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Feasibility study for different grid-connected hybrid renewable energy system configurations, for five selected locations in Norway

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Preface

This thesis concludes my time as a student and my Master’s degree in the Renewable Energy program at the Norwegian University of Life Sciences. During the time as a student I have gotten both friends and professional experience that will guide me through life.

The thesis has combined the knowledge from my bachelor’s degree in economics and master’s degree in renewable energy. During the thesis writing I have gotten the chance to learn more about both solar and wind energy, which has interested me most during my time at the renewable energy program. From a personal perspective, the thesis has given me good faith in the possibility of more implementation of renewable energy in the years to come.

I am grateful to my superviser Muyiwa Samuel Adaramola for the introduction, guidance and help with my thesis. Your humor and availability have been most appreciated.

I would like to thank my family, friends and fellow students for support, laughs and good times during my time as a student.

Nils Ola Hansen, Ås, May 14, 2018

Abstract

This thesis investigates the net present cost (NPC) and levelized cost of energy (LCOE) for different grid connected energy systems with focus on renewable hybrid configurations for the locations Grinder, Trondheim, Bergen, Stavanger and Kristiansand in Norway. The load demand is retrieved in hourly data from the household at Grinder for the year 2017, and used for the other selected locations. The renewable resources and grid prices are retrieved for each selected location. The renewable technologies used in the thesis is the solar PV IBC poly 270 CS4 and the wind turbine Gaia-Wind 133. To conduct the analysis, HOMER software is used. HOMER calculates the optimal system configurations and the belonging net present cost and levelized cost of energy for each system configuration. The analysis conducts different scenarios which includes subsidies from Enova, feed-in tariff from Otovo, three different production subsidies from the el-certificate market and future grid prices.

The Grid-only without local power generation had the lowest NPC for all the selected locations, but several of the HRES achieved lower LCOE.

When the subsidy from Enova and the feed-in tariff from Otovo were included, the Grid+PV system achieved the lowest NPC for Kristiansand. For Grinder and Stavanger it was close to the NPC for the Grid-only system.

When future grid price was included with subsidy from Enova, feed-in tariff from Otovo and production subsidies for el-certificates, the Grid+WT system achieved the lowest NPC for both Stavanger and Bergen. Even the Grid+PV+WT(1) achieved lower NPC than the Grid-only system. For Grinder, Trondheim and Krisitansand, the Grid+PV was the system with the lowest NPC.

By reducing the PV cost multiplier by 60%, the Grid+PV system would have the lowest NPC without any form of financial support. If the wind turbine cost multiplier is reduced by 60%, the NPC would still be higher than the Grid-only system.

Sammendrag

Denne oppgaven undersøker netto nåtidskostnad og energikostnad for ulike nettilkoblede energisystemer med fokus på fornybare hybridkonfigurasjoner. I oppgaven er stedene Grinder, Trondheim, Bergen, Stavanger og Kristiansand undersøkt for å sammenligne potensialet for et hybrid energisystem ulike steder i Norge. I analysen er elektrisitetsbehovet hentet i timesdata fra husstanden på Grinder for året 2017, og brukt for de resterende stedene. Energiressursene og strømprisene er hentet fra hver enkelt lokasjon. De fornybare teknologiene som er brukt i analysen er solcellene IBC poly 270 CS4 og vindturbinen Gaia-Wind 133. For å utføre analysen er dataprogrammet HOMER benyttet. HOMER beregner de optimale systemkonfigurasjonene og tilhørende netto nåtidskostnad og energikostnad for hver av de. I analysen er det utført ulike scenarioer som tar for seg investeringsstøtte fra Enova, tilbakesalgspris for overskuddstrøm fra Otovo, tre ulike produksjonspriser fra Elsertifikater og fremtidig pris på strøm.

Strømnettet uten lokal kraftproduksjon leverte den laveste netto nåtidskostnaden for alle lokasjonene, mens flere av de fornybare systemkonfigurasjonene leverte lavere energikostnad.

Når investeringsstøtte fra Enova og tilbakesalgsprisen fra Otovo ble inkludert leverte Strømnett+PV den laveste netto nåtidskostnaden i Kristiansand. For Grinder og Stavanger var Strømnett+PV også nærme netto nåtidskostnaden til strømnettet.

Når fremtidig strømpris ble lagt inn med investeringsstøtte fra Enova, tilbakesalgspris fra Otovo og elsertifikater ble Strømnett+Vindturbin systemet med lavest netto nåtidskostnad for både Stavanger og Bergen. Strømnett+PV+Vindturbin(1) hadde også lavere netto nåtidskostnad enn kun strømnettet. For Grinder, Trondheim og Kristiansand var Strømnett+PV systemet med lavest netto nåtidskostnad.

Ved å senke kostnadene med 60% på investeringskostnaden for solcellene vil Strømnett+PV bli systemet med lavest netto nåtidskostnader uten noen form for støtteordninger. Senkes kostnadene på vindturbinen med 60% vil Strømnett+Vindturbin fortsatt ha for høye netto nåtidskostnader.

Table of Contents

List of abbreviations

NPC	Net present cost
LCOE	Levelized cost of energy
HRES	Hybrid renewable energy system
PV	Photovoltaic
WT	Wind turbine
GHG	Greenhouse gas
RES	Renewable energy sources
HOMER	Hybrid Optimization of Multiple Electric Renewables
AMS	Smart Metric Meter
kWh	Kilowatt hours
kW	Kilowatt
W	Watt
kWp	Kilowatt peak
MWh	Megawatt hours
SSE	Surface meteorology and Solar Energy
NASA	National Aeronautics and Space Administration
GHI	Global horizontal radiation
NREL	U.S National Renewable Energy Laboratory
NOCT	Nominal operating cell temperature
NOK	Norwegian kroner
SEK	Swedish kroner
STC	Standard test conditions
AC	Alternating current
VAT	Value added tax
NVE	Norges vassdrags- og energidirektorat
El	Electricity
CRF	Capital recovery factor
COE	Cost of energy
USD	United States Dollar
AUD	Australian Dollar

List of figures

List of tables

1 Introduction

1.1 Background for the thesis

The population on earth increases and are expected to increase in the future (Tønnessen et al. 2016), the same accounts for the energy consumption in Europe (Amundsen et al. 2017) and in Norway (U.S Energy Information Administration 2017). To prevent dangerous climate changes, the EU is working hard in cooperation with their member countries to cut the greenhouse gas emissions (GHG). Through the EU climate action, the targets and goals for these cuts in GHG emissions have been stated for the EU member countries to achieve (European Commision 2018). To reach these targets and goals there will be need for heavy investments in renewable energy sources (RES) for many countries, in addition to increase the energy efficiency. A part of the solution to this can be hybrid renewable energy system (HRES) for residentials. In Germany, their energy is very dependent on coal, to achieve their goals, subsidies and feed-in tariffs have been introduced. These subsidies and feed-in tariffs have made the growth of solar PV significant over the last years (Fraunhofer ISE 2018), and made Germany one of the school examples. The same accounts for UK with their feed-in tariffs. By introducing the feed-in tariffs a significantly increase have occurred for both solar PV and small scale wind turbines (WT) (Nolden 2015).

Compared to electricity prices in Europe, Norway is in the mid-range (Gundersen 2017). Those countries with lower prices are mostly eastblock countries, while the western countries in Europe have higher prices. With the upcoming ACER contract for Norway and the planning of building new transmission lines to western Europe, it is likely that the electricity prices in Norway will increase and get closer to the electricity prices in western Europe (Molnes 2018). Furthermore, the EU Emission Trading System (European Commision Unknown) could impact the electricity prices.

As Norway have the second highest electricity consumption in the world per person in residentials (Bøeng 2014), an increase in the electricity prices will have relatively big impact on the electricity bill. Dependent on the size of the increase, more and more consumers would consider installing either solar PV or for larger demands small scale wind turbines. Until now, solar PV have mostly been used for standalone systems like cabins, but the last years there have been a large increase in grid connected PV systems (Multiconsult 2016). Small scale wind turbines have not had the same increase in installed capacity, mostly because of the need for good wind conditions and high investment costs (Nilsen 2014). Although, if the demand for electricity is high and there are good wind conditions, a small scale wind turbine might be just as good as installing a solar PV system (Revheim 2107).

With the large number of new installments of solar PV around in the world, the investments costs have decreased as well (Accenture & WWF 2016). The investment costs in Norway are quite high compared to Germany, but with larger actors in the industry, both the installation costs and costs for the PV modules will decrease. The combination of higher electricity prices and lower investment costs for solar PV systems will make it much more attractive to invest in HRES. Since the wind turbines have much higher investment costs, this might not follow the same price development as for the solar PV, but with larger amount of installed capacity, the investment costs for small scale wind turbines will most likely decrease in the future.

The main barriers for Norwegians to install a HRES is often poor conditions, high investment costs and too little knowledge. The sun conditions in Norway are slightly lower than for Germany, but because of colder climate that increases the efficiency, the production is almost the same for solar PV. Furthermore, the wind resources along the coast are very good for wind turbines.

1.2 Goal and objective

This intrigued me to investigate the potential for a HRES for different locations in Norway. The objective in this thesis is to investigate if a HRES is profitable for several locations in Norway, and if so, which locations have the best opportunities. This objective includes the following:

- Collect renewable energy resources
- Find components for the HRES
- Investigate different system configurations for the HRES
- Conduct analysis to find the optimal solutions and estimate the power output
- Conduct different scenarios for subsidies, feed-in tariffs and future electricity prices
- Calculate the profitability of the different optimal solutions with and without the subsidies, feed-in tariffs and the future grid prices.
- Conduct sensitivity analysis for the HRES.

This thesis is a hypothetical study. The load is collected from an actual electricity consumption for the location at Grinder and the renewable energy resources are historical data based on satellite-derived data. It is not taken into consideration required space for both solar PV and the wind turbine, application process to install the wind turbine and the thermal load from the wood stove.

1.3 Research questions

1. Can a HRES configuration be profitable compared to the grid?
2. How does financial support affect the optimal system configuration?
3. Which of the selected location is the most suitable based on production from solar PV and wind turbine, both separate and combined?

1.4 Structure

Content in this thesis is based on the optimization of a HRES for Grinder, Trondheim, Bergen, Stavanger and Kristiansand in Norway, to find out if it is any feasible system configurations for the locations which can compete with today's solution, the Grid-only configuration.

Chapter 2 explains the methodology used in the thesis with the belonging theory used for the calculations.

Chapter 3 presents the simulations and optimization results obtained from Hybrid Optimization of Multiple Energy Resources (HOMER). This includes a selection of optimal HRES configurations with and without subsidies and feed-in tariffs and future grid prices. The economic viability for the HRES configurations is presented along with a sensitivity analysis.

Chapter 4 contain the discussion.

Chapter 5 presents the conclusion and recommendations for further work.

2 Methodology

2.1 Locations

The chosen locations in this thesis is Grinder, Trondheim, Bergen, Stavanger and Kristiansand. These locations are selected to see the differences around in Norway. By choosing these locations, most of the country are covered. The placement of the HRES for each location have been set to a small distance from the city center because of space requirements for the wind turbine. Solar PV can be set up almost everywhere. In order to not get to much wind losses for the wind turbine because of surroundings such as high buildings, agricultural areas are preferable. Latitude and longitude for each location are presented in Table 2.1, while a visual presentation of the selected locations is given in Figure 2.1.

Table 2.1: Latitude, longitude and altitude above sea level for each of the selected location.

Location	Latitude	Longitude	Altitude above sea level (m)
Grinder	60,4	12,06	160
Trondheim	63,37	10,15	80,6
Bergen	60,27	5,26	40
Stavanger	58,916	5,7	37,8
Kristiansand	58,13	8,12	46,1

Figure 2.1: Visual presentation of the selected locations in Norway. The map is retrieved from (Kartverket 2018).

2.2 Load

The load is the total amount of energy consumed by components within the system and is the amount of energy the energy system need to provide. In this thesis, the load is mainly electrical load consumed by all electrical appliances installed in the household. A household or community energy consumption depends on living standards, weather conditions, type of residence, number of residents and time of day, and so on. By adding up all the consumption from each of the electrical appliances over a period, total energy consumed or use in this given household can be estimated. Using this information, a load profile can then be deduced.

The load profile shows the variation of load over a specific time, such as daily, monthly or annually. This is essential to optimally design the system to meet the demand for electricity for the household. The load data used in this thesis are provided in form of hourly timesteps from the year 2017 from a smallholding, which consists of two detached houses, located at Grinder, Norway. Grinder is a village in the municipality of Grue in Hedmark County. One of the houses is used for storage and use electricity for heating, while the other house is where the resident lives. These load data are obtained from a Smart Metric Meter (AMS) that was installed in this premise in December 2016. It should be mentioned that it would be preferable to have load data for more years, so that it would be more representative based on seasonal variation in ambient temperature throughout the year in this location.

The load from the smallholding at Grinder will be the reference load for all the locations. Facts about the smallholding is presented in Table 2.2.

Table 2.2: Facts about the smallholding.

Variable type	**Value**
Dwelling type	Two detached houses
Number of residents	1
Floor space	$180m^2 + 50m^2$
Building year	Ca. 1970
Heating source	Electricity + wood stove

From the collected hourly electricity consumption data, the annual daily average electricity consumption is 56,65 kWh/day. The annual maximum-, minimum- and average load are respectively 6 kW, 0 kW and 2,36 kW at this site. Hence, the load factor is estimated as 39%. Figure 2.2 presents the monthly load values and Figure 2.3 presents average daily load profile.

There are two variability values calculated from the input load data, named “Day-to-day”- and “Timestep”-variability. “Day-to-day” and “Timestep” variables allow you to modify the randomness for the load to achieve a more realistic load. By changing the Day-to-day variability, it will make a curve that shows you how much the load curve varies from day to day. It is not realistic that the load curve is similar for each day. The same accounts for the “Timestep” variability, only that it changes the variability within the day for each timestep. The “Day-to-day” variability for the load is 15,723 and the “Timestep” variability is 38,216.

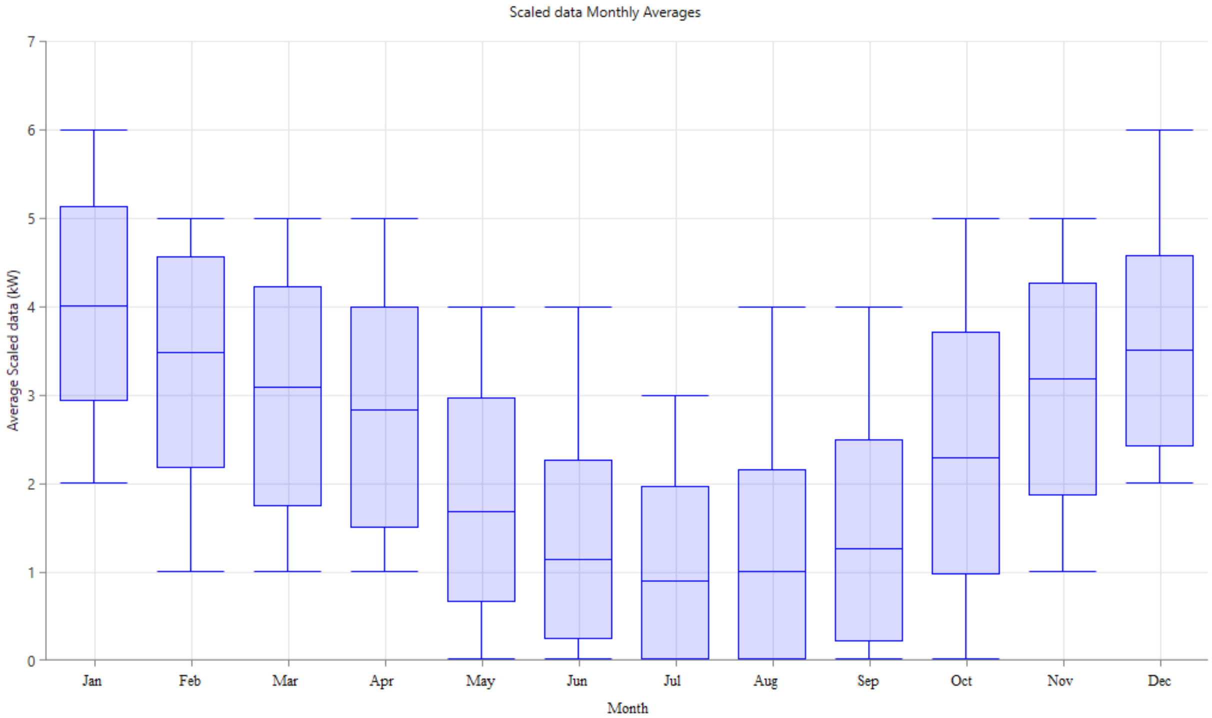

Figure 2.2: Monthly load values. The line at the top and bottom show maximum and minimum values respectively. The line in the middle shows the average monthly load. The top and bottom of the boxes shows the maximum and minimum daily average respectively. The load values are created on the input values from Grinder.

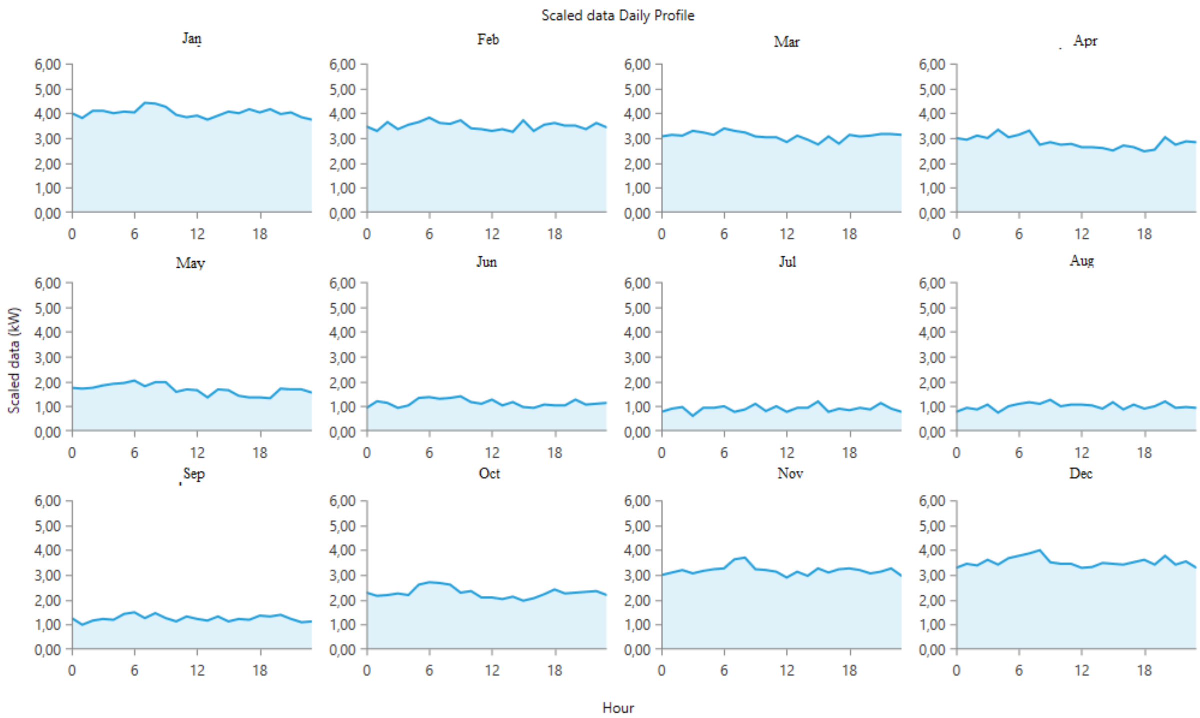

Figure 2.3: Average daily load profile for each month. The daily average is the area under the line.

2.3 Renewable energy resources

Due to lack of accessible detailed ground-measured data and for the simplicity of this thesis due to the time constraint, the meteorological and environmental data for the five selected locations are derived from the built-in resource function in HOMER software, which is the design and analysis tool used in this work (see section 2.4). This function allows you to pinpoint an exact point from the entire world or type in the coordinates based on a spatial resolution of 0,5 degrees latitude by 0,5 degrees longitude. The resources are provided from NASA Surface meteorology and Solar Energy database (SSE) (NASA Surface meteorology and Solar Energy 2018b) and are monthly averaged values over a 22-year period from July 1983 to June 2005. The parameters contained in the archive are based primarily upon solar radiation derived from observations and meteorological data from assimilation models.

The validation of the available SSE parameters is based on comparison of the SSE primary parameters to surface observation of the corresponding parameters. Although it is recommended to use surface-measurements for more precise predictions, the satellite-derived data have shown to be accurate enough to provide reliable solar and meteorological resource data. This is validated by Zawilska and Brooks (2011) and Ineichen (2014).

2.3.1 Solar energy resources

Energy from the sun can mainly be exploited in two ways, thermal as in passive heating or with a solar collector to heat up water, and to produce electricity with either solar PV or concentrated solar power. Solar PV is the technology examined in this thesis.

There are two metrics used to measure the amount of solar energy resource, which are irradiance and irradiation. Irradiance is the amount of solar radiation falling on a particular area at any given time. It is a measure of power and does not consider time and is given in W/m^2. On the order, irradiation is a measure of the amount of irradiance that falls on a location over time. It's a measure of solar energy and is given in kWh/m^2/day. Radiation from the sun that strikes the horizontal surface is divided into a combination of direct radiation (G_d) and diffuse radiation (G_{di}). Direct radiation is the solar radiation that goes directly from the sun without any scattering from the atmosphere to the surface of the earth. Diffuse radiation is the radiation that have changed direction because of the atmosphere and strikes from all parts of the sky (HOMER Energy 2017). The sum of the total radiation on a horizontal surface is expressed in Equation 2.1.

$$\overline{G} = \overline{G}_d + \overline{G}_{di} \qquad 2.1$$

It is possible for an inclined surface to receive additional radiation, called reflected radiation (G_r). Reflected radiation is reflected from the earth's surface or other obstacles. The reflection varies with different surface types, resulting in difference reflection factor, also called albedo (p). The albedo takes a value between 0 and 1, where fresh snow has a factor of 0,9 and asphalt has a factor of 0,1 (HOMER Energy 2017). The factor used for albedo effect in this thesis is based on Table 2.3, which is derived from NASA Surface meteorology and Solar Energy (2018a). Reflected radiation can be found using Equation 2.2.

$$G_r = p * (G_d + G_{di}) \qquad 2.2$$

Table 2.3: 22-year monthly averages of albedo for the selected locations.

