Master Thesis

MSc Energy for the Smart City

Electrification of E18 highway: Renewables Integration Analysis

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List of Abbreviations

MT	Master Thesis
FCS	Fast Charging Stations
EV	Electric Vehicle
CAPEX	Capital Expenditure or Investment Cost
OPEX	Operational Expenditure or Operational Cost
PV	Photo-voltaic
EU	European Union
RES	Renewable Energy Sources
ERS	Electric Road System
LDV	Light Duty Vehicle
HDV	Heavy Duty Vehicle
kW	Kilowatt or 10^3 Watt
MW	Megawatt or 10^6 Watt
GW	Gigawatt or 10^9 Watt
kWh	Kilowatt-hour or 10^3 Watt-hour
MWh	Megawatt-hour or 10^6 Watt-hour
GWh	Gigawatt-hour or 10^9 Watt-hour
TWh	Terawatt-hour or 10^{12} Watt-hour
V2G	Vehicle-to-Grid
SoC	State of Charge
kWp	Kilowatt-peak
GE	General Electric
O&M	Operation and Maintenance
NPV	Net Present Value
IRR	Internal Rate of Return
SPBP	Simplified Payback Period
DPBP	Discounted Payback Period
SCF	Simplified Cash Flow
DCF	Discounted Cash Flow
PI	Profitability Index
KPI	Key Performance Indicator
ROI	Return on Investment

Executive Summary

This master thesis investigates a renewable energy integration to supply partially the E18 highway fast-charging stations, planned to be installed due to the electrification of the transportation sector.

First, the energy demand of those ones was simulated, considering an uncontrolled charging behaviour, which is more likely in an highway environment. Then, three clusters have been created in order to group the FCS and simplify the dimensioning of the renewable power plants.

The renewable capacity to install was then elected by considering three different case studies in a sensitivity analysis, each meeting a different share of the demand with greener energy.

Once, dimensioned accordingly, the generation performance was evaluated, adding the storage component of lithium-ion battery pack.

In the next step, the economical performance was evaluated by calculating different quantities to assess the investment: CAPEX, OPEX, revenues and finally a list of profitability indexes.

To conclude the analysis, an environmental assessment of the life-cycle impact of the introduction of renewable power plants compared to a business as usual scenario was conducted.

The two analysis lead to the conclusion, that all the scenarios represent a good investment, but some are more interesting both on the economical and the environmental point of view as will be shown in the end of the thesis.

1 Introduction

The recent introduction of the European Green Deal by the European Commission, pointed out that the transportation sector accounts for a quarter of the EU's greenhouse gas emissions, and still growing. As such, to achieve climate neutrality, a 90% reduction in transport emissions is needed by 2050 [2]. The electrification of the sector can effectively contribute to reach this ambitious goal, in particular if the electricity is generated by renewable energy sources.

The scope of the thesis is to conduct a renewable energy integration feasibility analysis to meet the increased electrical demand due to the proposed electrification of the E18 highway section between Kristiansand and Oslo [3], with the focus on a static-charging electrification scenario (A.2).

In particular, the integration of a mix of wind and solar capacity is investigated after a resource assessment in the area of the highway and in particular for the three clusters (see 5.1), in order to reduce the peak power needed to recharge electric vehicles travelling in the highway section and have a lower environmental impact in the electrification of the infrastructure.

The feasibility of integrate renewable energy sources, to fuel the electric vehicles, depends mainly on the return on investment (ROI), which nowadays is becoming more and more attractive due to the introduction of fees for the users of the recharging stations [4], as well as the green certificates that are awarded for each unit of renewable energy produced, no matter what the technology [5], [6].

Moreover, the feasibility clearly relies on the environmental impact that the introduction of new renewable capacity causes. Indeed, the effect of reducing the electricity generation with conventional technology is more impactful when high polluting generation is avoided [7]. As such, the integration of renewable capacity can really contribute to a sustainable electrification in those countries with a high share of thermal generation in the electricity mix relying on fossil fuels like coal, petroleum products and gas. The electrification may be then possible, without increase the impact on the environment in particular during the climate emergency we are living, and guaranteeing a viable economical investment.

2 Methodology

The Master Thesis has been elaborated by following a methodology summarized in the flowchart of figure 1.

First, 8 FCS have been considered along the E18 highway in South Norway and the energy demand forecast at these has been simulated by analyzing the traffic flow along the highway section selected and by randomly characterize it (see 4.1). Once obtained the energy demand for the 8 FCS, an aggregation in 3 clusters located in 3 different locations along the highway to simplify the planning of the renewable capacity to install was adopted. Indeed, the first three FCS have been aggregated in the Grimstad group, the second three in the Sandefjord group and the last two in the Oslo group (see 3.1).

Then, each Cluster has been studied for three different renewable integration scenario, meaning that different shares of the energy demand has been considered to be met by renewable generation within the different scenarios (see 5.2).

Finally, the core of the master thesis was elaborated after introducing all the different variables (energy demand, FCS grouping and renewable integration scenarios). This is the feasibility analysis of the renewable capacity integration (see 5, 6, 7, 8). In fact, after dimensioning the renewable capacity (see 6) and the consequent generation performance (see 7) a deep economical analysis is performed to assess the profitability of investing in each of the proposed capacity to install, depending on the different scenarios (see 8). All in all, an environmental evaluation for each scenario of renewable introduction is performed (see 8.5), because the assessment of the feasibility of a project must not rely only on economical performance indicators but also on an environmental ones.

