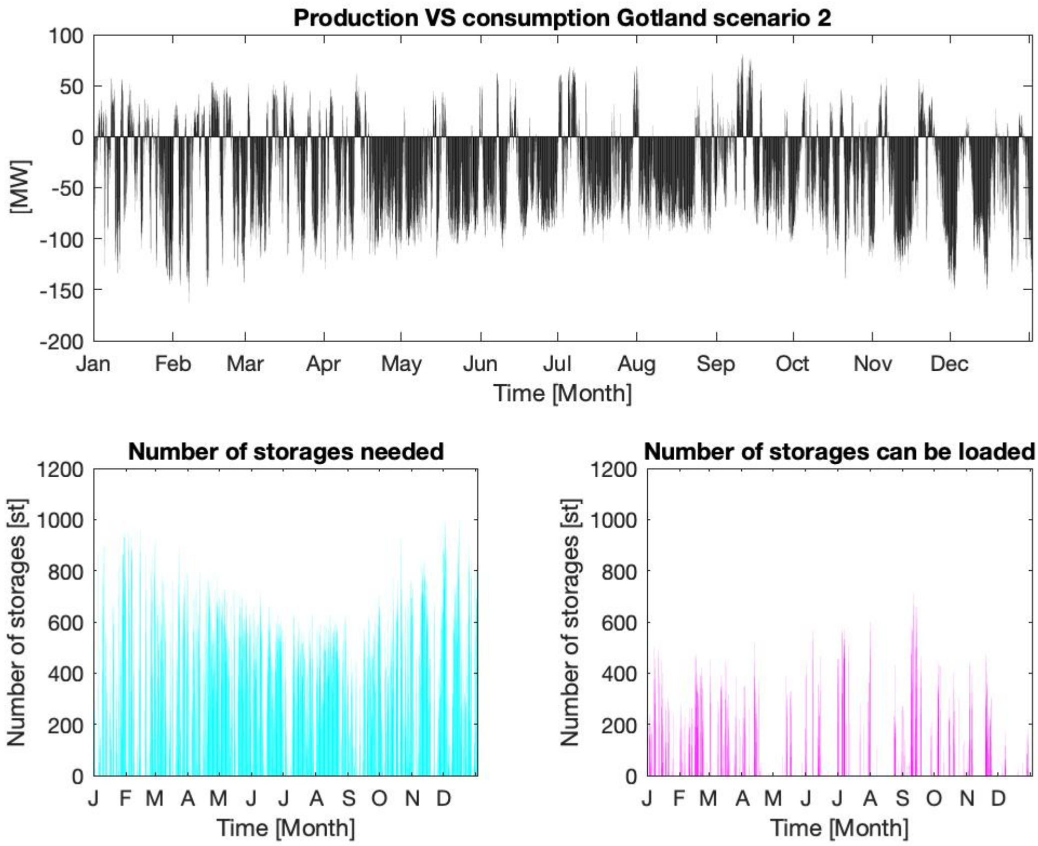


Figure 16: Calculated production VS consumption, number of storages needed and can be loaded scenario 2 on Gotland.

The number of storages needed for the FLH can be noticed in figure 17, for them to be over 2,500 is ca 420 and the number for the storage needed never reach 2,500 FLH. The storages needed are larger than 6,000 FLH if more than ca 140 storages are active in the system.

