CHALMERS
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Degree of self-sufficiency of an electrified road coupled to renewable energy production

A case-study on the European road E39

Master's thesis in Sustainable Energy Systems

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Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

MASTER'S THESIS 2017

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Abstract

Electrified road systems (ERS) are an attempt to mitigate limitations occurring in Battery Electric vehicles considering range and large battery sizes. Such an ERS would require large investments into grid infrastructure and efforts to balance the demand. This thesis therefore investigates the connection of an ERS to renewable energy production with the aim to reduce dependency on an electricity grid. It is carried out as a case study for the European Road 39 in Western Norway.
Two optimisation models for an ERS combined with renewable energy production capacity were designed for this study: (i) The ERS is decoupled from the electricity grid and the investments into renewable energy production capacity needed to fulfil the demand is minimised. (ii) The transfer of electricity through a grid connection to the ERS is minimised under a fixed budget for investment into renewable energy production capacity. The models are combined with scenarios allowing or disallowing the use of battery storage and pumped hydro power storage.
The results show that the most effective way to power an ERS for the E39 is to combine wind power production with pumped hydro power storage, in this case, the cost for production capacity per driven kilometre is comparable to current gasoline prices. Without the use of storage, a large overproduction occurs and can be sold on the electricity market, however large investments into grid infrastructure are then necessary. A connection to the grid can be used to bridge large and rare shortages and demand peaks resulting in significantly lower investment costs for energy production capacity.

Keywords: Battery Electric Vehicles, Electrified Road System, investment cost minimisation, renewable energy production, wind power, solar power, electricity storage, pumped hydro power storage

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Nils Grashorn, Gothenburg, July 2017

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Introduction

Climate change is one of the biggest challenges for human societies in the 21st century. The emission of an extensive amount of greenhouse gases is endangering the perspectives for humanity to fulfil even the most basic of their needs in a not so distant future. Of the current CO_2 emissions, roughly 40 % are belonging to the sectors of power production and transport [1]. Discussions about future developments in these sectors always include the need to reduce greenhouse gas emissions.

One solution proposed to mitigate emissions in transportation is the use of electric vehicles. Electric vehicles in combination with a production of electricity with a high share of renewable energy sources gives a great potential to reduce climate impacts from both sectors.

In recent times, sales of battery electric vehicles have shown an exponential growth, with the global mass market opening in 2010 and a total amount of electric cars on the streets globally reaching 700 000 in 2016 [2]. The number of electric vehicles is expected to increase further in the future. As an example, American manufacturer Tesla faces close to 400 000 reservations for their upcoming Model 3 as of May 2016 [3], a hype situation that comes close to the release of the first iPhone [4].

The country with the highest market share of electric cars is Norway. For new cars in 2015, all-electric cars and hybrid-electric vehicles had a market share of 17.1 % and 12.4 % respectively [5]. The increase of electric vehicles is mostly due to incentives given to the owners, e.g. exemption from taxes, exemption from road and parking fees, free use of ferry lines and the allowance to use lanes reserved for public transport [6]. At the same time, 95 % of Norway's electricity production originates from hydro power [7] and therefore the emissions from the transport sector are reduced significantly with the introduction of electric vehicles. The Norwegian government adopted a target that by 2025 all new cars and 50 % of new heavy transport vehicles should be zero-emission vehicles [8].

Given that a significant share of traffic is reliant on electricity as a fuel, investment in new infrastructure needs to be taken into account as well. Today's plug-in electric vehicles rely on a battery being charged while the car is not in use, e.g. at work, home or public places with a charging station. The battery size limits the distance a car can travel after being charged and the battery weight adds to the mass of the car. On top of that the manufacturing costs are increased significantly by the cost of the battery. Consequently, the concept of so called electric road systems (ERS) arose to charge vehicles while driving on a road. Electricity is transferred either through direct contact (i.e. conductive charging) or induction technologies. With an ERS it would not be necessary to equip the vehicles with a large battery while solving the range issues. ERS would be especially important for heavy vehicles, such as long distance lorries, due to their high energy demand that lead to requirements for very large batteries.

The introduction of a large number of electric vehicles would unquestionably increase the demand for electricity and raise the need for additional electricity production. Given the aim to reduce greenhouse gas emissions, the sources have to be renewable. Renewable power sources, like wind and solar, have intermittent characteristics, i.e. they do not deliver a constant production, but the output changes after availability of the underlying source. On the other hand, the electricity demand from electric vehicles is dependent on the usage patterns of vehicle users. Therefore, production and demand are not related and the system cannot be regulated as it is known from a classical electricity system present in the 20th century with a large amount of fossil fuels. The variability of renewable energy production has to be balanced, however, large electricity flows into the ERS would put strains on the existing surrounding electricity system. Therefore, this thesis investigates how the road can act as self-sufficient as possible, i.e. using as little electricity from the surrounding electricity grid as possible, or even be operated without a connection to the grid.

Previous studies have investigated the interplay between renewable energy production and the use of electric vehicles. Göransson, Karlsson, and Johnsson [9] investigate the change in emissions from an electricity network that is supplied by a mix of wind power and fossil fuel generation when plug-in hybrid electric vehicles are introduced. Dallinger [10] designs a method to model the interaction of plug-in electric vehicles with the power system and investigates the potential of balancing fluctuating renewable energy production. Grahn [11] quantifies the influence of charging electric vehicles on load profiles and variations and describes models to estimate charging behaviour and its impact on the load characteristics.Other studies concentrated on the technology of electrified roads. Chen, Taylor, and Kringos [12] analyse the technology and challenges of pilots and future projects using inductive charging systems. Olsson [13] describes the Swedish pilot project of an electrified road consisting of a test facility and an analysis about the costs and feasibility of such a project. Finally, Stamati and Bauer [14] discuss the optimal design of a microgrid to supply a segment of an electrified road. The microgrid is connected to wind turbines, solar panels and a storage system and data is used from a small area in the Netherlands.

The literature review shows that there is a lack of studies to investigate the combination of an electrified road system stretching over several regions with a renewable energy system.

This work aims therefore to investigate the combination of a long-distance electric road system (ERS) with renewable energy production assuming a completely self-sufficient electricity system or an electricity system including a connection to the electricity grid. Complete self-sufficiency means the road would act as an island system. The vehicles driving on the road are assumed to not be equipped with a battery, so they are solely fuelled by the electricity transferred from the road.

In particular, this work analyses in a cost minimisation approach how much investment into renewable energy power plants and electricity storage are needed to fulfil the electricity demand from the road. The production technologies investigated are wind and solar power, and for storage technology, battery storage and pumped hydro power are taken into account. The investigation is carried out under two different maxims: (i) the electrified road using electricity solely produced by newly installed power plants and (ii) allowing the use of electricity from the surrounding electricity system. For the second case, the investment costs are fixed and the electricity import is minimised. For the self-sufficient electricity system, it is examined on what levels investment costs are to be expected, using a combination of the named technologies. Furthermore, characteristics (e.g. use of storage and overproduction) of production and storage are examined. For the electricity system using electricity from the grid, it is analysed how the available investment is distributed to the the named technology options.

The method is then applied to the possible electrification of an existing road in Norway. The chosen road is the E39, a European road stretching along the Southern and Western coast of Norway.

This work is divided into the following chapters: Background information is given on the technologies expected to be used in a system containing an electrified road and the sources of electricity production and storage (chapter 2), the optimisation models are explained (chapter 3) and the used data is characterised (chapter 4). Finally, the results are presented (chapter 5) and discussed (chapter 6).

2

Background

2.1 The E39

The European road 39 leads from the municipality of Klett south of Trondheim to Kristiansand on the Southern coast. It connects the big cities of Trondheim, Bergen, Stavanger, Kristiansand and several other, smaller settlements. These joint regions make up about half of Norway's traditional export and traffic on the route has increased with higher numbers compared to the rest of the country [15]. Running along the Norwegian Western and South-Western coast, the road crosses several fjords and stretches over a total length of around 1100 km [16]. An overview of the course of the E39 can be found in figure 2.1.

Figure 2.1: Course of the E39 in Western Norway [17]

Seven of the fjords along the E39 are today crossed by ferry connections, a transport mode that takes considerably longer than if the route consisted of bridges or tunnels. Travelling time can be translated into costs for society e.g. in terms of barriers for labour markets or lost revenues for companies. Therefore, in 2010 the Norwegian ministry of transport and communication gave the mandate to the Public Roads Administration to look for alternatives to the ferry connections [18].

In the "Coastal Highway route E39" project, the technical possibilities for fjord-crossings and the impact on traffic and society are investigated. For the project, efforts are taken to redesign the road and to investigate climate alternatives to fossil fuels like an electrification, which makes this road is a good choice for a study.

2.2 Electrifying a road

In order to reduce the size of a vehicle's battery or to make it even obsolete, an option is to supply vehicles with electricity by using an electric road system (ERS). Classical technologies to supply vehicles on the road with electricity have included overhead lines and side rails. Both technologies however are not suitable for the described purpose, the former needs a too long collector for passenger vehicles and the latter limits the supply to one lane [13]. Technical solutions using the driving surface instead include a conductive approach with a direct connection between the vehicle and a rail in the road and an inductive approach using a magnetic field. Both approaches are calculated to have an efficiency of close to 80 %, considering the energy transmission from an electrical substation to the torque an electrical engine provides in a vehicle [19] [13]. The results of the optimisations in this work are therefore not altered if either technology is used.

2.2.1 Conduction

A system using conduction to transfer electricity to a vehicle needs a direct contact between the vehicle and the road. Typically, given a road with multiple lanes, each lane would have a built-in supply rail that the vehicles can connect to. The vehicle itself needs a collector connected to the rail to take in electricity. This collector should be designed to connect and disconnect to the road when needed, e.g. for changing lanes. Care has to be applied when considering road maintenance in terms of reconstruction and winter clearance. The electrical rails and the system could be damaged e.g. by ploughing vehicles or frost [13].

2.2.2 Induction

Similar to a transformer, an inductive system would create a magnetic field through a conductor loop under the road's surface. The vehicles driving on the road obtain the field and convert it into electrical current through their receptive loop. This arrangement is contactless and would not be visible from the outside which means advantages in safety, as no conductors are present that could harm anyone touching them and the road surface is not altered. Furthermore, the system would still be operable under wet, icy or snowy conditions. On the other hand, the vehicles need to go at a certain minimum speed in order to be charged (currently 50 km/h), so this system would not be operating under heavy traffic circumstances [19].

2.3 Power production and storage

Due to the intermittent characteristics of the power sources, it can be advisable to use electricity storage. In hours of excess production, electricity can be transferred to the storage units and used again when production is on a lower level at times when wind speeds are low and the sky is clouded. Storage can be needed both in short and long terms. Short terms would include bridging a production shortage in the range of hours while long terms mean handling differences in seasonal production. Pumped hydro power is considered as being the only cost-efficient large scale storage technology [20].

In this work, pumped hydro power storage is assumed to be realised as equipping existing hydro power plants with pumped-storage technology. With an upgrade of a hydro power plant to a pumped hydro storage power plant, the output can be expanded and the storage capability can be superimposed to the other regular use of the plant. On the other hand, chemical storage is considered in the form of lithium batteries to include cases where no suitable sites for pumped hydro power storage plants are available. These batteries are generally used for short-term storage and have seen a surge in popularity in recent times. For the scenarios, lithium batteries are used, because they are expected to become a lot cheaper in the near future and are seen as a vital part of the future energy system [21].

By only using wind and solar power, the system is dependent on the case that production is always possible, which is based on the assumption that the area is large enough to allow geographical smoothing. This concept describes the idea that the conditions between regions are that different from each other that production from one region is enough to cover the demand in all areas if weather conditions are unfavourable in one region.

2.3.1 Wind power

Wind power is the production technology with the most newly built capacity worldwide in 2015. In total an amount of 433 GW exists as of 2015, that results in the second highest total capacity in the renewable energy sector after hydro power [22].

Along the Western coast of Norway in the period from 1990 to 2015, the average wind speed is measured to 6.18 m/s which is well above the mean for the Nordic countries (3.83 m/s) and for the region of Denmark, Germany and Netherlands (4.46 m/s) [23].

Wind turbines are regulated using a power curve, which can be used to estimate the possible production resulting from the current wind speed situation. The calculation takes into account the behaviour of a real turbine, which is explained in the following: The wind is measured on the top of the housing and according to a defined power curve, the speed of the rotor and the power output from the generator is regulated. The lowest and highest wind speeds for the turbine to operate in are called “cut-in” and “cut-out” wind speeds respectively (see Figure 2.2). Following just the energy possible to be harvested from the wind, the power curve would have an exponential character. However due to material and design restrictions, a wind turbine is limited to a maximum power output in a trade-off decision between possible yield and material costs [24].