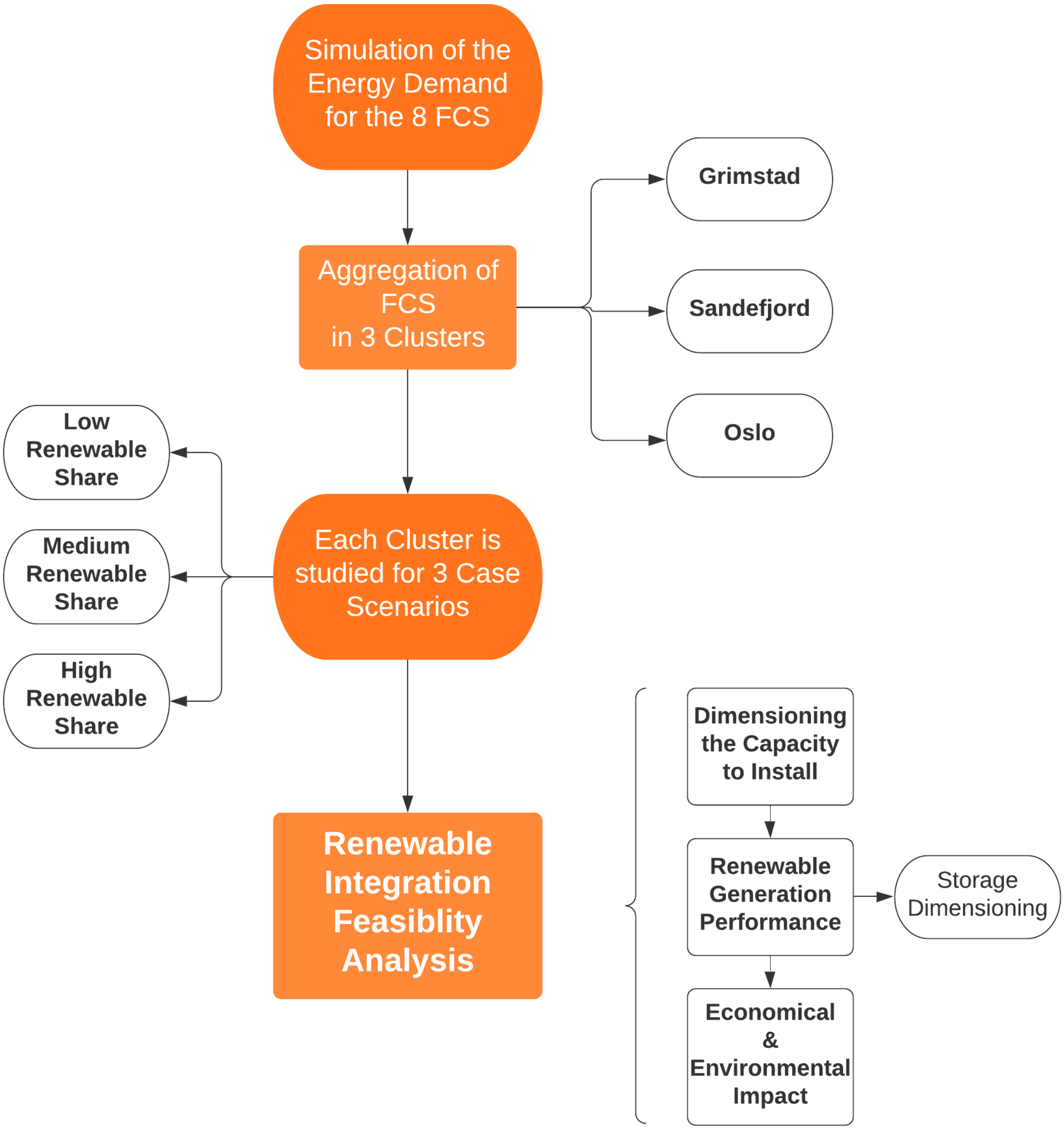


Figure 1: Flowchart of the MT

3 Preliminary analysis

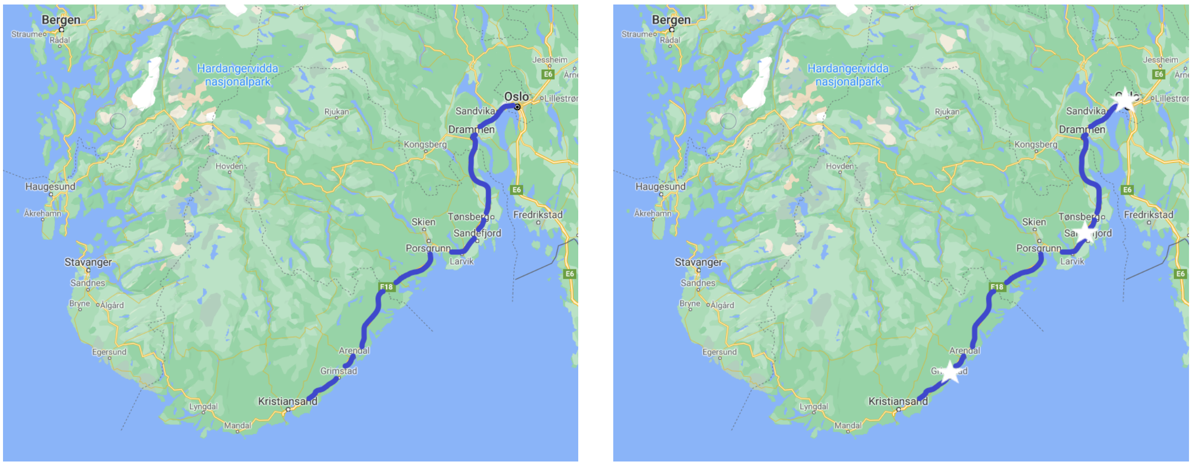
In this introductory section, the location of the case-study of this MT will be presented, as well as the boundary conditions regarding the energy mix and the potential for renewable integration.

3.1 Location

The highway considered in the analysis is the E18, of which a branch of approximately 300 km going from Kristiansand to Oslo was selected and highlighted in blue, as visible in figure 2a, as well as the three clusters in figure 2b, where the FCS have been grouped and marked with a white star.

The branch has also been object of investigation during the research internship I formerly carried out the last winter and where we developed the energy demand simulation at the FCS (see 4).

The branch is located in Southern Norway, in norwegian Sørlandet [8], where the economy is mainly driven by tourism especially in the summer due to the mild climate but also in the winter because of its good skiing conditions. This is a reason why the highway traffic flow is higher during the summer months, as well as the need for recharging EV's (see 4.1).



(a) E18 branch of the case study (b) Clusters Location

Figure 2: Geographical Location of the MT case study (source Google Maps)

3.2 Norway Energy Mix

Norway has the highest share of electricity produced from renewable sources in Europe, and the lowest emissions from the power sector. At the end of 2020, the total installed capacity of the Norwegian power supply system was 372 GW with a normal annual production of 153 TWh [9].

Hydropower accounts for roughly about 90% of Norway total power production, being the main power supply of the country. Moreover, total reservoir capacity corresponds to 70 % of annual Norwegian electricity consumption. This makes the Norwegian electricity production extremely flexible, meaning that production can be rapidly increased or decreased as needed, to balance supply and demand at all times, in particular with a growing share of intermittent generation technologies, such as wind and solar.

The flexibility of power plants and reservoirs varies. Indeed, some hydropower plants with small reservoirs offer short-term flexibility, moving production from base-load hours (at night) to peak-load hours (daytime), while other hydropower plants with larger reservoirs can store water for longer periods (long-term flexibility) so that they usually produce electricity when consumption and prices are higher.

Reservoirs make it possible to manage water use to maximise income from the available water resources. From a society point of view, the aim is to spread production so as to make optimal use of water inflow over the year, or even over several years. Clearly, the market plays an important part in ensuring efficient management of the reservoirs with adequate financial incentives for producers that reflect the underlying physical conditions.

Hydropower producers, with the availability of storage reservoirs, constantly assess whether producing electricity instantly, or keeping the water in reservoirs. It is straightforward to understand that the decision criteria will be the difference between the current and the expected electricity price that determines whether it is profitable to store water for short or long periods. However, the management of storage reservoirs remains challenging, because there is a certain degree of uncertainty both of future inflow and market conditions.

Regarding the Renewable Energy share in the Norwegian generation mix, wind and solar plant account for a non-negligible share. In fact, at the beginning of 2021, wind power installed capacity was of almost 4 GW, with the possibility of generating roughly about 13.1 TWh in a normal year. On the other hand, solar power installed capacity at the same time, was of 160 MW, with the most of them coming from small power plants of about 15 kW [10].

While solar power is still in a development phase and accounts for a small part of the electricity generation in Norway, wind power, in 2020, accounted for 6.4% of total electricity production, setting a new production record.

Regarding the non-renewable generation capacity, Norway's thermal power plants accounted for about 2% of total production capacity in 2020. Many of them are located in large industrial installations that use the electricity generated themselves. As such, CO_2 and greenhouse gases emissions related to electricity generation mostly depend on industry electricity demand.