22 year average	Grinder	Trondheim	Stavanger	Bergen	Kristiansand
Jan	15 %	20 %	12 %	15 %	14 %
Feb	21 %	28 %	9 %	22 %	15 %
Mar	25 %	31 %	8 %	10 %	20 %
Apr	19 %	27 %	6 %	10 %	15 %
May	9 %	20 %	7 %	8 %	9 %
Jun	10 %	19 %	7 %	8 %	7 %
Jul	14 %	13 %	6 %	10 %	8 %
Aug	14 %	15 %	7 %	10 %	9 %
Sep	14 %	14 %	8 %	11 %	9 %
Oct	11 %	17 %	8 %	12 %	8 %
Nov	16 %	22 %	10 %	19 %	1 %
Dec	14 %	21 %	11 %	14 %	1 %
Annual average	15 %	21 %	8 %	12 %	10 %

Equation 2.3 represents the total radiation on an inclined surface and is visualized in Figure 2.4.

$$\overline{G} = \overline{G}_d + \overline{G}_{di} + \overline{G}_r \qquad 2.3$$

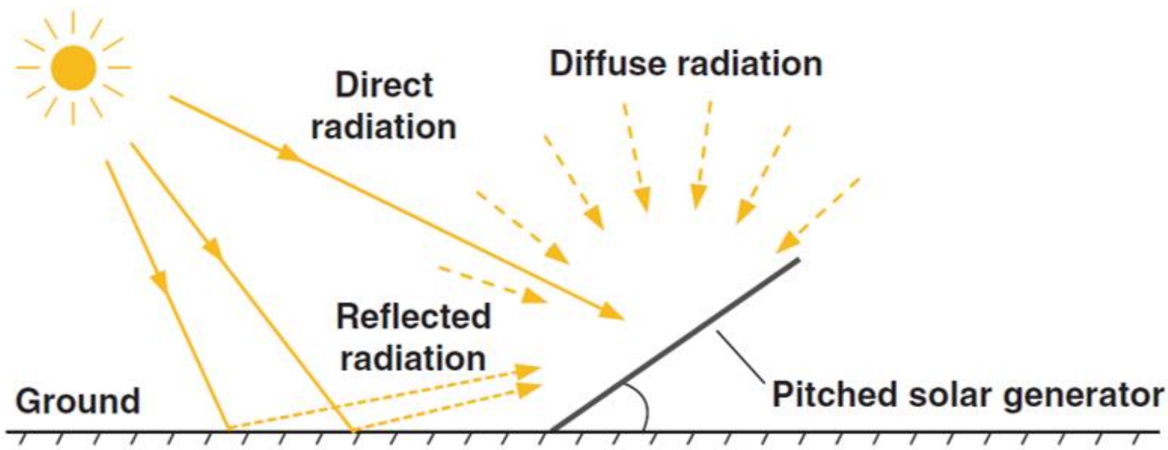

Figure 2.4: Visualization of direct, diffuse and reflected radiation on an inclined surface (K. Mertens: textbook-pv.org).

Global horizontal radiation (GHI) is the only radiation input in the model, since the GHI does not consider its direct and diffuse components, the clearness index is used to calculate the amount of diffuse radiation. Clearness index indicates the fraction of solar radiation striking the top of the atmosphere that makes it through the atmosphere and striking the surface of the earth (HOMER Energy 2017). The monthly average clearness index is defined in Equation 2.4.

$$K_T = \frac{H_{ave}}{H_{0,ave}} \qquad 2.4$$

where: K_T is the clearness index in month T, H_{ave} is the monthly average radiation on the horizontal surface of the earth (kWh/m^2/day) and $H_{0,ave}$ is the radiation on a horizontal surface at the top of the earth's atmosphere, extraterrestrial horizontal radiation (kWh/m^2/day)

Altitude and azimuth angle

Location of the sun at any time of the day can be described by altitude angle (β) and azimuth angle (ϕ). These angles are dependent on latitude, number of day and time of the day. From Figure 2.5 the altitude angle is the suns height at the sky at a given time while azimuth angle is the compass direction from where the solar radiation arrives. For the northern hemisphere, the sun is at position in southward direction (Masters 2013). The optimal orientation will therefore be south-facing, which can be calculated from equation 2.6.

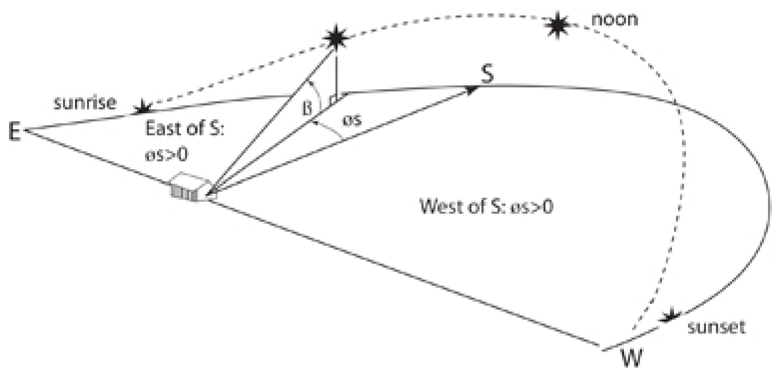

Figure 2.5: Illustration of the suns altitude- and azimuth angle (Jenkins & Bolivar-Mendoza 2014).

Equation 2.5 and Equation 2.6 are used to calculate the altitude and azimuth angles of the sun, respectively.

$$\sin\beta = \cos L \cos H + \sin L \sin\delta \qquad 2.5$$

$$\sin\phi_s = \frac{\cos\ \delta \sin H}{\cos\beta} \qquad 2.6$$

where: L is the latitude, H is the hour angle and δ is the declination angle

The hour angle is the number of degrees the earth must rotate until the sun is directly over the local meridian. The angle is the difference between local meridian and the sun's meridian (Masters 2013). Hour angle is expressed in Equation 2.7.

$$H = \frac{15°}{hour} * (t_s - 12\ hour) \qquad 2.7$$

where: t_s is the solar time (hour)

It is common for most solar work to operate exclusively with solar time, where everything is measured relative to solar noon. However, HOMER software assumes that all input values that are dependent on time is given in civil time (HOMER Energy 2017), as solar radiation and electric load are given in civil time, not in solar time. To adjust solar time to civil time Equation 2.8 is used.

$$t_s = t_c + \frac{\lambda}{15°/hour} - Z_c + E \qquad 2.8$$

where: t_c is the civil time in hours corresponding to the midpoint of the timestep (hour), λ is the longitude (°) of the site, Z_c is the time zone in hours east of GMT (hour) and E is the equation of time. Equation of time accounts for the tilt of the earth's axis of rotation relative to the plane of ecliptic and the eccentricity of the earth, is given by Equation 2.9 (HOMER Energy 2017).

$$E = 3{,}82\ (0{,}000075 + 0{,}001868 \cos B - 0{,}032077 \sin B - 0{,}014615 \cos 2B - 0{,}04089 \sin 2B) \qquad 2.9$$

where B is given by

$$B = 360° \frac{(n-1)}{365} \qquad 2.10$$

Declination angle

Predicting exact where the sun will be at any time, location and any day of the year is very useful. This information about solar angles is used for determining the best tilt angle for our solar PV modules to expose them to the greatest insolation available. As shown in Figure 2.6, the declination angle is the angle formed between a line from equator and line drawn from the center of the sun to the center of the earth, also called solar declination (Masters 2013). Exact values for the declination angle can be calculated using Equation 2.11.

$$\delta = 23{,}45 \sin\left(\frac{360}{365}(n-81)\right) \quad 2.11$$

where: n is the day of the year with Jan 1 as n=1.

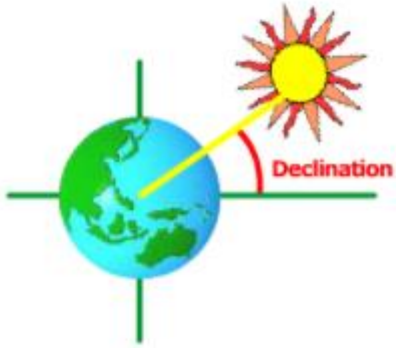

Figure 2.6: Illustration of the declination angle (Honsberg & Bowden 2018).

Optimum tilt angle

The tilt angle (θ) will influence the power output from the solar PV system. To optimize the amount of solar radiation that strikes the solar PV panels, it would be appropriate to orientate the panels in the angle where the sun is at its highest and brightest. This will typically be at 12 o'clock. Equation 2.12 is used to calculate the altitude angle of the sun at 12 o'clock (β_N) by using the declination angle (Masters 2013).

$$\beta_N = 90° - L + \delta \quad 2.12$$

The optimum tilt angle varies between summer time and winter time. Using a tracking system could increase the amount of solar radiation striking the inclined surface. However, a tracking system has higher investment costs and require higher maintenance costs than a fixed tilted system. The difference in power output from changing the tilt once every month and a fixed system is less than 4% (Stanciu & Stanciu 2014). In this thesis, therefore, a fixed tilt angle is adopted for the solar PV system. An average of optimum tilt angle for the seasons in a year is often used as the optimum tilt angle throughout the year. For calculating optimum tilt angle for a season Equation 2.13 is used (Masters 2013).

$$\delta_a = \frac{2\delta_a}{\pi} \quad 2.13$$

where δ_a for summer, winter and spring/autumn is respectively 23,45°, -23,45° and 0°. Optimum tilt angle (θ) for the solar PV modules at 12 o'clock for a given day is calculated with Equation 2.14 (Masters 2013).

$$\theta = 90 - \beta_n \rightarrow\ L - \delta \qquad 2.14$$

By replacing δ with δ_a the seasonal optimum tilt angle is found and presented in Table 2.4.

Table 2.4: Latitude, tilt angles for the different seasons and optimal tilt angle for the selected locations.

Location	Latitude, L (°)	Summer (°)	Winter (°)	Spring/Autumn (°)	Average (°)	Optimal tilt angle (θ_{opt})
Grinder	60,4	36,95	83,85	60,4	60,4	60,4
Trondheim	63,37	39,92	86,82	63,37	63,37	63,37
Bergen	60,27	36,82	83,72	60,27	60,27	60,27
Stavanger	58,9	35,45	82,35	58,9	58,9	58,9
Kristiansand	58,13	34,68	81,58	58,13	58,13	58,13

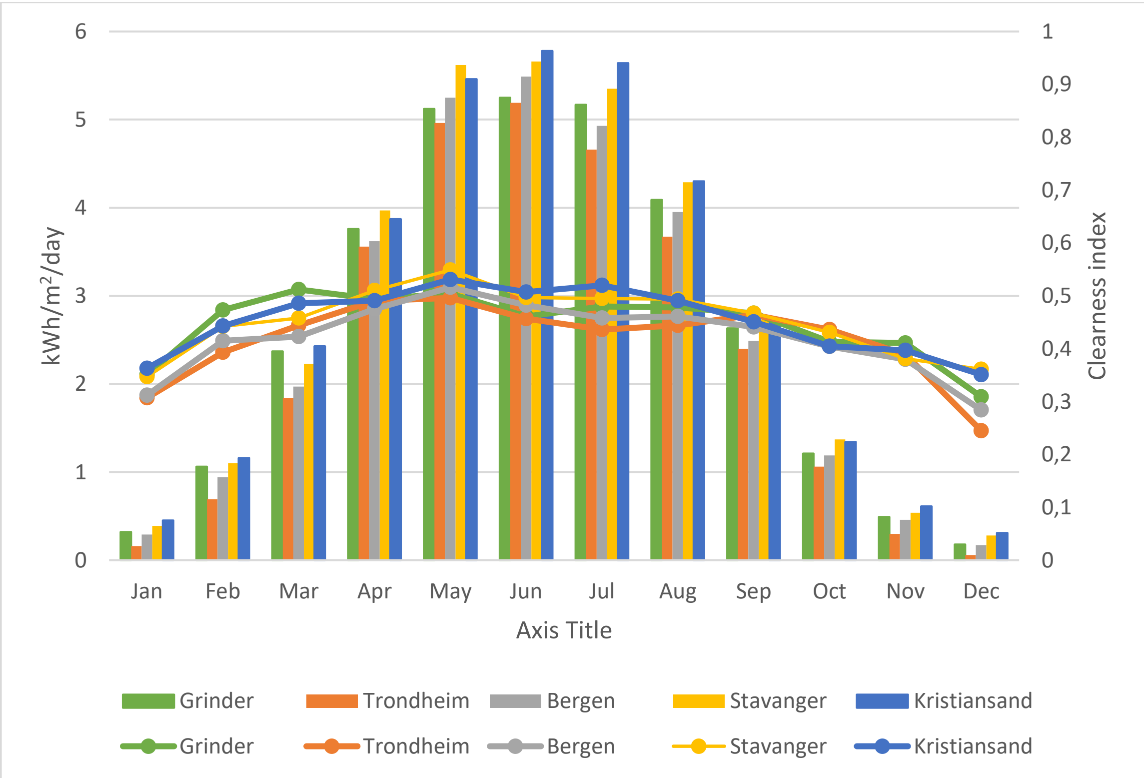

Figure 2.7: Average daily radiation on a horizontal surface and clearness index for the selected locations. The columns present the average daily radiation and the lines presents the clearness index.

Figure 2.7 presents the daily average radiation and the clearness index on a horizontal surface for the selected locations. During the months May, June, July and August, Stavanger and Kristiansand have the highest radiation. This is also the time of the year where the radiation is at its highest. From January to April, Grinder is quite similar to Stavanger and Kristiansand. Trondheim has the lowest radiation throughout the year, while Bergen have slightly higher radiation than Trondheim, except for May and June when the radiation is at its highest in Bergen.

2.3.2 Wind resources

For calculating the wind power output, the wind speed is essential. HOMER software uses three different parameters to calculate the output of a wind turbine in each timestep. These parameters are: altitude, anemometer height and variation with height.

Altitude is the elevation above mean sea level. The altitude affects the air density (HOMER Energy 2017), which is according to the ideal gas law given by Equation 2.15:

$$p = \frac{P}{RT} \tag{2.15}$$

where: p is the air density (kg/m^3), P is the pressure (Pa), R is the gas constant (287 J/kgK) and T is the temperature (K).

When HOMER calculates the output of the wind turbine at the specific altitude, it uses the air density ratio, which is the actual air density divided by air density under standard test conditions (sea level, 15 degrees Celsius). The air density ratio is multiplied by the power output retrieved from the power curve of the wind turbine (HOMER Energy 2017). The air density ratio is expressed as following:

$$\frac{p}{p_0} = \frac{P}{P_0}\left(\frac{T_0}{T}\right) \tag{2.16}$$

where: P_o is the standard pressure (101,325 Pa) and T_0 is the standard temperature (288,16 K). It should be noted that both pressure and temperature is affected by altitude. The US Standard Atmosphere uses the simplified assumption that temperature decreases linearly with altitude up to an altitude of 11 000 m (HOMER Energy 2017), and is given as:

$$T = T_0 - Bz \tag{2.17}$$

where: B is the lapse rate (0,0065 K/m) and z is the altitude (m). With this assumption air pressure can be shown to depend on the altitude by Equation 2.18:

$$P = P_0 \left(1 - \frac{Bz}{T_0}\right)^{\frac{g}{RB}} \qquad 2.18$$

where: g is the gravitational acceleration (9,81 m/s^2).

By substituting Equation 2.17 and Equation 2.18 into Equation 2.16, the air density ratio can be expressed as:

$$\frac{p}{p_0} = \left(1 - \frac{Bz}{T_0}\right)^{\frac{g}{RB}} \left(\frac{T_0}{T_0 - Bz}\right) \qquad 2.19$$

The wind speed data retrieved from NASA SSE are performed at height, of 50 m above sea level. Ground-level obstacles tends to slow the wind speed near the ground while wind speed tends to increase with height above ground, leading a phenomenon called wind shear. In most cases, the anemometer measurement height and the hub height of the wind turbine, may not be the same. The measured wind speed data are generally adjusted using two different mathematical models, which are logarithmic profile and the power law profile. Hub height for the wind turbine in this thesis is 18 m above ground.

In this thesis the logarithmic profile is used (HOMER Energy 2017). The logarithmic profile assumes that the wind speed is proportional to the height above ground which is given in Equation 2.20:

$$U_{hub} = U_{anem} * \frac{\ln\left(\frac{Z_{hub}}{Z_0}\right)}{\ln\left(\frac{Z_{anem}}{Z_0}\right)} \qquad 2.20$$

where: U_{hub} is the windspeed at the hub height of the wind turbine (m/s), U_{anem} is the windspeed at anemometer height (m/s), Z_{hub} is the hub height of the wind turbine (m), Z_{anem} is the anemometer height (m) and Z_0 is the surface roughness length (m).

The surface roughness characterizes the surrounding terrain and its roughness. The default value of 0,01m in HOMER is used.

Figure 2.8 presents the wind speeds for the selected locations. Stavanger and Bergen have the highest wind speeds and are relative equal throughout the year. Trondheim and Kristiansand have lower wind speeds, where Trondheim have relative low wind speeds through the summer months. Grinder have the poorest wind speeds throughout the year.

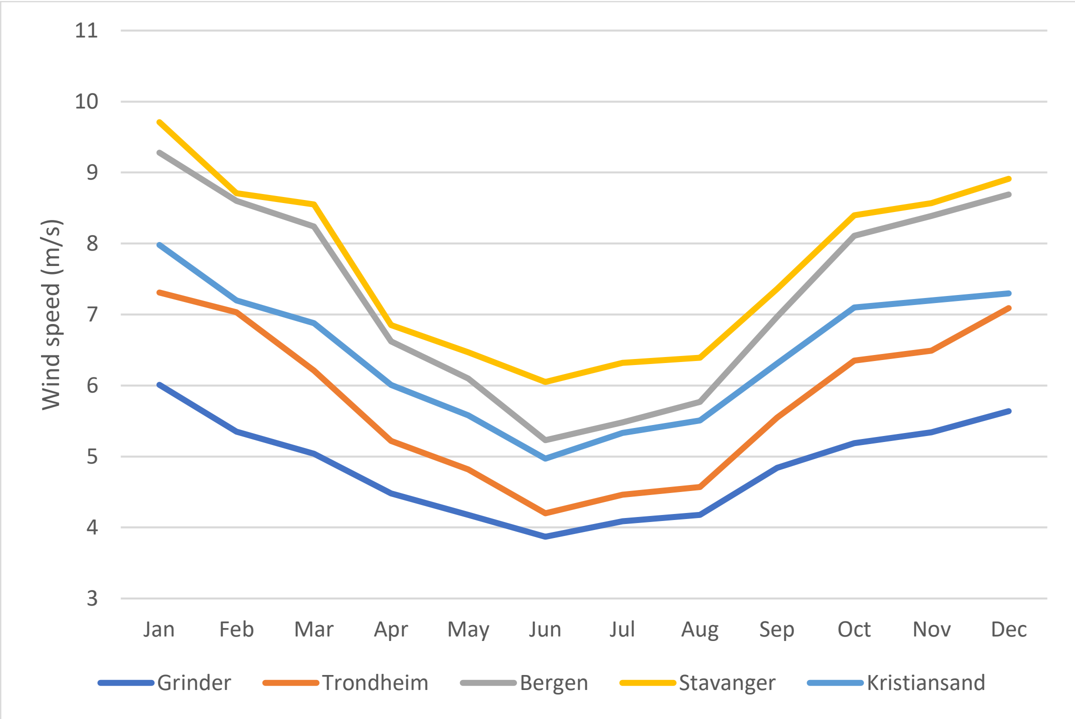

Figure 2.8: Average wind speeds during the year for the selected locations.

2.3.3 Ambient temperature

The ambient temperature is used for both the PV system and the wind turbine. For the PV system, it is used to calculate the PV cell temperature, which affect the performance for the PV system. With increasing temperatures, the efficiency of the PV system decreases. This explains how a solar PV system can be almost as efficient in Norway as in Germany. Even though it is a bit lower radiation in Norway than in Germany, the temperature is lower so that the power output from the PV system is almost equal (Accenture & WWF 2016).

For the wind turbine, the temperature affects the air density as explained previously. Lower ambient temperatures give rise to higher density. The effects of temperature are important for the accuracy of the results.

Figure 2.9 presents the ambient temperature for the selected locations. Grinder is the locations which varies the most, with the coldest temperatures in the winter, and second highest temperatures in the summer. Trondheim have almost the same temperatures as Grinder, except for approximately 2 degrees lower during June to August. Bergen, Kristiansand and Stavanger have the highest average ambient temperatures throughout the year. The largest differences in ambient temperature is from November to March.

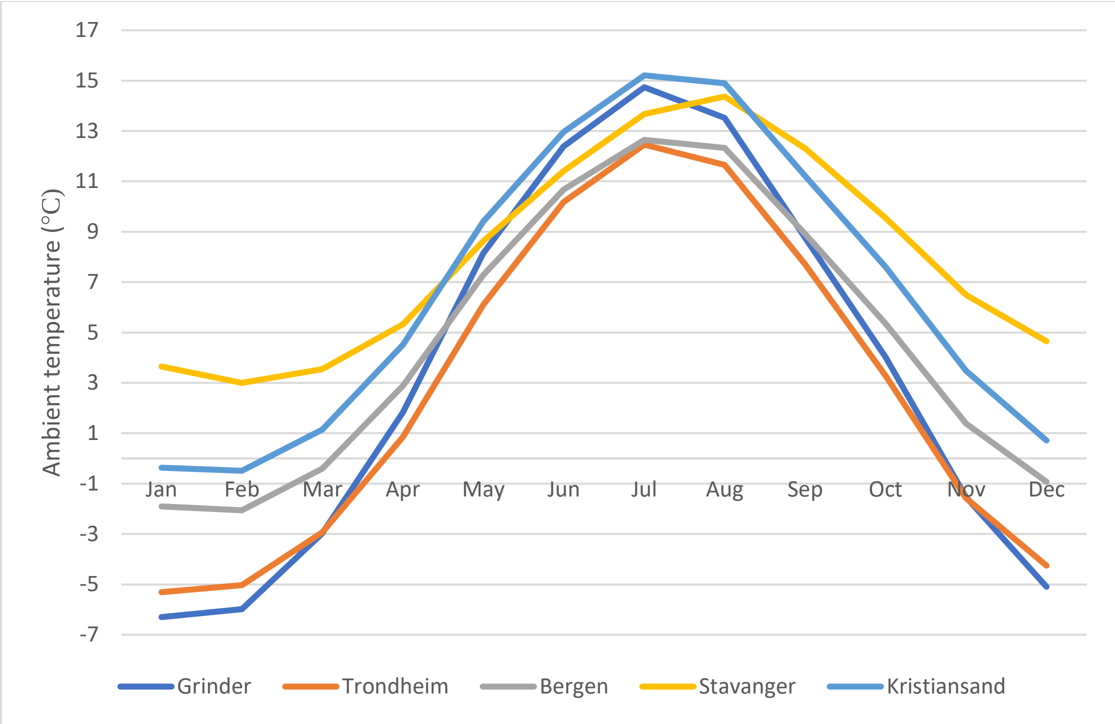

Figure 2.9: Average ambient temperatures during the year for the selected locations.

2.4 HOMER software

Hybrid Optimization of Multiple Electric Renewables (HOMER) is the model used to conduct the analyze in this thesis. It is developed by the U.S National Renewable Energy Laboratory (NREL) with the purpose to assist in the design and facilitate comparison of power generation technologies of micropower systems.

HOMER is given inputs by the user which describe technology options, component costs and resource availability. These inputs are used to simulate many different system configurations, or mix the technologies into combinations of components and generates results sorted by net present cost. Simulation, optimization and sensitivity analysis is the three principal tasks HOMER performs.