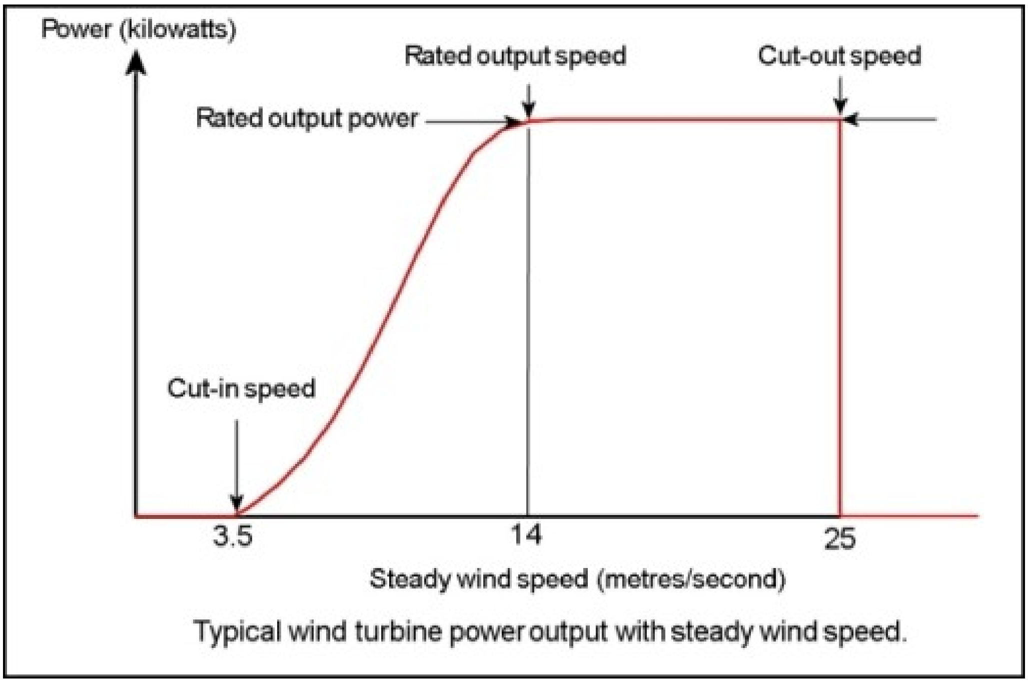

Figure 2.2: Power curve of a wind turbine [25]

In the calculation of the possible power output of an accumulation of a large amount of turbines, the turbines are never able to produce electricity according to their maximum rated capacity due to different types of losses. One factor are wake losses of turbines being placed in a farm structure – the wind is slowed down behind the rotor of a turbine and becomes turbulent, the next turbine in wind direction will therefore experience lower wind speeds and with that lower production. Furthermore, when looking at a fleet of power plants, the probability is high that at least some turbines are under maintenance or are standing still with a failure. Another factor are losses in the electricity transmission within the farms and to the distribution points [26].

2.3.2 Solar power

For the calculation of a possible power output from a solar photovoltaic (PV) module, the character of solar irradiation has to be taken into account. Solar radiation can either fall directly onto the collectors or be shattered first, e.g. through clouds. In places around the equator and sunny areas, direct sunlight is the common situation, whereas diffuse light (shattered and reflected light) mostly occurs in polar regions and cloudy areas [27]. Sunlight can either be transformed into electricity via radiation collection in semi-conductor plates or by concentration and transformation into heat that is then used in a thermal process. The latter require direct radiation from the sun while the former can also exploit diffuse radiation. In winter times, production will be low due to little daylight with the opposite being present in summer.

2.3.3 Battery storage

The battery type looked at in this work is using Lithium ions that move between the electrodes. This type of battery is more and more used in a wide spectrum of applications due to a steep decline in prices, which makes it interesting as a storage option for grids [21].

Batteries have recently been used as grid storage to stabilise frequency and balance varying outputs of renewable energy farms with wind and solar power in the range of hours [28], which implicates that batteries are generally used as a short-term storage. For a grid connection, a large amount of batteries is connected together and equipped with inverters to transform between direct current and alternating current.

2.3.4 Pumped hydro power storage

Pumped hydro storage power plants can be designed from two artificial waterbodies being connected by the plant (closed loop) or the use of natural waterbodies that can even involve an influx of water into the storage reservoir (open loop) [29]. In Norway, some existing regular hydroelectric power plants have an upper and lower reservoir, which makes them suitable for a redesign to be able to be used as pumped storage [30]. Especially for a connection to renewable energies as it is the case in this work, a setup is useful with variable turbine speeds to balance variable production outputs from wind and solar power plants [31].

3 Method

In this thesis, two different approaches are discussed answering two different questions. The first approach examines how much investment is needed to make an electrified road completely self-sufficient. Self-sufficient in this study means the electricity demand is only covered by newly built renewable energy power plants that are installed solely for the road. For the second approach, a constant annualised investment volume is set to be invested into production and storage plants along the whole length of the road, and it is examined how much extra electricity imported from the regular electricity network is needed to fulfil the demand of the vehicles on the road. The approaches are translated into two optimisation models. They share the same model structure, but the objective goal differs for the two approaches and so does the objective function the optimisation process in the two model versions.

In this study, three scenarios (A, B and C) are investigated with the models assuming that a different number of technologies are available for the models to be invested in. Scenario A allows only investment in wind and solar power plants, scenario B adds the possibility of battery storage to the conditions in scenario A and scenario C adds the construction of pumped hydro storage power plants to the conditions in scenario B. For an overview over the technologies allowed in each scenario see table 3.1

Table 3.1: Technologies allowed to be invested in in the three different scenarios.

Investment options	Scenario A	Scenario B	Scenario C
Wind and solar power	x	x	x
Battery storage		x	x
Hydro storage power plants			x

3.1 Complete self-sufficiency model objectives

The complete self-sufficiency model covers the idea to let the electrified road be operated without a connection to a larger grid and therefore relies only on newly installed power. Demand should be covered by the technologies chosen in the optimisation at all times of the year. This includes the possibility that production exceeds demand and therefore can be exported, stored or curtailed. The model objective is set to minimise the investment in new generation and storage capacity, which happens in order to balance the electricity demand of the road with the production of electricity from wind and solar along the road. Depending on the scenario, electricity storage in the form of batteries or pumped hydro power is added to the investment options.

3.2 Import model objectives

The import model allows a grid connection, but is given a maximum annualised investment volume (for production and storage along the whole road) to avoid importing electricity from the grid. The model objective in this case is to minimise the amount of electricity to be imported to cover the demand. The minimisation concerns the sum of imported electricity over the year. Just as for the complete self-sufficiency model, the import model is allowed to invest in generation and storage technologies to balance the electricity demand of the road. The investment volume is set to a maximum value, therefore electricity imports from the surrounding grid can be necessary to fulfil the demand.

3.3 Time and space resolution

The time period of the model is set to one year and the geographical area contains the whole coastal road E39. An hourly resolution is chosen for the time dimension and the road is separated into 588 segments in total. In the optimisation, production capacity is distributed between the road segments and demand is calculated for every road segment. However, the balance is not calculated for every road segment, but for the road as a whole (see chapter 3.4) Two types of vehicles are modelled to represent the traffic characteristics: passenger cars and lorries.

The road segments vary in length since they are adapted to the location of the counting points for traffic volumes (see chapter 4.4) which are not distributed evenly along the road. The counting devices generally have a shorter distance between each other close to larger settlements compared to areas with a lower population density. The higher density occurs due to the fact that the measurement units are placed at large road exits which are more frequent close to cities rather than the countryside.

The distance between two traffic measurement points, which is the same as the modelled segment length, is in most cases smaller than the resolution for wind and solar data that have a resolution of 11 and 100 km respectively. However, for a small amount of segments, the assumption of the traffic data having a better resolution than the wind speed data is violated. If a segment is longer than the wind speed resolution, it is modelled as several segments and is assigned the same traffic data, which is done to not lose geographical weather data.

3.4 Model structure

The models determine the distribution of investments into production and storage technologies. The distribution is executed under the objectives given by the model description, either minimising the total investment costs (complete self-sufficiency model) or the total electricity import from the grid (import model). The models use perfect foresight, i.e. demand and production of the whole time period are known before the optimisation is carried out.

The models do not include any constraints or costs for the transport of electricity along the electrified road or to a surrounding grid if that is allowed in the model. Therefore, it is assumed that electricity can be transported freely to cover the demand at any other spot of the road. Hence, both demand and production are summed up for the whole road and compared to each other. Durations for start-up are neglected as well for all technologies.

For each segment and hour, the model determines the electricity demand resulting from vehicles driving in that segment. The electricity demand per segment is calculated by multiplying the electricity demand needed per vehicle to travel through the segment times the amount of vehicles per hour. The calculation is done separately for the two vehicle types and then summed up to form the total demand per segment.

As the models distribute the investment costs on different technologies in order to execute an optimisation, the installed capacity has the form of a variable. To yield the electricity production in every segment and time step, the share of installed capacity available to use for electricity production is calculated. The calculation is based on the weather conditions present at that time step according to the wind or solar irradiation profile of a specific year. The weather data is taken from the data point with shortest distance to the geographical middle point of the segment in question.

In scenario B and C, the model is allowed to use electricity storage, which is included into the equation to compare production and demand. In the case of an excess in total production, the optimisation solver can choose to store electricity and in case of a shortage, stored electricity can be used, which is considered in the form of battery bulk storage units and pumped hydro power plants. This relationship is described in equation 3.1.

$$D(t) = P(t) - E(t)_{to\,storage} + E(t)_{from\,storage} \tag{3.1}$$

where:

D = Electricity demand over all road segments
P = Electricity production from all installed power plants
E = Transfer of electricity from or to storage

The amount of available energy to be taken from or saved to the storage at a time step depends on the storage level at the previous time step, the available storage energy capacity and the maximum power flow to and from the storage. This is shown in equations 3.2 to 3.4 which are applied separately for every storage technology in the model.

$$S(t) = S(t-1) - E(t)_{from\,storage} + E(t)_{to\,storage} \cdot p_{eff} \tag{3.2}$$

$$0 < S(t) < S_{max} \tag{3.3}$$

$$0 < E(t)_{from\,storage}, E(t)_{to\,storage} < E_{max} \tag{3.4}$$

where:

S = Storage level
p_{eff} = Roundtrip efficiency of the respective storage technology

4

Data

The optimisations carried out for this work consist of the models described in chapter 3 combined with value assumptions and data sets on weather conditions for renewable energy production, amount of traffic and the energy needed for vehicles to travel through the road segments.

4.1 Value assumptions

Table 4.1 shows the values used for parameters in the optimisations and their respective literature references.

Table 4.1: Assumptions on values used in the models

Parameter name	Value	Reference
Wind onshore		
Investment cost	1100 €/kW$_{el}$	[32]
Economic lifetime	25 years	[32]
Geographical density of installed capacity	0.45 MW/km^2	[33]
Solar photovoltaic		
Investment cost	2800 €/kW$_{el}$	[32]
Economic lifetime	25 years	[32]
Geographical density of installed capacity	0.75 MW/km^2	[34]
Battery storage		
Investment cost in terms of power	500 €/kWh	[21]
Economic lifetime	15 years	[35]
Rate energy/power	1 Wh/W	[35]
Roundtrip efficiency	95 %	[36]
Pumped hydro power storage		
Investment cost	650 €/kW	[30]
Economic lifetime	60 years	[20]
Rate energy/power	285 Wh/W	[37]
Roundtrip efficiency	95 %	[37]
Discount rate to calculate annual investment costs	8%	
Width of corridor along the road to place power plants	60 km	
Efficiency of power transmission from net to vehicles	80 %	[19]

All production and storage technologies are characterised by their initial investment cost and economic lifetime. In the models, they are compared on the basis of their annualised investment costs, given a discount rate of 8 % and the respective life times.

Wind and solar power are usually arranged in a park structure, but not the whole area around the road can be used for these parks. The values for the geographical density of installed capacity in table 4.1 result from a reflection taking into consideration previous attempts [33] and the topography of Western Norway. A maximum distance of those parks to the road has to be defined, which is done according to the requirements of scenario A (where no storage is available) combined with the complete self-sufficiency model. The amount of installed power has to be sufficient to cover demand at all times and enough space for the needed wind and solar farms has to be available. The electricity balance is calculated for the road as a whole, therefore the needed area is made up of all road segments together. A corridor next to the road is chosen in such a way that the optimisation is feasible with the least possible width which is found to be 60 km.

The storage technologies are set to have a ratio between their storage capacity and the power with which they feed in the electricity back into the net, i.e. one technical configuration. For batteries, the ratio is 1 Wh/W while pumped hydro storage power plants in Norway reach an average value of 285 Wh/W. Table 4.2 illustrates the cost difference between battery and pumped hydro storage with comparing the costs in terms of power and storage capacity. The assumptions on prices for battery and pumped hydro storage were connected with the assumptions on the ratio between storage capacity and power flow. As it was mentioned in chapter 2.3.4, it is assumed that hydro storage power plants are constructed refurbishing existing hydro power plants. The investment costs reflect this case for Norway.

Table 4.2: Assumptions on investment costs of storage technologies.

	In terms of power	In terms of storage capacity
Pumped hydro storage	650 €/kW	2.28 €/kWh
Battery storage	500 €/kW	500 €/kWh

For some of the assumptions sensitivity analyses are carried out and the results can be found in chapter 5.3.

4.2 Wind

The wind data is retrieved from the Norwegian Meteorological Institute. It contains the wind speeds projected and modelled for a height of 100 meters with a data point for every three hours in a grid with a resolution of 11 km. Three years are picked as an input to the optimisations to resemble years with high, medium and low wind speeds and corresponding yields. Possible years to fulfil the criteria are found by comparing the average wind speed of the respective year from a time span between

1990 and 2015. The average wind speeds between 1990 and 2015 can be found in figure 4.1. The years chosen for the optimisation are 2015 (high wind speeds), 1998 (medium wind speeds) and 2010 (low wind speeds).