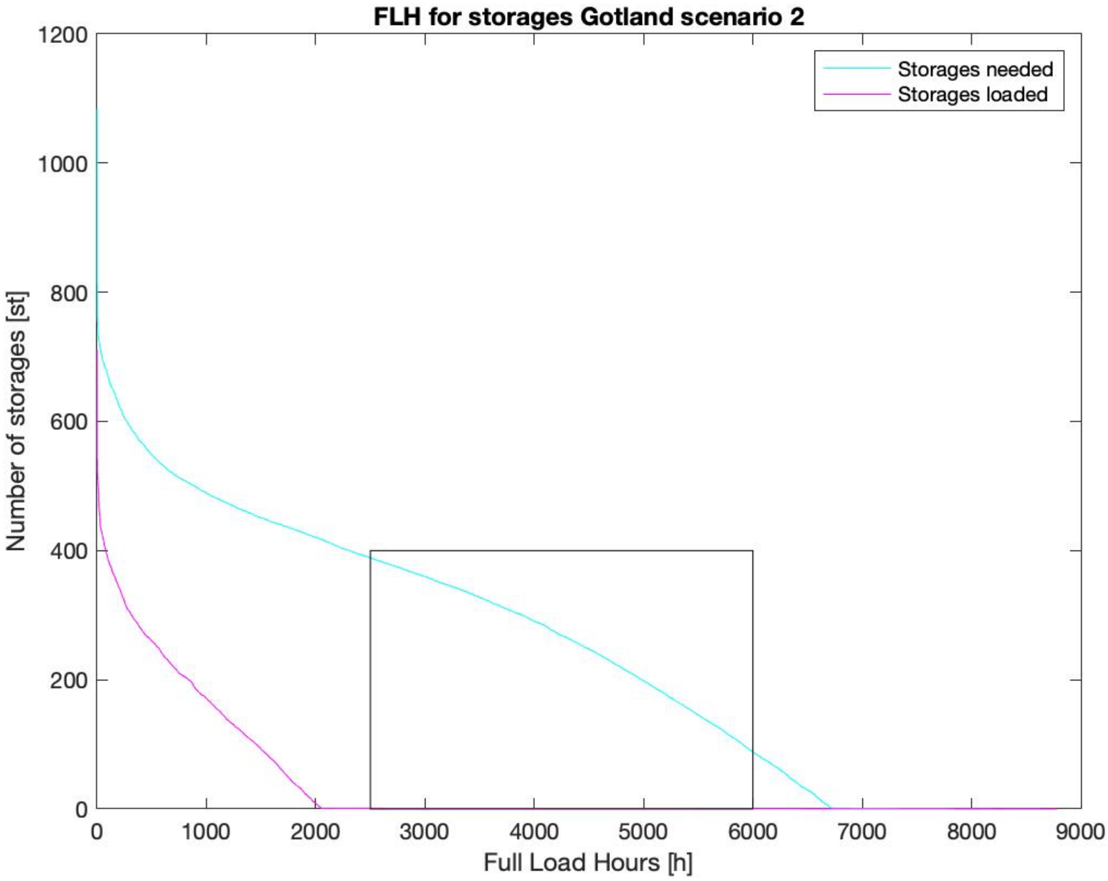


Figure 17: Full loading hours for storage needed and storage that can be loaded on Gotland scenario 2.

Table 2 is a compilation of the figure 14, 15, 16 and 17 for both islands. The total number of storages needed on Gotland is 1,085 and the number of storages that can be loaded is 712. On Åland, the total storages needed is 385 and the number of storages that can be loaded is 280.

Table 2: Summary of results from the figures for both islands in scenario 2.

Scenario 2	**Gotland**	**Åland**
Consumption [GWh/year]	944.1	298.7
Renewable electricity production [GWh/year]	567	179.3
Electrolyser is used [h/year]	2056	1997
Fuel cell is used [h/year]	6728	6787
Max number of storages needed [st]	1084.9	385.2
Max number of storages loaded [st]	712.2	279.6

3.2.3 Scenario 3

In this scenario, the amount of locally produced renewable electricity must correspond to the annual electricity consumption on both islands. The scenario is based on the goal that the amount of locally produced renewable electricity must correspond to the annual electricity consumption on Åland by 2030 and the goal that by 2040, Sweden will have 100 percent renewable electricity production.

Åland

For Åland to produce 100 % of the consumption from renewable sources the renewable production must increase from 59.7 GWh/year to 298.7 GWh yearly. That gives an increase of ca 5 times the daily renewable production. This scenario shows that the surplus electricity is larger than the deficit, which means that the number of storages that can be loaded is greater than the number of storages needed to cover the electricity deficit. This is presented in figure 18.

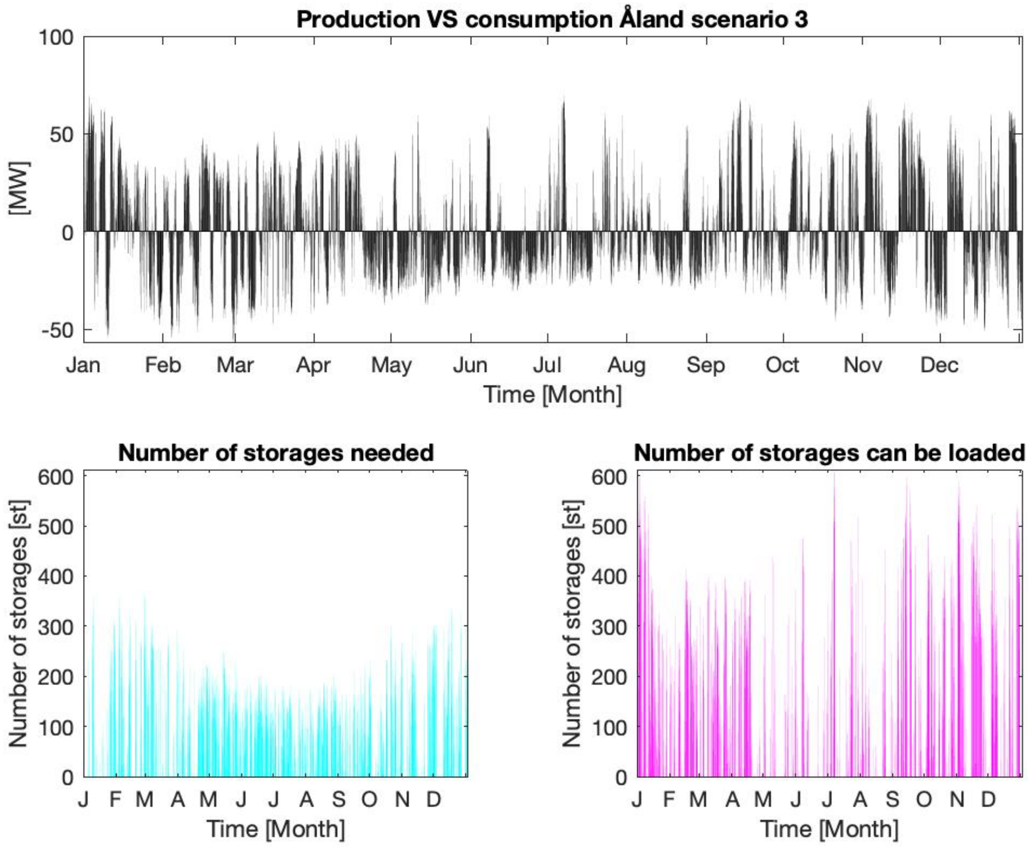


Figure 18: Calculated production VS consumption, number of storages needed and can be loaded scenario 3 on Åland.