3.3 Renewable Energy Potential

As a consequence of the EU Directive 2009/28/EC [11], which obliges member states to draft and submit to the European Commission a national renewable action plans that outline the pathway that will allow them to meet their 2020 renewable energy targets. Norway submitted its national action plan in 2012, with as main energy targets: 67,5% share of renewable energy in the gross final energy consumption and 10% of transportation energy demand met by RES [1]. Beyond 2020, the EU Commission has proposed a target for the share of renewable energy in the European Union in 2030 of at least 27%.

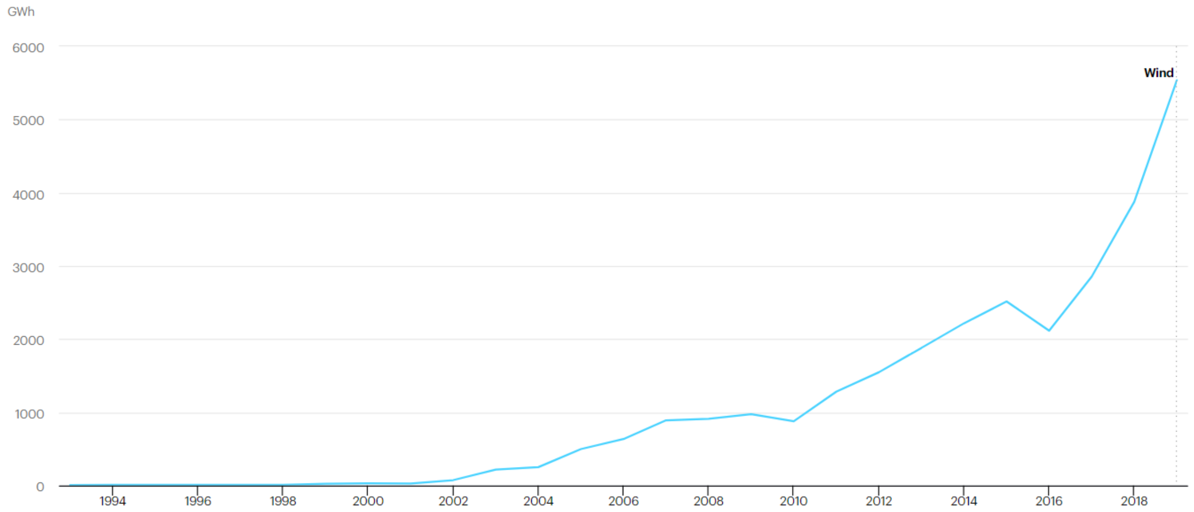


Figure 3: Norway's wind energy production in the period 1993-2019, [1]

As already introduced in the previous subsection, Norway has an increasing share of renewable electricity generation, in particular from wind power.

As clearly visible from Figure 3, from 2016 onwards there has been a steep increase in the electricity from wind produced, doubling almost the energy produced in 2019 with respect to 2016.

The growing of wind power allows Norway to curtail its hydropower production, which because of its dispatchability it is a valuable asset in the international power market. To further reduce its consumption of hydroelectricity, Norway imports electricity when there is an excess wind production in neighbouring countries like Denmark or Germany due to lower prices. Moreover, to enhance both the use of cheap wind power and dispatchable hydropower, Norway is planning the construction of new transmission lines to allow more trades with Scotland and Germany.

Regarding solar power, in 2019 the solar capacity increased of 50 MW, while in 2020 around 40 MW of new solar power was installed in Norway. Considering the already installed capacity, the growth was of about 40% and it is expected to grow in the following years due to the economies of scale for solar cells, cheaper energy storage and due to the deployment of smart grids and digitalization [12]. In fact, state subsidies and investment, especially in China and Germany, have led to an increase in large-scale production of solar cells, lowering the price of about 62% between 2009 to 2016, and solar energy is estimated to be the cheapest form of energy in most countries, between

2030 and 2040 [13].

Moreover, battery prices have fallen by about 80% since 2010 and are expected to keep falling and as such the necessary storage capacity for solar power will be more and more available, boosting the investment in new solar capacity.

Finally, in Norway the deployment of smart meters has been starting leading to an easier coordination between storage and consumption of energy. Also, the deployment of digital platforms will simplify the selling of prosumers[1] own energy in "virtual power plants". Those two factors, will lead to an expansion in solar capacity.

3.4 Fast-Charging Stations

The cost of the electrifying E18 is considerable, as for every road electrification [15]. However, by reducing the need of new transmission and distribution infrastructure (like cabling and the need of new substations to handle the additional power flow), the cost can be sensibly reduced. As such, the FCS have been placed closer to existing substations along the E18, since a connection to the power grid is necessary by all means, but in this way at a limited cost. Indeed, the option of building the FCS with an off-grid configuration was not taken into account, but can be investigated in further analysis.

More information about the fast-charging technology is given in the appendix A.1.

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[1] A prosumer is an individual who both consumes and produces. The term is a portmanteau of the words producer and consumer [14]

4 Energy Demand Simulation at FCS

As mentioned in the introduction section, I have been working during 4 months, as an intern at the Electrical and Electronics Engineering Research Centre of UPC.

The main objective we tackled, was the simulation of the Energy Demand at the different Fast-Charging stations to be installed along the E18 highway section already described in section 3.4 and A.1.

My work is part of a deeper research and problematic thoroughly analysed in literature: the electrification of road transport sector (see appendix A.2).

In the analysis, we focused on the static charging deployment scenario (see A.2), considering 8 FCS to be constructed along the E18 branch and as a main input to determine the energy demand at each of these, we used the traffic flow between the starting and final point of the highway, as it will be explained in the next sub-section.

All the data analysis has been conducted with Python programming language and in particular with Pandas, a dedicated environment for data elaboration [16].

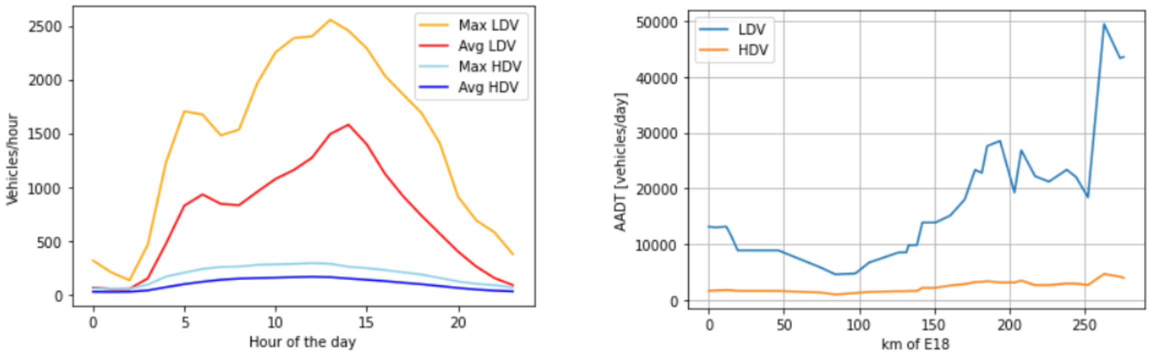
4.1 Traffic analysis

In the analysis to derive the energy demand at the FCS, the main data input we worked with has been the traffic flow along the E18 [17], shown in figure 4. It is necessary to clarify that LDV stands for Light Duty Vehicle and refers to passenger cars, while HDV stands for Heavy Duty Vehicle like trucks, buses and coaches.