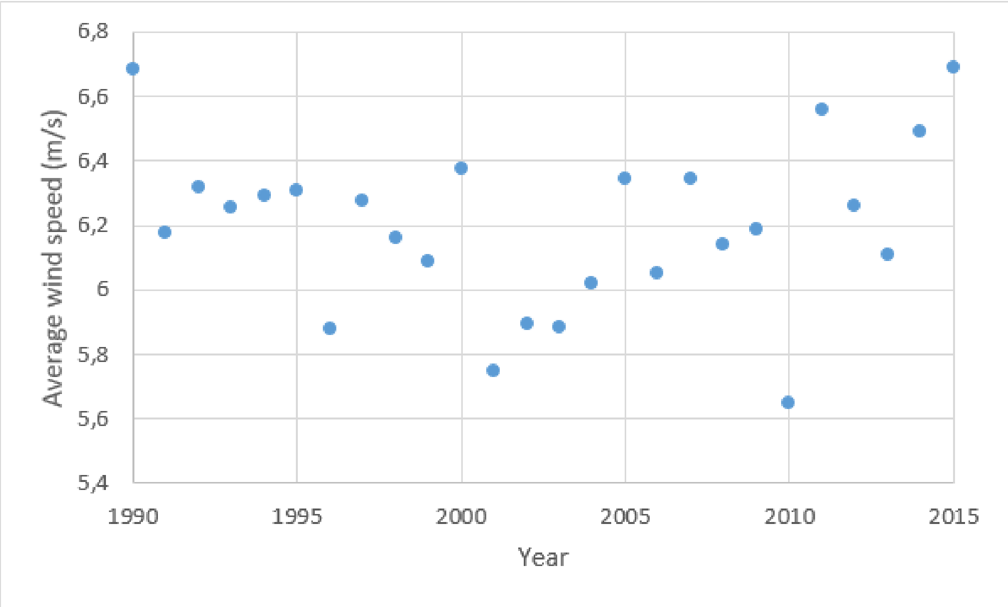

Figure 4.1: Average wind speeds in the received data (Western coast of Norway) for the years 1990 to 2015. The years chosen are 2015 (high wind speeds), 2010 (low wind speeds) and 1998 (medium wind speeds).

To transfer the information about wind speeds into possible electricity production, a power curve is calculated according to the method proposed in [38]: A wind turbine with a power of 2 MW is taken as a base reference and losses in aerodynamics and mechanical friction as well as effects of wind parks and electricity networks are taken into account. With the help of the generated power curve the wind speed information is translated to a power output for a turbine. To be used in the model described in chapter 3, the power output is calculated as a share of the maximum possible output. This factor never reaches one, because the procedure includes the possibility that some turbines are always stopped for maintenance or failures and park effects like turbines ending up in wind shadows of others. The maximum hourly capacity factor observed during the optimisations was 0.93.

4.3 Solar irradiation

Information about the irradiation from the sun is taken for the three years chosen in section 4.2 corresponding to high, medium and low wind speeds. This is done to give a realistic picture of the weather conditions and a combined production from wind and solar power. The solar data stems from the meteonorm database with a resolution of 100 km [39]. A method described in [27] is used to translate the information on direct and diffuse radiation into a production factor similar to the one described for the wind data. In this calculation method different technologies to use solar power are compared and the most suitable are chosen for the area in question.

4.4 Traffic

The Norwegian public roads administration runs a database with a vast amount of information about the road system in Norway. Among other things, the record of traffic counting points is publicly accessible. There are two types of traffic recording units that are interesting for this study. Along the E39, around 70 points are installed that record the number of vehicles passing for every hour. They are not equally distributed along the way, but show a denser pattern close to larger settlements. Another type of counting point documents the average amount of vehicles per day (average daily traffic) over one year and the share of heavy vehicles in the traffic. The data for the average vehicle amount is available in a higher spatial resolution than the hourly vehicle amount (770 locations).

The hourly measurement is used to generate a distribution profile over the hours of the year. Every of the 770 counting points recording average daily traffic is assigned to the geographically closest of the 70 hourly measurement point. In that way a distribution profile for the average daily traffic counting point is created.

Data is taken for the most recent year available, 2014, and profile data is filled up with data from 2013 if information is missing, for example due to technical failures. This filled-in information is however scaled up by the average increase between those two years. In the models, the traffic numbers are used without altering and it is assumed that all vehicles in the data are fuelled by electricity. The numbers used in this report therefore reflect a scenario with an amount of electric vehicles comparable to today's total traffic volume.

4.5 Required energy

The energy a vehicle needs while travelling through a segment is calculated from information about the road characteristics, taken from the database of the Norwegian public roads administration, and assumptions about the average characteristics of two kinds of vehicles. The road information includes topographical data, surface roughness and speed limits.

The traffic is split into large and small vehicles, with the former represented by a lorry with a mass of 40 tons and the latter by a car with a mass of 1.5 tons. A model to calculate the fuel demand of vehicles travelling through the road segments was used according to Taljegård, Göransson, Odenberger, *et al.* (2016) [40]. Assumptions taken into the calculation can be seen in table 4.3.

Table 4.3: Assumptions on values used in calculating the required energy of the selected vehicle types.

Parameter	Passenger cars	Lorries
Air temperature	8 °C	8 °C
Mass	1.5 tons	40 tons
Front area vertical to flow	2.3 m^2	9.7 m^2
Drag coefficient	0.3	0.53
Acceleration	2 m/s^2	1 m/s^2
Constant load used for in-car-appliances, e.g. air conditioning	1500 W	3000 W

The total electricity demand throughout the year adds up to 0.98 TWh which includes the efficiency of power transmission from the electricity system to the vehicles. The peak demand in terms of power lies at 376 MW. The demand of the vehicles running on the road changes in long and short-term patterns (see Figure 4.2). It is shifting between seasons due to different traffic, e.g. during holidays, and through the course of one day. It changes between close to nothing at night to a maximum between 250 and 370 MW at the peaks on Fridays which is the busiest day of the week. General electricity demand behaves similarly with a change between day and night time.

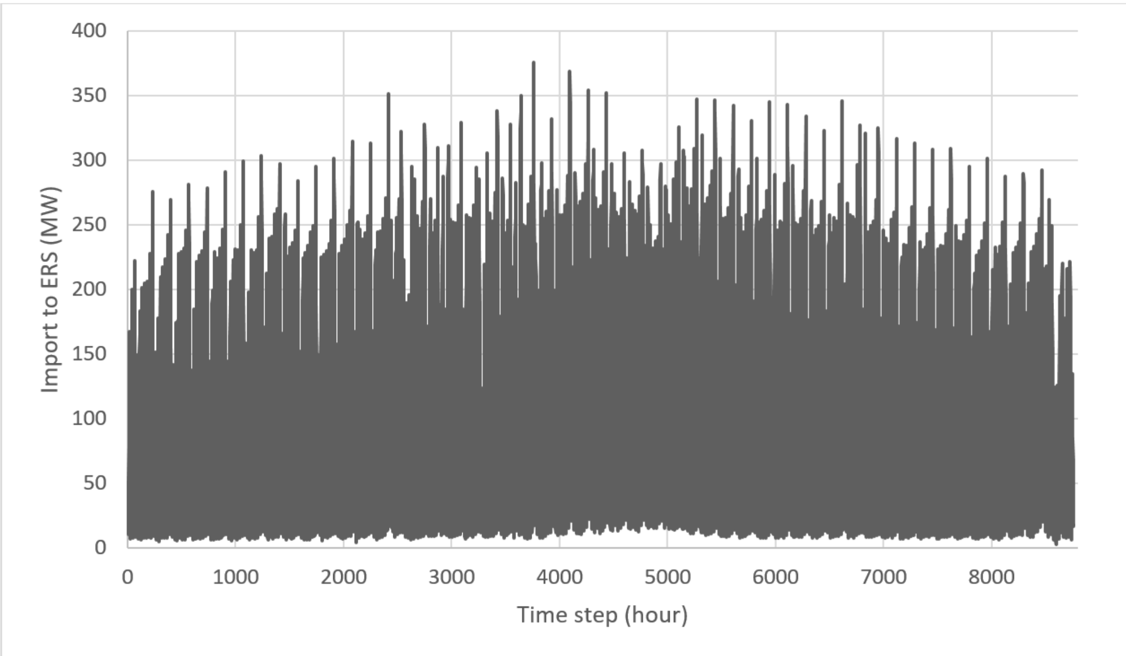

Figure 4.2: Electricity import to the ERS with no investments allowed. All demand is covered by the surrounding electricity system.

5

Results

This study is carried out by using two models, a complete self-sufficiency model minimising investment costs and an import model minimising the import of electricity from a surrounding electricity grid. Both models were executed with three different wind years and three different scenarios concerning technology options. The E39 in Western Norway is used as a case study. Furthermore, a sensitivity analysis is carried out and implications for a realisation of an electrified road E39 are illustrated.

5.1 Complete self-sufficiency model

5.1.1 Annualised investment costs through the scenarios

Figure 5.1 shows the annualised investment costs split by the different technologies for electricity production and storage included in each scenario for a year with medium wind speeds. It can be seen in figure 5.1 when comparing the three different scenarios that the results in annualised investment costs differ with as much as half an order of magnitude between the scenarios. In scenario A, with only wind and solar power plants allowed and using a year with medium wind speeds, the annualised investment costs are in the range of 1.05 billion Euros per year. In scenario B that allows for battery storage, the annualised investment cost is optimised to 272 million Euros and in scenario C which allows also for pumped hydro power the annualised investment cost ends up at around 46 million Euros. The mechanisms behind these results are explained in the following paragraphs.

This work considers a directly electrified road by an ERS. Therefore, in scenario A without the possibility to use storage options, the electricity production from solar and wind power has to be at least as high as the electricity demand from E39 at every hour of the year and the power system has to be dimensioned accordingly. This means that if very low wind speeds are present and simultaneously solar irradiation is low, a lot of capacity has to be installed to still fulfil the demand at that certain hour. In fact, the hour within the year with the lowest possible production compared to demand is decisive for the amount of capacity to be installed. For other parts of the year with better solar and/or wind conditions, the wind turbines and solar modules will then produce a lot more electricity than is needed to fulfil the demand from E39 (see figure 5.2).

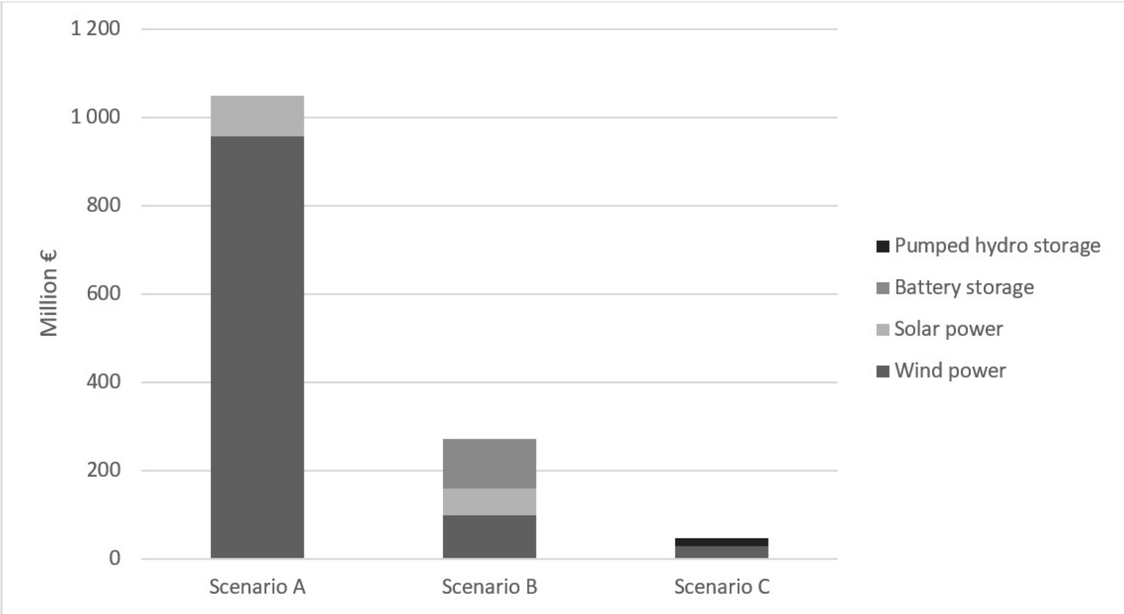

Figure 5.1: Annualised investment costs split by the technology used in each scenario for a year with medium wind speeds.

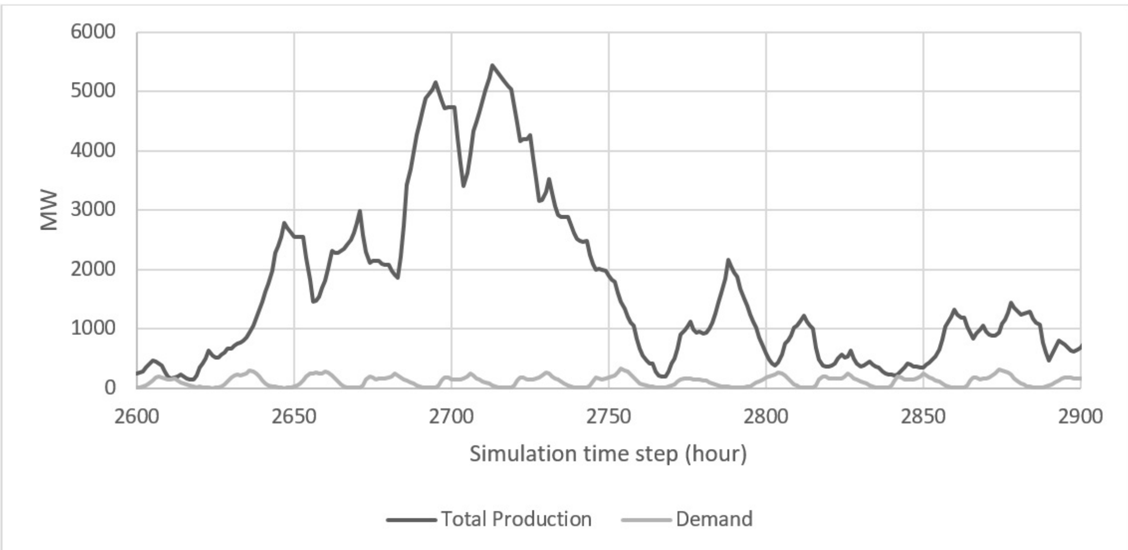

Figure 5.2: Hourly production and demand during two weeks in April for scenario A using a year with medium wind speeds.