The number of storages needed for the FLH to be over 2,500 is ca 110 and the number for storages needed and 110 for storages that can be loaded. This can be noticed in figure 19.

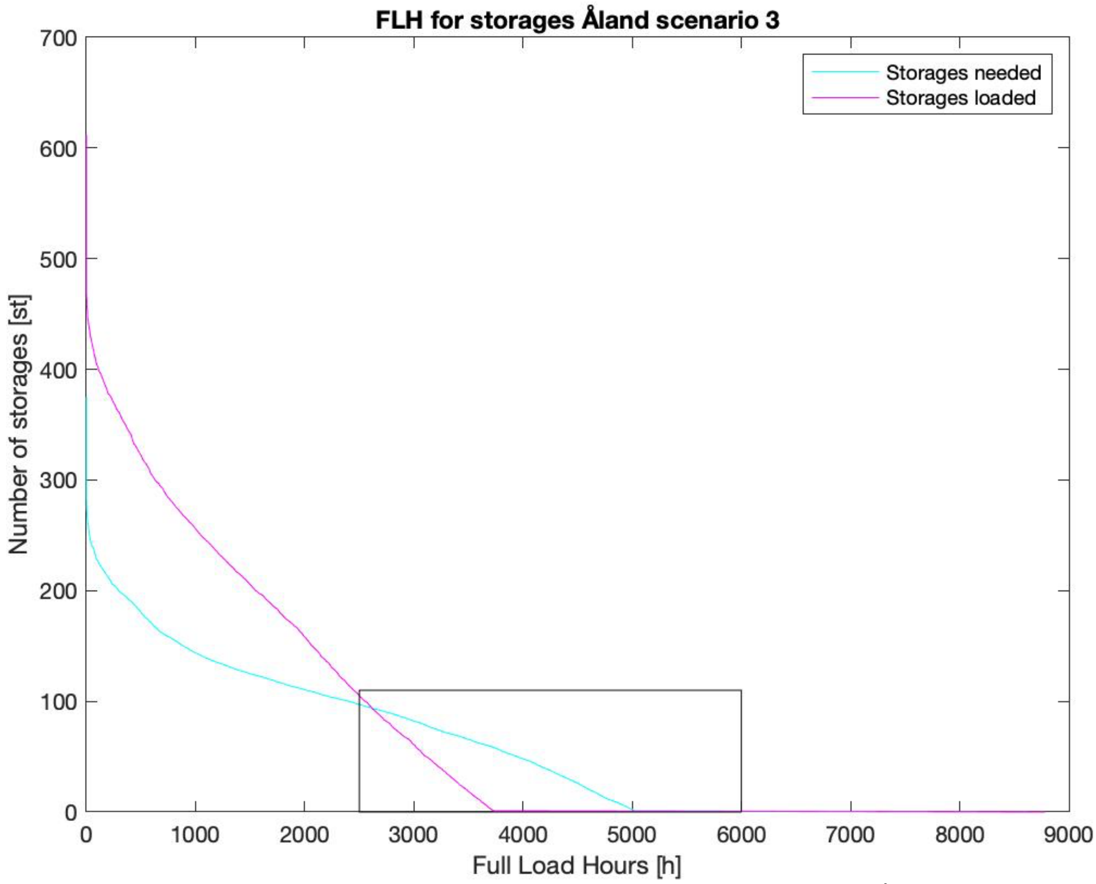


Figure 19: Full loading hours for storage needed and storage that can be loaded on Åland scenario 3.

Gotland

For Gotland to produce 100 % of the consumption from renewable sources the renewable production most increase from 535.6 GWh/year to 944.1 GWh yearly. Which gives an increase of ca 1.76 times the daily renewable production. The electricity surplus is larger in this scenario than the electricity deficit. That's gives the result that the number of storages that can be loaded is greater than the storages that are needed. This is presented in figure 20.