As can be seen, HDV traffic flow is fairly constant due to the fact that they travel usually longer distances than LDV, once they have entered the system. Indeed, the net traffic flow of LDV is varying much more not only on a time scale (4a), but also on a space scale (4b).

Even if in figure 4 both types of vehicles are depicted, the focus has been on the LDV energy demand simulation since the deployment of plug-in HDV vehicles would have probably lead to high recharging times in order to limit the peak power flow from the grid or spike to the power system due to higher recharging rates. Deployment scenarios for HDV are briefly introduced in the appendix A.2 and [15].

First, rearranging the main input data set, namely: the traffic flow or number of vehicle



(a) Average Traffic Flow per Hour (b) Daily Average Traffic Flow

Figure 4: E18 Average Traffic Flow

per given stretch[2], the stretches location in km from the beginning of the branch considered, vital in the decision process of the best station where to stop for charging, and finally the stations' location in km from the starting point of the branch. These data have been made more relevant for our model as such: the stretches' traffic flow has been converted into a both entering and exiting nodes' traffic flow.

The conversion has been executed by following this algorithm:

Figure 5: Nodes' traffic flow algorithm

The algorithm shown in figure can be obtained with the following simple relationships: First to get the Δs, we applied 1:

$$\Delta_n = Stretch_{n+1} - Stretch_n \tag{1}$$

Then the entry and exit ratio are calculated with 2 and 3:

$$\Pi_n = \frac{\Delta}{Stretch_n} \tag{2}$$

$$\bar{\Pi} = \frac{\sum_{k=1}^{N} \Pi_k}{N} \tag{3}$$

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[2] Distance between two points in between two nodes of the highway

Finally, the nodes are just obtained with 4:

$$Node_n = \Delta_n * \bar{\Pi} \tag{4}$$

By looking at the input traffic data set, among all the stretches' measurements, one node's entry and exit traffic flow was provided, thus we were able to calculate the value obtained in 3 by obtaining an actual value from the ratio between entering and exiting vehicles at the reference node and the total number of the total vehicles travelling in the stretch.

As a consequence, we compared a value obtained using an assumption algorithm (equation 3) and an actual value from the data set. The values revealed to be similar, so we used the one calculated in (3) for the analysis.

All in all, we obtained the main input for the energy demand simulation that will be extensively dealt with in 4.3.

4.2 Charging Strategy

The aim of this subsection is to explain different possible recharging strategy and justify the choice made for our analysis.

The use of Plug-In charging without any constraint is usually defined as "Dumb Charge" [18], and usually may lead to a large number of electric vehicles connected the grid nearly at the same time, potentially causing a peak demand. On the other hand, there are two charging strategies with some constraints in order to reduce the impact on the grid, avoiding spikes in the peak demand: "smart charge" and "V2G" (Vehicle to Grid).

In the Smart Charge, the process is controlled by a controller embedded in the vehicle or in the charging station, which is provided with real-time information about the price of energy, by the System Operator. The aim is to offer lower energy prices at moments when the grid is less stressed, to foster the recharge of EV´s, resulting in a more stable energy demand.

V2G or Vehicle to Grid basically consists of putting EV's to work, not only as consumers, when they charge their batteries, but also as producers, like emergency generators, supplying energy back to the grid [19], when needed. In fact, EV's could speed up the integration of renewable sources generation, by absorbing excess electricity production when the wind and sunshine conditions are favourable or injecting it back on the grid in low renewable electricity production periods. As such, the EV fleet can be seen as an enormous distributed energy storage system.

However, this charging strategy seems hardly applicable for several reasons like very cheap oil prices, energy density of traditional batteries, limited life cycles, and the still reduced number of EV's. Still, V2G can easily provide an ancillary grid service characterised by short dispatch times in order to regulate the frequency and voltage.

With respect to the above mentioned charging strategy, the one that better suits in the considered case study is the uncontrolled charging or "dumb charging". This is because a fleet travelling on an highway offers less flexibility of shifting the recharge periods sooner or later in the day, in order to keep the demand as stable as possible. Indeed, the EV user will only recharge his vehicle to complete his journey, and never to a full battery level. Clearly, for the same reasons, the user will not provide any grid regulation services while at the FCS, and thus also V2G is not a viable option in our case study. All in all, the EV user will recharge only if he must to reach his destination and without any other constraints at the FCS.

4.3 Simulation

After defining the charging strategy of our case study, the energy demand simulation at the FCS along the highway was performed (also on Python) and here presented.

This simulation was basically run thanks to a function, taking different quantities as inputs: the share of EV's with respect to the entire fleet (or EV's penetration rate), the mileage, the inlet traffic at the nodes (see 4.1), the power rate of the chargers at the stations, the battery capacity of EV's (in kWh) and the final destination of each vehicle.

On the other hand, the outputs obtained, once the function has been called and executed, were two data frames[3]: the total energy charged at each station and the time that each electric vehicle spends charging at the station. From this last output is possible to see the share of EV's charging with respect to the total EV's entering the system.

The energy charged at each FCS can vary depending on different conditions to be satisfied and depending basically on a list of characteristic assigned to each EV, some of

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[3] A data frame is a table or a two-dimensional array-like structure in which each column contains values of one variable and each row contains one set of values from each column [20].

them previously mentioned:

- Relative position of the EV in the highway section when entering (in km);
- EV final destination randomly assigned from a range we selected making an assumption;
- Direction of the vehicle when entering the system, since the vehicle can go on both directions in the highway (randomly assigned);
- Initial State of Charge (SoC) assigned depending on the starting time of the vehicle. Indeed, if the vehicle starts his journey between 6 a.m. and 12 a.m., the state of charge assigned will be higher (between 60 and 80 percent), while if the EV enters the system in the remaining hours of the day it will start with a lower state of charge (between 30 and 50 percent);
- Battery capacity or size of the EV (in kWh)

After setting all of these input characteristics, to calculate the energy recharged is straightforward, but it needs to be adapted to the different situations that may occur inside the system that will now be clarified.

The main condition regulating whether the vehicle needs to recharge in the system or not is the level of charge at the end of its journey. If this value is below a threshold we set equal to 20%, then the vehicle will have to recharge to complete his journey, otherwise the energy to be recharged will be set equal to 0.

In addition, if the vehicle would end his journey out of the highway section bounds considered, the final State of Charge will be calculated considering only the section of the highway traveled and not the entire journey.

The last condition we defined, has been excluding the vehicles entering the systems before the first station and after the last one, that would like to recharge but find themselves further than 5 km from the first or last station. In this particular case, they will not recharge.

Finally, the main equation to solve to find the energy to be recharged, which has been adapted for the different cases explained above, is here presented:

$$E_{charged} = \frac{|Journey|}{Mileage} - Battery * (SoC_{start} - SoC_{low}) \tag{5}$$

Where battery represents the battery size or capacity in kWh and State of Charge low stands for the 20% threshold already mentioned.

Once every vehicle has been assigned the energy to be recharged, the closest recharge station to the recharge point is selected and assigned to the vehicle which will spend there a certain amount of time there recharging. This time interval is stored in the recharge time data frame which is one of the main output.