Simulation

The simulation process determines the behavior over time for a particular system configuration, a combination of system components of specified size and an operating strategy on how the components work together. HOMER configures the system by performing an hourly time series of its operation over one year. It steps through the first year one hour at a time, calculating renewable power generated, comparing it to the electric load and deciding what to do with surplus power. After the simulation of year one, HOMER assumes that the key simulation results for that year are representative for every other year in the given project life time. It does not consider change over time, but the modeler can analyze these effects using the sensitivity analysis (Lambert et al. 2006).

The simulation process serves two purposes. First it considers if the system is feasible, given that it satisfies the demand and other constraints given by the user. Secondly, it estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its life time. The total net present cost (NPC) quantifies the life-cycle cost of the system. The NPC includes all costs and revenues that occur within the project lifetime (Lambert et al. 2006).

Optimization

The optimization process determines the best possible system configuration. This is by HOMER defined as the system that satisfies the user-specified constraints at the lowest NPC. In the optimization process many simulations are done with different system configurations, HOMER discards the infeasible ones and ranks the feasible ones by total NPC, where the one with the lowest NPC is presented as the optimal system configuration. The goal is to determine the optimal value for the decision variables that interest the modeler, like the size of PV array or the number of wind turbines (Lambert et al. 2006).

The user can either choose to let HOMER uses its optimizer tool and find the optimal size of the system or the user can enter a search space for the technologies. Regarding the size of the search space, HOMER gets a number of combinations. HOMER simulates all these combinations and gives out the most feasible ones and ranks them in a table sorted by NPC. The optimal results also allow the user to sort them by either technology, levelized cost of energy (LCOE) or what the user wants is to be ranked by. This makes it easy for the user itself to determine which one of the optimized results to use (Lambert et al. 2006).

Sensitivity analysis

In the sensitivity analysis HOMER performs multiple optimizations, each using a different set of input assumptions. The analysis reveals how sensitive the outputs are to changes in the input. This is a good way to deal with uncertainty. For instance, if the user suspects that the wind resource input contain uncertainty, the user can enter several values for the scaled average wind speed likely to cover the range, to see how these variations affect the output values. This can be useful to see different scenarios like at which electricity price or wind speed a wind turbine can compete with the other alternatives. (Lambert et al. 2006)

The relationship between simulation, optimization and sensitivity analysis are visually presented in Figure 2.10.

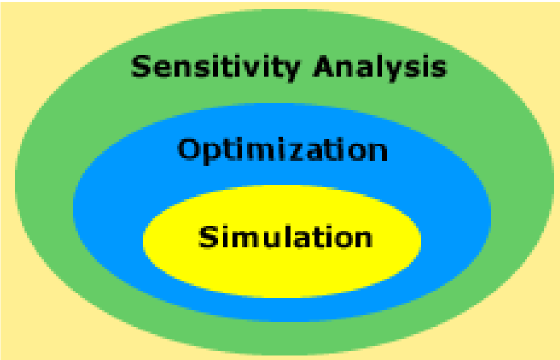

Figure 2.10: Visualization of the relationship between simulation, optimization and sensitivity analysis in HOMER (HOMER Energy 2017).

2.5 The hybrid energy system and technologies

Selection of the components used in the hybrid energy system are presented in Figure 2.11. The figure also represents the system boundary of this thesis. The main objective is to examine if the technologies put into the system can be feasible and used for households with fairly equal electrical consumptions as Grinder, around in Norway. The components in the system is solar PV, wind turbine, inverter, grid and the electric load.

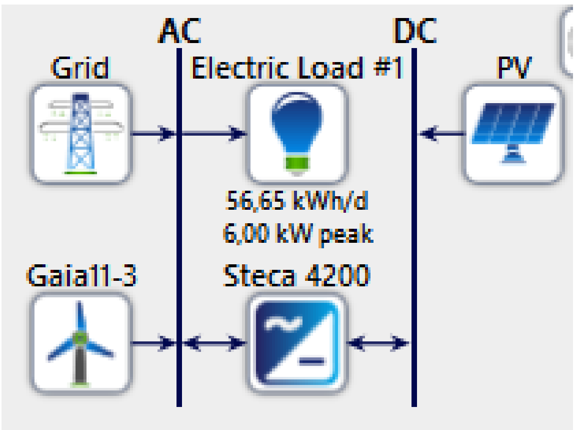

Figure 2.11: Visualization of the components in the HRES and the system boundary.

2.6 Technologies

Finding technologies available at the Norwegian market have been a priority. For solar PV and inverters, due to increased installed capacity the last years in Norway, have been easy to find. Since installed capacity in Norway for small scale wind turbines are low, it has been more difficult to find a wind turbine. After much research, the Gaia-Wind 133 seemed like a good match for locations with mid-range wind speeds. Since the wind turbine is designed in Denmark and have been produced for over 20 years it seemed like an appropriate choice.

2.6.1 Solar PV

The selected solar PV in this analysis is IBC Poly 270 CS4. It is a polycrystalline 270 W module with a rated efficiency of 16,2% (Solcellespesialisten 2018). The module has been chosen because it has the lowest cost per kWp installed and its relative high efficiency compared to the other Solar PV offered in the same price range at Solcellespesialisten (2018). It is also the currently bestseller. Module specification retrieved and used in the analysis is presented in the Table 2.5 while further details are provided in Appendix A. The operation and maintenance cost for the solar PV covers both the solar PV and the inverter based on Accenture and WWF (2016).

Table 2.5: Selected specifications for IBC Poly 270 CS4 and search space used in HOMER. The fractional values used in the search space is to optimize number of modules for each inverter.

Parameter	Value	Unit
Module technology	Polycrystalline solar cells	
Power, peak capacity	0,27	kWp
Efficiency	16,2	%
Lifetime	25	Years
Electrical bus	DC	
Non-temperature derating factor	80	%
Temperature coefficient	-0,36	%/°C
Nominal operating cell temperature (NOCT)	47	°C
Unit cost, incl.installation	4091	NOK
Operation and maintenance costs	29,7	NOK
Replacement cost	0	NOK
Search space	0 5,13 10,26	kWp

Power output

Equation 2.21 is used to calculate the power output of the solar PV (HOMER Energy 2017). It is a function of solar radiation and cell temperature.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right)\left[1 + \alpha_p\left(T_c - T_{c,STC}\right)\right] \quad 2.21$$

where: $Y_{pv}$is the rated capacity of the PV array under standard test conditions (kW), f_{pv} is the PV derating factor, $\bar{G}_T$ is the solar radiation incident on PV array in the current timestep (kW/m^2), $\bar{G}_{T,STC}$ is the incident radiation at standard test conditions (1kW/m^2), α_p is the temperature coefficient of power (%/°C), T_c is the PV cell temperature in the current timestep (°C) and $T_{c,STC}$ is the PV cell temperature under standard test conditions (25°C).

Derating factor is a scaling factor HOMER use to account for reduced power output in real-world operating conditions compared to standard test conditions (STC) which the solar PV was rated in (HOMER Energy 2017). Derating factor can be divided into temperature related factors and non-temperature related factors, overall derating factor are expressed by Equation 2.22.

$$f_d = f_{temp} * f_{non-temp} \qquad 2.22$$

When considering temperature related factors, cell temperature is calculated for the hourly ambient temperature and the radiation striking the PV array. Cell temperature for each timestep is calculated by HOMER using Equation 2.23 (HOMER Energy 2017).

$$T_c = \frac{T_a + (T_{c,NOCT} - T_{a,NOCT})\left(\frac{G_T}{G_{T,NOCT}}\right)[1 - \frac{\eta_{mp,STC}(1-\alpha_p T_{c,STC})}{\tau\alpha}}{1 + (T_{c,NOCT} - T_{a,NOCT})\left(\frac{G_T}{G_{T,NOCT}}\right)\left(\frac{\alpha_p \eta_{mp,STC}}{\tau\alpha}\right)} \qquad 2.23$$

where: T_a is the ambient temperature (°C), $T_{c,NOCT}$ is the nominal operating cell temperature (°C), $T_{a,NOCT}$ is the ambient temperature where NOCT is defined (20°C), $G_{T,NOCT}$ is the solar radiation where NOCT is defined (0,8kW/m^2), $\eta_{mp,STC}$ is the maximum power point efficiency under STC (%), a_p is the temperature coefficient of power (%/°C), $T_{c,STC}$ is the cell temperature under STC (25°C), τ is the solar transmittance of any cover over the PV array (%) and α is the solar absorptance of the PV array (%).

HOMER assumes a factor of 0,9 for τα according to Duffie and Beckman (2013). Another assumption is that the PV array always is at its maximum power point which means it assumes that the cell efficiency is always equal to the maximum power point efficiency.

For the non-temperature relating factor the default value of 0,8 in HOMER has been used. The non-temperature relating factor takes into account factors as soiling, wiring losses, shading, aging and so on (HOMER Energy 2017).

Costs

The cost of buying and installing a solar PV system are mainly divided into module cost, inverter cost and installation cost. To make the solar PV system most viable as possible per kWp installed, the search space has been set to the cheapest price per kWp installed for the inverter. The chosen inverter has a recommended maximum AC power of 5,2 kWp, which gives the lowest price per kWp installed.

Figure 2.12 shows the cost distribution for 1 kWp installed of the solar PV system which are based on Accenture and WWF (2016).

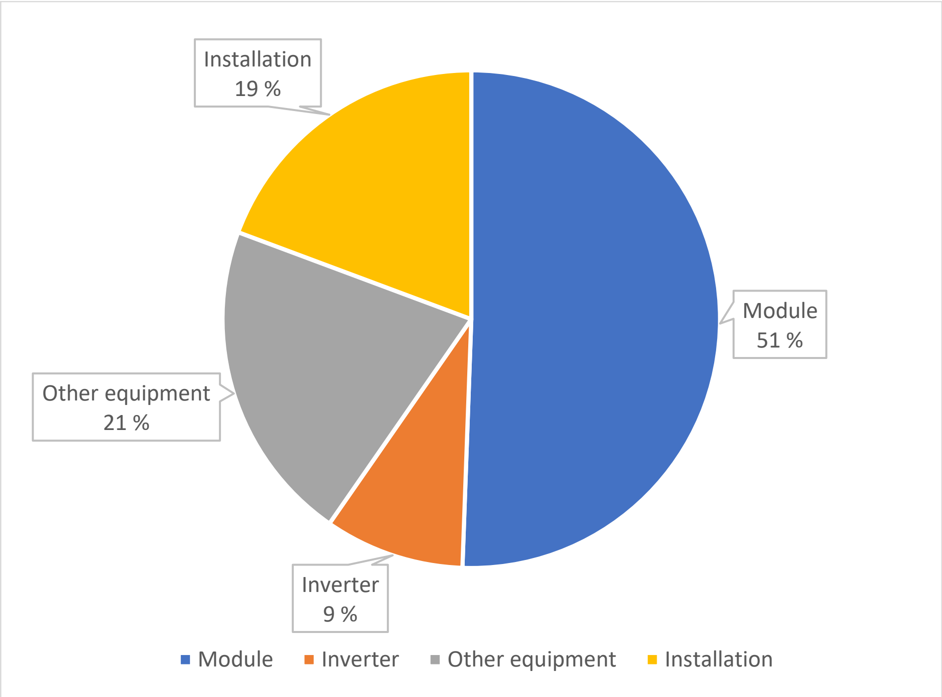

Figure 2.12: Cost distribution for buying and installing Solar PV based on number from Accenture and WWF (2016).

Interpreted from the Figure 2.12, installation and other equipment stands for 40% of the total costs of the system. These are average prices per kWp installed for solar PV system below 10 kWp. The installation and other equipment costs has been kept fixed, while the module and inverter costs has been changed according to the prices collected from Solcellespesialisten (2018). The inverter cost is shown in the Figure 2.12 and Figure 2.13, but is kept separate in this thesis and in the simulations in HOMER software. This gives us the cost distribution in Figure 2.13 based on prices retrieved from Solcellespesialisten (2018).

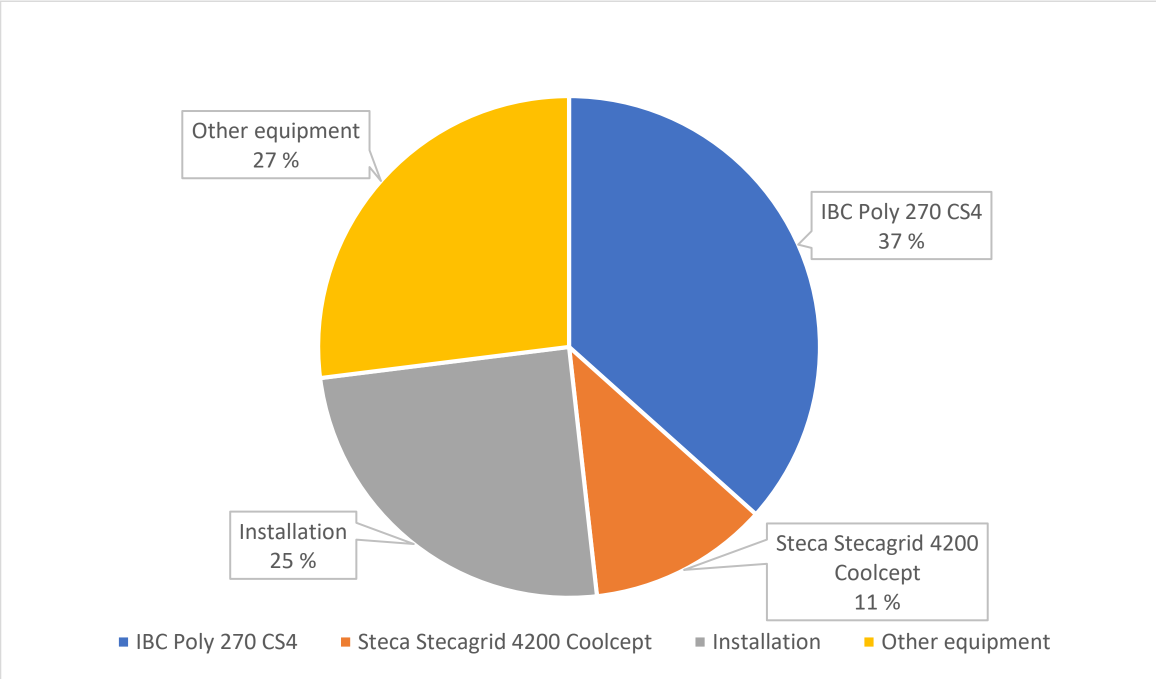

Figure 2.13: Cost distribution for buying and installing Solar PV. "Other equipment" and "installation" are kept as fixed values from Figure 2.12, while prices for the solar PV and the inverter are retrieved from Solcellespesialisten (2018).

The investment cost of the solar PV module is set to be 6278 kr/kWp incl. value added tax (VAT). The installation and other equipment cost is set to be respectively 4250 kr/kWp and 4625 kr/kWp. Final investment cost for solar PV without funding and inverter cost is presented in Equation 2.22:

$$C_{PV} = C_{module} + C_{installation} + C_{other\ equipment} = 15\ 153\,\frac{kr}{kWp} \qquad 2.22$$

2.6.2 Inverter

The chosen inverter in this thesis is the Steca Stecagrid 4200 Coolcept. The inverter is chosen from a selection at Solcellespesialisten (2018). The most emphasized criteria when choosing the inverter was a size that gives a low unit cost per kWp installed. Since the average size of a solar PV system in Norway is 4 kW (Accenture & WWF 2016), the chosen inverter size is most likely a representative size. The search space has been adjusted according to this inverter size to get the lowest cost per installed kWp.

Table 2.6 presents the specifications and search space for the inverter used in HOMER. The warranty for the inverter is 7 years, but according to Solcelleguiden (2016) approximately lifetime for an inverter is 15 years. The European efficiency in Table 2.6 is used in the analysis, further details are provided in Appendix B.

Table 2.6: Selected specifications for Steca Stecagrid 4200 Coolcept with search space used in HOMER. The fractional values used in the search space is to optimize the number of modules for each inverter.

Inverter specifications	Value	Unit
Power peak capacity	5,2	kWp
Lifetime	15	Years
Maximum efficiency	98,6	%
European efficiency	98,2	%
Phases	1	#
Capital cost	1988	NOK/kWp
Replacement cost (2018-price)	1988	NOK/kWp
Search space	0 5,13 10,26	kWp

2.6.3 Wind turbine

The chosen wind turbine in this thesis is the Gaia-Wind 133 11kW. The turbine is designed in Denmark and manufactured in Scotland, and can show for a long track record of reliability. It operates and performs good under moderate wind speed areas which makes the wind turbine very well suited for farms and households. Along the coast in Norway the wind speeds are all over good, but in more inland locations the wind speed varies much and are often too low to see any large wind farm projects being realized. These places are where it is interesting to see if the Gaia-Wind 133 can be viable compared to more coastal areas.

Retrieving information about price from manufacturer has not been successful, so the prices for the wind turbine project has been based on sources like newspaper articles in Denmark where farmers have installed the Gaia-Wind 133 and listed the price (Tønnesen 2014), (Jensen 2013), (Frandsen 2014) and cost estimates from The Renewable Energy Hub (Unknown) and Natural Energy (2017). The cost used in this thesis have therefore been an average cost retrieved from these newspaper articles and some other rough cost estimates found. This gives an investment cost of 600 000 NOK.

The specifications used for the wind turbine is shown in Table 2.7, while further details are provided in Appendix C. The wind turbine has a design lifetime of 20 years, but it has been assumed that it last for 25 years in this thesis.

Table 2.7: Selected specifications for Gaia-Wind 133 with search space used in HOMER.

Wind turbine specifications	Value	Unit
Power peak capacity	11	kWp
Lifetime	25	Years
Hub height	18	Meters
Rotor diameter	13	Meters
Capital cost	600 000	NOK
Replacement cost	0	NOK
Operation and maintenance	7000	NOK/year
Search space	0	kWp
	11	

Power output

The power curve is a graphical presentation of how large the predicted electrical power output will be for the wind turbine with a given wind speed at hub height. Startup speed for the wind turbine is at 2,5 m/s, the turbine blades will then start rotating, but it is not rotating enough to produce electricity. At 3,5 m/s the wind turbine reaches the cut-in speed and starts producing electricity. As the wind speed increases the power output increases rapidly because of the impact of the velocity in the wind as explained in Equation 2.23. At wind speed of 9,5 m/s the wind turbine reaches it rated capacity of 11 kW and cut-out speed is at 25 m/s even though it stops producing energy at 19,5 m/s. The power curve is presented in Figure 2.14.

$$P_{wind} = \frac{1}{2} p v^3 \pi r^2 \qquad 2.23$$

where: P_{wind} is the power of the wind (W), p is the density of air (1,225 kg/m^3 at STC), v is the velocity of the wind (m/s) and r is the radius of the rotor (m).

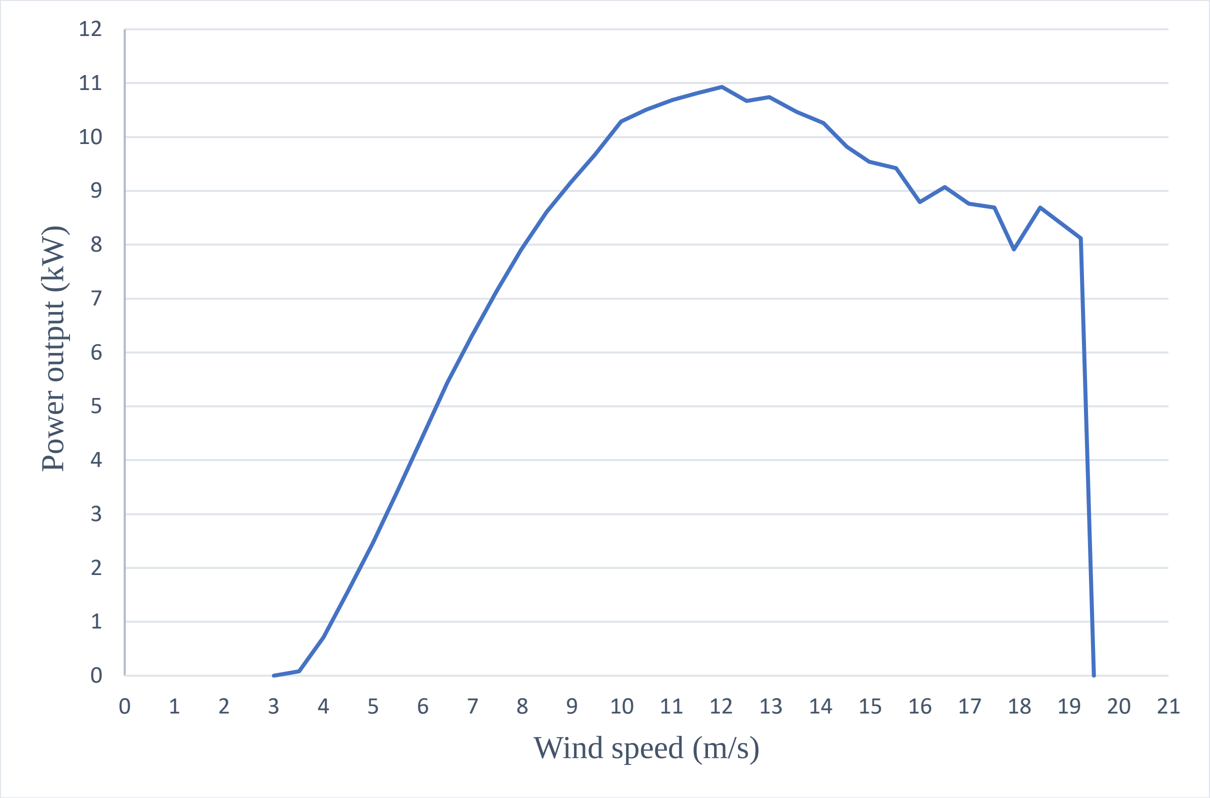

Figure 2.14: Power curve for Gaia-Wind 133.

As for the solar PV, the power curve specifies the wind turbines performance under standard test conditions. To adjust temperature and pressure to actual conditions, the predicted power value from the power curve is multiplied with the air density ratio according to Equation 2.24 (HOMER Energy 2017).

$$P_{WTG} = \left(\frac{p}{p_0}\right) P_{WTG,STC} \qquad 2.24$$

where: P_{WTG} is the wind turbine power output (kW), $P_{WTG,STC}$ is the wind turbine power output at standard test conditions (kW), p is the actual air density (kg/m^3) and p_0 is the air density at standard test conditions (1,225 kg/m^3).

Costs

Due to poor results in retrieving prices from manufacturer, Figure 2.15 is based on Natural Energy (2017). The turbine and tower stands for almost the entire investment costs. Some of the installation and groundworks can be done on its own to save some in the costs, but it will not have much of an impact on the total investment costs. Operation and maintenance cost is approximately 7000 NOK/year.