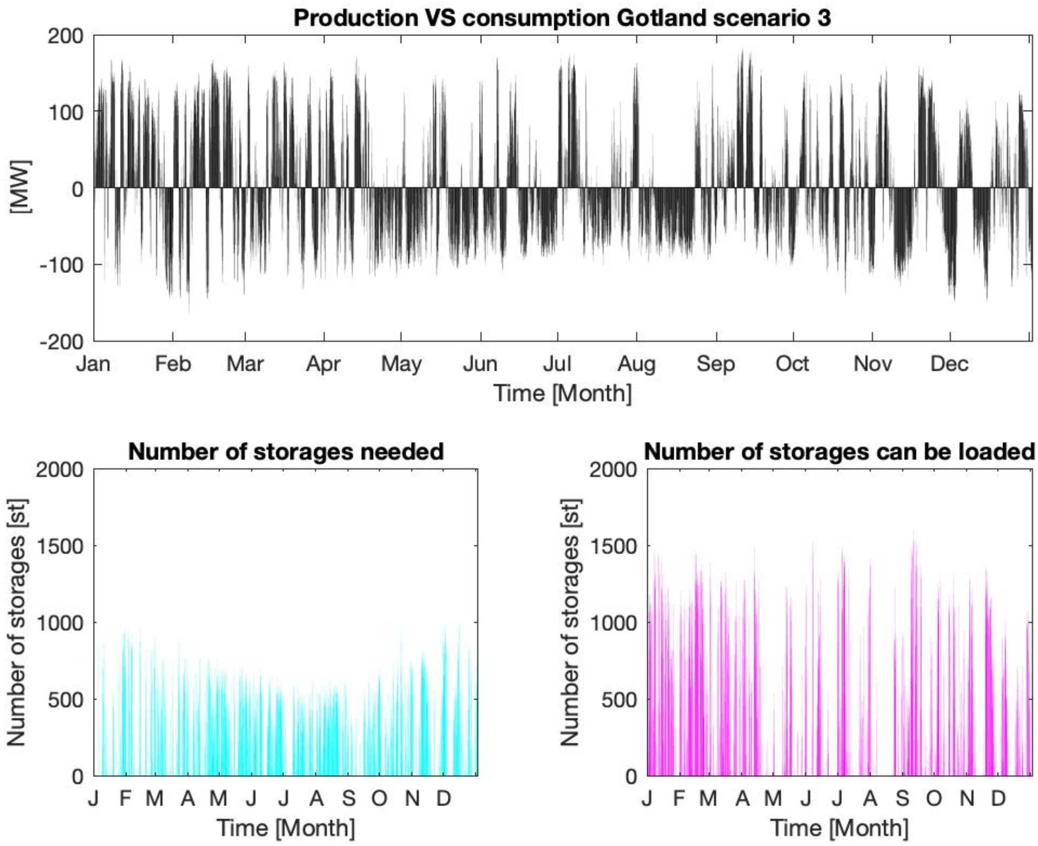


Figure 20: Calculated production VS consumption, number of storages needed and can be loaded scenario 3 on Gotland.

The FLH are greater for the storages needed than for the storages that can be loaded. In figure 21 it can be observed that the number of storages needed for the FLH to be over 2,500 is ca 300 and 400 for storages that can be loaded. This can be noticed in figure 21.

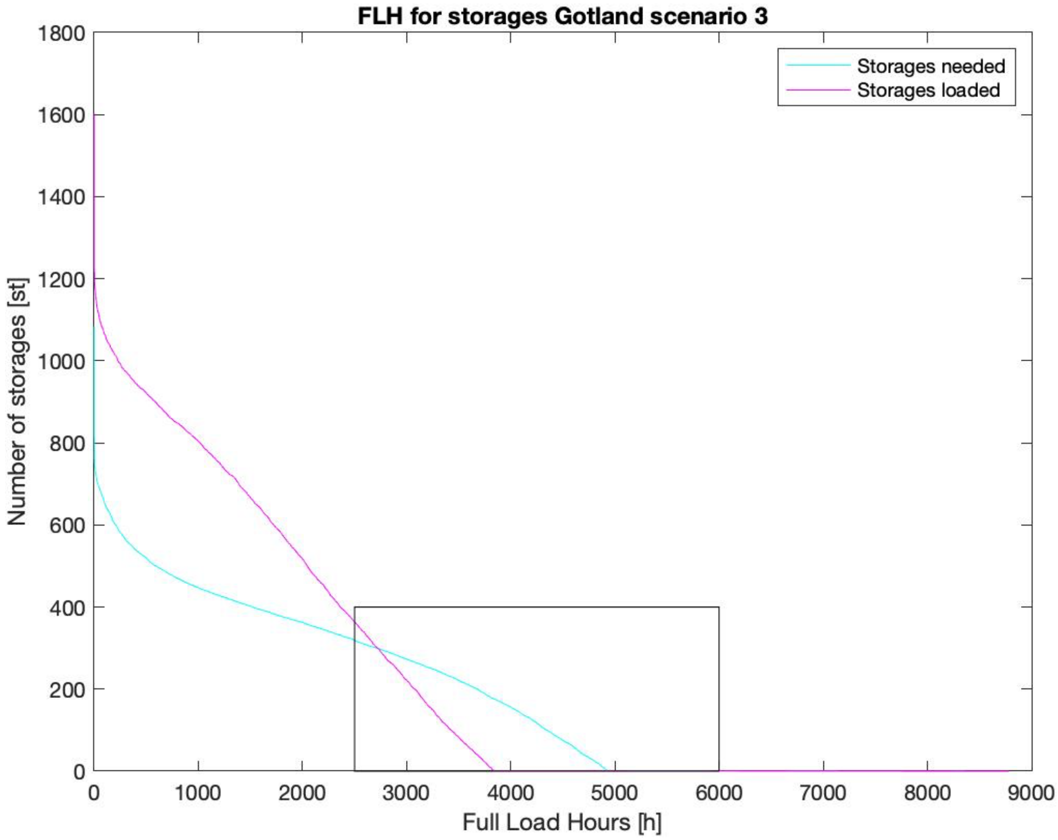


Figure 21: Full loading hours for storage needed and storage that can be loaded on Gotland scenario 3.