In scenario B, the overproduction of electricity can be made useful by using electricity storage. Batteries as storage technology allow to store electricity production from one hour with overproduction of electricity to an hour when electricity production from wind and solar power is lower than the demand for electricity, see figure 5.3. Electricity transferred to batteries is not stored for a longer time, but used again rather quickly after the initial charge as seen in figure 5.4. The short time in the using patterns indicates that the batteries are used to bridge short production shortages and not to mitigate production differences between different parts of the year. The ratio of power flow to storage capacity for batteries is assumed to be one in the models and the optimisation prefers batteries for the storage capacity, not for their ability to take in a large power flow at a time, which can be derived from the fact that power flow to batteries always remains below the maximum possible value.

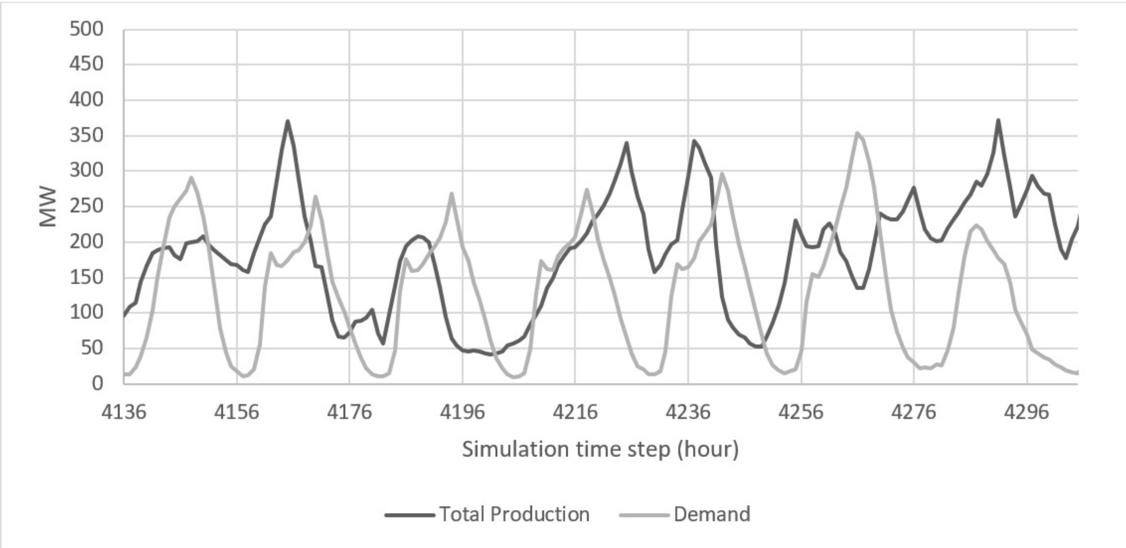

Figure 5.3: Hourly production and demand in MW during one week in summer for scenario B using a year with medium wind speeds.

Given the assumptions on costs for pumped hydro storage, the model for scenario C results in the lowest annualised investment costs compared to the other scenarios and show an investment only in pumped hydro power storage combined with wind power. The optimisation chooses this combination, because pumped hydro power storage is cheaper than batteries in terms of storage capacity (see chapter 4.1), while wind power in the investigated regions is able to produce more electricity throughout the year compared to solar power. The higher production of wind power is reflected in the capacity factor: For wind power and solar power in Western Norway, this factor is 0.256 and 0.123, respectively, for the year 2010.

The ability to balance electricity production over a longer time can be seen in the storage level of pumped hydro storage power plants in scenario C. With stronger wind during winter, the production levels are higher during that time of the year. In case production is higher than demand, electricity is then transferred to storage. During summer, with lower wind speeds, more electricity is used from the storage

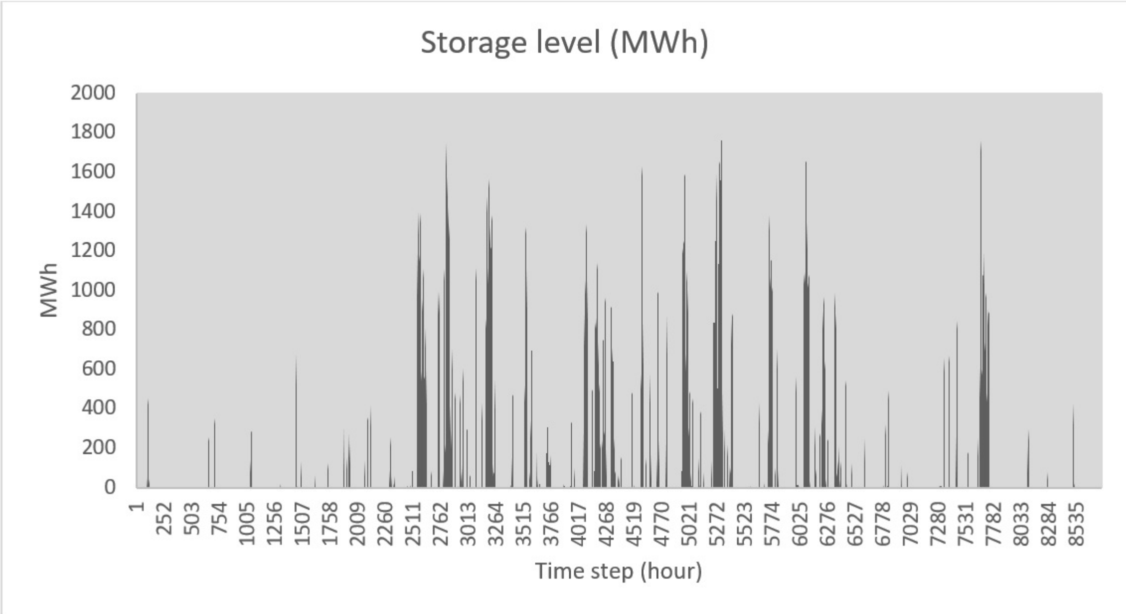

Figure 5.4: Charging level of battery storage in scenario B using a year with medium wind speeds.

to cover the demand (see figure 5.5). The storage level during the year rises during winter when wind production is higher and decreases again during late spring.

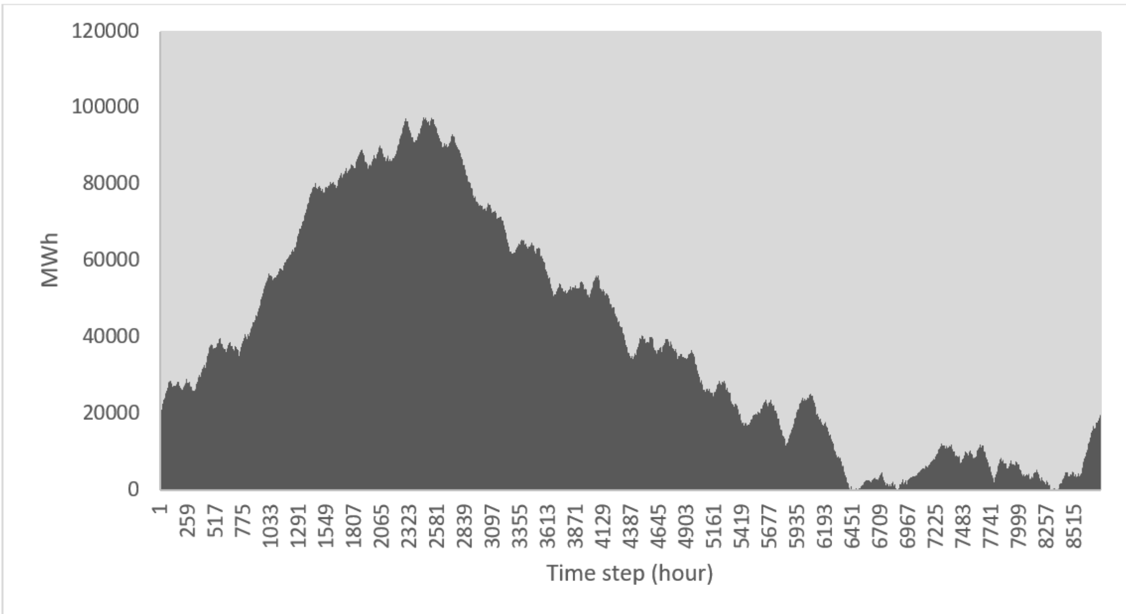

Figure 5.5: Storage level of pumped hydro power in scenario C using a year with medium wind speeds.

5.1.2 Wind speed years

In order to execute the models under different conditions, three different years are used in terms of wind and solar irradiation profiles. With different data fed into the optimisation, a change in capacity investment considered optimal can be achieved. By comparing the results for different wind speed years, the models' behaviour can be examined considering e.g. defining factors for needed capacity and the interplay of production and storage.

The amount of production capacity invested in for scenario A is determined from the hour with the largest production shortage compared to demand. More specifically, the dimensioning hour for scenario A occurs where the ratio between high demand and low production is the largest, e.g. at rush hour times during a calm day in winter, when the sun has not risen yet. Windless winter days could occur along the whole road every year and it is random at what times and for how long they appear. This situation is not connected to the average wind speed or other categorisations for the wind speeds during a year. Therefore, it is possible that years with high average wind speeds can result in higher investment volumes in generation capacity than years with lower average wind speeds as it can be seen in figure 5.6.

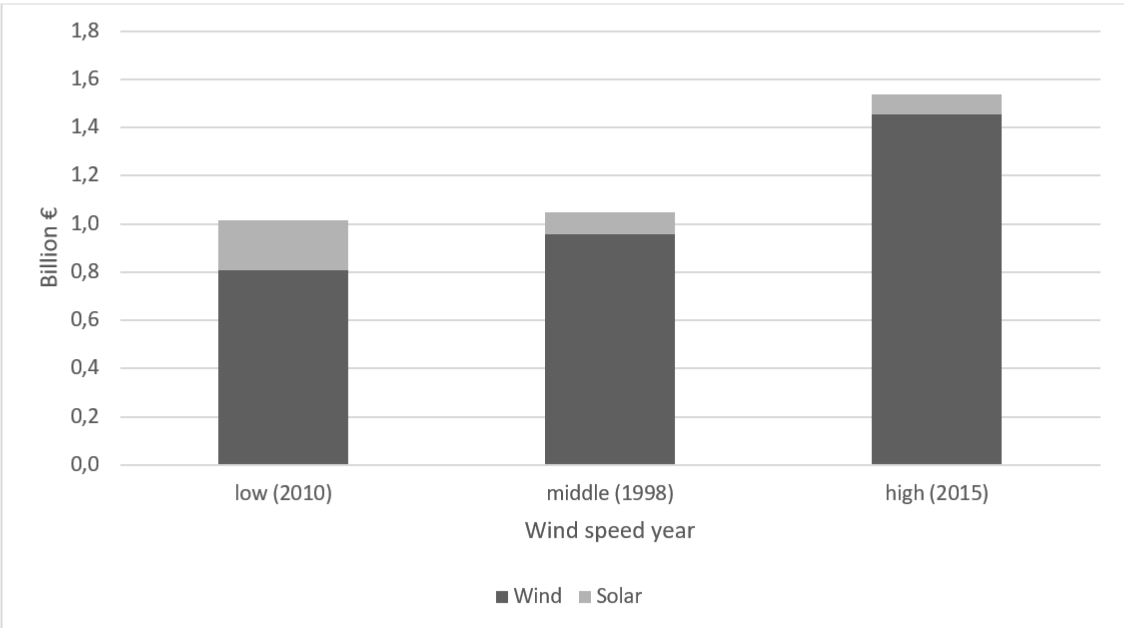

Figure 5.6: Annualised investment costs in scenario A using a year with high, medium and low average wind speeds.

In scenario C the produced electricity is stored over long time periods, therefore less installed production capacity is needed to fulfil the demand. Because a strong wind year allows more production throughout the year from wind power than a weak one, the investment into pumped hydro power is increased slightly between a weak and strong wind year in order to store the higher amount of electricity (see figure 5.7). A slightly higher capacity is considered optimal to be able to store larger amounts

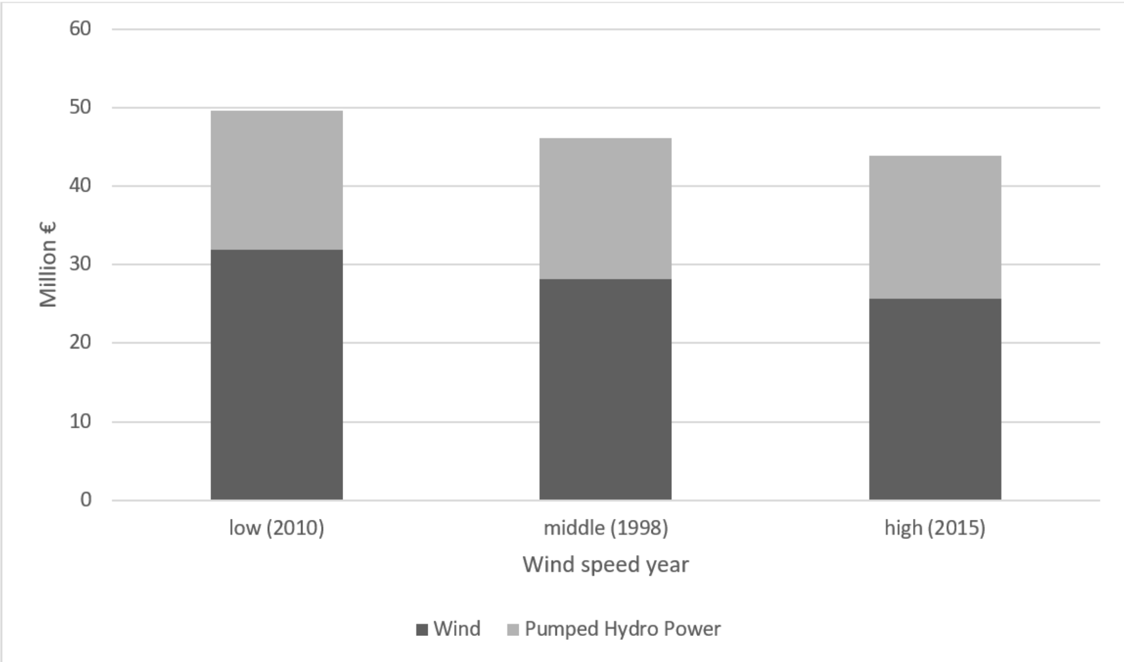

Figure 5.7: Annualised investment costs in scenario C using a year with high, medium and low average wind speeds.

of electricity over a long time period. A small part of the production is not saved into storage but curtailed (see chapter 5.1.3). It is cost optimal to have a little more installed production capacity than necessary if one would just look at how much electricity is needed over the year, since additional storage would have a very low marginal use.