Similarly, all the energy to be recharged at every station for every hour is summed to obtain a cumulative value, which is then stored on each cell of the output energy data frame.

4.4 Simulation Results

The simulation led us to obtain the energy demand at FCS on an hourly basis, then averaged on a daily basis (figure 7). This is a vital data in order to do a renewable integration feasibility analysis, which is the main scope of the master thesis.

First, it is pretty interesting to look at the average energy demand at each FCS depicted in figure 6 and see that this has a clear connection with the traffic flow along the highway already seen in figure 4b. Indeed, the last FCS have an higher energy demand on average, especially station 5 (4) and 7 (6) due to a higher traffic flow in their proximity. In addition, the average daily energy demand at each FCS is depicted in figure 7, finding again the observation already mentioned that station 5 (4) and 7 (6) have a higher energy demand on average.

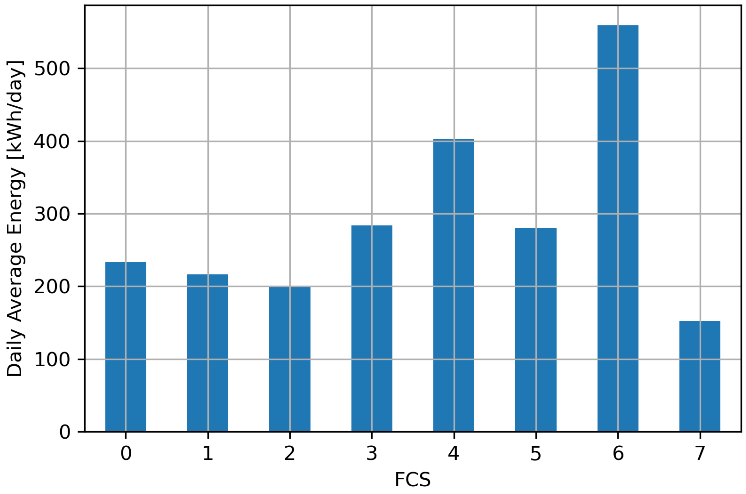


Figure 6: Average Energy Demand at FCS

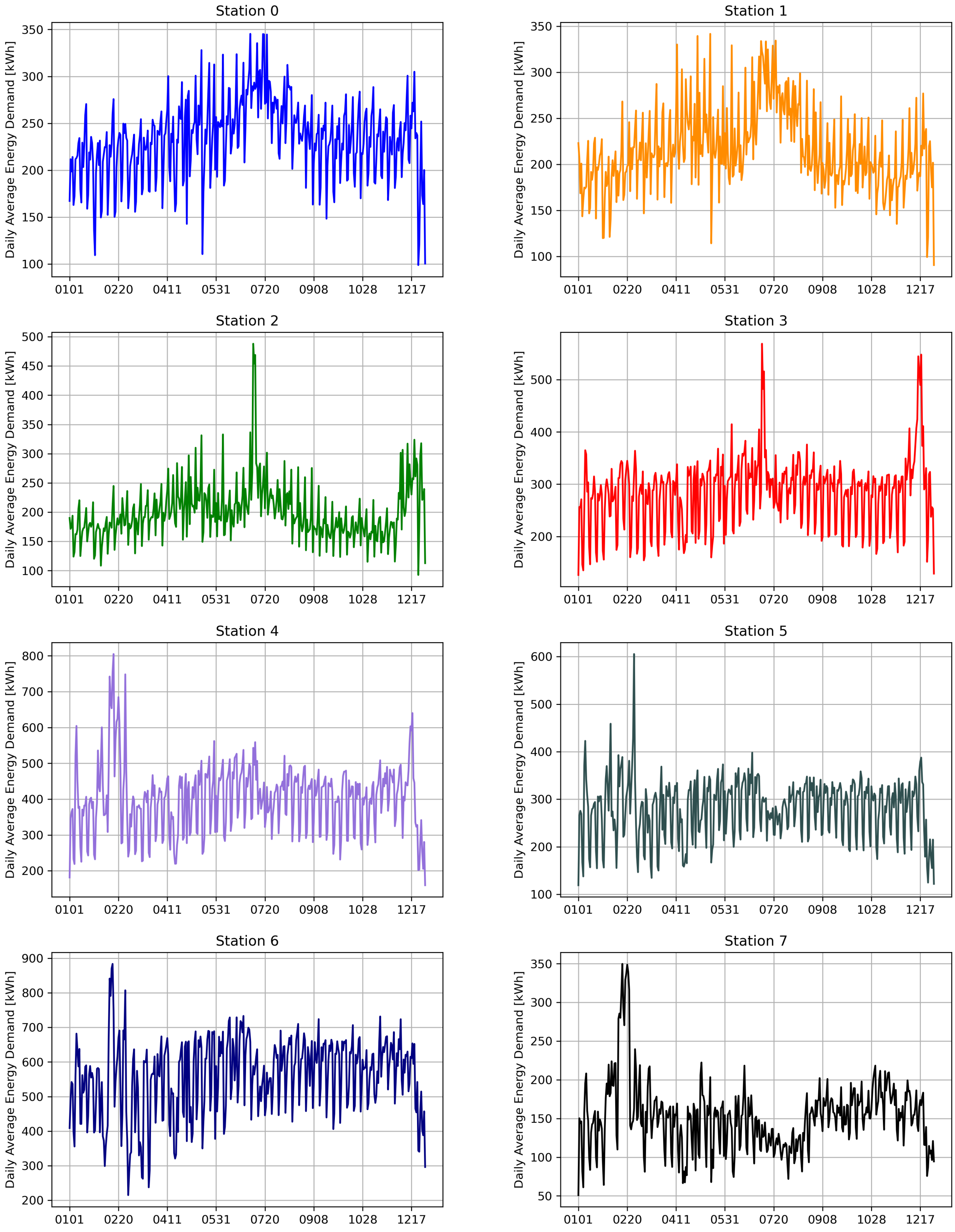


Figure 7: Daily Average Energy Demand at the 8 FCS

5 Renewable Integration Feasibility Analysis

In this section, a renewable integration feasibility analysis will be conducted, in order to evaluate the economical and environmental benefits that a renewable generation system would bring to the grid, in the highway electrification scenario described in the previous sections.
The methodology followed in this analysis articulates onto these different steps:

- Solar and Wind Resource Assessment
- Case Studies
- Dimensioning of the RES power plants
- Renewable Generation Performance for each Cluster and Case Studies

First, different case studies are proposed for the feasibility analysis in order to have a bigger picture regarding the impact of renewable energy integration. Then, solar and wind potential are investigated for the Southern Norway region, leading to the dimensioning of new capacity to install in order to meet partially or completely the energy demand of the FCS for different scenarios of renewable capacity installed. Finally, an economical and environmental impact assessment is performed for the different case studies considered to show the best viable option in the renewable energy power capacity integration.

5.1 Solar and Wind Resource Assessment

Norway is a virtuous country for renewable energy as already mentioned in section 3.2 and 3.3, especially because of hydropower plants but also for a growing installed capacity of wind and solar in the last decade, in particular wind power because of the more favourable conditions in the region.

5.1.1 Solar Potential

In such a growing renewable scenario that the country is experiencing, the new solar capacity will have an increasing relevance in the achievement of sustainable goals for

Norway.