Table 3 is a compilation of the results for both of the islands. The total number of storages needed on Gotland is 1,084 and the number of storages that can be loaded is 1,603. On Åland the total number of storages needed is 376 and the storages that can be loaded is 612.

Table 3: Summary of results from the figures for both islands in scenario 3.

Scenario 3	**Gotland**	**Åland**
Consumption [GWh/year]	944.1	298.7
Renewable electricity production [GWh/year]	941.4	298.7
Electrolyser is used [h/year]	3845	3739
Fuel cell is used [h/year]	4939	5045
Max number of storages needed [st]	1084.5	375.8
Max number of storages loaded [st]	1603.4	612.4

3.2.4 Scenario 4

In scenario 4 the amount of locally produced renewable electricity must correspond to 130 % of the electricity consumption.

Åland

For Åland to produce 130 % of the consumption from renewable sources the renewable production must increase from 59.7 GWh/year to 388.3 GWh yearly. That gives an increase of ca 6.5 times the daily renewable production. Figure 22 shows that the electricity surplus is considerable larger in this scenario than the electricity deficit. And that's gives the result that the number of storages that can be loaded is much greater than the storages that are needed. This is presented in figure 22.

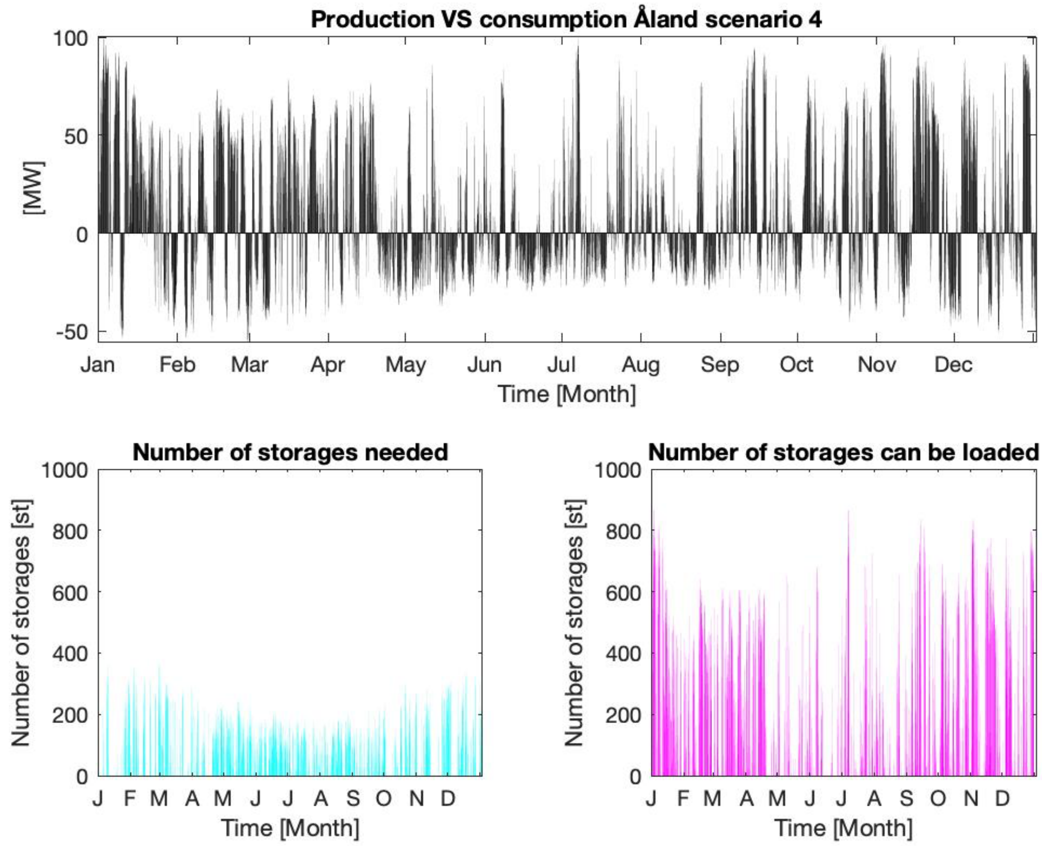


Figure 22: Calculated production VS consumption, number of storages needed and can be loaded scenario 4 on Åland.

The FLH can be noticed in figure 23, are over 2,500 for both the storages needed and storages loaded which can be observed in figure 23. It can be seen that the number of storages needed for the FLH to be over 2,500 is ca 100 and ca 210 for storages that can be loaded.