In scenario B, one can observe a mixture between building up more production capacity and investing into storage to use electricity at low production times. Battery storage is more expensive than pumped hydro storage calculated per Wh storage capacity. Long term storage means low usage, therefore the capital cost is concentrated on few Wh stored. If longer time periods have to be bridged, it can therefore be more cost effective to invest in additional production instead. The behaviour of the optimisation in scenario B can be described as a mix between characteristics from scenario A and C: In general, higher wind speeds mean more production that can be stored and used in other hours, however, a long and large production shortage can lead to the need of larger investments. How long the periods with low wind speeds last is not connected to the average wind speed of a year. In Figure 5.8, one can see that for scenario B investment costs are higher for a medium wind speed year than for a weak or a strong year due to the longer time span of low production times.

5.1.3 Overproduction

In scenario A, overproduction occurs at every hour except for the one that decides the minimum level for installed capacity. The characteristics of overproduction can

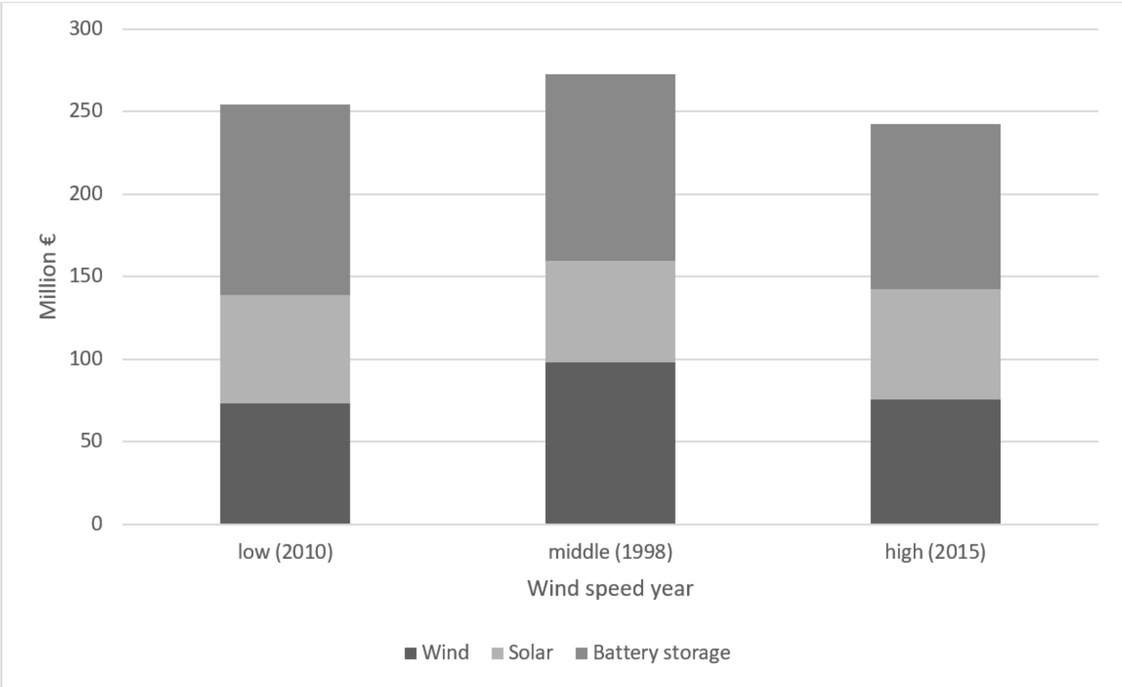

Figure 5.8: Annualised investment costs in scenario B using a year with high, medium and low average wind speeds.

be examined in terms of electric power and energy produced. In an electricity system setting like in scenario A, the power being produced in excess is related to the amount of power installed and only a small share of the capacity i actually used during the year. If the power plants produce electricity at their maximum capacity, a large overproduction will occur. The largest overproduction power through all optimisations occurs in scenario A, using a year with high average wind speeds. In that case, overproduction peaks at 13.1 GW (see table 5.1). In comparison, the power demand of the vehicles travelling on the road does not excess a peak power of 376 MW throughout the year.

Table 5.1: Maximum overproduction in MW in different wind speed years and scenarios.

	Scenario A	Scenario B	Scenario C
Low wind speed year	7155	676	281
Medium wind speed year	8393	875	249
High wind speed year	13103	705	225

In terms of produced electricity throughout the year, it is interesting to compare the numbers found in table 5.2 with Norway's overall electricity production. In 2014, 142.0 TWh of electricity were produced (of which 2.2 TWh from wind power and 21.9 TWh were exported) [41]. As one can see from table 5.2 in scenario A, depending on the chosen year (a year with higher or lower wind speeds), the road's power plants could produce between 13 % and 30 % of today's electricity production in Norway

Table 5.2: Sum of overproduced electricity throughout the whole year in TWh in different wind speed years and scenarios.

	Scenario A	Scenario B	Scenario C
Low wind speed year	18.25	1.60	0.08
Medium wind speed year	22.75	2.01	0.08
High wind speed year	42.42	1.85	0.04

assuming sufficient transmission capacities. In contrast, the energy demand of the road throughout a year sums up to 0.98 TWh (see chapter 4.5). As can be seen, to cover the energy demand of the road, only a small generation capacity would be required. But under the premise of not allowing the import of electricity from the electricity net and not using storage, the generation system becomes very large to be able to supply the required capacity at all times.

In scenarios B and C overproduction occurs although storage is in place due to the fact that it is not cost effective to invest in enough storage and thereby not all production can be stored and instead has to be exported or curtailed at certain times of the year. In scenario B, the results show lower levels of storage capacity than in scenario C. Therefore, battery storage is less likely to take in the full amount of electricity being produced minus the demand. Both the overproduction power peaks and the total electricity overproduction over the year are higher for battery storage compared to pumped hydro.

5.1.4 Area use of wind and solar power

The power plants calculated to be installed in the optimisations are assumed to be arranged in a farm structure. That means that several turbines or solar arrays are installed in a small area to keep installation and maintenance costs low. The average density of how much capacity can be installed in an area can be used to calculate the land use of the installed farms. The results can be retrieved from table 5.3

Land use of battery storage facilities is not included in the calculation and pumped hydro storage is assumed to be converted from regular hydro power and is therefore not calculated as covering additional area.

Table 5.3: Area use of wind and solar PV farms in km^2 in different scenarios and different wind speed years.

	Scenario A	Scenario B	Scenario C
Low wind speed year	18471	1910	688
Medium wind speed year	21100	2430	606
High wind speed year	31750	1971	553

To compare numbers in table 5.3, the Norwegian county of Rogaland (which is one of the regions the road crosses) covers an area of 9376 km^2 and the city of Oslo has an area of 481 km^2.

5.1.5 Cost per kilometre driven

The total amount of investments in the different scenarios can also be displayed as investment cost per vehicle per kilometre driven on the road. The results give a hindsight to what customers would have to pay if that system was in place (see table 5.4). The results are calculated by dividing the annualised investment costs with the total vehicle kilometres, i.e the traffic numbers multiplied with the total amount of kilometres driven by vehicles on the road during one year. It is important to remember that investment costs for infrastructure are not included in these numbers.

Table 5.4: Cost per kilometre and vehicle in Eurocents in scenarios A, B and C and different wind speed years.

	Scenario A	Scenario B	Scenario C
Low wind speed year	39.30	9.83	1.92
Medium wind speed year	40.58	10.55	1.78
High wind speed year	59.48	9.38	1.70

5.2 Import model

The import model minimises the total amount of electricity being fed into the road system from an outside electricity system. The minimisation was run for different maximum annual investment costs, from no investments allowed at all (all electricity is received from the surrounding net) until the complete self-sufficiency condition is met. The results are presented for a year with medium wind speeds (1998).

5.2.1 Electricity import

Figure 5.9 compares the amount of imported electricity in the three scenarios using a year with medium wind speeds. All three scenarios show a negative logarithmic behaviour. The results reveal that, speaking for all scenarios, additional investments have a large impact when the total investment value is low, but an increase in the budget has a lower marginal value with a lot of money already being allocated to the project. The intersection of the graphs with the horizontal axis refers to the results of the previous section where no import from a surrounding electricity system is allowed.

Just as in section 5.1.1 the cost effectiveness of the combination of wind power and pumped storage power plants in scenario C is visible in figure 5.9. Already for comparably small investments of 15 million Euros (annually speaking), scenario C

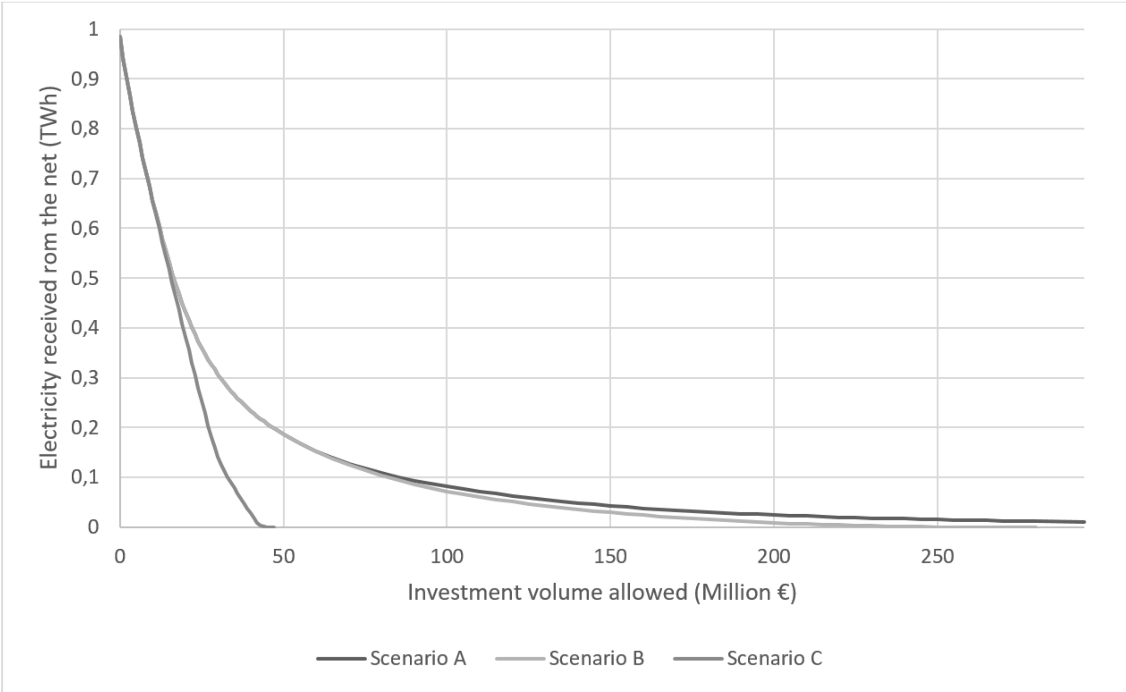

Figure 5.9: Electricity received from the net as a function of the annual investment volume allocated to the project for all three scenarios using a year with medium wind speeds.

shows lower imports of electricity from the regional system than the other two scenarios. On the other hand, the differences between scenario A and B are relatively small. Battery storage can help the system to achieve more independence from a connected regional system compared to a no storage option, but it cannot bridge seasonal production differences or shortages in the range of days as explained in section 5.1.1. Therefore, the total amount of avoided imports from the surrounding system is rather small compared to scenario A. The negative logarithmic characteristic of the graph explains the large difference between the two scenarios in the complete self-sufficiency model of the previous section, the intersection with the x-Axis is at a far higher investment volume for scenario A than for scenario B.

5.2.2 Installed capacity for different investment levels

In all three scenarios, the "first" millions are used to invest in wind power. As it was explained before, wind power can produce more electricity per amount of investment than solar power in Norway and is therefore more effective in avoiding imports from the surrounding system. But with a bigger investment volume at disposal, the optimisation starts to use other production and storage technologies to avoid imports.