Therefore, we analyzed for Southern Norway region, the solar irradiation in kWh/m^2 and the monthly average PV potential production in kWh/kWp*day [21], but in particular the latter founding an interesting resemblance with the average energy demand at FCS.

To clarify, the Solar Potential curve represent an average amount of energy producible per kilowatt peak, which is the rate at which the PV system generates energy at peak performance, for example at noon on a sunny day [22]. Instead, the total amount of electricity the system actually generates in a year is measured in kilowatt hours (kWh), and this will depend on the system's orientation, shading, level of irradiance in the site, as well as the size of the system (in kWp) installed.

Regarding the resemblance between energy demand an solar potential, indeed the solar production is more favourable during the warmest months when also an higher energy demand for recharging the electric vehicles is observed. This is a key factor to bear in mind on how suitable can be solar energy to meet the planned energy demand at the FCS. Moreover, this can reduce the need for peak electricity production and preserve the grid infrastructure from overload.

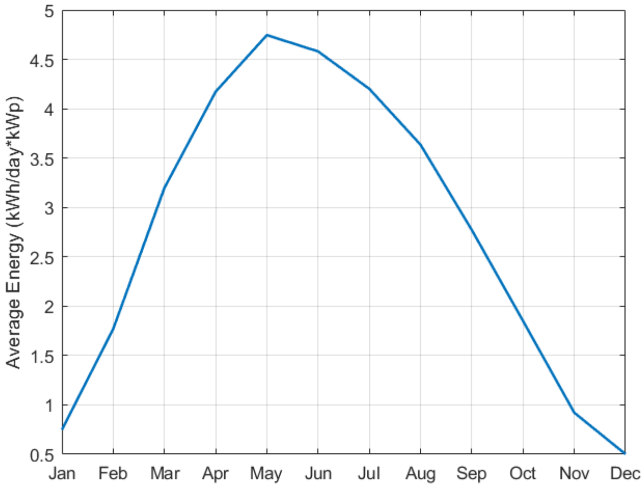


Figure 8: PV Production Potential for Southern Norway

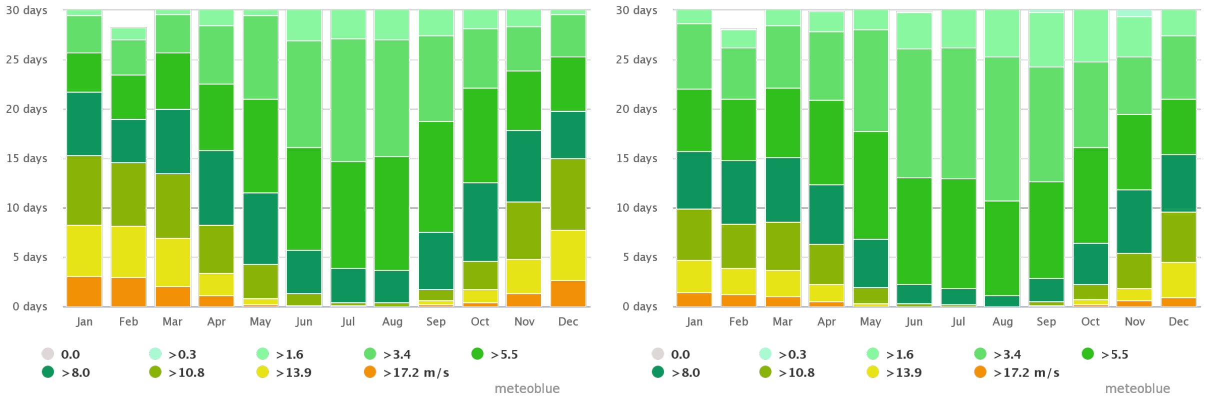
5.1.2 Wind Potential

The wind flow in the Southern Norwegian Region is pretty complicated due to mainly a variegate surface typology causing an asymmetric rotation of the wind jet streams [23]. Indeed, many areas in northern Norway had better conditions for wind power, but onshore wind farms are more suitable for the south of the country due to limited network capacity in the north and large areas used by reindeer herders [24].

In figure 9, it is possible to see the mean wind speed for the three clusters. Usually, from 3-5 m/s wind mean speed the conditions are favourable for wind power generation. As visible from the figure, the best months for wind generation are usually the coldest ones (January to March and November-December).

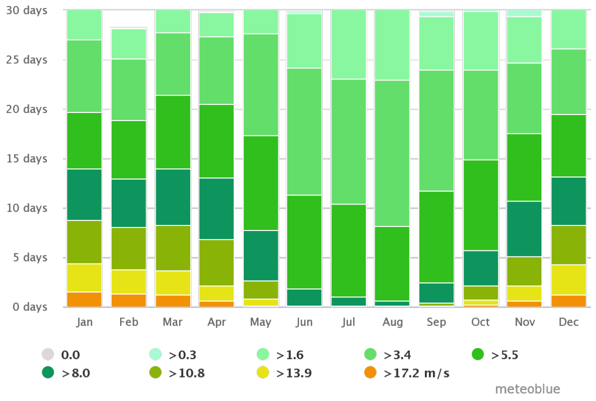
Moreover, when moving the southest cluster of Grimstad has better wind conditions than the northest two, which makes it combined with the solar potential already mentioned, the best for renewable generation.

Clearly, the total power generation depends on the capacity installed and the different case studies analyzed.



(a) Wind Mean Speed Grimstad [25]

(b) Wind Mean Speed Sandefjord [26]



(c) Wind Mean Speed Oslo [27]

Figure 9: Mean Monthly Wind Speed Distribution

5.2 Case Studies

The methodology aims to start from the analysis of the renewable energy sources potential, in particular solar and wind, and lead to a proposed capacity to install, to meet the FCS energy demand, which is then evaluated on a environmental and economical point of view. Different case studies are analyzed in order to see the configuration that has the best impact on the environment but also the one more viable on the economical side.

While, initially only new solar capacity was planned, the analysis of wind potential in the region has been showing a clearly predominance of this renewable source, mainly due to the high latitude which is less favourable for solar energy. This is the reason why, we decided to include in all of the three case studies an high share of wind capacity. Without further ado, here are the different case studies we chose to investigate:

- Case Study 1: A small penetration degree of new renewable capacity installed is considered for the three clusters, in particular a share of less than 20% of the total energy demand is covered with a mix of wind and solar capacity.

- Case Study 2: A medium penetration degree of new renewable capacity is considered, in particular around 50% of the total energy demand is planned to be covered with wind and solar generation. As wind is planned as the predominant source of generation, the higher share of renewable capacity installed in all of three clusters will be wind power in the order of MW turbines.

- Case Study 3: An high penetration of renewable capacity is then finally analyzed aiming to cover 90 and up to 99% of the total energy demand of the different clusters.

6 Dimensioning of the RES power plants

The dimensioning of the Renewable Power Plants has been conducted with Ninja Renewables [28], [29], a free web simulator of the hourly energy output from wind and solar power plants located anywhere in the world. Despite its simplicity of use, weather and energy data are of a good quality.

To be more detailed, the solar calculation are performed with the Global Solar Energy Estimator (GSEE) [30], while the wind calculation are executed with the Virtual Wind Farm (VWF) [31].