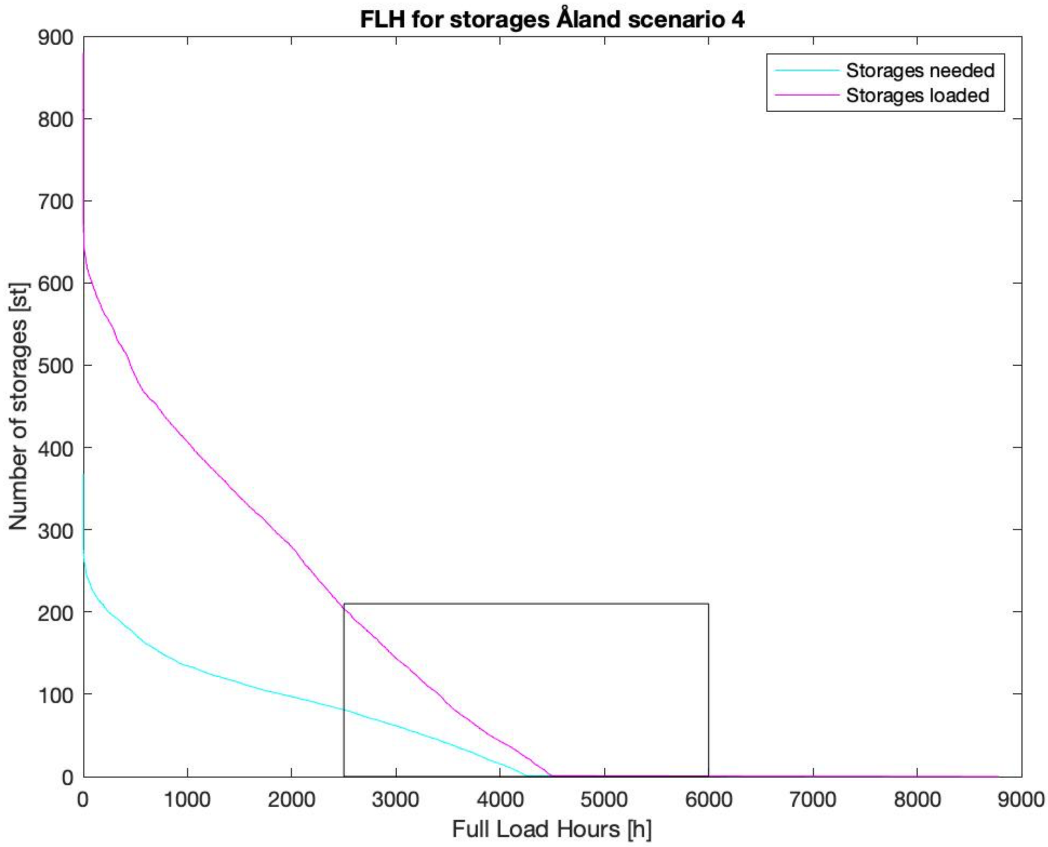


Figure 23: Full loading hours for storage needed and storage that can be loaded on Åland scenario 4.

Gotland

For Gotland to produce 130 % of the consumption from renewable sources the renewable production most increase from 535.6 GWh/year to 1227.3 GWh yearly. That gives an increase of ca 2.3 times the daily renewable production. The electricity surplus is much larger in this scenario than the electricity deficit. That's gives the result that the number of storages that can be loaded is much greater than the storages that are needed. This is presented in figure 24.

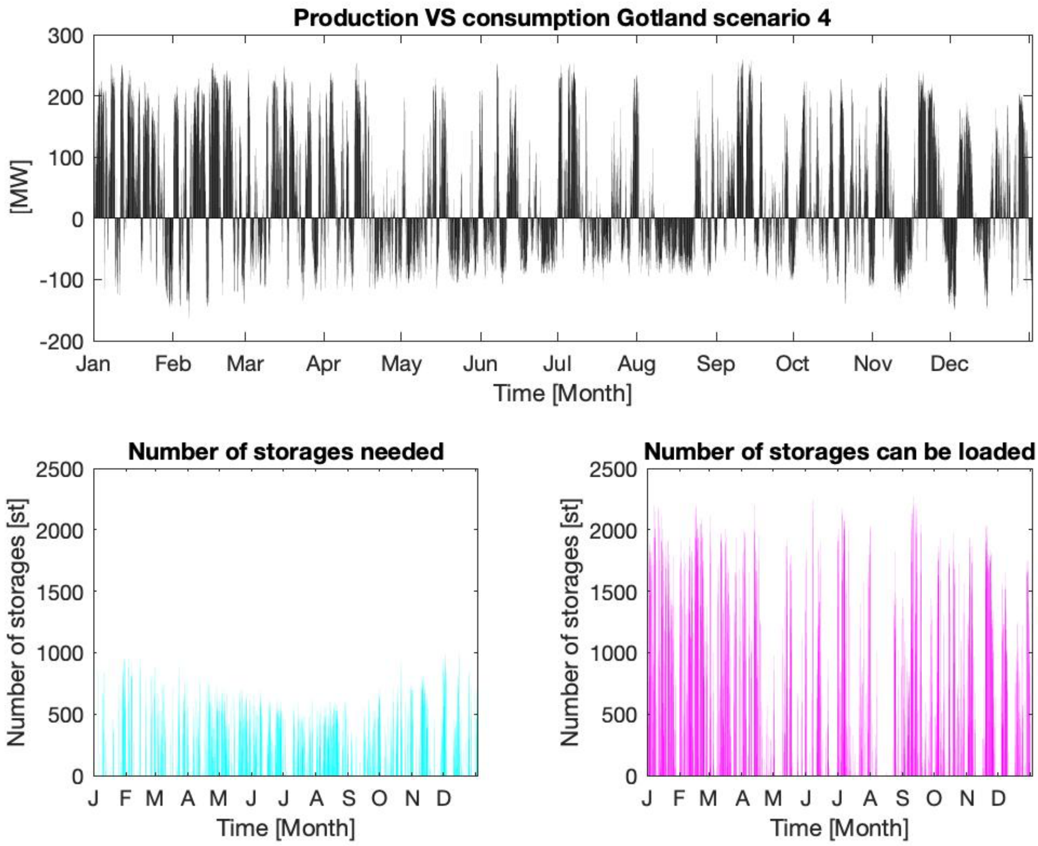


Figure 24: Calculated production VS consumption, number of storages needed and can be loaded scenario 4 on Gotland.