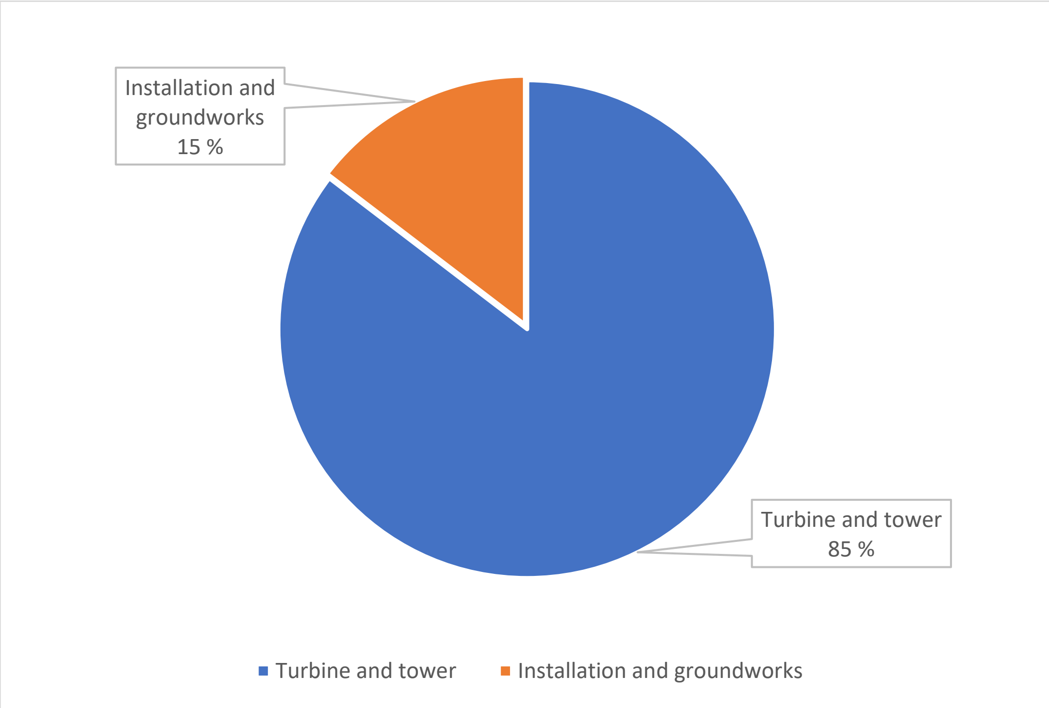

Figure 2.15: Cost distribution for the wind turbine.

2.7 Grid

The Norwegian power market got liberalized in 1991. From then everyone has been able to choose their own power supplier and the power market got exposed for competition. The Norwegian power market can be divided into the wholesale market and the retail market. In the wholesale market the producers and supplier's trades power between each other and on the power exchange, Nord Pool Spot. In the retail market regular consumers buys power from the suppliers which compete between each other (Fornybar.no 2018).

Consumers pays for the electricity to two different actors, to the grid supplier and the power supplier. Payment to the grid supplier is for the transportation of the electricity on the grid to the location where it is consumed, while the payment to the power supplier is for the actual consumption of electricity. The prices used in this thesis are the spot prices. Spot prices are set by the market and are determined of demand and supply. The marketplace for power in the Norwegian market is Nord Pool Spot. Nord Pool Spot is one of the best working power markets in the world and is often used as a reference for other power markets around the world (Fornybar.no 2018).

The Norwegian power market is divided into 5 different regions and are presented in Figure 2.16. The system price in the market is calculated under the assumption that there are no transmission limitations. Due to bottlenecks in the system, the regional prices can differ. For each selected location analyzed in this thesis, the regional prices have been used (Fornybar.no 2018).

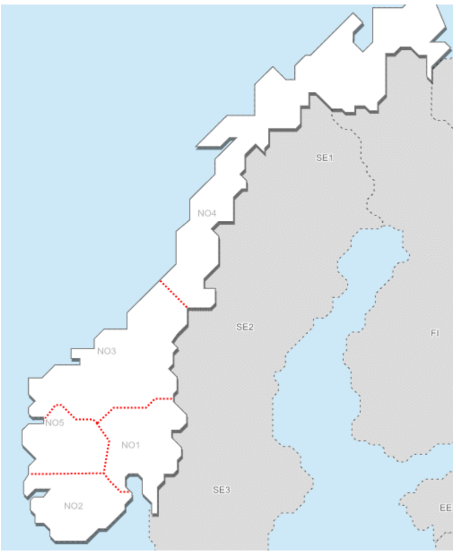

Figure 2.16: Visualization of the 5 different regions of the Norwegian power market. Figure is retrieved from Statnett (2016).

Hourly values for the spot prices from the years 2013 to 2017 have been collected from Nord Pool Spot (Nord Pool 2018) and are given in NOK/MWh. Since HOMER requires the input data to be NOK/kWh the spot prices have been changed correspondingly. The hourly spot prices from the years 2013 to 2017 have been used to calculate an average hourly spot price for a year which is used in HOMER. Hourly prices for the year used in HOMER and for each relevant region is presented in Figure 2.17. The spot prices retrieved from Nord Pool Spot are exclusive VAT, so the prices have been multiplied with 25% to include VAT (Skatteetaten 2018). In addition, it is usual that the power suppliers add on a small fee on top of the spot price to cover their costs as operating as a power supplier, in this thesis 0,025 NOK/kWh are used (TrønderEnergi 2018).

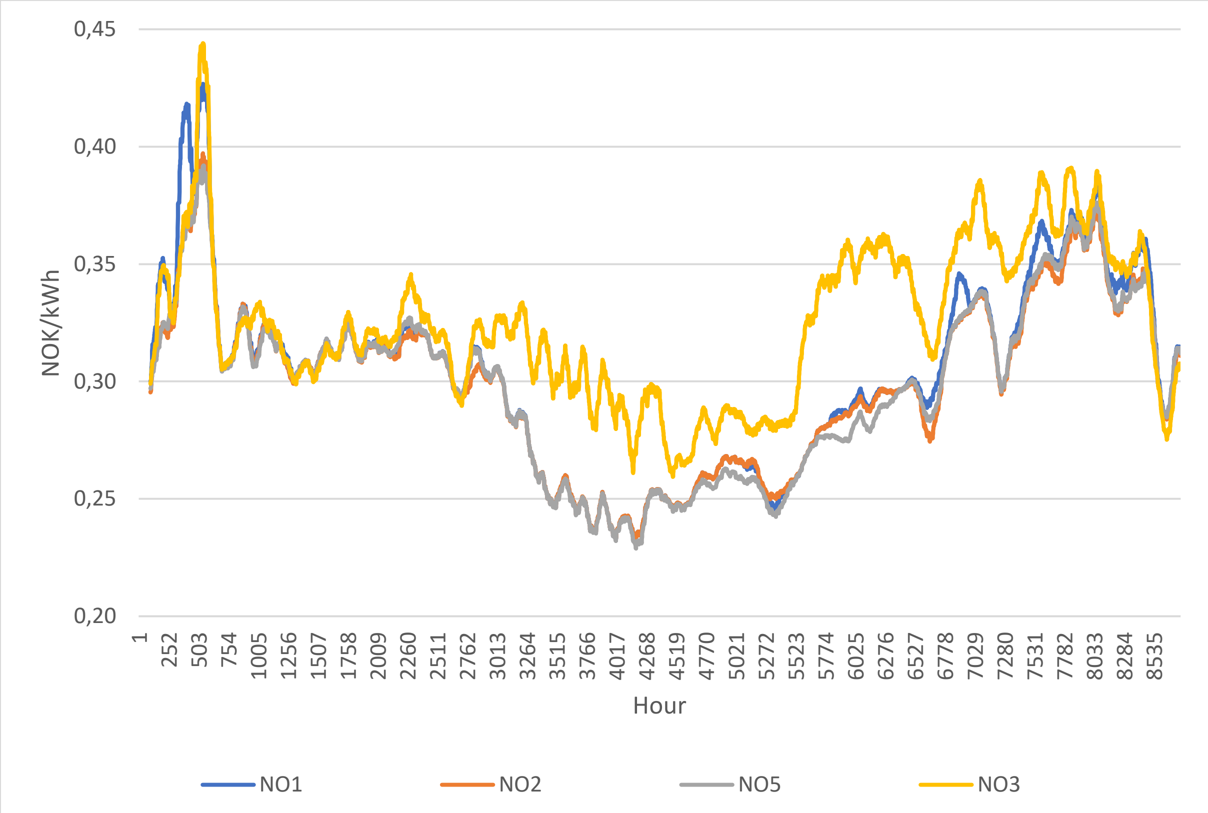

Figure 2.17: Average spot prices from Nord Pool spot inclusive VAT. The lines in the figure are trend lines with moving averages for a period of 100 hours.

Grid tariff are meant to cover the grid suppliers cost of transport of electricity, secure effective operation, exploitation and development of the grid. The grid supplier sets the price for themselves, but Norges Vassdrags- og Energidirektorat (NVE) controls that the fee is not higher than what the grid suppliers are allowed to charge the consumers.

Grid tariff are collected from the years 2013 to 2017 for each relevant region (Norges vassdrags- og energidirektorat 2015). The grid tariff is given in annually values and like the spot prices the grid prices have been calculated to an average value to be used as input value in HOMER. Table 2.8 presents the grid tariff, where both VAT and electricity consumption tax are included. Electricity consumption tax is collected from the grid suppliers on the behalf of Skattedirektoratet (Skattedirektoratet 2018) and is adjusted annually.

Table 2.8: Annually grid tariff for each of the selected locations from 2013 to 2017 with average used in this thesis, prices in NOK/kWh.

Location	2013	2014	2015	2016	2017	Average
Grinder	0,519	0,526	0,526	0,507	0,506	0,517
Trondheim	0,444	0,514	0,529	0,503	0,507	0,499
Bergen	0,428	0,437	0,427	0,428	0,489	0,442
Stavanger	0,403	0,403	0,428	0,493	0,529	0,451
Kristiansand	0,533	0,527	0,536	0,528	0,576	0,540

Since 2012 Norway has been a part of a joint el-certificate market with Sweden. The intention with this market is to increase power production from new renewable energy sources with 28,4 TWh by the end of 2020. Power producers that are certified receives one el-certificate per MWh produced for the next 15 years after they have been approved. This is an extra income for the producers on top of the power price to make projects more profitable. For the consumers this means a small fee on every kWh consumed. The average annually el-certificate prices/kWh for the consumer, incl. VAT is 0,025 NOK/kWh for the years 2012 to 2017 (Norges vassdrags- og energidirektorat 2014).

In total, the annual average grid power price for the selected locations are given in Figure 2.18. These prices include all the parts mentioned above; spot prices, grid tariff, electricity consumption tax and el-certificate prices, incl. VAT.

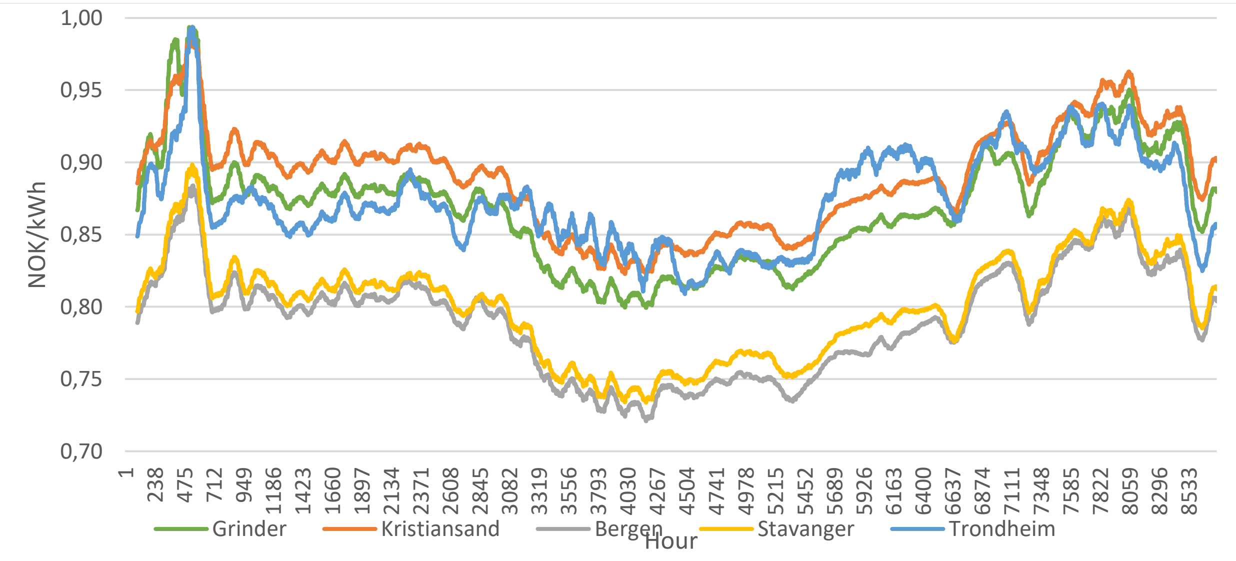

Figure 2.18: Average grid prices used as input value in HOMER for each selected location. The lines in the figure are trend lines with moving averages for a period of 100 hours.

Grid sellback rate

In general, the grid sellback rate is lower than the total grid price. The grid sellback rate is equal to the regional spot prices at the current timestep of the production and some power suppliers gives a small sum for marginal loss on the transmission line. To sell back surplus power a deal must be done with your power supplier. When this deal is done you are called a "plusskunde".

There are also three companies that offers a way better deal for the surplus electricity than the regular power suppliers. Two of them, Fredrikstad EnergiSalg and Otovo offers 1 NOK/kWh for up to 5000 kWh per year, if these 5000 kWh are exceeded you receive the respectively spot prices for the surplus electricity for the rest of the year. Otovo is referred to further in this thesis.

Since HOMER does not allow the user to add different payments for the grid sellback like Otovo offers, a simplification has been made. When the simulations have been run, the value of the Otovo sellback rate have been calculated manually. This has been done according to Equation 2.25.

$$Sellback = (1\ NOK - average\ spot\ price) * surplus\ electricity\ up\ to\ 5000\ kWh \quad 2.25$$

The amount of sellback has been multiplied for the project life time and discounted. The amount during the project lifetime has been subtracted from the NPC to show the new NPC and used to calculate a new LCOE.

2.8 Economics

The economical outputs from HOMER are NPC and LCOE. NPC are the main metric used to rank the different system configurations between each other. The total NPC includes all costs and revenues during the lifetime, and represent them in one sum in today's value. Future cash flows are discounted back to present value by using the discount rate. With NPC, costs are a positive value, while revenue are negative value. This is opposite from net present value (NPV), but apart from the sign, it is the same. For each component HOMER combines the capital, replacement, maintenance and fuel costs, along with salvage cost and any other revenue, to find the annualized cost. This is a hypothetical annualized cost. If it had occurred each year of the project lifetime it would yield a net present cost equivalent to that of all individual costs and revenues associated with that component over the project lifetime.

HOMER summarize the annualized cost of each component to find the total annualized cost of the system. This value is important in order for HOMER to calculate to calculate the two principal economic figures of merit for the system; the levelized cost of energy and net present cost. Equation 2.26 is used to calculate the total net present cost (Lambert et al. 2006).

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i,R_{proj})} \qquad 2.26$$

where: $C_{ann,tot}$ is the total annualized cost, I is the annual real discount rate, R_{proj} is the project lifetime and CRF is the capital recovery factor. CRF is given by Equation 2.27.

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad 2.27$$

where: N is the number of years.

To calculate LCOE Equation 2.28 is used.

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \qquad 2.28$$

where: E_{prim} is the total amount primary load, E_{def} is the total amount deferrable load and $E_{grid,sales}$ is the amount of energy sold to the grid per year.

Rates

The real discount rate is used to convert between one-time costs and annualized costs. Inflation is factored out of the economic analysis this way, and all costs are real costs. HOMER use the real discount rate to calculate the NPC. The real discount rate is given by Equation 2.29. Inflation rate in this thesis is set to 2,5% according to the inflation goal of Norges bank (2018). The nominal discount rate should reflect the alternative value for the investment, which depend on if the capital is received through a loan or what discount rate you would get if the capital were invested in bank savings or stocks. The nominal discount rate has been set to 4,5% based on the interest rate from Eika Spar (Grue Sparebank 2018) for the last three years.

$$i = \frac{i' - f}{1 + f} \qquad 2.29$$

Where: i’ is the nominal discount rate and f is the expected inflation rate.

Subsidies

ENOVA offers an investment subsidy for those who choose to produce their own electricity at home. They cover 35% of documented total investment cost incl. VAT up to 10 000 NOK for the power system and an extra 1250 NOK for each kW installed effect up to 15 kW. In total, if you for instance install a 15kW solar PV system the total subsidy you receive is 28 750 NOK (Enova 2016).

El-certificates

As mentioned in the section about the grid, Norway is part of the el-certificate market with Sweden. This means all renewable power producers can apply to receive el-certificates. All new power plants based on renewable sources or existing power plants with lasting increase with construction start after 8.9.2009 have the rights to receive el-certificates. New hydropower plants with construction start after 1.1.2004 also have rights to receive el-certificates. This includes small scale producers as well (Elsertifikatloven §8).

When the requirements for the power plant (Elsertifikatloven §9) and requirements for documentation of construction start (Elsertifikatloven §10) are met, the producer has rights to receive el-certificates for 15 years (Elsertifikatloven §12). The power suppliers are obliged to buy a certain amount of el-certificates and they distribute it further to the consumers (Elsertifikatloven §§17-18).

When applying for el-certificates, you agree a onetime fee if the application is approved. For small scale producers with an installed effect less than 100 kW, this fee is at 15 000 NOK (Norges vassdrags- og energidirektorat 2012). In this thesis it will be most applicable for the system configurations where the wind turbine is included because of its high production rate.

The historical price development for el-certificates are shown in Figure 2.19. The average price since the start in 2012 to 2017 are 137,8 NOK/MWh. A significantly reduction by the end of 2016 that lasted through 2017 have made it difficult to use an overall average price for future scenarios. The average price for 2017 was 63,2 NOK/MWh (Svensk Kraftmäkling 2018a).

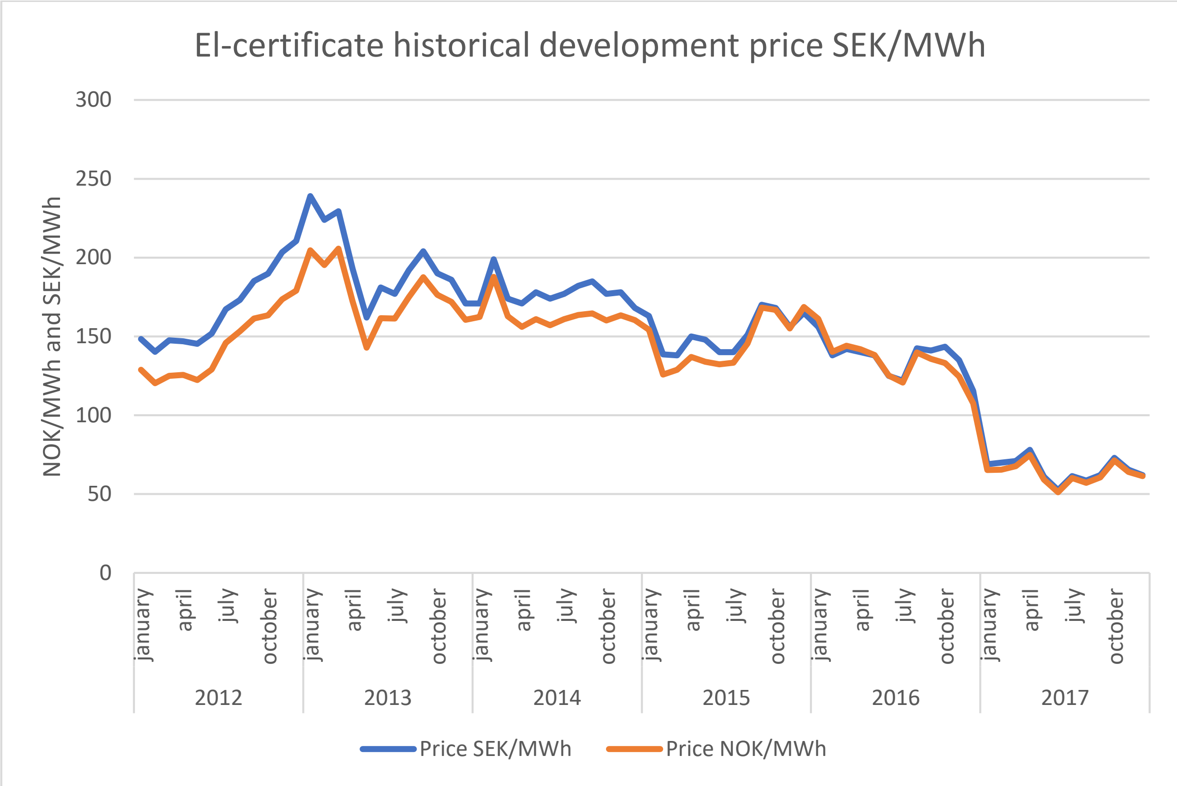

Figure 2.19: Historical price development in the el-certificate market since 2012 in NOK and SEK. The historical prices have been collected from (Svensk Kraftmäkling 2018a) and been adjusted with historical monthly currencies from (OFX 2018).

The price is set by supply and demand. The supply is driven by new installment of renewable energy and the new production, while the demand is driven by requirements for quota duties. Power suppliers are required to purchase a certain amount based on their delivered amount of energy to the consumers (Elsertifikatloven §17). The price is therefore difficult to predict, but in general the prices will be at its highest around 2020, and steadily decrease by the end of the el-certificate market in 2035.

Given that one 11 kW wind turbine and 5,13 kW solar PV are in the system, this will in average for the selected locations produce 591 MWh of electricity through the 15 years they receive el-certificates. This will require an average el-certificate price of 25 NOK/MWh to break-even with the fee of 15 000 NOK.

Based on “Ask-price” from (Svensk Kraftmäkling 2018b) for March 2022 and March 2023 this price is 41,4 NOK/MWh.

Future grid prices

As mentioned in the introduction, large investments in the grid, building of new transmission lines to Europe and the emissions trading system could make significantly impact on the grid prices.

Based on reports from Reiten et al. (2014) and Statnett (2015), Otovo (2017) estimates that the increase in grid prices will increase with 4% each year for the next 10 years, the energy prices could also be increase with 4% each year towards 2030, and historically the consumption tax on electricity has increased with 5% each year. Based on these estimates, an assumption of 4,4% increase for the next 25 years has been made. This assumption might not be realistic because they are based on a high price scenario from the reports, and it is difficult to predict so far into the future. However, it is still interesting to see how the feasibility of the hybrid system would be affected by these changes. Figure 2.20 presents the increase in grid prices for the selected locations for the next 25 years. Grinder, Trondheim and Kristiansand have the highest grid prices and are close to each other, while Bergen and Stavanger have the lowest grid prices.