Thus, for each case study a wind turbine and a solar field of different size has been selected in order to meet the target of renewable generation set. Because of the predominance of wind, most of the demand has been covered by wind capacity, meaning that bigger turbines has been selected. Indeed, bigger blades can sweep larger areas and access faster wind speeds available at higher heights above the ground. Capturing more of the wind and tapping into better wind resources help drive down the cost of energy. Rotor growth may also increase capacity factors, or the amount of power a turbine outputs on average over the course of a year. In some circumstances, higher capacity factors may increase the value of wind energy to the electricity system [32]. Yet, bigger blades also face transportation and manufacturing challenges that prevent scaling turbines up to sizes needed to deliver additional cost-of-energy advantages. Those are the main reasons, why we chose to consider only MW-scale turbines in the planning of the wind capacity.

As following, the description of the three Clusters' renewable power plants for each case scenario.

6.1 Grimstad Cluster

Regarding the Southest Cluster, which is the more favourable for solar generation, two different solar capacity configurations has been chosen depending on the generation scenario:

- 250 kW of installed solar capacity for case study 1;
- 500 kW of installed solar capacity for case studies 2 and 3;

The module technology is the mono-crystalline silicon with an efficiency of 15%, and both configurations present a tracking system on the azimuth axis and an optimal tilt inclination for the latitude of 35°. Moreover an average system losses of 10% is taken into account. PV field size is directly proportional to the kWp installed [33], and for each of them approximately a 5 m^2 area is required. It is straightforward to obtain a required soil or roof area of 1250 and 2500 m^2 for low renewable penetration and medium and high renewable penetration respectively. This corresponds to approximately a third and two third of an acre in the Imperial and US customary system.
It is pretty clear that if soil occupation would be a problem a space optimization by installing the required solar capacity onto rooftop of the to be FCS can be performed, but this is not the scope of this master thesis.
On the other hand, talking about the wind capacity and keeping in mind the choice of big-scale wind turbines, we selected the following:

- 225 kW Vestas model V27/225 for case study 1;
- 900 kW GE Energy model 900S for case study 2;
- 1,5 MW GE Energy model 1.5 xle for case study 3;

All in all, table 1, group the renewable capacity for the cluster depending on the scenario investigated.

Grimstad Cluster	
Low Renewable	250 kW Solar + 225 kW Wind (Vestas V27/225)
Medium Renewable	500 kW Solar + 900 kW Wind (GE 900S)
High Renewable	500 kW Solar + 1,5 MW Wind (GE 1.5 xle)

Table 1: Grimstad Solar and Wind Planned Capacity

6.2 Sandefjord Cluster

The Central Cluster is the one with the highest energy demand because of the highest traffic flow, and thus has been planned to be installed with an higher wind capacity:

- 900 kW GE Energy model 900S for case study 1;
- 1,5 MW GE Energy model 1.5 xle for case study 2;
- 3 MW Siemens model SWT 3.0-101 for case study 3;

With respect to solar capacity, the parameters and characteristics of the solar panels technology are the same as already mentioned for Grimstad cluster (see 6.1), as well as the choice of capacity to be installed: 250 kW for case study 1, 500 kW for case study 2 and 3, leading to the same required soil or roof area of 1250 and 2500 m^2 for low renewable penetration and medium and high renewable penetration respectively, as already described for the Grimstad Cluster (see 6.1).
Again, table 2 shows the capacity planning for the cluster.

Sandefjord Cluster	
Low Renewable	250 kW Solar + 900 kW Wind (GE 900S)
Medium Renewable	500 kW Solar + 1,5 MW Wind (GE 1.5 xle)
High Renewable	500 kW Solar + 3 MW Wind (Siemens SWT 3.0-101)

Table 2: Sandefjord Solar and Wind Planned Capacity

6.3 Oslo Cluster

The Northern Cluster has also an high energy demand due to the fact that the traffic flow in proximity of the city of Oslo is without any surprises fairly high. Although, less wind capacity is required than the central cluster of Sandefjord to reach an high renewable penetration scenario. Here are listed the turbines selected:

- 900 kW GE Energy model 900S for case study 1;
- 1,5 MW GE Energy model 1.5 xle for case study 2;
- 2,75 MW GE Energy model 2.75-103 for case study 3;

Again the choice of solar capacity to be installed remains the same: 250 kW for case study 1, 500 kW for case study 2 and 3. One more time, all the panels' characteristics have already been introduced for the Grimstad Cluster (see 6.1).

Finally, in table 3 the capacity planning is shown for each case scenario.

Oslo Cluster	
Low Renewable	250 kW Solar + 900 kW Wind (GE 900S)
Medium Renewable	500 kW Solar + 1,5 MW Wind (GE 1.5 xle)
High Renewable	500 kW Solar + 2,75 MW Wind (GE 2.75-103)

Table 3: Oslo Solar and Wind Planned Capacity

6.4 Wind Turbines Power Curves

All in all, before moving to the actual energy production of the above mentioned renewable power plants, it is necessary to show and comment the power curves of the wind turbines selected and introduced for each cluster.

The wind turbine power curve (WTPC) shows the relationship between the wind speed and power output of the turbine. Indeed, at a certain wind speed (cut-in speed), the turbine will start generate electrical power until reaching the nominal power at the rated wind speed. Once reached a limit wind speed (cut-out speed), the turbine stop generating power to prevent unnecessary strain on the rotor. This plots are fundamental to evaluate the turbine that best fit in a certain location after a deep wind resource assessment.