In scenario A, at around 100 million €, solar power is invested in (see Figure 5.10). Solar power is beneficial in hours with very low wind speeds throughout all segments of the road. Solar power is invested in when the hourly capacity factor for a

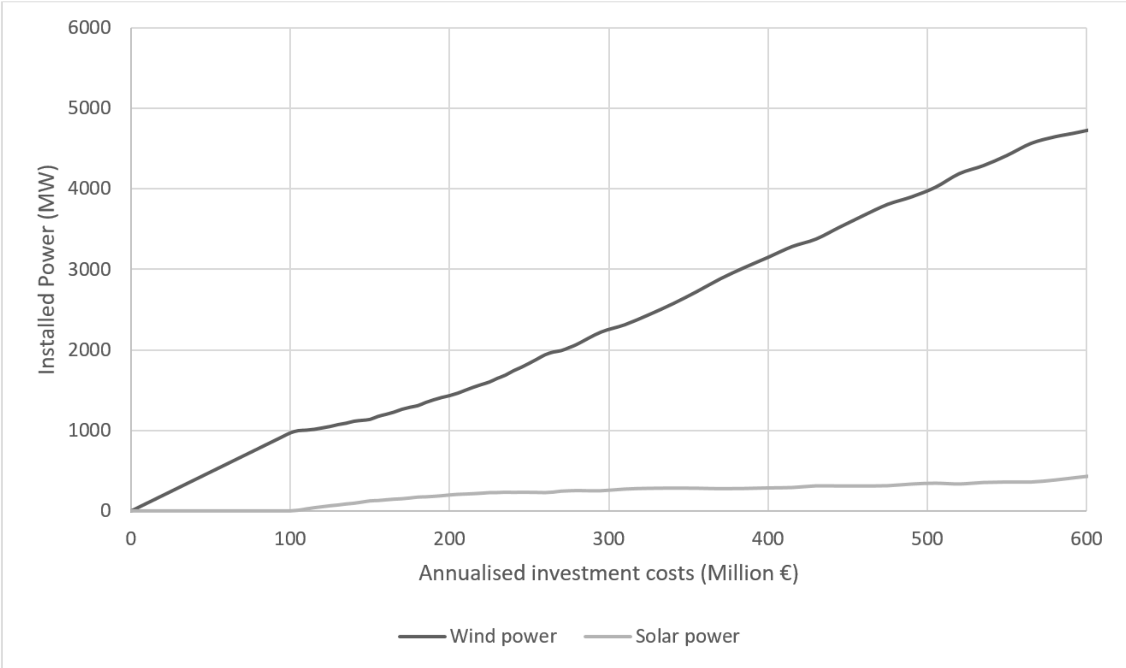

Figure 5.10: Import minimisation in scenario A, installed wind and solar power depending on allowed annualised investment costs using a year with medium wind speeds.

segment is higher for solar power than for wind. The potential is however limited and a behaviour similar to saturation is visible for higher investment volumes. More investment is then used to scale up the more abundant wind power to reach demand in hours where it was not effective with a smaller budget.

In scenario B, battery power is the first technology used to be added to wind power for covering the demand at around 45 million € annualised investments (see Figure 5.11). Solar power is first invested in at amounts of 115 million € for similar reasons as mentioned for scenario A. It is notable that both wind power and solar power reach a saturation with greater investments and battery storage is used to cover demand towards a greater self-sufficiency.

Pumped hydro power storage is used very early in scenario C, already at investments of 8 million € a built-up of pumped hydro storage is visible (see figure 5.12). At higher annualised investment costs , both wind power and pumped hydro power grow in comparable amounts, which reflects the fact that the optimisation considers it to be optimal to shift produced electricity between hours. It is more effective to accompany newly built-up production by storage options than to invest all of the additional investments into production.

5.2.3 Characteristics of electricity import to the ERS

The import characteristic for scenario A can be seen in figure 5.13 for a maximum volume of annualised investments of 100 million €. The imports have the form of

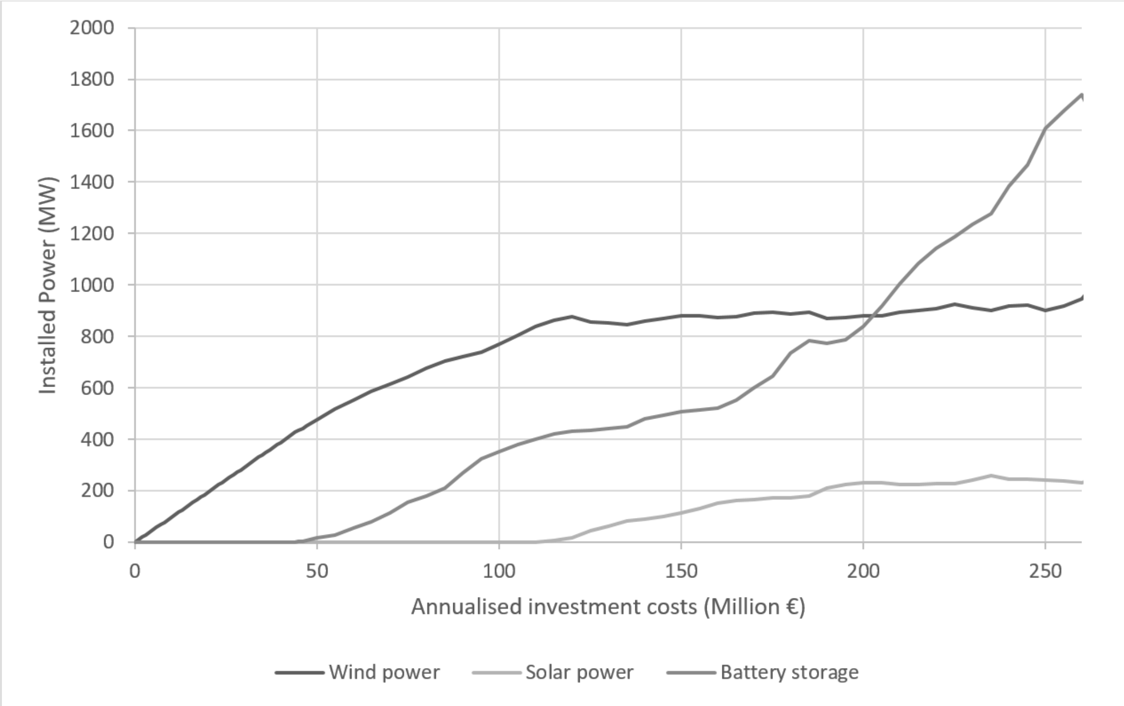

Figure 5.11: Import minimisation in scenario B, installed wind, solar and battery power depending on allowed annualised investment costs using a year with medium wind speeds.

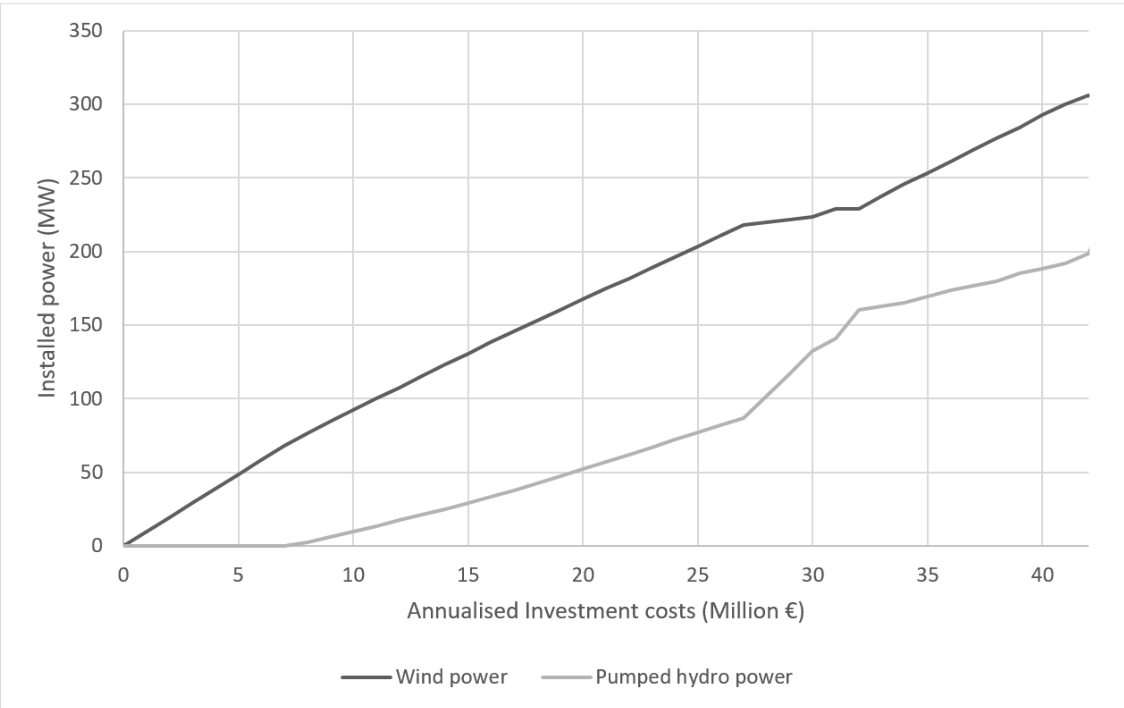

Figure 5.12: Import minimisation in scenario C, installed wind and pumped hydro power depending on allowed annualised investment costs using a year with medium wind speeds.

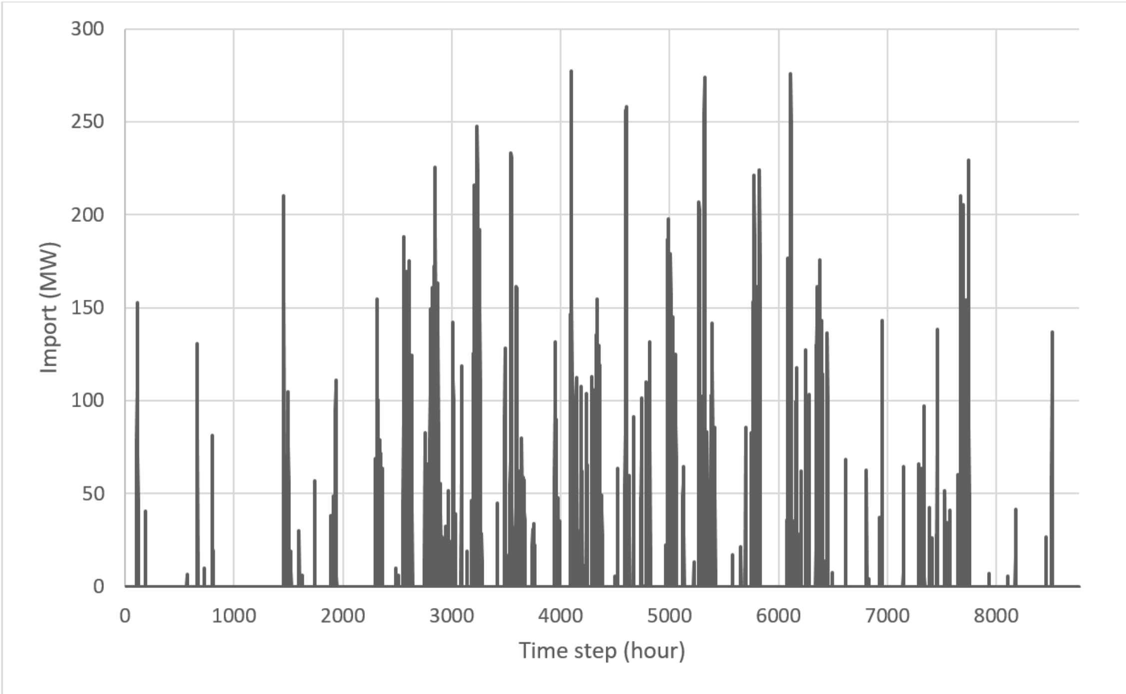

Figure 5.13: Import from the surrounding net (production deficit) in scenario A with 100 million € allowed investments using a year with medium wind speeds.

short peaks with a maximum duration of 22 hours and a maximum value of 277 MW. The peaks occur with a higher frequency for low import values, while the highest peaks are relatively rare. The frequency differences for high and low peaks are a different expression for the behaviour of the investment curves in figure 5.9, because the lower import peaks can be avoided with a slight increase of the total investment volume, while the larger ones crave a significant increase of the total investment volume. Since the higher import peaks (or in other terms the production deficits) amount to a smaller amount of energy than the lower peaks, a total investment volume increase has less of an impact just as it is resembled in figure 5.9 for higher investment volumes on the horizontal axis.

Batteries can help bridge the shortages, however, the potential is limited as described before. Figure 5.14 shows an optimisation with the same allowed investment as figure 5.13, but for scenario B. There are less low peaks occurring than for scenario A, but the height of the high peaks differs just slightly. The results indicate that the installed battery storage is exhausted quite quickly and too small for the electricity amounts needed to bridge the large production shortages. Some import peaks are even increased in their value, which is due to the fact that less of the total investment volume is distributed to production capacity and is instead used for batteries, which are exhausted before the shortage reaches its maximum.

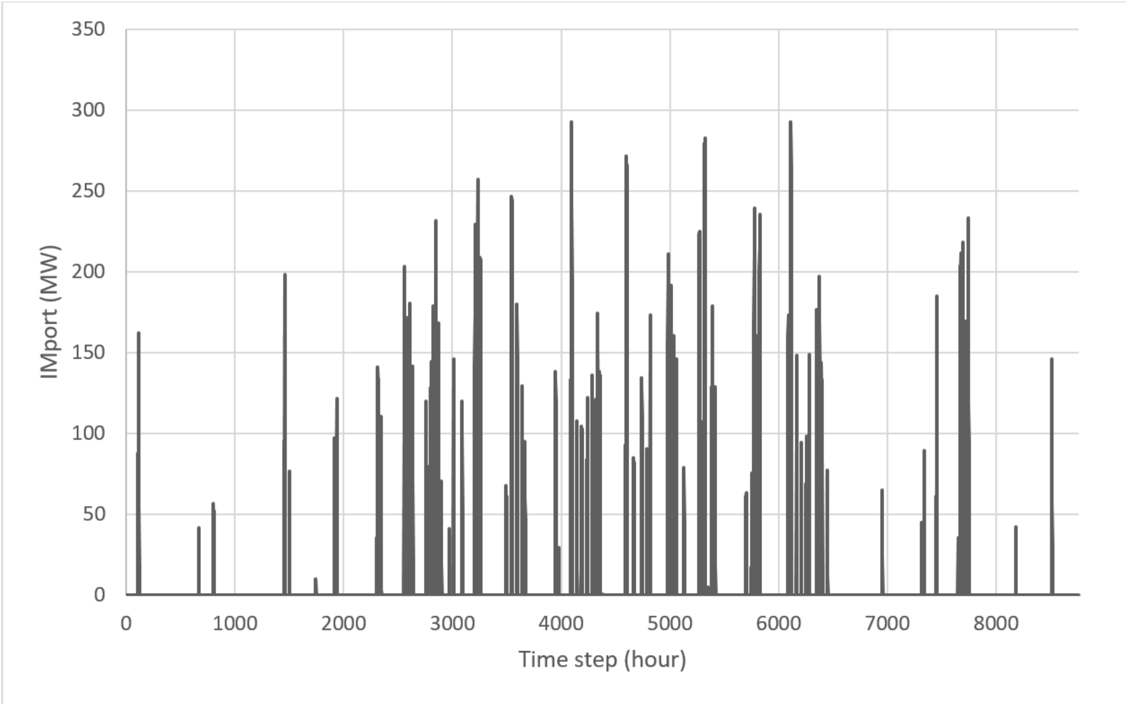

Figure 5.14: Import from the surrounding net (production deficit), scenario B, 300 million € allowed investments using a year with medium wind speeds

5.3 Sensitivity analysis

For selected parameters, sensitivity analyses were carried out. The parameters were: the area allowed to be used to install power plants, investment costs for different technologies and the ratio between storage capacity and generator power for pumped hydro storage power plants. For every sensitivity analysis, the complete self-sufficiency model was used and the average wind year (1998) was taken to determine the required investment into power and storage plants. Only the named parameter was changed, all others remained at their default values.