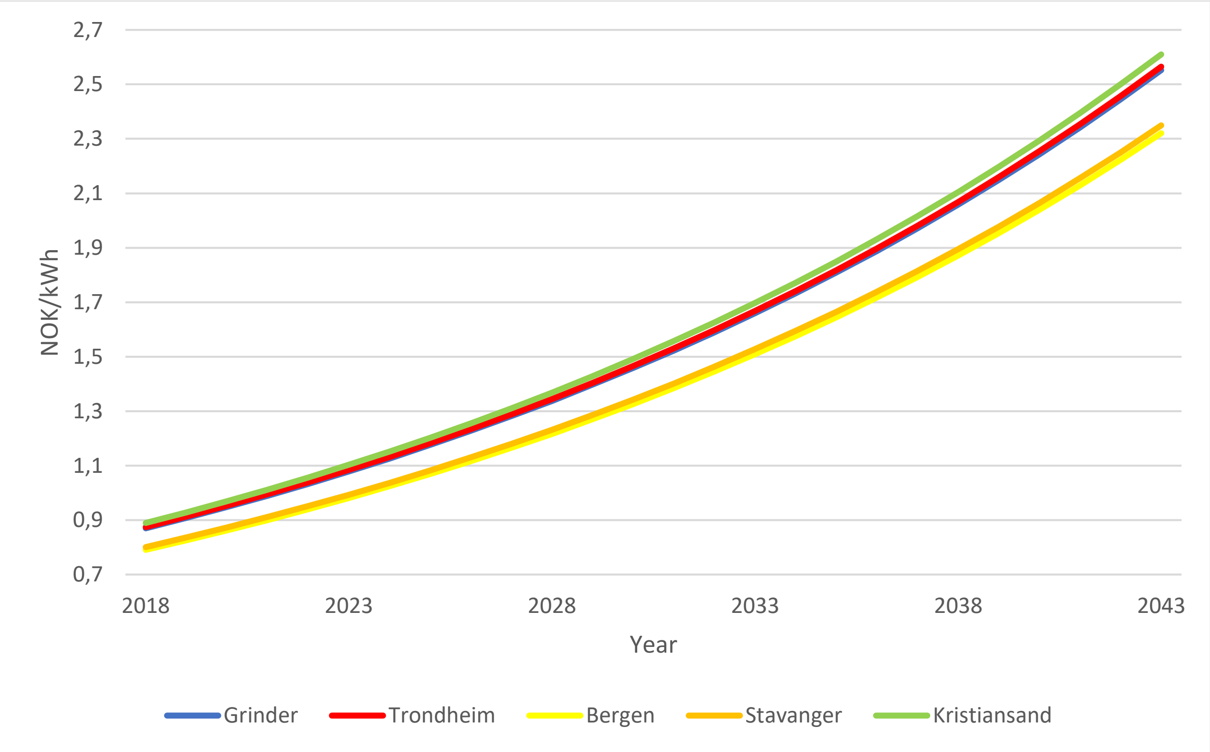

Figure 2.20: Development of today's grid prices for the selected locations with a annually 4,4% increase towards 2043.

HOMER uses the multiyear module to calculate the 4,4% annually increase in grid rates, but it does not allow the user to increase the sellback rates the same way. Since the grid rates includes the spot prices which is the sellback rate, it would be fair to assume that the sellback rate would increase with the same annual percentage as the grid rate. To include this increase in sellback rate as well, a simplification has been made. The same increase has been calculated for the sellback rate, and the average of the sellback rate during the project lifetime have been set as fixed for the entire project lifetime. Figure 2.21 presents the increase in sellback rate for the next 25 years. Kristiansand and Stavanger belong to the same price area, so they have the same line, Bergen is almost equal and lay above the line for Kristiansand and Stavanger in the figure.

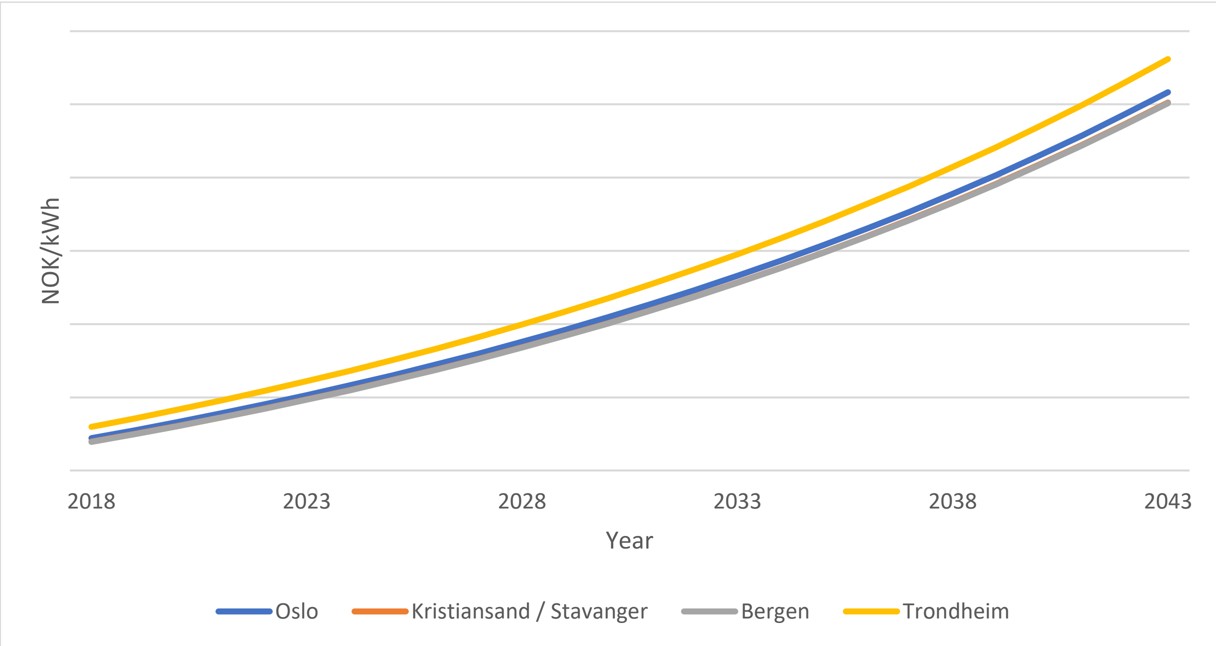

Figure 2.21: Development of the sellback rate for each of the selected location with a 4,4% increase for the next 25 years. Kristiansand and Stavanger belong to the same price area and therefore have the same line.

2.9 Sensitivity variables

Many sensitivity variables have been added into HOMER, but only the most interesting variables has been used to see how much each variable will influence the total NPC and LCOE. Adding sensitivity variables is a good way to deal with uncertainties. The sensitivity analysis will only be conducted for Kristiansand which is the location with variable values closest to the average overall. The change in variables have been set to 60% in order to cover all the selected locations.

All the sensitivity variables are presented in Table 2.9.

Table 2.9: All sensitivity variables used in the sensitivity analysis with increase and decrease in percentage.

Change	%	%	%
PV cost multiplier	- 60	0	+ 60
PV lifetime	- 60	0	+ 60
Wind turbine cost multiplier	- 60	0	+ 60
Wind turbine lifetime	- 60	0	+ 60
Solar scaled average	- 60	0	+ 60
Wind speed scaled average	- 60	0	+ 60

3 Results

In this chapter the results for each selected location is presented. For each selected location, the categorized optimization results from HOMER presented with NPC and LCOE. The results also include the amount of each technology installed, how much each technology produces annually and amount of energy purchased and sold.

NPC and LCOE are presented graphically and with changes after including Enova subsidies, Otovo feed-in tariff and production subsidy from the el-certificate market for three different prices. As explained earlier these have been calculated manually since HOMER does not allow to have different inputs in the grid sellback rate. Results based on the assumption of increased future electricity price are also presented.

A sensitivity analysis is presented to show the influence on each input variable. The range of the sensitivity analysis includes all of the locations.

3.1 Grinder

The optimized results for Grinder presented in Table 3.1, shows that the Grid-only system have the lowest NPC and LCOE, while the Grid+PV is relative close in LCOE but has a slightly higher NPC. Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) have much higher NPC and LCOE due to too low wind speeds. The LCOE values are 0,862 kr/kWh, 0,9 kr/kWh, 1,45 kr/kWh, 1,41 kr/kWh and 1,35 kr/kWh respectively for Grid, Grid+PV, Grid+Wind, Grid+PV+Wind(1), and Grid+PV+Wind(2).

Table 3.1: Optimized results with NPC, LCOE, amount of energy purchased and sold for each system configuration for Grinder.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	4957	-	4957	9915
WT (kWh)	-	-	19726	19726	19726
Energy purchased	20679	17210	10887	9229	8668
Energy sold	0	1419	9934	13164	17490
NPC	350120	390306	873870	936311	1012178
LCOE	0,862	0,9	1,45	1,41	1,35

Figure 3.1 and Figure 3.2 presents the change in NPC and LCOE respectively, with the effect of financial support from Enova, Otovo and the el-certificate market. The column named "NPC all included" contains all the subsidies and feed-in tariffs, where the production subsidy for the el-certificate market is based on the average el-certificate price from 2012 to 2017.

With all subsidies included the Grid+PV system have more or less an identical NPC as the Grid-only system, but a lower LCOE. Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) have much higher NPC and LCOE than Grid-only and Grid+PV.

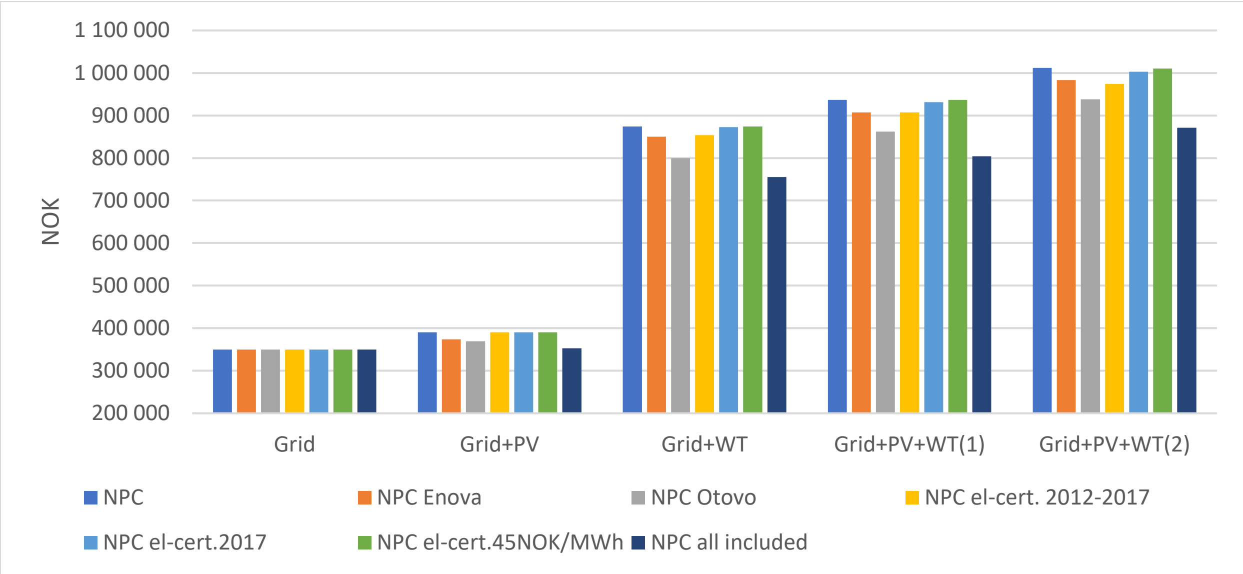

Figure 3.1: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on NPC for each system configuration for Grinder.

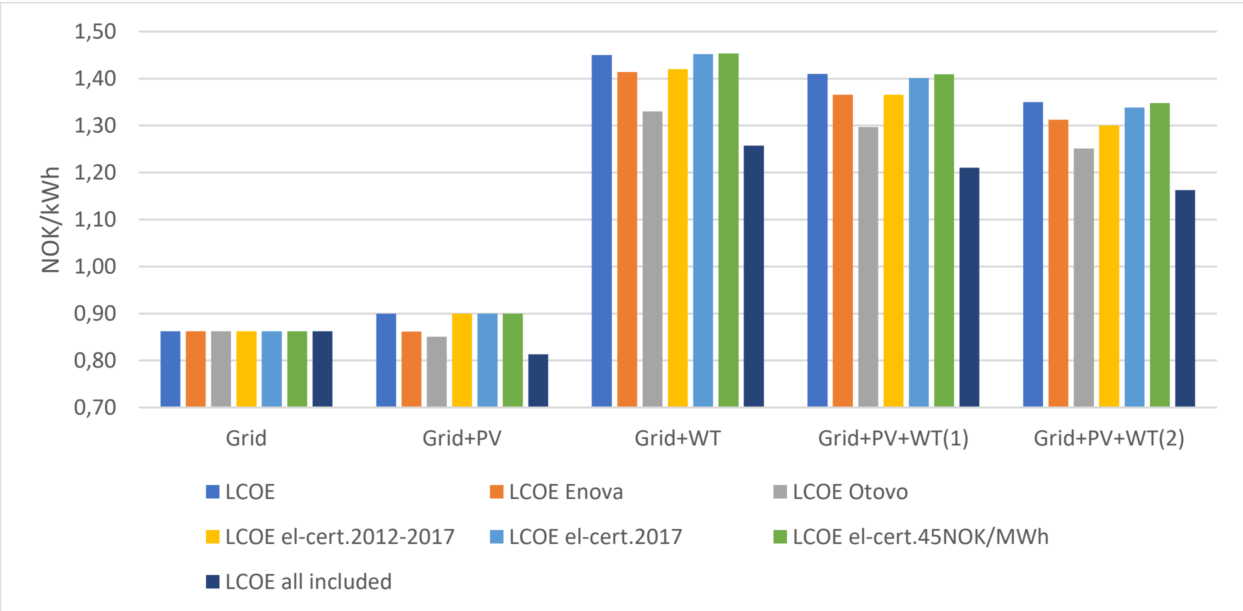

Figure 3.2: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on LCOE for each system configuration for Grinder.

Future grid prices

Optimized results with future prices are presented in Table 3.2. The Grid+PV system have the lowest NPC and LCOE. The gap in NPC and LCOE between the Grid-only system and the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) have been significantly reduces.

Table 3.2: Optimized results with NPC and LCOE included subsidies and feed-in tariffs, amount of energy purchased and sold for each system configuration for Grinder.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	4957	-	4957	9915
WT (kWh)	-	-	19726	19726	19726
Energy purchased	20679	17210	10887	9229	8668
Energy sold	0	1419	9934	13164	17490
NPC	595035	588118	966960	995878	1049102
LCOE	1,47	1,36	1,61	1,5	1,4
NPC all subsidies and feed-in tariff	595035	550590	848743	863850	908261
LCOE all subsidies and feed-in tariff	1,47	1,27	1,41	1,30	1,21

3.2 Trondheim

The optimized results for Trondheim are presented in Table 3.3. The Grid-only system has both the lowest NPC and LCOE.

Table 3.3: Optimized results with NPC, LCOE, amount of energy purchased and sold for each system configuration for Trondheim.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	4450	-	4450	8900
WT (kWh)	-	-	29228	29228	29228
Energy purchased	20679	17608	8158	7005	6597
Energy sold	0	1317	16708	19942	23923
NPC	348599	394792	792732	861997	940234
LCOE	0,859	0,914	1,08	1,08	1,07

Figure 3.3 and Figure 3.4 presents the change in NPC and LCOE respectively, with the effect of financial support from Enova, Otovo and the el-certificate market. With all these applied, the Grid+PV system is closer to the NPC of the Grid-only system, but it is still higher. The financial support manages to get a slightly lower LCOE.

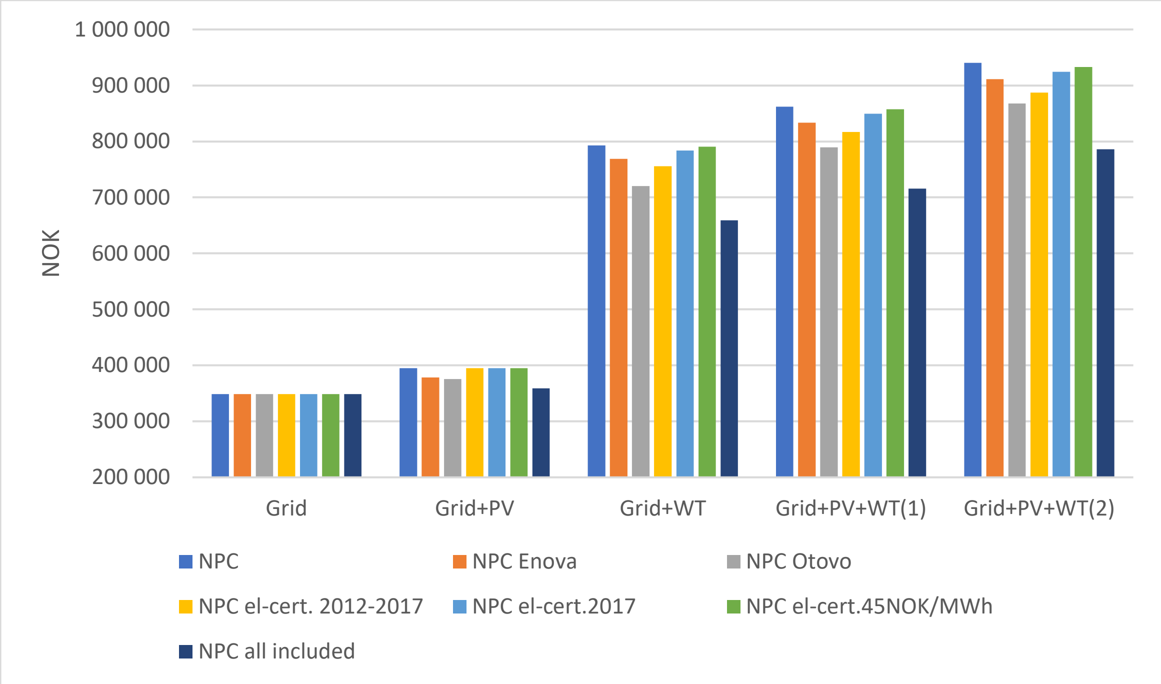

Figure 3.3: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on NPC for each system configuration for Trondheim.

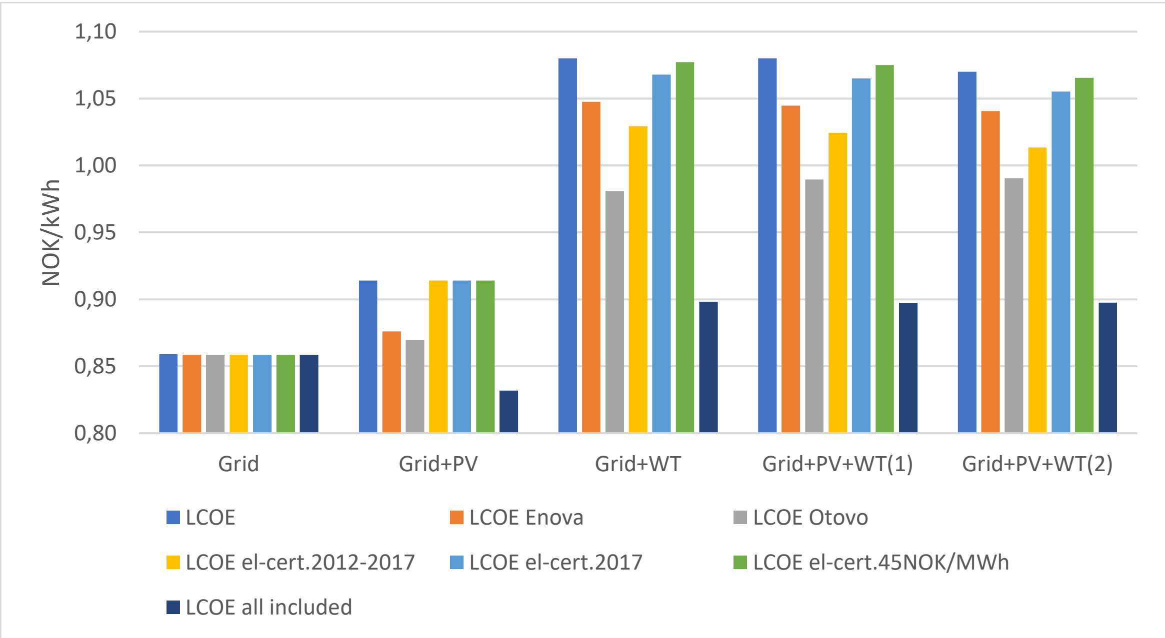

Figure 3.4: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on LCOE for each system configuration for Trondheim.

Future grid price

Optimized results with future prices are presented in Table 3.4. The Grid-only system still have the lowest NPC, but only marginally compared to Grid+PV. The Grid-only system now has the highest LCOE.

Table 3.4: Optimized results with NPC and LCOE included subsidies and feed-in tariff, amount of energy purchased and sold for each system configuration for Trondheim.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	4450	-	4450	8900
WT (kWh)	-	-	29228	29228	29228
Energy purchased	20679	17608	8158	7005	6597
Energy sold	0	1317	16708	19942	23923
NPC	597994	602242	823579	866090	923492
LCOE	1,47	1,39	1,12	1,09	1,05
NPC all subsidies and feed-in tariff	597994	566681	690179	719780	769272
LCOE all subsidies and feed-in tariff	1,47	1,31	0,94	0,90	0,88

3.3 Bergen

The optimized results for Bergen are presented in Table 3.5. The Grid-only system have the lowest NPC, but the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) have lower LCOE. Although, these systems have a much higher NPC.

Table 3.5: Optimized results with NPC, LCOE, amount of energy purchased and sold for each system configuration for Bergen.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	4595	-	4595	9190
WT (kWh)	-	-	42737	42737	42737
Energy purchased	20679	17487	5479	4764	4505
Energy sold	0	1338	27537	31352	35624
NPC	318550	368779	694322	771234	853070
LCOE	0,785	0,853	0,733	0,755	0,772

Figure 3.5 and Figure 3.6 presents the change in NPC and LCOE respectively, with the effect of financial support from Enova, Otovo and the el-certificate market. Even with a high reduction in NPC with all the financial support, the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) still have a much higher NPC. Financial support makes the LCOE for these systems even lower compared to the Grid-only solution in the optimized results.