The FLH are over 2,500 for both the storages needed and storages loaded, and the pattern of the plots are very similar to the one above with Åland which can be observed in figure 25. It can be seen that the number of storages needed for the FLH to be over 2,500 is ca 300 and ca 750 for storages that can be loaded. This can be noticed in figure 25.

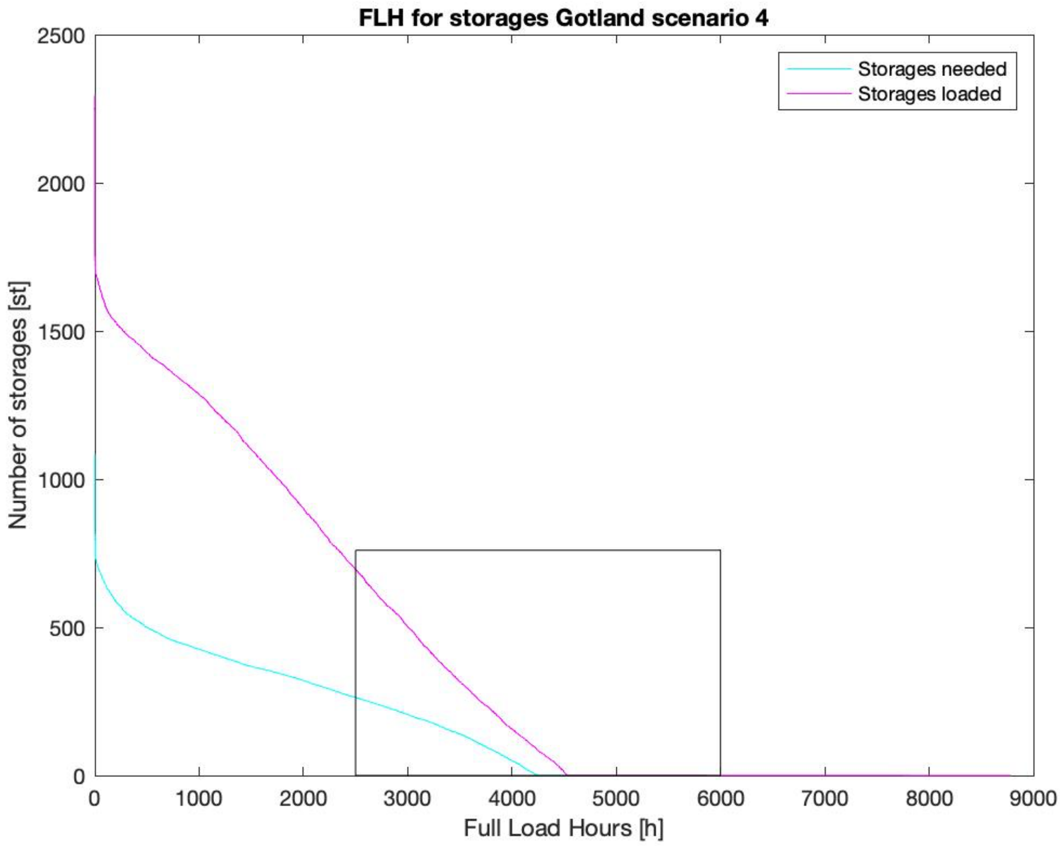


Figure 25: Full loading hours for storage needed and storage that can be loaded on Gotland scenario 4.

Table 4 is a compilation of the results for both of the islands. The total number of storages needed on Gotland is the same as for scenario 3. The number of storages needed for Åland is nearly the same as for Åland in scenario 3, the difference is that it is 7.8 storages less in this scenario.

Table 4: Summary of results from the figures for both islands in scenario 4.

Scenario 4	**Gotland**	**Åland**
Consumption [GWh/year]	944.1	298.7
Renewable electricity production [GWh/year]	1224.9	388.4
Electrolyser is used [h/year]	4532	4515
Fuel cell is used [h/year]	4252	4269
Max number of storages needed [st]	1084.2	368.7
Max number of storages loaded [st]	2295.8	880.1

3.2.5 Compilation of scenarios

Table 5 is a is a summary to see how FLH looks like for each scenario and island. It also shows if the number of storages that can be loaded is larger than the number of storages that is needed. The “-“ means that there is no result to extract or that the FLH never reach 2,500.

Table 5: Summary of results from the figures for all of the scenarios.