5.3.1 Area use

The size of the area surrounding the road allowed to be used for the investment of power plants is highly uncertain. To get exact data, the whole area has to be analysed thoroughly but to assess the impact of uncertain data, a sensitivity analysis on this parameter was carried out.

The allowed area of land to be used for building wind and solar PV farms was included in the optimisation as a share of the total area available. With a higher share of the land being allowed to use, regions with higher yields from renewable energy sources can be exploited to a higher degree. A higher exploitation means regions with lower capacity factors will be used less and in total less capacity has to be installed leading to lower investment costs. However, as it can be seen from figure 5.15, the effect is rather small. The small effect indicates that the regions in Western Norway would perform rather similarly in terms of renewable energy production, as the benefits of using the best regions are rather small compared to worse ones.

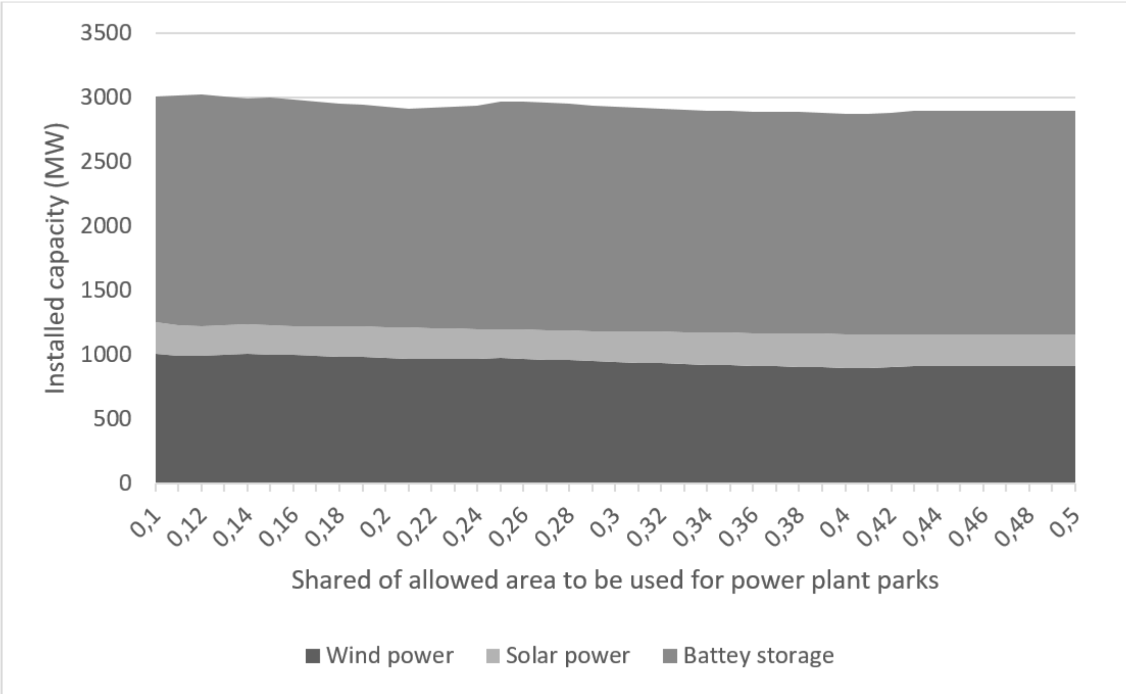

Figure 5.15: Self-sufficiency optimisation with varying settings for the allowed share of the area allowed to be used in scenario B using a year with medium wind speeds.

5.3.2 Battery cost

The cost for battery storage using lithium is expected to decrease drastically in the future. Therefore, it is analysed how the optimisations are influenced by lower battery prices.

A sensitivity analysis on battery costs shows that batteries are more used the cheaper they are (see figure 5.16). On one hand, more battery capacity is installed with lower prices, on the other hand a smaller share of the total investment volume is allocated to production capacity. Instead of investing in production units, more produced electricity is stored for later use. It is estimated that prices for Lithium batteries will fall to 200 US$ per kWh by 2020 [21]. For the investigated self-sufficiency scenario B with an average wind year, this price development would mean a reduction of total investment costs from roughly 270 Million € to 140 Million € at current exchange rates.

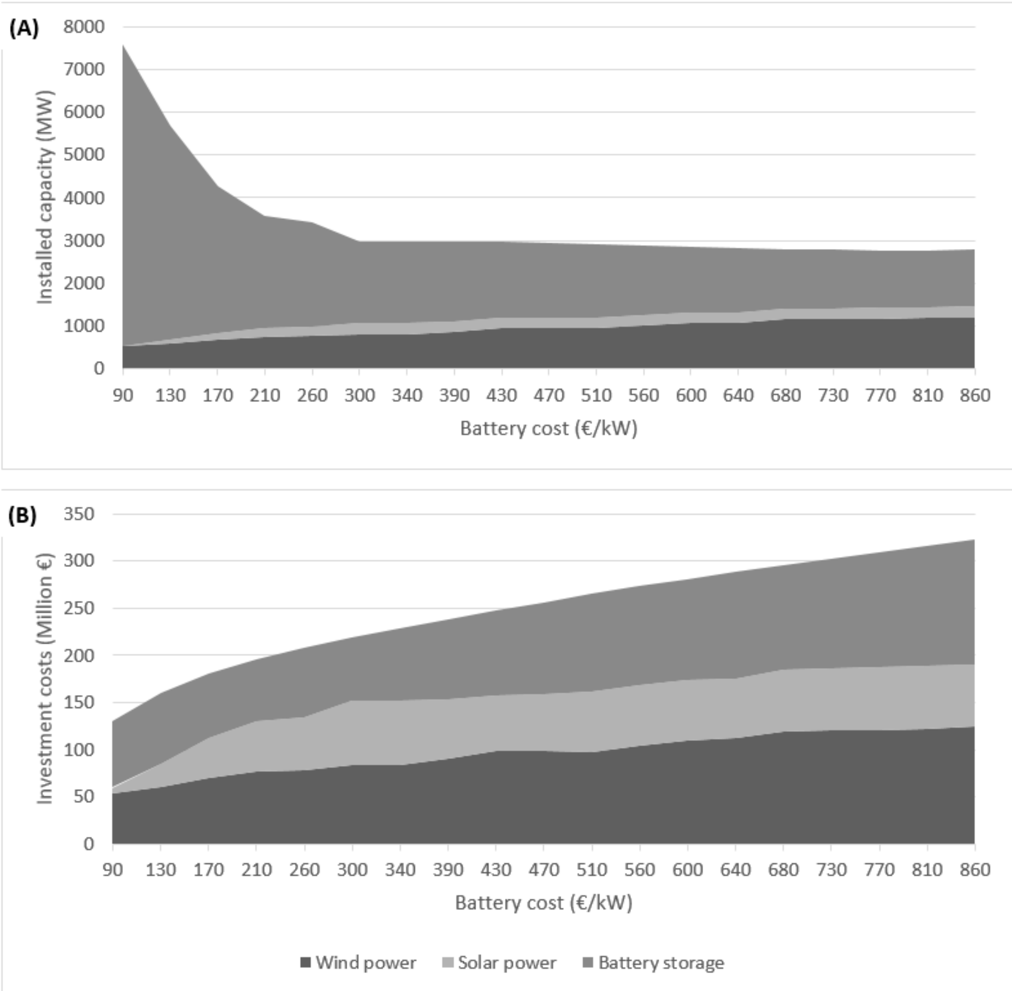

Figure 5.16: (A) Installed capacity and (B) investment costs in a scenario A self-sufficiency optimisation with varying values for the battery cost per Kilowatt-hour using a year with medium wind speeds. The assumed standard battery cost in all optimisations in previous chapters is 550 €/kWh.

5.3.3 Cost of pumped hydro storage

Norway is a country with large and abundant hydro power resources. Hydro power (also in its storage form of pumped hydro power) is a mature technology, so the costs for this technology are not expected to change greatly [20]. However, the costs are very dependent on the site and surrounding conditions, therefore it is interesting to see the optimisations' reaction on different pricing on this technology, also to allow conclusions for regions with other conditions than Norway.

As it can be seen from figure 5.17, when the cost of pumped hydro storage is changed, it has a low impact on the choice of installed capacity. Only with low costs below 300 €/kW, an increase of installed capacity for pumped hydro storage is observed. The total investment costs increase linearly for higher pumped hydro storage costs as no significant changes are made to the distribution of investments. For large costs above 900 €/kW, a very small share of investment into battery storage not exceeding 26 MW is visible, indicating that a mix of technologies can be suitable for high pumped hydro storage costs.

5.3.4 Cost of solar power

The costs of solar power have plummeted in recent years becoming competitive with classical generation sources in some few areas of the world. However, wind power is the preferred production technology in the optimisations. A sensitivity analysis for the cost of solar PV is carried out to examine how this technology mix is changed with lower prices for solar power.

The results of the sensitivity analysis (see figure 5.18) show a point where a reduction in costs per kW leads to a shift of investment from wind to solar power in scenario B. For a price reduction from 2600 €/kW to 1600 €/kW in scenario B, the amount of installed solar capacity reaches parity with the amount of installed wind power. In a sensitivity analysis with scenario C, no solar power was chosen in the technology mix despite of the cost reductions in the model.

5.3.5 Ratio between storage capacity and power for pumped hydro storage

Conditions are generally favourable for hydro power in Norway with high precipitation rates and large valleys to collect water in. In other European countries, conditions may be different than in Norway. One example is the size of the reservoir compared to the output of the generator.

In the results for scenario C (see figure 5.19) it can be seen that the amount of installed pumped hydro storage power (judged by power output) is not changed with the ratio of the reservoir sizes to the power output of the plants. The optimisation determines an optimal power output and the reservoir size regulates how much produced electricity can be stored. With higher ratios of storage capacity to generator power, less wind power plants are installed, because more energy can be saved and used from the storage.

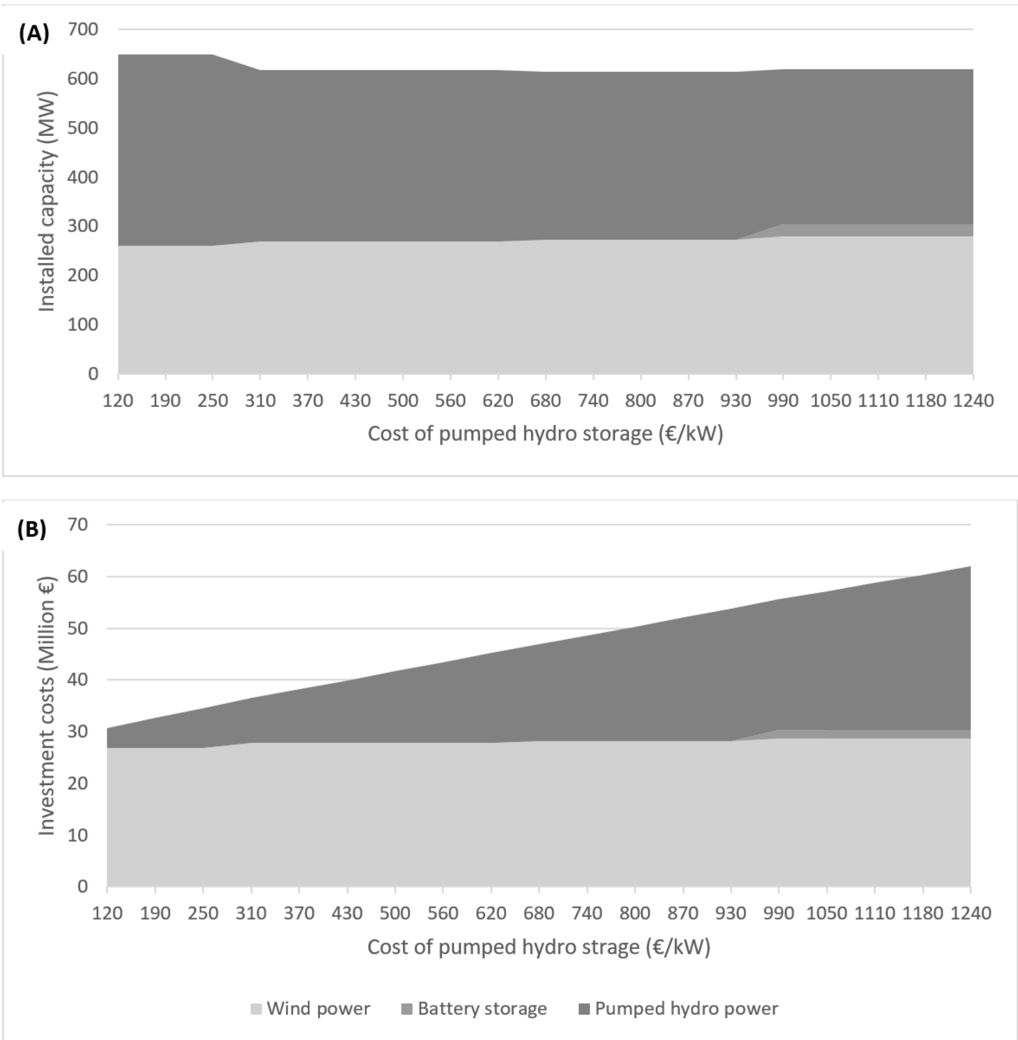

Figure 5.17: (A) Installed capacity and (B) investment costs in a scenario C self-sufficiency optimisation with varying values for the pumped hydro storage cost per Kilowatt using a year with medium wind speeds. The assumed standard pumped hydro storage cost in optimisations in all previous chapters is 650 €/kW.