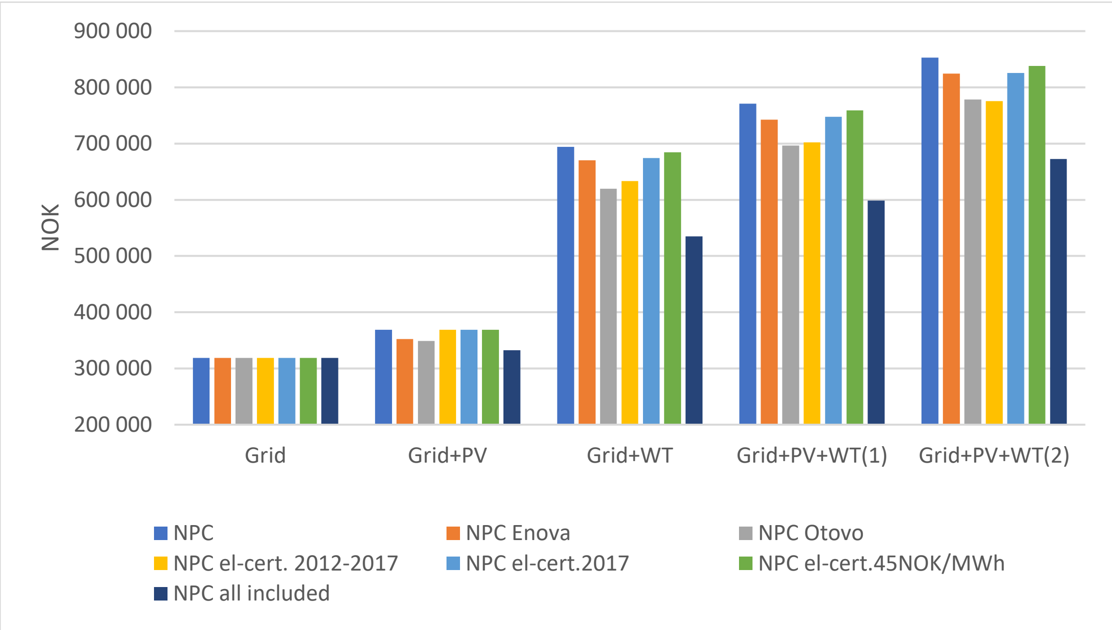

Figure 3.5: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on NPC for each system configuration for Bergen.

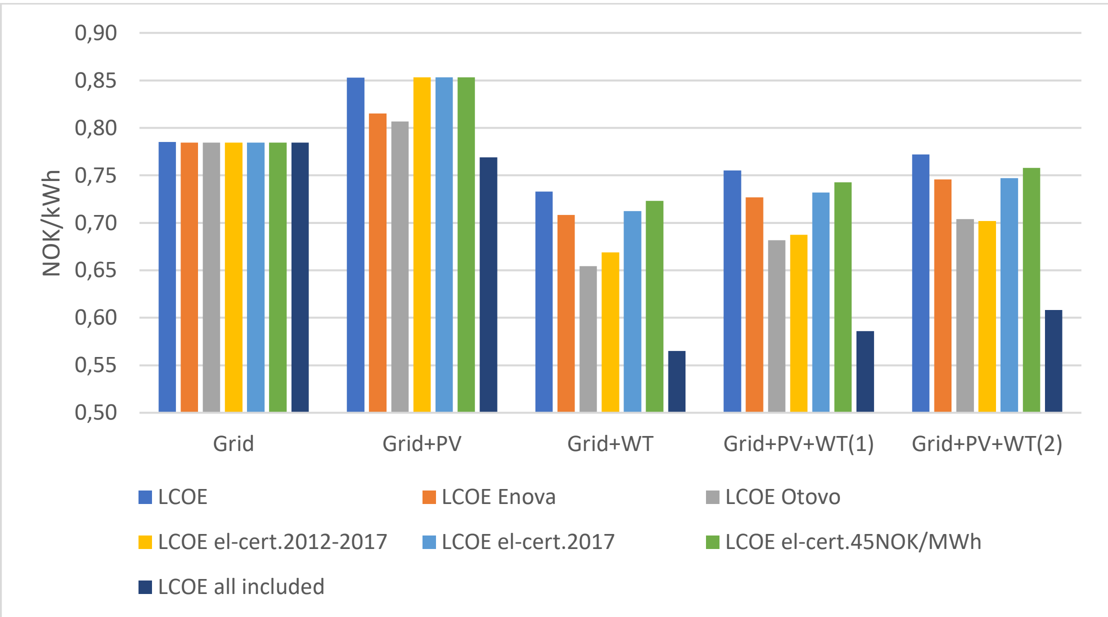

Figure 3.6: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on LCOE for each system configuration for Bergen.

Future grid price

Optimized results with future grid prices are presented in Table 3.6. The Grid-only still has the lowest NPC, but now it has the highest LCOE compared to all the other systems.

Table 3.6: Optimized results with NPC and LCOE included subsidies and feed-in tariff, amount of energy purchased and sold for each system configuration for Bergen.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(1)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	4595	-	4595	9190
WT (kWh)	-	-	42737	42737	42737
Energy purchased	20679	17487	5479	4764	4505
Energy sold	0	1338	27537	31352	35624
NPC	540983	551286	653423	708074	770903
LCOE	1,33	1,28	0,69	0,693	0,697
NPC all subsidies and feed-in tariff	540983	514880	493993	535476	590137
LCOE all subsidies and feed-in tariff	1,33	1,19	0,52	0,52	0,53

3.4 Stavanger

Optimized results for Stavanger are presented in Table 3.7. The Grid-only system have the lowest NPC, but the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) have lower LCOE than the Grid-only system. The Grid+WT system have the lowest LCOE of all, due to good wind resources.

Table 3.7: Optimized results with NPC, LCOE, amount of energy purchased and sold for each system configuration for Stavanger.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	5024	-	5024	10048
WT (kWh)	-	-	45182	45182	45182
Energy purchased	20679	17193	5304	4656	4423
Energy sold	0	1468	29807	34113	38833
NPC	322157	366671	680963	756580	836696
LCOE	0,793	0,843	0,687	0,703	0,716

Figure 3.7 and Figure 3.8 presents the change in respectively NPC and LCOE with the effect of financial support from Enova, Otovo and the el-certificate market. The Grid+PV system have almost the same NPC as the Grid-only system, but have a slightly lower LCOE. The systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) still have a significantly higher NPC, but the LCOE is lower than for Grid-only with each of the financial supports separated and together.

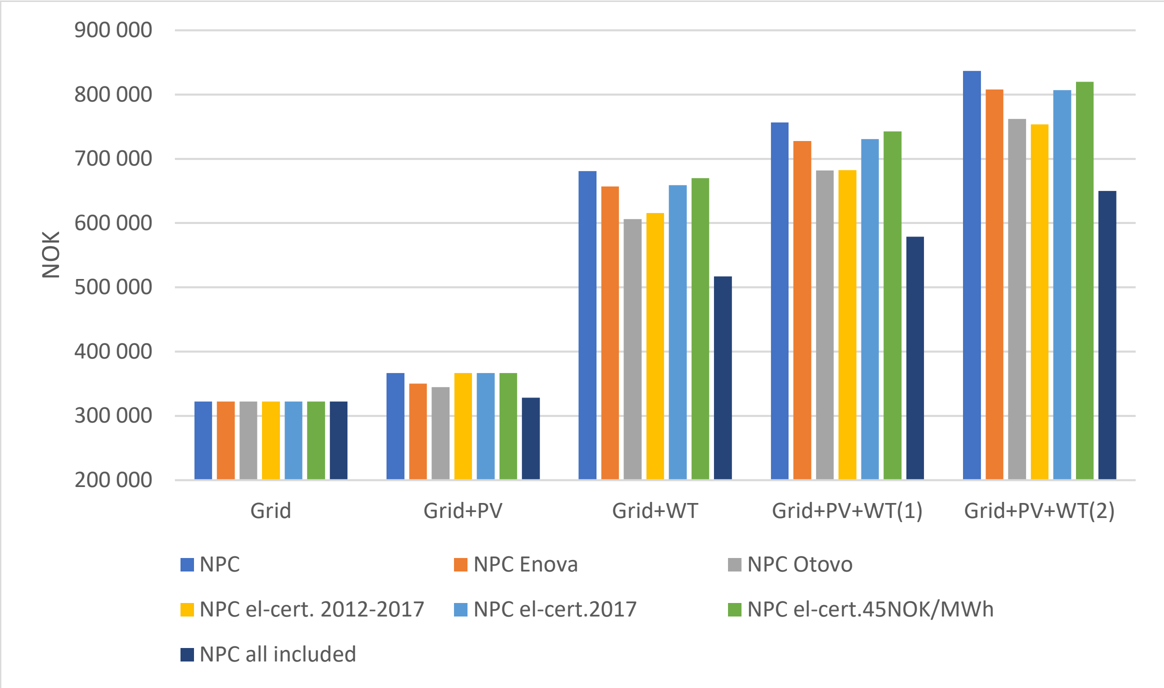

Figure 3.7: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on NPC for each system configuration for Stavanger.

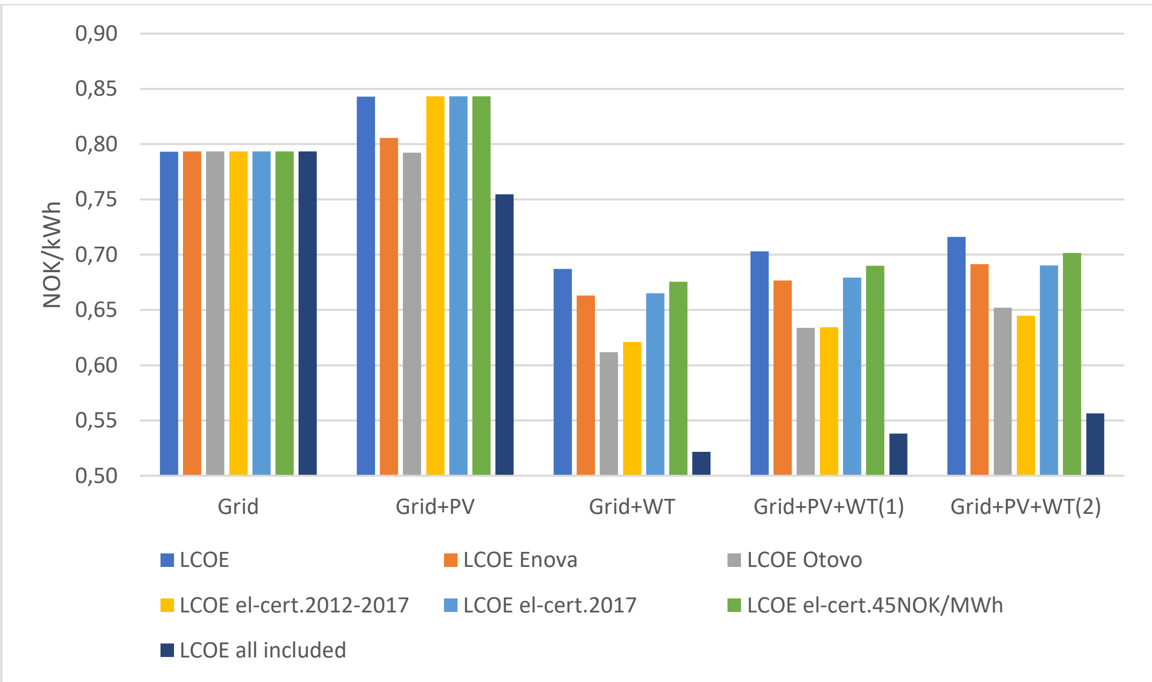

Figure 3.8: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on LCOE for each system configuration for Stavanger.

Future grid price

Optimized results with future prices are presented in Table 3.8. The Grid-only still has the lowest NPC, but only marginally compared to the Grid+PV system. Grid-only has the highest LCOE.

Table 3.8: Optimized results with NPC and LCOE included subsidies and feed-in tariff, amount of energy purchased and sold for each system configuration for Stavanger.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	5024	-	5024	10048
WT (kWh)	-	-	45182	45182	45182
Energy purchased	20679	17193	5304	4656	4423
Energy sold	0	1468	29807	34113	38833
NPC	547276	547759	631411	683551	743222
LCOE	1,35	1,26	0,637	0,635	0,636
NPC all subsidies and feed-in tariff	547276	509226	467667	505877	556618
LCOE all subsidies and feed-in tariff	1,35	1,17	0,47	0,47	0,48

3.5 Kristiansand

The optimized results for Kristiansand are presented in Table 3.9. The Grid-only system have both the lowest NPC and LCOE.

Table 3.9: Optimized results with NPC, LCOE, amount of energy purchased and sold for each system configuration for Kristiansand.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	5111	-	5111	10222
WT (kWh)	-	-	35435	35435	35435
Energy purchased	20679	17120	7062	6100	5779
Energy sold	0	1481	21819	25896	30615
NPC	357310	394456	756826	826957	905156
LCOE	0,88	0,907	0,907	0,904	0,899

Figure 3.9 and Figure 3.10 presents the change in NPC and LCOE respectively, with the effect of financial support from Enova, Otovo and the el-certificate market. With all the subsidies included the Grid+PV system have both a lower NPC and LCOE. The systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) have lower LCOE than Grid-only and Grid+PV, but also a significantly higher NPC.

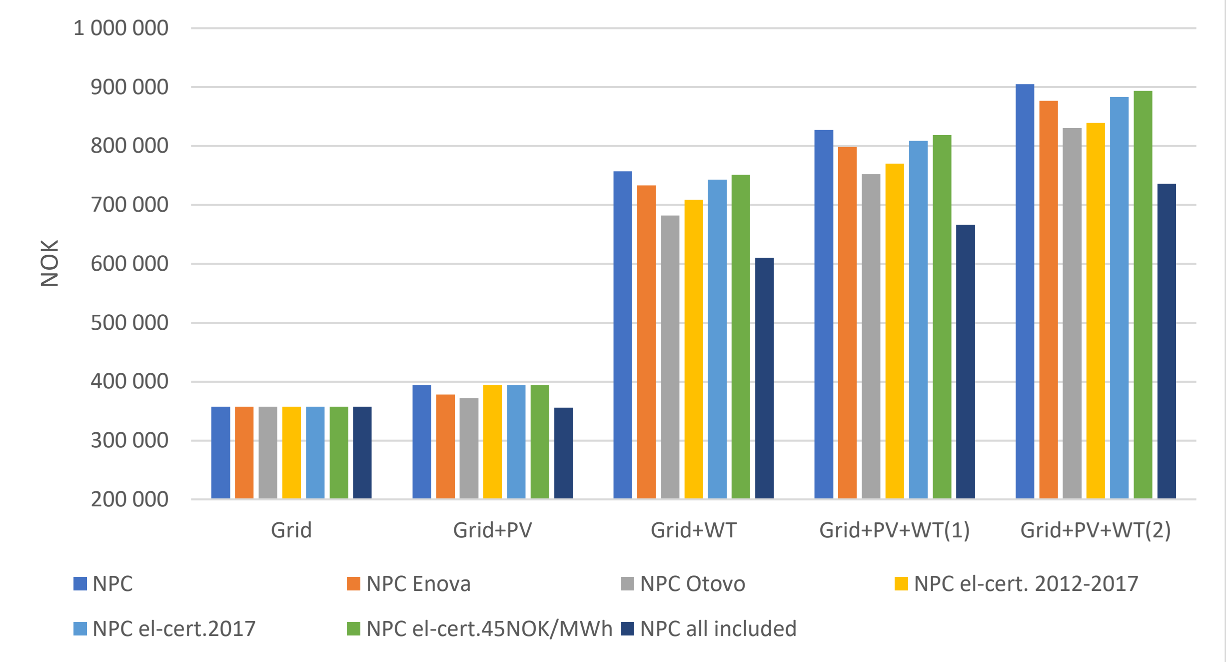

Figure 3.9: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on NPC for each system configuration for Kristiansand.

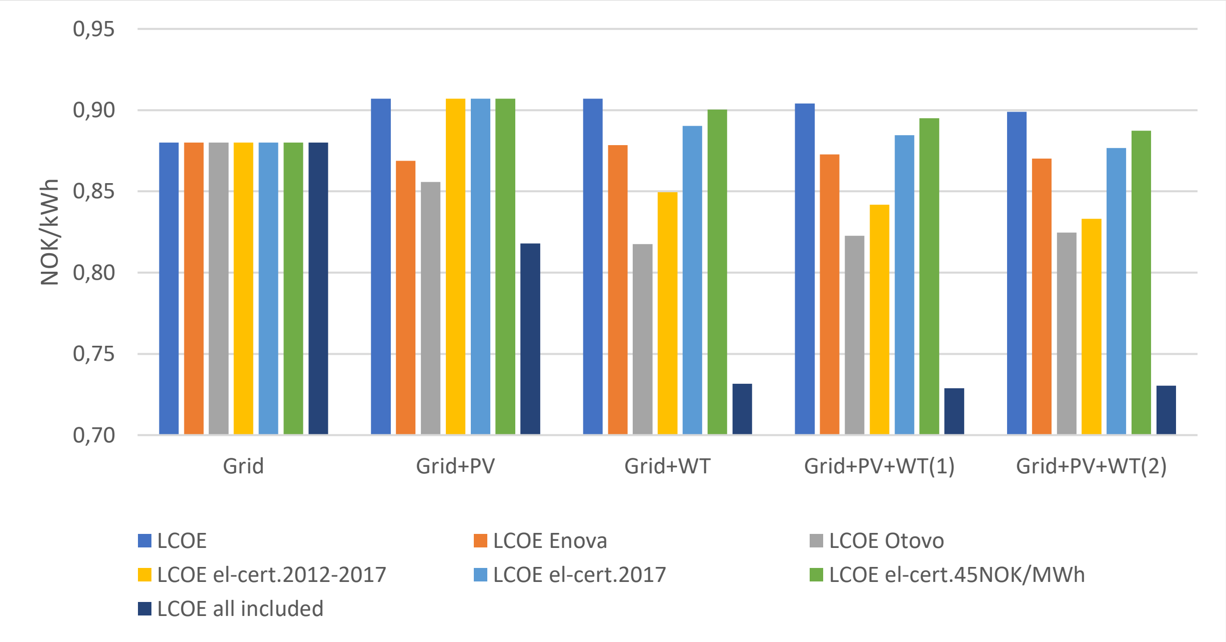

Figure 3.10: Effect of Enova subsidy, feed-in tariff from Otovo and three different production subsidies for el-certificates on LCOE for each system configuration for Kristiansand.

Future grid price

Optimized results with future grid prices are presented in Table 3.10. Grid+PV has the lowest NPC and lower LCOE compared to the Grid-only system, but compared to the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) it has a higher LCOE.

Table 3.10: Optimized results with NPC and LCOE included subsidies and feed-in tariff, amount of energy purchased and sold for each system configuration for Kristiansand.

System	Grid	Grid+PV	Grid+WT	Grid+PV+WT(1)	Grid+PV+WT(2)
PV(kW)	-	5,13	-	5,13	10,26
WT (kW)	-	-	11	11	11
Inverter (kW)	-	5,2	-	5,2	10,4
PV(kWh)	-	5111	-	5111	10222
WT (kWh)	-	-	35435	35435	35435
Energy purchased	20679	17120	7062	6100	5779
Energy sold	0	1481	21819	25896	30615
NPC	608480	596384	764888	807733	864159
LCOE	1,5	1,37	0,917	0,883	0,858
NPC all subsidies and feed-in tariff	608480	557851	618470	647230	694571
LCOE all subsidies and feed-in tariff	1,50	1,28	0,74	0,71	0,69

3.6 Sensitivity analysis

The sensitivity analysis presents the effect of a change in each variable on both NPC and LCOE for the systems Grid+PV and Grid+PV+WT(1). The change in NPC and LCOE for Grid+PV is presented respectively in Figure 3.11 and Figure 3.12, and the change in NPC and LCOE for Grid+PV+WT(1) is presented respectively in Figure 3.13 and 3.14.

For Grid+PV, naturally the variables which makes an impact on the NPC and LCOE are the variables related to the solar PV. Furthermore, on the opposite the variables related to the solar PV have almost none significance for NPC and LCOE for Grid+PV+WT(1) even though solar PV is included. Since the wind turbine have much larger investment costs, an increase or decrease in variables relate to the wind turbine have much more significant effect on NPC and LCOE.

Grid+PV

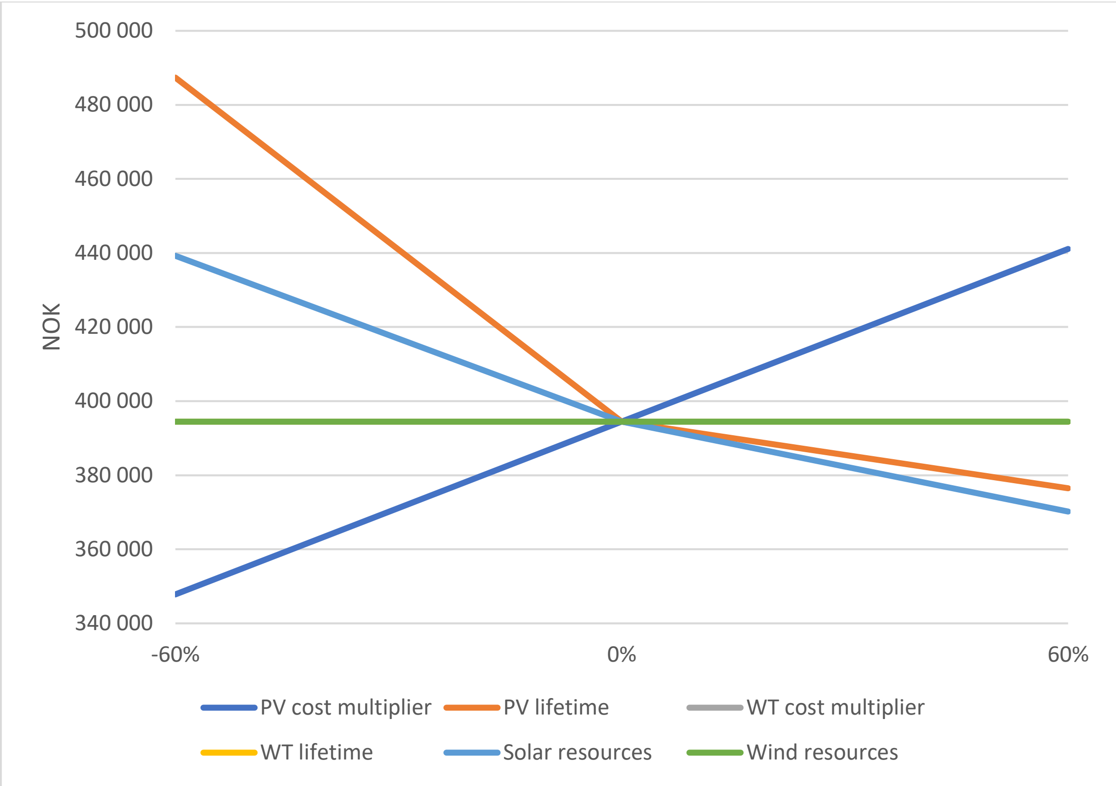

Figure 3.11: Illustrates the effect on NPC with change in the sensitivity variables.