Scenario	Storages needed at 2,500 FLH	Storages loaded at 2,500 FLH	Number of storages can be loaded bigger than needed
Åland 1	-	-	-
Gotland 1	400	-	No
Åland 2	125	-	No
Gotland 2	420	-	No
Åland 3	110	110	Yes
Gotland 3	300	400	Yes
Åland 4	100	210	Yes
Gotland 4	300	710	Yes

4. Discussion

The boundaries that were set and should be discussed are the input parameters in the PVGIS model and in the calculation model. The azimuth angle who was set to 0° gives that all of the PV-systems on both of the islands was strictly angled towards the south which is likely not the actual case. This did probably influence the production of electricity from solar to be larger. Another parameter that was chosen was that the slope of the roof was fixed to 30° but because of the 1-2 % difference, this difference was very limited and was considered reasonable. That the global radiation was received from the year 2016, this because of the lack of data for the islands for the year 2020. Although the installed solar power for both islands was from the year 2020, this could affect the production to be larger or smaller than it would be if the data was from the year 2020. This could be included in a further study to identify if this would change the outcome significantly. An additional parameter that was used was the consumption, it was revived in different ways for the islands. The data for consumption on Åland was received in one single document. While the data of electrical consumption on Gotland was calculated from a measuring point, where the export and import were measured, and the wind power added which both were received in separate documents but from the same source. This number was 6 % less than from another source from 2019. This difference was at such a low level that it was considered to not make any major difference to the result.

It can be observed that with the production and consumption for the year 2020 in scenario 1, there is not any recommendation to have a large number of storages on Åland because no hydrogen storage can be loaded, considering there is no surplus electricity to store. On Gotland, the year 2020 the number of storages needed was larger than the number of storages that could be loaded. This indicates that the island can't be self-sufficient with help of these hydrogen storages if the production of electricity isn't increased. But there is electricity that could be stored, it could be supportive to store the amount of electricity that can be covered by the surplus electricity and charge these storages to use for balance in the grid or from personal use to save money by selling when electricity has a higher cost and store when the price is low. The FLH for storages loaded did not reach 2,500 but the FLH would have been higher if the additional load would be inserted in the system.

For scenario 2 when 60 % of the consumed electricity is produced with local renewable electricity sources, the amount of produced electricity of Gotland hasn't increased a lot and are therefore almost giving the same result as in the result for 2020. In the same scenario, even though the produced electricity on Åland has increased 3 times, there is not enough for the FLH to exceed 2,500 hours for the storages that can be loaded. For both islands in this scenario, the number of storages that can be loaded is less than the number of storages that are needed. The number of storages that are needed on Gotland in this scenario is 1,084 which is a large number. This result was however expected because of the lack of electricity of 40 %.

In scenario 3 when 100 % of the consumption is produced with local renewable electricity sources the production on Gotland was increased by 1.76 times and for Åland as much as 5 times. The FLH for both Åland and Gotland are somewhat high. The number of storages that are needed on Gotland is also in this scenario 1,084 and on Åland 376. The storages that can be loaded is higher than the number of storages needed which imply that the result is reasonable and realistic. If figure 21 is observed the conclusion can be drawn that the FLH on Gotland for a high number of storages needed that the FLH reduces quite fast. For more than 700 storages the FLH is zero which gives an indication that 1 084 is not ideal economically if the surplus electricity isn't provided with any other load. On Åland, the limit for the economic indicative is at ca 150 for the storages needed. That means that less than half of the number of storages needed would be most reasonable from this economical indicative.

In Scenario 4 when 130 % of the electricity consumption is produced with local renewable sources the production on Gotland was increased by 2.3 times and for Åland as much as 6.3 times which would mean a large expansion of the renewable electricity sources. The electricity surplus is like expected high. Which result in a higher number of storages that can be loaded than the number of storages needed. Regarding the FLH the number of storages needed on Åland is 100 for not undergo the limit of 2,500 FLH. The result of the number of storages needed based on the electricity deficit is 369. This means that the result for scenario 3 for Åland would be better than scenario 4 from this economical indicative based on the FLH. On Gotland was the total number of storages needed 1,084 which is the same as for scenario for the year 1, 2 and 3 for Gotland. But for the FLH to be over 2,500, the number of storages could not exceed 300 storages which are also the same as for scenario 3.

The conclusion that was made was that the possibilities for the islands to be self-sufficient with renewable electricity and hydrogen storages are from this economical indicative low, because the number of storages that are needed is too high regarding the FLH. The possibilities are best for scenario 3 when 100 % of the consumed electricity is produced with local renewable electricity sources. This is because scenario 4 have the same numbers of storages needed, but for the numbers of storages that could be loaded the FLH is less for scenario 4 than for scenario 3. Scenario 2 was like expected not good enough because of the lack of produced electricity. For none of the islands was the storages that could be loaded higher than for the storages needed for this scenario.

For future studies, the data that was received would need to be less than hourly based. Then the result would be more realistic, and a real-time model would be possible to create. This would be important because then the power balance could be taken into account which would be an interesting prospect for both of these islands. What could also be investigated in further studies is the energy security aspect if the hydrogen storages could be used when a power failure occurs on the islands and how it would impact the energy security as opposed to how the energy security looks like today on the islands. Another analysis that could have been done is to calculate how many additional windmills and solar facilities would be installed to cover the production in each scenario in this report.

4.1 Conclusions

The conclusion that was drawn was that the possibilities for Gotland and Åland to become self-sufficient in electricity with the help of renewable electricity and storage in hydrogen is low for scenario 1, 2 and 4 with this economical indicative. But it is achievable, and the possibilities are best for scenario 3 for both islands.

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