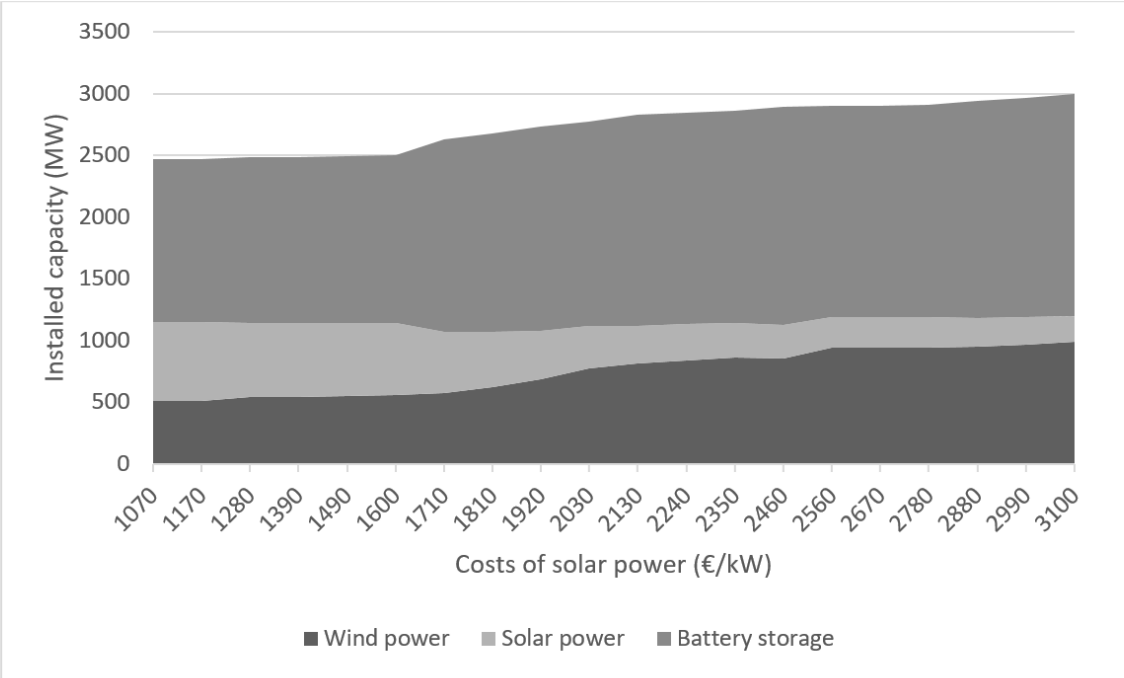

Figure 5.18: Self-sufficiency optimisation with varying values for the solar power cost per Kilowatt in scenario B using a year with average wind speeds. The assumed standard solar power cost in the optimisations in all previous chapters is 2800 €/kW.

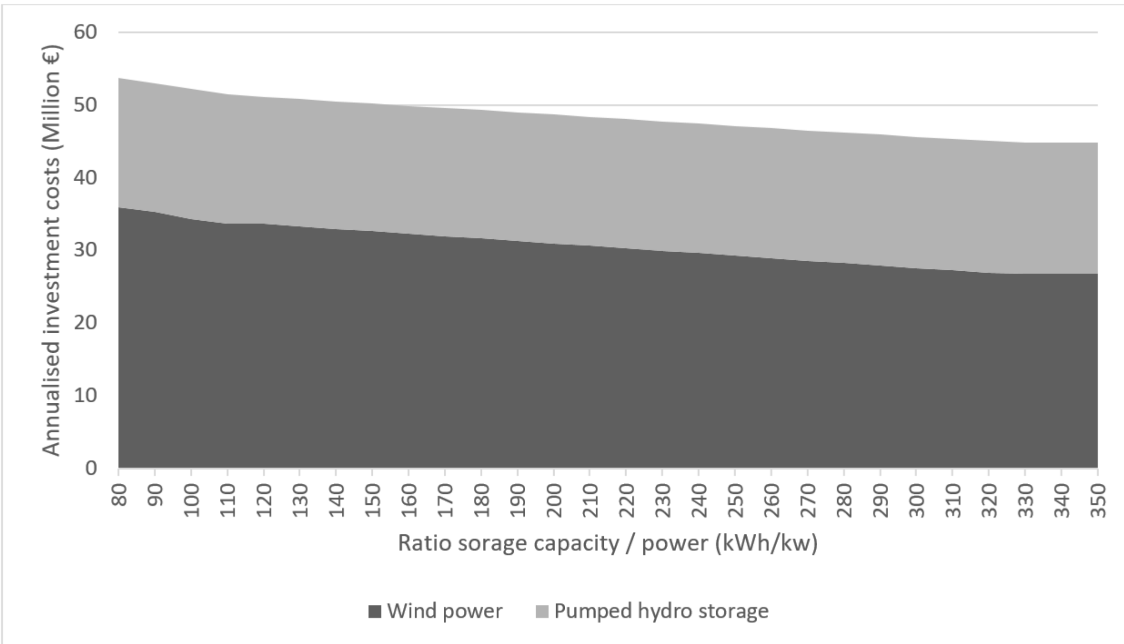

Figure 5.19: Self-sufficiency optimisation with varying values for the ratio between storage capacity and plant power in scenario C using a year with medium wind speeds. The assumed standard ratio in the optimisations in all previous chapters is 285 kWh/kW.

6
Discussion

The results of the optimisations showed a large difference in required annual investments between the three different scenarios. Investment costs are high for a completely self-sufficient ERS, but can be lowered by introducing battery or pumped hydro power storage into the system or allowing imports from the electricity net.

In the case of a completely self-sufficient ERS, combining wind power and pumped hydro power storage leads to a system with comparably low investment costs. Without pumped hydro power storage, the production system for the ERS becomes large and inefficient, large parts of the electricity production are either curtailed or have to be exported to the electricity net. In the case of not using any electricity storage for the ERS, the total electricity production over the year is 27.3 times higher than the total demand in a year with average wind speeds, when battery storage is included, production is still 2.2 times higher. This shows that covering demand in terms of power at all times of the year requires larger investments than covering demand in terms of energy. Pumped hydro power storage makes it instead possible to a higher degree to shift produced electricity between different times of the year. The use of saved electricity makes it less necessary to cover power demand at all times and therefore allows the production side to produce electricity to just cover demand in terms of energy plus efficiency losses.

The complete self-sufficiency optimisation according to scenario A is only allowed to use wind and solar power and thus relies on the principle that somewhere along the road, production has to be possible. The high investment costs point at the fact that geographical smoothing does not work efficiently with the road, because the regions are too similar in their production characteristic. With an effective geographical smoothing, the storage would have a lower impact and the scenarios would produce comparable results. Additionally, the high amount of installed wind and solar PV farms can pose acceptance problems with the local population.

The input to the optimisations carried out in this work include the investment costs for new generation and storage. However, cost calculations could be altered by also including revenue from selling electricity. Overproduction occurs in greater amounts in scenarios A and B than in scenario C and can potentially be used as a source of income for the company or the municipality investing in renewable energy power plants at the road side. Especially for scenario A with the complete self.sufficiency model, overproduction is large. If all production in this scenario was fed into the electricity net, Norway could increase its electricity production with up to 30 %.

Selling overproduction on the market craves investments into infrastructure. In scenario A combined with the complete self-sufficiency model, overproduction is larger than the transmission capacity of 9700 MW from the road's market regions to the surrounding ones for at least 1055 hours per year. Already today, transmission lines between Norway's power market areas are often congested, with the connections to Denmark and Southern Sweden being congested for more than 50 % of the time [42]. These lines have to be expanded massively to take over a large portion of the new generated electricity. It also remains in question if the electricity sold on the market will yield a satisfactory revenue, because other market areas, such as Denmark and Sweden, will also produce power from wind. At times with strong winds and thus high wind power production, prices will be low due to a large supply of power in the Nordic Market. Similarly, the stability of the electricity net will be affected by adding large intermittent production capacities in a region. This means that not only transmission capacity has to be increased, but also investments into other parts of the electricity net are needed to ensure frequency stability and a balancing of the intermittent production. For scenario C, overproduction might not be high enough for a realistic selling scenario as the transmission lines to the electricity net would be unused for most of the time.

When one considers the allowance of import from the surrounding electricity grid as seen in chapter 5.2, a variety of combinations are thinkable that yield lower investment costs than the self-sufficiency model with scenarios A and B. The amount of production power to be installed is then determined by a trade-off between the costs of buying electricity from the net and of building up production and infrastructure. Admittedly, the grid connection to the road then has to be dimensioned as if no production was present at the road to include cases when no power production is possible, which goes against the aim to reduce pressure to the electricity system stated in the beginning of this work. Moreover, the connection has to be constructed to be able to transmit electricity in both directions with the same power and should allow a high flexibility considering a rapid change in power flow. On the other hand, the energy balance of the total grid over the year will not be changed significantly, because additional demand is covered by new production and Norway's abundant hydro power resources can shift produced electricity around the year and react to load changes within a short time. The placement of the wind and solar power plants and the connection to the electricity net has to consider the architecture of the net to keep infrastructure investments low.

The costs per kilometre driven that were calculated in table 5.4 can be compared to fuel costs for cars of today. Gasoline car owners spend around 10 euro cents per kilometre [43] and electric car owners between 2 to 3 cents [44]. The results in the optimisations show costs of 22 to 25 cents for a completely self-sufficient road in scenario B and 4 to 4.5 cents for scenario C. Therefore, the investment costs have to remain on similar levels as the optimisation results for a self-sufficient road in scenario C to be competitive in today's conditions. One must also consider that the electrified road would allow the construction of vehicles with smaller or no batteries at all. Smaller batteries would allow significant price reductions compared to today's electric vehicles and should be considered in the decision process. Furthermore, possible overproduction can be sold on the electricity market and generate revenue for the road owner, thus decreasing fees for car owners. On the other hand, the costs for the investment in the charging infrastructure would increase the prices customers have to pay for using the road.

6.1 Opportunity for further research

To assess the long term costs for an electrified road using a connection to the surrounding electricity grid, a market model to simulate price developments has to be part of the optimisation. This could provide a useful insight to economically viable solutions apart from the focus on self-sufficiency of the road. On top of that, for realistic projects, the infrastructure costs have to be taken into account. These costs include the construction of the electrified road, the connection to its supply and possible transmission infrastructure to interact with the surrounding electricity grid.

Today's all-electric vehicles typically use a battery which opens up possibilities to interact with the production side and bridge short production gaps. This has the potential to lower investment costs as less investments are needed for storage. However, the impact of car batteries is very hard to predict as production shortages vary in length and the charging level of car batteries is decisive. To model the various charging states that are dependent on previous actions, a modelling approach different to the one in this work has to be used. It would include modelling the vehicles not as aggregates, but as individual units with a charging history. The model can be realised using probabilities for the behaviour of car owners in every time step, depending on previous actions. An example can be found in [10].

An assumption behind the energy consumption of vehicles travelling on the road is that all of them go with the same speed. To make the traffic more realistic, a speed distribution can be used and traffic jams can be taken into account as they influence the energy use and can even inhibit charging, e.g. because inductive charging is dependent on a certain minimum speed of the charged vehicles.

7

Conclusion

In this work, two different optimisation models were developed to assess the possibilities of electrifying the European road E39 connected to renewable electricity production with the aim to achieve a high degree of self-sufficiency. The first model optimised the investments in wind and solar power and storage technologies necessary to obtain a self-sufficient road system. The second model minimised the electricity import from the electricity net to the ERS in order to cover the demand for electricity from E39, assuming a fixed maximum investment volume.

It was shown that the most cost effective solution in the complete self-sufficiency model is to combine wind power production with pumped hydro storage. The pumped hydro storage balances both small production shortages and seasonal production differences. Investment costs were significantly higher with systems using only wind and solar production and allowing only batteries as storage options. With a combination of wind power and pumped hydro storage, prices for vehicle drivers using the road could be competitive to contemporary gasoline cars.

In other scenarios in the complete self-sufficiency model , electricity overproduction occurs in large quantities and can be sold on the electricity market. However, the selling will require large investments in infrastructure and it is uncertain if a satisfactory revenue can be generated.

Characteristics of investment and demand coverage were investigated for the model allowing imports from the electricity net. Additional investments into generation and storage were found to have a smaller marginal impact the more investments already had been made. It was concluded that lower investment costs than in the self-sufficiency model scenarios without pumped hydro power storage can be obtained through allowing electricity imports to the ERS. It has to be investigated how the surrounding electricity grid has to be reinforced to deal with the additional demand and how much power has to be installed along the road to achieve an optimal trade-off with importing electricity.

In conclusion it can be said that the most cost optimal solution is to combine wind power with pumped hydro power storage in a complete self-sufficiency scenario for the ERS. If no pumped hydro power storage is available, a connection to the electricity net should be established and cost calculations be made about how to balance between electricity import and own production.

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