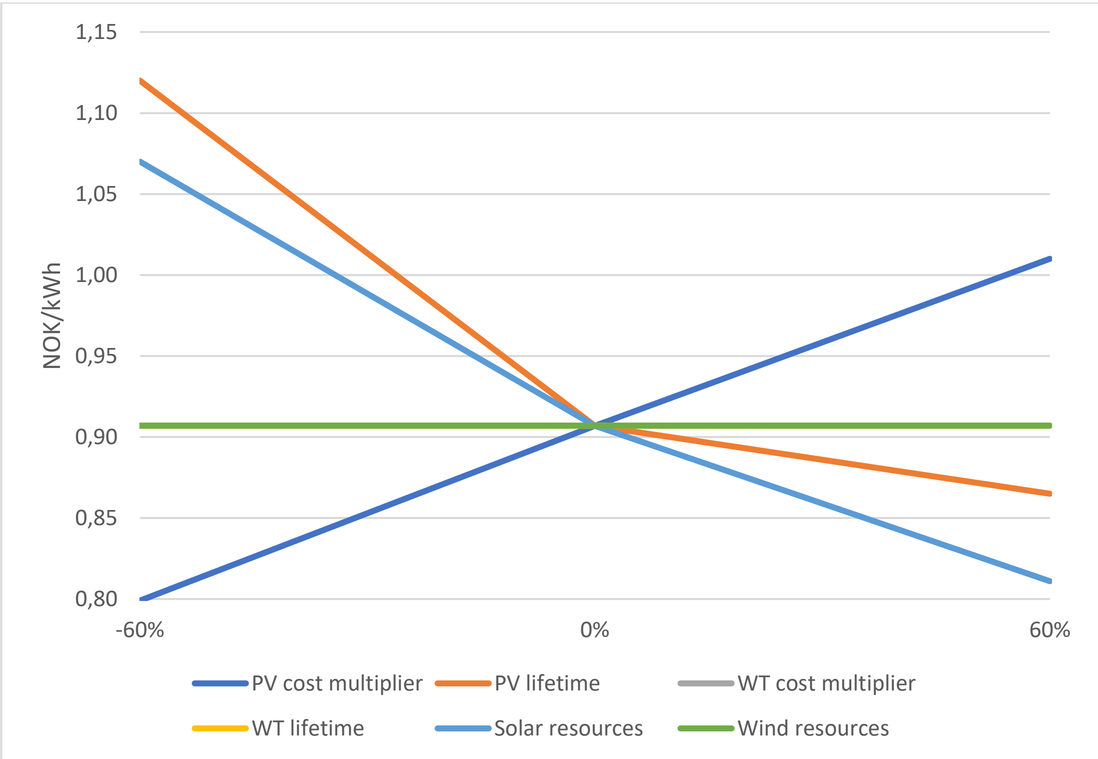

Figure 3.12: Illustrates the effect on LCOE with change in the sensitivity variables.

Grid+PV+WT(1)

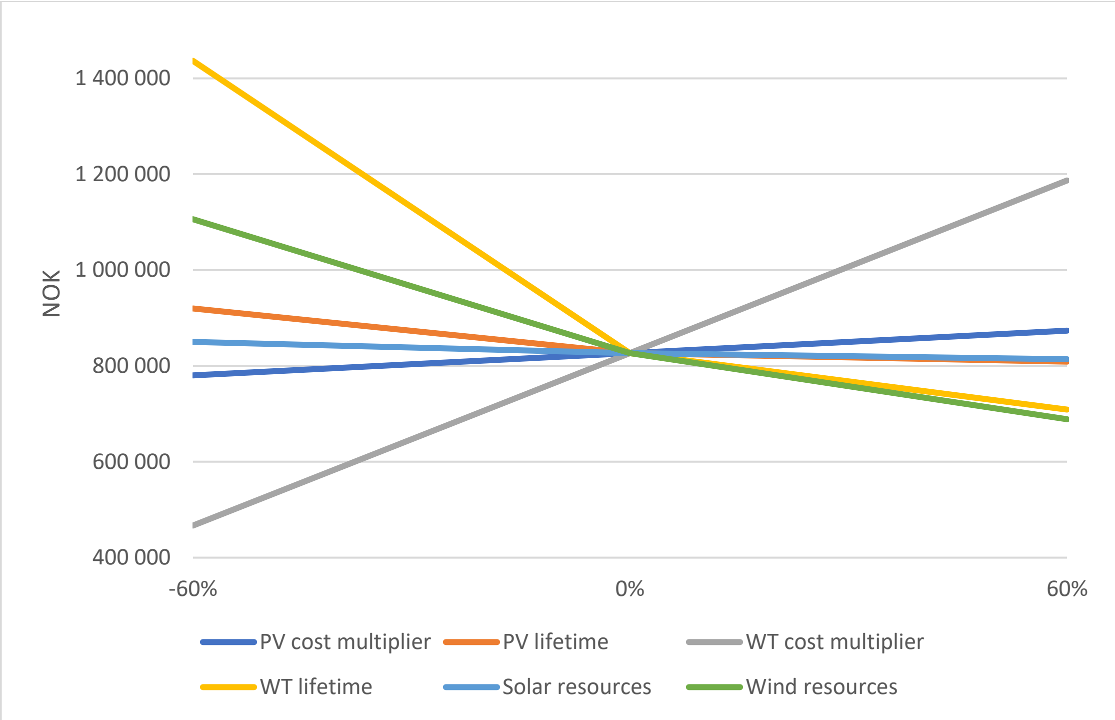

Figure 3.13: Illustrates the effect on NPC with change in the sensitivity variables.

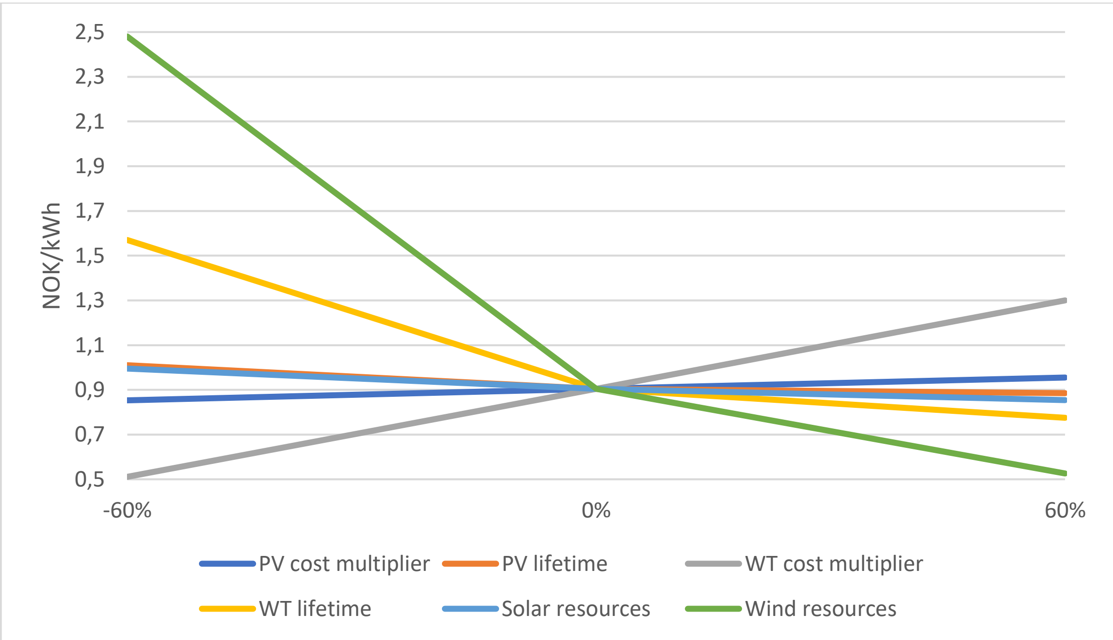

Figure 3.14: Illustrates the effect on LCOE with change in the sensitivity variables.

4 Discussion

4.1 Optimization results

For all the locations studied in this thesis the Grid-only system have the lowest NPC. This is supported by (Dalton et al. 2009). They conducted a feasibility analysis of renewable energy supply options for a grid-connected hotel in Australia. For the base scenario, the Grid-only configuration was the most profitable solution, but when future prices were considered, the optimal system configuration shifted into Grid+WT.

However, for some of the locations, some or all the other system configurations have lower LCOE than the Grid-only system. For Bergen and Stavanger which are the windiest locations, the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) returns a lower LCOE than grid. Notwithstanding, because of the high installation costs for the wind turbine and low sellback rate, the NPC is much higher and may not be viable compared to the Grid-only system. Based on the LCOE, Table 4.1 presents the summary of optimal energy systems for the selected locations. From chapter 2.3.2, Grinder and Trondheim had the lowest wind energy resources, and as shown in Table 4.1, the wind turbine is not included in any of the two best ranked system configurations. Bergen and Stavanger had the highest wind energy resources and the ranked number one system is Grid+WT. From chapter 2.3.1 Kristiansand had the highest solar energy resources, but the ranked number 1 system in Table 4.1 is still Grid-only. The ranked number two system Grid+PV+WT(2) for Kristiansand reflects the good solar energy resources and relatively high wind energy resources. The solar energy resources had not high enough impact to get a lower LCOE than Grid-only.

Table 4.1: Summary of the optimal energy system based on LCOE.

Location	Ranked 1 system	Ranked 2 system
Grinder	Grid-only	Grid+PV
Trondheim	Grid-only	Grid+PV
Bergen	Grid+WT	Grid+PV+WT (1)
Stavanger	Grid+WT	Grid+PV+WT (1)
Kristiansand	Grid-only	Grid+PV+WT (2)

Furthermore, for the windiest locations the wind turbine produced a substantial amount of surplus energy. To achieve a relatively lower NPC for this system, it would require either higher sellback rate or co-investment between two or more neighbours or higher energy demand as assumed in this thesis. A co-investment or higher demand would cause more of the energy to be utilized, instead of large amount surplus energy would be sold to at low sellback rate.

4.2 Comparison of the selected locations

For the system Grid-only and Grid+PV, the optimized results look almost the same for all the selected locations, where the difference is mostly based on different grid prices. Kristiansand is slightly better than the other selected locations for the Grid+PV system, due to better sun locations. Even though, none of the Grid+PV systems returns lower NPC or LCOE than the Grid-only system.

When comparing the three last systems, Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) there are significant differences in their LCOE. Since the wind resources varies more than the solar resources, the optimized results also vary more, which is supported by (Rehman et al. 2012). They conducted a feasibility study for a hybrid energy system consisting of a wind turbine, solar PV and diesel generator for a village in Saudi Arabia. When they conducted a sensitivity analysis on solar and wind, the system was most affected by the wind resource.

Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) for both Stavanger and Bergen returns lower LCOE than the Grid-only system, but the NPC costs are much higher. For the other selected locations, both NPC and LCOE are higher than the Grid-only system.

4.3 Effect of financial support

4.3.1 Enova subsidy

For Grinder and Trondheim, the subsidies received from Enova had a small impact on NPC for the Grid+PV system, and made the gap from Grid-only a bit smaller. The subsidy made the LCOE for Grid+PV decrease to the same level as for Grid-only for Grinder, but it is still higher for Trondheim.

For Bergen and Stavanger, the subsidy decreases the gap a bit for the solar PV compared to Grid-only, but the Grid-only still has the lowest NPC. Basically, the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) have lower LCOE than the Grid-only, and the subsidy makes the difference in LCOE bigger.

For Kristiansand, due to the best solar resources in this analysis, is the location where the NPC for Grid+PV is closest to the Grid-only, and with this subsidy it gets a bit closer, but not enough. The subsidy makes the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) to get a lower LCOE than Grid-only, but NPC is still too high.

Türkay and Telli (2011) made an economic analysis for a standalone system and grid connected system in Turkey. The system configuration consisted of solar PV, wind turbine, fuel cell, hydrogen tank and electrolyzer. They analyzed the effect of component costs to the grid connected system, where they lowered the cost by 50%. This is a larger impact than the Enova subsidy makes on the Grid+PV system, and way higher impact than on the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2). Although, the effect of reducing the component costs is the same as the investment subsidy from Enova, and is therefore comparable. When looking at the 50% reduction in solar PV costs, this represent a 12,6% decrease in COE for the system in the article, while the Enova subsidy represent approximately 5% decrease in the LCOE for approximately a 20% reduction of the initial cost for the Grid+PV in this thesis.

4.3.2 Otovo feed-in tariff

The feed-in tariff from Otovo makes the same impact as the Enova subsidy. The feed-in tariff from Otovo is a bit more favorable than the Enova subsidy since the surplus power gets more income during the project lifetime than the Enova subsidy offers.

The optimized system configurations could have changed if HOMER allowed to differentiate the sellback rate. Since the sellback rate from Otovo is slightly higher than the grid prices, the Grid+PV system configuration could have been sized larger in order to get enough surplus to fill up the 5000 kWh/year from Otovo.

4.3.2 Production subsidy from the El-certificate market

The Grid+PV system does not get affected by the production subsidy from the el-certificate market. The production from the solar PV is too low to defend paying the entry fee to the el-certificate market.

For the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) the production subsidy from the el-certificate market only changes the NPC notably for the selected locations with relatively high wind speeds. Grinder with relatively low wind speeds only get a small improvement with the average el-certificate prices from 2012 to 2017, while the average prices of 2017 and 45 NOK/MWh used is not feasible.

Generally, for the other selected locations there is only a slightly difference with average prices for 2017 and the 45 NOK/MWh, while the average prices between 2012-2017 gives a larger difference in NPC and LCOE. This is less likely to happen based on 2017 average prices and ask price for the el-certificates for the next 5 years. The ask price for March 2023 is set at 41,4 NOK/MWh (Svensk Kraftmäkling 2018b).

For the feed-in tariffs from Otovo and the production subsidy from the el-certificate market, Dalton et al. (2009) discuss the effect of sellback rate. When keeping the grid prices steady at 0,3AUD/kWh, the NPC decreases from approximately 9 million AUD with a sellback rate of 0,1AUD/kWh to approximately 2,7 million AUD with a sellback rate of 0,3AUD/kWh. The NPC of 2,7 million AUD have a 1:1 ratio with the grid rate, which is far from the case in Norway, where the ratio is approximately between 1:4 and 1:3 as in the case where the NPC are approximately 9 million AUD. The Otovo feed-in tariff have approximately ratio 1:1 up to 5000 kWh, because of this maximum and that the prices are about 3 times higher than in Norway the effect is much larger than in this thesis. With the 60% increase in grid sellback rate in this thesis, the grid sellback rate is still not high enough to make much of an impact. In order to get a significant impact, the ratio between the grid rates and the grid sellback rates, would most likely be closer to 1:1.

The Otovo feed-in tariff represents a smaller risk than the production subsidy from the el-certificate market. The Otovo feed-in tariff is a fixed price and market-independent up to 5000 kWh. This makes it much easier for the investor to calculate potential income for the system than with the production subsidy from the el-certificate market which is market-dependent. Market independent policies have proven more effective in renewable energy assessment and lowering risks according to Couture and Gagnon (2010).

4.3.3 All the subsidies and feed-in tariff combined

The most interesting finding when calculating new NPC and LCOE which includes all the subsidies and feed-in tariff is that the new optimized result for Kristiansand is the Grid+PV which both have a lower NPC and LCOE compared to Grid-only. Since the el-certificate production subsidy is not included in this system, the only uncertainty regarding these results are the renewable resources, some losses and degradation of the PV system.

When including all the subsidies and feed-in tariff for the other locations the NPC is not much higher for the Grid+PV compared to the Grid-only system for instance at Grinder there are only a difference of 2658. The LCOE is also lower for all the selected locations.

Looking at the systems Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2), the impact from all the subsidies and feed-in tariff are big. For Stavanger and Bergen the LCOE is about 0,3 NOK/kWh lower than for the Grid-only system. The impact on NPC are also big, but it is not enough to make it feasible compared to Grid-only and Grid+PV.

The subsidy in general had bigger impact on the Grid+WT, Grid+PV+WT(1) and Grid+PV+WT(2) in NPC than for the Grid+PV, this is naturally because of higher installed effect, but due to high investment costs, the bigger impact did not make the systems feasible.

4.4 Future grid prices

For Trondheim, Bergen and Stavanger the Grid-only system is still the optimized result with lowest NPC without subsidies. However, in comparison with the Grid-only system, the LCOE is lower for all systems both with and without subsidies situations. Hence, based on the projected future grid prices, all the hybrid systems would be more feasible than the Grid-only system. Furthermore, with subsidies and feed-in tariff, Grid+WT have the lowest NPC for Bergen and Stavanger, while Grid+PV has the lowest NPC for Trondheim. For Grinder and Kristiansand, the optimized result with the lowest NPC is Grid+PV with and without subsidies. Hence, based on the projected future electricity price, all the hybrid systems would be more feasible than Grid-only system in all the locations without any financial support.

In general, the gap in NPC for the systems with wind turbine compared to Grid-only is much smaller. For the first time in this thesis, the Grid+WT is also the system with the lowest NPC. However, it should be noted that the likeliness of this increase in price of electricity are debatable. For the last year of the simulation, the grid price is nearly 3 times higher than today's prices. Arguments for this increase is that the grid in Norway need large re-investments because of age and higher demand, due to many factors, for instance charging electric cars. Also, the planning and building of new transmission cables to Europe would most likely mean that the Norwegian prices, which is generally lower, could get closer to the prices in Europe, which are currently higher than that of Norway (Gundersen 2017).

The results in this section is supported by Türkay and Telli (2011) and Dalton et al. (2009). When Türkay and Telli (2011) increased the grid rate to 2 USD/kWh the optimal system changed and included the wind turbine. 2 USD/kWh is a much higher price than in this thesis, but this is the same that happens for Bergen and Stavanger when including future price of electricity, subsidies and feed-in tariff. From Dalton et al. (2009), an increase in electricity prices had larger impact on the Grid-only system configuration than the HRES, due to the renewable fraction. This supports the results in this thesis as well.

4.5 NPC and LCOE

The LCOE is a good metric to compare the different systems at the different locations, but the LCOE can also be misleading (Ueckerdt et al. 2013). In this thesis, the system configurations with a wind turbine at locations with good wind conditions, achieve a low LCOE. These system configurations also have a large surplus amount of electricity sold cheaply back to the grid. HOMER includes the electricity sold back to the grid and not only the demand, which makes the LCOE somewhat arbitrary and disputable. The NPC is a simple mathematical model that does not require any judgements (HOMER Energy 2018).

If only looking at the LCOE, the system configurations with a wind turbine and with good wind conditions would be favorable, but at the same time the NPC would be much higher and the systems would not be feasible compared to the other system configurations. The NPC is therefore primary used to rank the systems, where the LCOE is secondly for comparison.

4.6 Sensitivity analysis

Sensitivity analysis for Grid+PV and Grid+PV+WT(1) are discussed in this section. Since the sensitivity analysis for Grid+WT and Grid+PV+WT(1) were almost identical, the Grid+WT were excluded from the discussion and the effects are discussed in Grid+PV+WT(1) instead. The main difference between the two are that the sensitivity variables which affect solar PV will affect the NPC and LCOE for Grid+PV+WT(1), which it would not for Grid+WT.

When looking at NPC for the Grid+PV system the PV cost multiplier makes a significant impact, with a 60% decrease in solar PV costs, the new optimal solution would be Grid+PV even without subsidies. The PV lifetime has the largest impact if it decreases, the need for a replacement during the project lifetime would affect the NPC very bad. An increase in PV lifetime does not have the same significance as the decrease. If only the lifetime of the PV increases without an equal increase in the project lifetime the only difference will be a small salvage value at the end of the project time, instead of the potential for more energy produced. The salvage value would work like a revenue at the end of the project lifetime. The solar energy resources have also a more significant effect if it decreases compared to if it increases. Naturally, the variables associated with the wind turbine does not have any effect of the Grid+PV system.

When looking at LCOE for Grid+PV, the effects are almost identical as for the NPC. The main difference is that the solar energy resources have a slightly more significant effect if it is increased compared with NPC

When looking at NPC for Grid+PV+WT(1) the sensitivity variables with highest impact are WT cost multiplier, WT lifetime and wind resources. Since the wind turbine have by far the largest investment costs, it is naturally that the variables that can have an impact on the wind turbine have the largest impact. This statement is supported by González et al. (2015). Compared with the lifetime of solar PV, the lifetime of the WT alone has a higher impact measured in NOK, but compared relatively to the size of the NPC the effect is almost the same. As mentioned about the salvage value for the solar PV, the salvage value for the wind turbine would be higher since the investment costs are much higher. Wind resources and lifetime WT have higher impact if the values decrease than if they increase.

When looking at LCOE for Grid+PV+WT(1) the effects are almost the same as for NPC. The main difference is that WT lifetime and wind resources have changed significance. A decrease in wind resources have higher impact than a decrease in WT lifetime now.

5 Conclusion and further research

5.1 Conclusion

The object of the thesis has been to investigate for the selected locations if local power production from grid connected solar PV and wind turbine could be economic feasible compared to today's solution with grid only. In order to do so, HOMER has been used to calculate optimized system configurations with NPC and LCOE. Financial support has been added to the optimal system configurations to calculate the effect of financial support that is available today. Based on reports which includes forecasts for future grid prices, NPC and LCOE has been calculated for a possible future scenario. Based on the findings in this thesis some conclusions and recommendations are presented.

From an economical point of view, none of the HRES systems are profitable compared to today's grid only solution based on NPC without financial support. Although, it is interesting that many of the HRES systems achieves a lower LCOE. To invest in a HRES, other decision variables than economic feasibility must be considered.

Financial support makes the HRES more competitive. Only for Kristiansand, the financial support makes a HRES the most economic feasible system based on NPC. For the other selected locations, a higher amount of financial support is required to change the optimal system solution.

With the forecast of future grid price, todays system is affected the most since the entire amount of energy used within the system depends on the grid prices. This makes the new optimal system solution change for Grinder and Kristiansand even without financial support. With financial support included with the future grid price, all the new optimal system solutions for all the selected locations contain HRES.

To achieve a higher implementation of renewable energy sources for householdings today, a financial support equal to the difference between todays grid price and the predicted future grid price used in this thesis. A higher sellback rate could also have a significant effect on the implementation of HRES.

Of the selected locations, Kristiansand is the most suitable locations considering power generation from only solar PV, while Stavanger is the most suitable locations only considering power generation from a wind turbine. Combining power generation from solar PV and a wind turbine, Stavanger is the most suitable location with the best wind resources and second best solar energy resources.

5.2 Further research

Based on experience gained during this thesis some recommendations for further research are suggested:

- The renewable energy resources include some uncertainty, for more accurate calculations, real-time ground measured resource data can be used.
- Different software can be used to compare the results.
- Higher demand for energy, for instance a co-investment or a farm could utilize more of the produced energy instead of high amounts of surplus energy sold cheap to the grid. This regards mostly the wind turbine.
- Study can be conducted to find out how much the subsidies or feed-in tariff needs to be increased in order to get the different system configurations feasible, and how much this will affect socioeconomically.
- Other locations can be studied, especially inland. A HRES might be more feasible for locations inland with better resources.

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Appendices

Appendix A: Specifications for IBC Poly 270 CS4

Smart Systems
for Solar Power

IBC SOLAR

IBC EcoLine – For particulary stable output

IBC MonoSol 265 CS, 270 CS

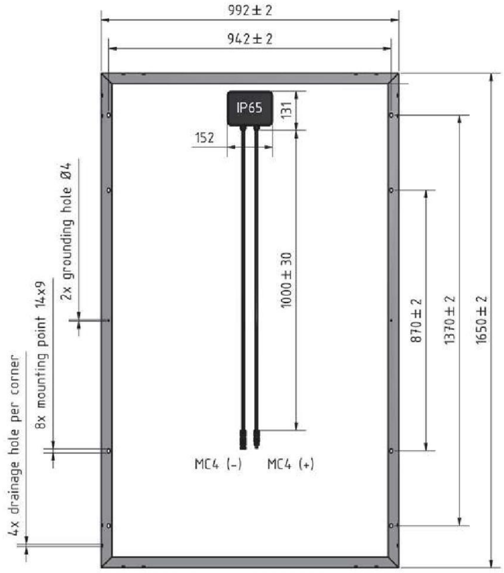
Solar modules made by monocrystalline silicon

Regardless of whether it is used on detached houses, the roofs of industrial properties or on open spaces, tried and tested IBC MonoSol CS photovoltaic modules are suitable for any application requiring a high quality, efficiency and profitability. Continuous quality assurance and process audits during production guarantee a particularly long service life of the modules with a maximum of output, efficiency and reliability. Thanks to the anti-reflective coating on the front glass panels, these modules capture even more light to be more efficient and produce optimum yields.

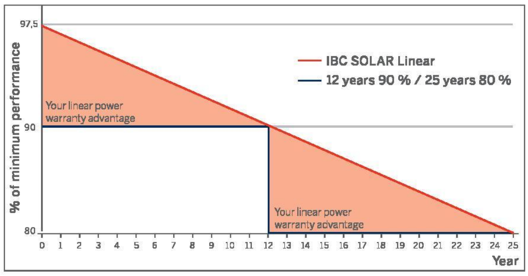
Highlights:

- 10-years product warranty*
- 25 years linear power warranty*
- Positive power tolerance: −0/+5 Wp
- Highly effective with low-iron photovoltaic glass and anti-reflective coating (thickness 3.2 mm)
- Sturdy hollow-chamber frame
- Tested according IEC 61215 for snow loads up to 5400 Pa (ca. 550 kg/m^2)
- IEC 61730, application class A for system voltages up to 1000 V, protection class II
- Produced in facilities certified as per ISO 9001, ISO 14001 and OHSAS 18001
- Regular product/process/quality assurance audits in production
- Quality tested by IBC SOLAR in own laboratory with climate chambers and flasher with integrated electroluminescence measurement

CE



Progression of the power warranty



TECHNIAL DATA

IBC MonoSol	265 CS	270 CS
STC Power Pmax (Wp)	265	270
STC Nominal Voltage Umpp (V)	31.4	31.77
STC Nominal Current Impp (A)	8.44	8.50
STC Open Circuit Voltage Uoc (V)	38.54	38.70
STC Short Circuit Current Isc (A)	8.99	9.04
800 W/m² NOCT AM 1.5 Power Pmax (Wp)	196.15	199.90
800 W/m² NOCT AM 1.5 Nominal Voltage Umpp (V)	28.51	28.68
800 W/m² NOCT AM 1.5 Open Circuit Voltage Uoc (V)	36.22	36.66
800 W/m² NOCT AM 1.5 Short Circuit Current Isc (A)	7.17	7.21
Rel. efficiency reduction 200 W/m² (%)	3.81	3.84
Tempkoeff Isc (%/°C)	+0.063	+0.063
Tempkoeff Uoc (mV/°C)	–138	–139
Tempkoeff Pmpp (%/°C)	–0.36	–0.36
Module Efficiency (%)	16.2	16.5
NOCT (°C)	47	47
Max. System Voltage (V)	1000	1000
Max. Reverse Current Ir (A)	20	20
Current value String fuse (A)	15	15
Fuse protection from parallel strings	4	4
Height (mm)	45	45
Weight (kg)	20.5	20.5
Article number	**2003800005** **2003800007**	**2003800006** **2003800008**

2014-07-18

Presented by:

* The linear power warranty is only valid for installations within Europe and Japan. For further information, please refer to the corresponding product and power warranty in accordance with the version of the full warranty conditions received from your specialized IBC SOLAR partner at the time of installation. This warranty is valid only when the product is installed in accordance with the applicable installation instructions. Electrical values under standard test conditions: 1000 W/m²; 25 °C, AM 1.5. 800 W/m², NOCT. Specifications according EN 60904-3 (STC). All datas according DIN EN 50380. Subject to modifications that represent progress.

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Appendix B: Specifications for Steca StecaGrid 4200

coolcept

StecaGrid 1800, StecaGrid 2300, StecaGrid 3010, StecaGrid 3000, StecaGrid 3600, StecaGrid 4200

Highest efficiency with longer service life

The high efficiency results in a peak efficiency of 98.6 % and a European efficiency of up to 98.3 %, which results in less lost power that must be dissipated into the environment. This improves your yields.

In addition to this, a new and unique cooling concept inside the inverter ensures an even distribution of the dissipated heat and a long service life for the device.

Product design and visualisation

The StecaGrid has a graphical LCD display for visualising the energy yield values, current performance and operating parameters of the system. Its innovative menu allows individual selection of the various measurements.

The guided, pre-programmed menu allows easy final commissioning of the device.

Installation

The lightweights weigh only 9 kg / 9.5 kg and can be easily and safely mounted on a wall. The supplied wall bracket and practical recessed grips for right and left handed installers make mounting of the device simple and convenient. The device does not need to be opened for installation. All connections and the DC circuit breaker are externally accessible.

Product features

- Highest efficiency
- Simple installation
- Integrated data logger
- Firmware update possible
- Low housing temperature at full load
- Functionally perfect, environmentally-friendly plastic housing
- Lowest possible own consumption
- Integrated DC circuit breaker
- Protective insulation according to protection class II
- Very long service life
- Droop Mode for integration in hybrid systems (further information: Catalogue Steca PV Off Grid / Single-phase and three-phase AC hybrid systems)
- Fixed voltage mode for other energy sources
- Service menu for parameter adjustment
- 7-year warranty after registration

Displays

- Multifunction graphical LCD display with backlighting
- Animated representation of yield

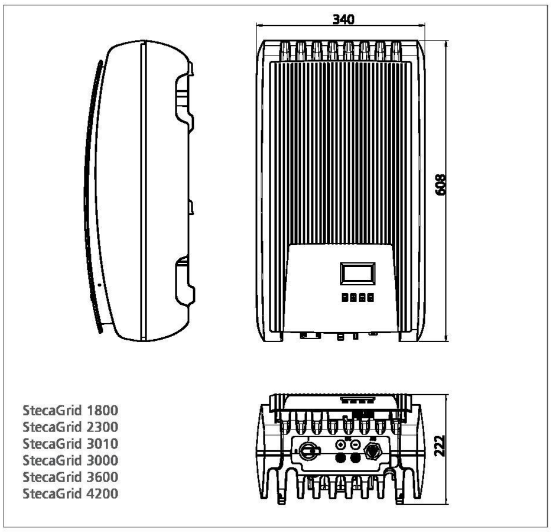
Operation

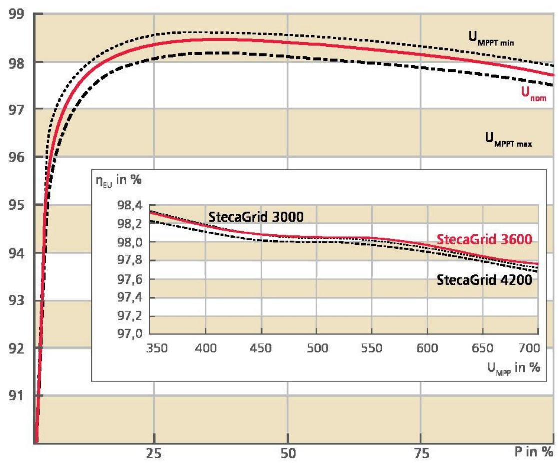
- Simple menu-driven operation
- Multilingual menu navigation

Options

- Can be connected to the StecaGrid Vision display unit or a large-format display

StecaGrid 1800
StecaGrid 2300
StecaGrid 3010
StecaGrid 3000
StecaGrid 3600
StecaGrid 4200





Efficiency values for the StecaGrid 3600 and comparison of the MPPT voltage of the StecaGrid 3000/3600/4200

System monitoring and accessories

StecaGrid User
Visualisation software

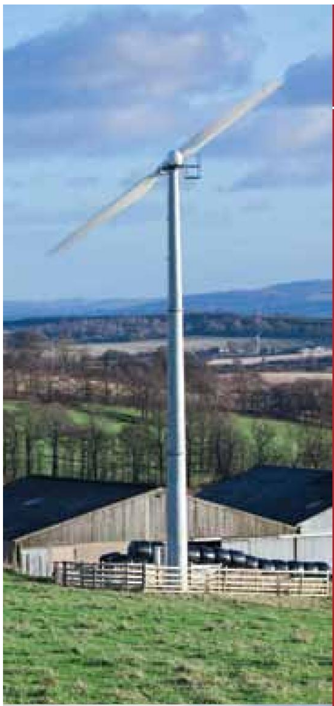
StecaGrid Portal
Web portal

StecaGrid SEM
Energy manager

Solar-Log 500/1000™ and Meteocontrol WEB'log Comfort
Accessories

	StecaGrid 1800	StecaGrid 2300	StecaGrid 3010	StecaGrid 3000	StecaGrid 3600	StecaGrid 4200
DC input side (PV-generator)						
Maximum input voltage	600 V			845 V		
Minimum input voltage for feeding	125 V			350 V		
MPP voltage for rated output	160 V ... 500 V	205 V ... 500 V	270 V ... 500 V	350 V ... 700 V		360 V ... 700 V
Maximum input current	11,5 A			12 A		
Maximum input power at maximum active output power	1.840 W	2.350 W	3.070 W	3.060 W	3.690 W	4.310 W
Maximum recommended PV power	2.200 Wp	2.900 Wp	3.800 Wp	3.800 Wp	4.500 Wp	5.200 Wp
AC output side (Grid connection)						
Grid voltage	185 V ... 276 V (depending on regional settings)					
Rated grid voltage	230 V					
Maximum output current	12 A	14 A		16 A		18,5 A
Maximum active power (cos phi = 1)	1.800 W	2.300 W	3.000 W	3.000 W	3.600 W [1]	4.200 W [1]
Maximum active power (cos phi = 0.95)	1.800 W	2.300 W	3.000 W	3.000 W	3.530 W	3.990 W
Maximum apparent power (cos phi = 0.95)	1.900 VA	2.420 VA	3.160 VA	3.130 VA	3.680 VA	4.200 VA
Rated power	1.800 W	2.300 W	3.000 W	3.000 W	3.600 W [2]	4.200 W [3]
Rated frequency	50 Hz and 60 Hz					
Frequency	45 Hz ... 65 Hz (depending on regional settings)					
Night-time power loss	< 1,2 W			< 0,7 W		
Feeding phases	single-phase					
Distortion factor (cos phi = 1)	< 2 %					
Power factor cos phi	0.95 capacitive ... 0.95 inductive					
Characterisation of the operating performance						
Maximum efficiency	98 %			98.6 %		
European efficiency	97.4 %	97.6 %	97.7 %	98.3 %	98.3 %	98.2 %
Californian efficiency	97.5 %	97.7 %	97.8 %	98.4 %	98.3 %	98.2 %
MPP efficiency	> 99,7 % (static), > 99 % (dynamic)					
Own consumption	< 4 W					
Power derating at full power	ab 50 °C (T_{amb})		ab 45 °C (T_{amb})	ab 50 °C (T_{amb})		ab 45 °C (T_{amb})
Safety						
Isolation principle	no galvanic isolation, transformerless					
Grid monitoring	yes, integrated					
Residual current monitoring	yes, integrated [4]					
Operating conditions						
Area of application	indoor rooms with or without air conditioning					
Ambient temperature	-15 °C ... +60 °C					
Storage temperature	-30 °C ... +80 °C					
Relative humidity	0 % ... 95 %, non-condensating					
Noise emission (typical)	23 dBA	25 dBA	29 dBA	26 dBA	29 dBA	31 dBA
Fitting and construction						
Degree of protection	IP 21 (casing: IP 51; display: IP 21)					
Overvoltage category	III (AC), II (DC)					
DC Input side connection	MultiContact MC 4 (1 pair)					
AC output side connection	Wieland RST25i3 plug, mating connector included					
Dimensions (X x Y x Z)	340 x 608 x 222 mm					
Weight	9,5 kg			9 kg		
Communication interface	RS485; 2 x RJ45 sockets; connectable to StecaGrid Vision, Meteocontrol WEB'log or Solar-Log™; Ethernet interface					
Integrated DC circuit breaker	yes, compliant with VDE 0100-712					
Cooling principle	temperature-controlled fan, variable speed					
Test certificate	CE mark, VDE AR N 4105, G83, CEI 0-21 under preparation: UTE C 15-712-1			CE mark, VDE AR N 4105, G83, UTE C 15-712-1, AS4777, CEI 0-21		CE markl, VDE AR N 4105, G83, CEI 0-21

[1] Belgium: 3,330 W [2] Portugal: 3,450 W [3] Portugal: 3,680 W [4] The design of the inverter prevents it from causing DC leakage current.



Appendix C: Specifications for Gaia-Wind 133

Gaia-Wind 133-11kW Data Sheet

Annual Energy Production (AEP)*	
Annual Average Wind Speed (measured at hub height)	**Annual Energy Production (AEP)**
4 m/s	16,220 kWh
5 m/s	27,502 kWh
6 m/s	37,959 kWh
7 m/s	46,527 kWh

NOTES:
Figures listed are for ‘clean wind sites’. Local topography such as buildings and trees can significantly influence turbine production.

Units shown in domestic electricity bills are in kilowatt-hours (kWh). 1 kWh is roughly equivalent to 1 bar of an electric fire burning for 1 hour.

*Microgeneration Certification Scheme (MCS) data

Target noise level (8m/s wind at hub height)	
Sound Power $L_{wd,8m/s}$	88.1 dB(A)
Noise Slope, SdB (dB/m/s)	1.015
Noise penalty	none

Target noise level (8m/s wind)	Distance required
45 dB(A)	57m
40 dB(A)	100m
35 dB(A)	180m

NOTES:
Since the rotor speed of rotation is constant, does not change with wind speed, and the blades do not pitch or furl, the noise profile of the turbine is very flat making it an exceptionally quiet machine.

*MCS data

Certification

UK: Microgeneration Certification Scheme. Certification no. TUV 0002
Denmark: Risø DTU 2009-1

Operational parameters

Cut in wind speed (adjustable)
Standard setting, 3.5 m/s (5.6 mph)
Shut down wind speed (adjustable)
Standard setting, 25 m/s (56 mph)
IEC turbine class
Conforms to IEC 61400 Class III (suitable for sites with an annual average wind speed up to 7.5 m/s)
Survival wind speed
52.5 m/s (117 mph)
Temperature range
-20°C +50°C
Lifetime and servicing
20 years design life Service once yearly

Key component parameters

Twin blade rotor	Glass fibre, 13m diameter, swept area 133m^2, mounted on TEETER hub, fixed rotation speed 56 rpm
Gearbox	Two stage, gear ratio 18:1, low noise
Generator	11kW, 3 phase, 400V@50Hz (marine grade)
Towers	Lattice: 15m, 18m monopole: 18m, 27m (hot dip galvanised steel)
Component weights	Nacelle and rotor 900 kg 15m lattice tower 1,556 kg 18m lattice tower 1,955 kg 18m monopole tower 2,511 kg 27m monopole tower 5,275 kg
Standard presentation	Towers: dull grey (galvanised), blade and nacelle cover: grey-white(RAL 9002), reflection free

Control and monitoring system

Data input and management
Integrated microprocessor with multiple sensor inputs.
Data: wind speed, power, voltages, currents and phase, rpm, vibration and temperature alerts.
LCD display in control box.

System protection
Base level: Passive stall of blades limits power output.
Second level: Control system activates mechanical brake if:

- Wind speed exceeds 25 m/s
- Abnormal vibration
- Grid disconnected or generator overheats

Third level: Centrifugally activated aerodynamic brakes built into rotor tips as a final safety measure. Also manual override button which activates mechanical brake.

Gaia-Wind Ltd
100 High Craighall Road, Port Dundas
Glasgow, G4 9UD, United Kingdom

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2 Power Performance

The Power Performance measurements on the GW 133-11 wind turbine are done by TUV NEL and reported in: TUV NEL Cert Report 2010-204.

2.1 Power Curve

The report gives the Noise Power Performance Results in table 6:

TABLE 6 POWER PERFORMANCE RESULTS (DATABASE B)

Measured power curve (database B)							
Reference air density: 1.225 kg/m3					Category A	Category B	Combined uncertainty
Bin no.	Hub Height Wind Speed m/s	Power output kW	Cp	No. of data sets (1 min. Avg.)	Standard uncertainty s_i kW	Standard uncertainty u_i kW	Standard uncertainty u_{ci} kW
1	0.64	-0.03	-1.40	23	0.0001	0.1300	0.1300
2	1.06	-0.03	-0.30	150	0.0002	0.1299	0.1299
3	1.53	-0.03	-0.10	404	0.0001	0.1299	0.1299
4	2.02	-0.03	-0.05	826	0.0010	0.1299	0.1299
5	2.50	-0.05	-0.04	1316	0.0028	0.1300	0.1300
6	3.01	-0.12	-0.05	1499	0.0050	0.1312	0.1313
7	3.51	0.08	0.02	1767	0.0099	0.1427	0.1430
8	4.00	0.71	0.14	1983	0.0153	0.2372	0.2377
9	4.49	1.56	0.21	2055	0.0187	0.3170	0.3176
10	4.99	2.46	0.24	1777	0.0226	0.3386	0.3393
11	5.49	3.44	0.26	1467	0.0256	0.3824	0.3833
12	5.99	4.43	0.25	1261	0.0310	0.3979	0.3991
13	6.49	5.44	0.24	1034	0.0329	0.4254	0.4267
14	6.98	6.30	0.23	793	0.0353	0.3943	0.3959
15	7.48	7.14	0.21	596	0.0383	0.4006	0.4024
16	7.98	7.91	0.19	380	0.0458	0.3805	0.3833
17	8.49	8.61	0.17	248	0.0561	0.3674	0.3717
18	8.98	9.16	0.16	165	0.0607	0.3177	0.3234
19	9.46	9.67	0.14	105	0.0677	0.3131	0.3203
20	9.99	10.29	0.13	73	0.0813	0.3549	0.3641
21	10.50	10.51	0.11	67	0.0677	0.2022	0.2132
22	11.02	10.69	0.10	39	0.0682	0.1888	0.2007
23	11.51	10.81	0.09	42	0.0791	0.1791	0.1958
24	12.02	10.93	0.08	41	0.0629	0.1762	0.1871
25	12.51	10.67	0.07	45	0.1287	0.2302	0.2637
26	12.97	10.74	0.06	29	0.0779	0.1675	0.1848
27	13.52	10.47	0.05	32	0.0761	0.2309	0.2432
28	14.06	10.26	0.05	36	0.0657	0.2132	0.2231
29	14.53	9.82	0.04	47	0.0669	0.3766	0.3825
30	14.98	9.54	0.03	50	0.1331	0.2841	0.3137
31	15.52	9.42	0.03	35	0.1062	0.1757	0.2053
32	16.00	8.79	0.03	17	0.3461	0.5527	0.6521
33	16.50	9.07	0.02	22	0.1154	0.2836	0.3061
34	16.98	8.76	0.02	15	0.1102	0.3165	0.3351
35	17.50	8.69	0.02	6	0.0000	0.1620	0.1620
36	17.89	7.91	0.02	3	0.0000	0.8911	0.8911
37	18.42	8.69	0.02	4	0.0000	0.6871	0.6871
38	19.24	8.12	0.01	1	0.0000	0.3612	0.3612
39	19.50	0.00	0.00	0	0.0000	0.1299	0.1299
40	20.00	0.00	0.00	0	0.0000	0.1299	0.1299
41	20.50	0.00	0.00	0	0.0000	0.1299	0.1299
42	21.00	0.00	0.00	0	0.0000	0.1299	0.1299
43	21.50	0.00	0.00	0	0.0000	0.1299	0.1299
44	22.00	0.00	0.00	0	0.0000	0.1299	0.1299
45	22.50	0.00	0.00	0	0.0000	0.1299	0.1299
46	23.00	0.00	0.00	0	0.0000	0.1299	0.1299
47	23.50	0.00	0.00	0	0.0000	0.1299	0.1299
48	24.00	0.00	0.00	0	0.0000	0.1299	0.1299
49	24.50	0.00	0.00	0	0.0000	0.1299	0.1299
50	25.00	0.00	0.00	0	0.0000	0.1299	0.1299

The power curve resulting from this date is given in Figure 11:

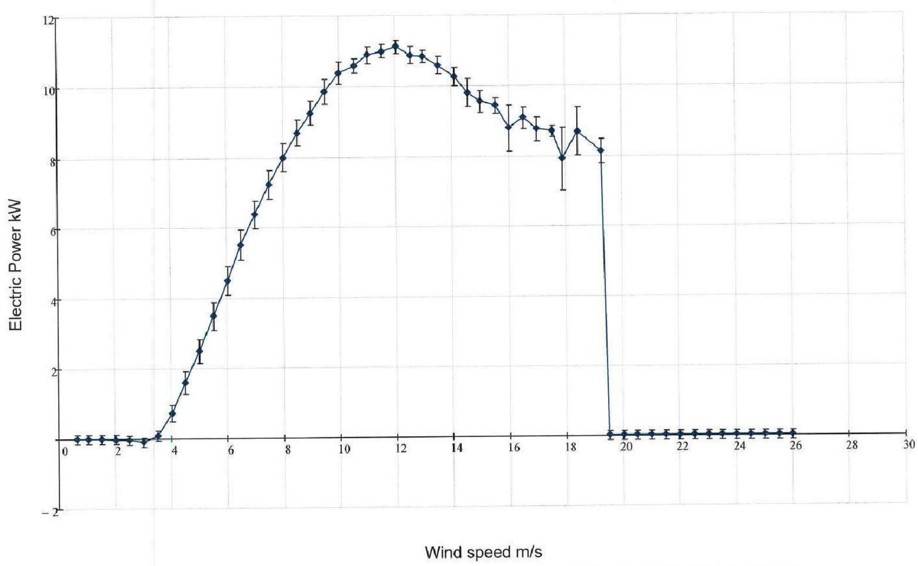

FIGURE 11 MEASURED POWER CURVE BASED ON BIN-AVERAGED RESULTS (DATABASE B)

2.2 Annual Electricity Production, AEP

The report gives the Estimated Annual Electricity Production in table 8:

TABLE 8 ESTIMATED ANNUAL ENERGY PRODUCTION (DATABASE B)

Estimated Annual Energy Production (database B) Reference Air density: 1.225 kg/m3 Cut-out windspeed: 25 m/s (extrapolation by constant power from last bin)				
Hub height annual average wind speed (Rayleigh) m/s	AEP-measured (measured power curve) kWh	Standard uncertainty in AEP kWh	Standard uncertainty in AEP %	AEP-extrapolated (extrapolated power curve) kWh
4	16220	2069	12.8	16220
5	27502	2345	8.5	27502
6	37959	2471	6.5	37959
7	46527	2519	5.4	46527
8	52783	2537	4.8	52783
9	56709	2541	4.5	56709
10	58567	2529	4.3	58567
11	58764	2498	4.3	58764

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