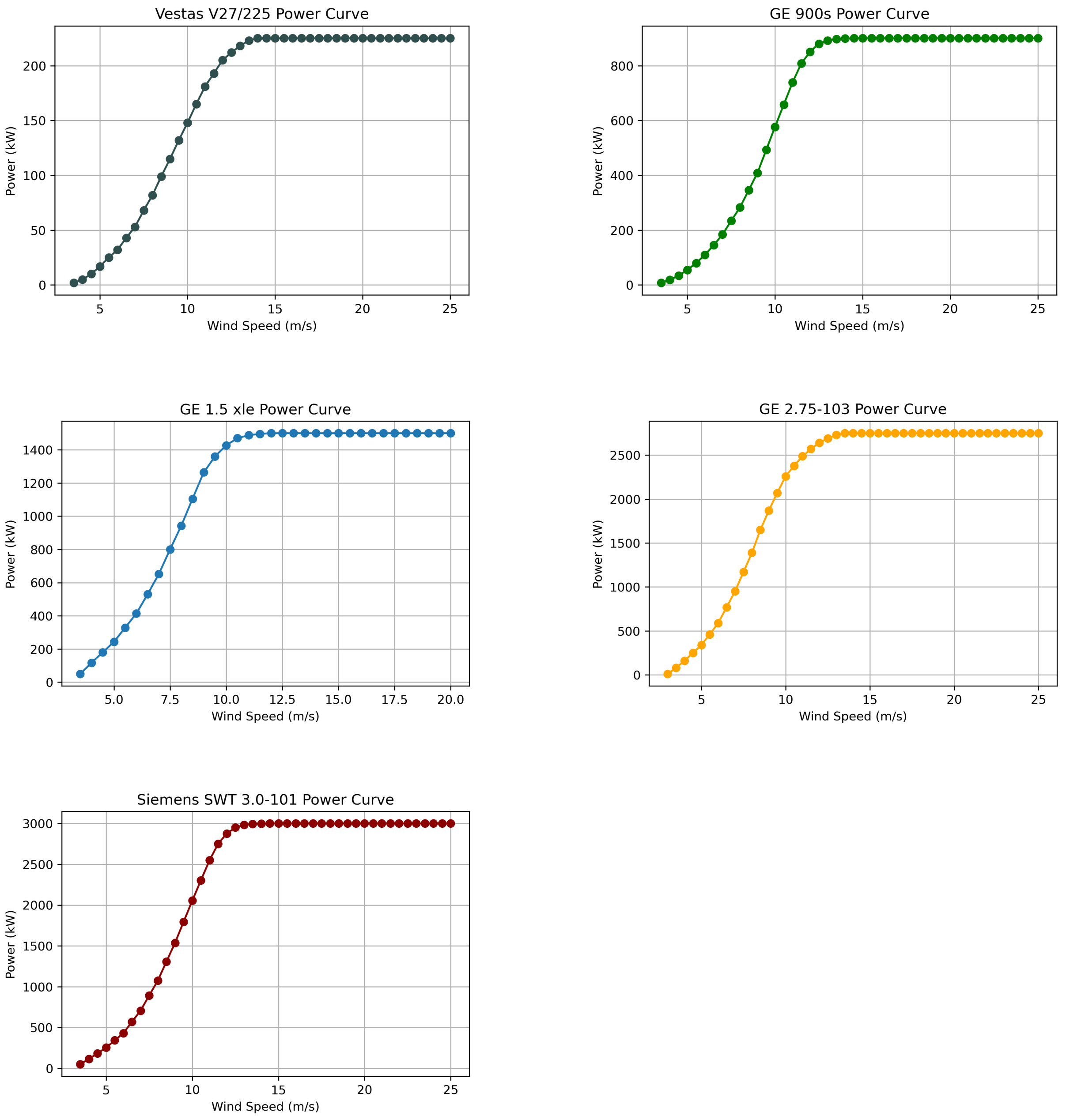
In table 4, more information about the wind turbine models are provided, like cut-in, cut-out and rated speeds, rotor diameter and tower height.

Model name	Installed Power	Hub height	Rotor Diameter	Cut-in and Cut-out Speeds	Rated Speed
Vestas V27/225	225 kW	40 m	27 m	3,5-25 m/s	14 m/s
GE 900S	900 kW	60 m	54 m	3,5-25 m/s	14,5 m/s
GE 1.5 xle	1,5 MW	80 m	82,5 m	3,5-20 m/s	12 m/s
GE 2.75-103	2,75 MW	100 m	103	3-25 m/s	13,5 m/s
Siemens SWT 3.0-101	3 MW	100 m	101 m	3,5-25 m/s	14,5 m/s

Table 4: Wind Turbines Specification

With no surprises, the higher the power, the bigger and taller the turbine. In the next section, when presenting the wind energy generation, it's gonna be possible to see that also the capacity factor will increase with the size of the turbine, but at an higher cost clearly (see 8).

The smallest turbine, elected for the low renewable penetration is the Vestas V27/225, which is the oldest turbine we selected for the analysis. This is because it is a small scale turbine of 225 kW nominal power and in the last decades there has been a shift towards big scale turbine of several MW nominal power. Although, a small turbine was the best choice to cover a small part of the energy demand in combination with a small solar field. However, the biggest multi-megawatt turbines selected are more recent and efficient, but clearly far more expensive.


Vestas V27/225 Power Curve

GE 900s Power Curve

GE 1.5 xle Power Curve

GE 2.75-103 Power Curve

Siemens SWT 3.0-101 Power Curve

Figure 10: Wind Turbines Power Curves

6.5 Storage Dimensioning

Battery electricity storage is a key technology in the world's transition to a sustainable energy system with a growing share of renewable capacity installed [34]. As it is widely known, those energy sources like wind and solar investigated in this analysis are intermittent and thus surplus or lack of generation is pretty common, thus the need of a storage system which can provide energy when missing, or storing when exceeding is essential in the introduction of new renewable capacity.

Batteries system supports “self-consumption” of solar and wind power, which means that the energy demand is met completely or partially just with energy generation system closely located. This avoid, the need of energy purchase from the grid leading to a monetary saving and moreover reduce the problem of frequency imbalances due to injections of surplus power in the grid as well as transportation losses and costs for the system operator and so on.

While pumped-hydro systems still dominate electricity storage (with 96% of installed storage capacity in mid-2017), battery systems for stationary applications have started growing rapidly, because of the wider deployment and commercialisation of new battery storage technologies leading to rapid cost reductions, notably for lithium-ion batteries, but also for high-temperature sodium-sulphur (“NAS”) and so-called “flow” batteries. Indeed, by 2030, total installed costs could fall between 50% and 60% (and battery cell costs by even more), while battery lifetimes and performance will also keep improving, helping to reduce the cost of services delivered. As an example, Lithium-ion battery costs for stationary applications could fall to below 200 $/kWh by 2030 for installed systems.

As such, we have considered to install a storage stationary system using lithium-ion battery pack for each cluster’s renewable power plant. The methodology we used to dimension the storage system is the "worst case scenario", working in the following way, visible also in equation 6.

We considered the worst day of renewable production throughout the year (d) and we simply evaluated the storage size required (SSS) as the difference between the energy demand that day (ED_d) and the renewable energy production also that day (RE_d).

$$SSS = ED_d - RE_d \tag{6}$$

Although the energy that can be stored may not be enough on some days of favourable wind and solar conditions, leading to the problem of managing an energy surplus. The possible solutions considered are two: production curtailment when reaching the maximum storage level or injection to the grid that may lead to additional revenues but also to additional cost for power injection like balancing fees and so on. Both strategies will be investigated in the economical section and one of them will be selected and applied.

The dimensioning will be conducted in the next section after evaluating the renewable generation profile throughout the year and applying the methodology just presented.

7 Renewable Generation Performance

After selecting the capacity to install for each cluster and case scenario, it is possible to see the renewable energy production, for each cluster, thanks to Renewable Ninja Simulation [28], [29]. In fact, by just selecting the capacity installed both for PV and wind as well as the turbine model and some PV characteristics, the energy output can be obtained. Moreover, after showing the generation performance the storage capacity is selected as explained in the previous section (see 6).

7.1 Grimstad Cluster

As already known, three different renewable penetration scenarios have been dealt with, and for each of them the solar field and wind farm will be described more in details, showing relevant figures and facts to better understand the performance achieved.

7.1.1 Solar Capacity

First of all, regarding the solar capacity installed, a mono-crystalline silicon module has been chosen since it is the most commercial available with an average efficiency of 15%, and a system loss considering the inverter stage of 10%. A 1-axis tracking system and an optimal tilt inclination of 35° have been taken into account, which improves the system performance in terms of energy produced.

As already mentioned in the previous section, two capacity setups have been elected: 250 and 500 kW.

In figure 11, it is possible to see the monthly solar production for the considered Cluster for each renewable penetration scenario. It is simple to understand that the lines have a similar trend due to the same meteorological conditions applying for all the renewable production scenarios. Also, medium and high renewable penetration overlap because the same capacity is planned for both.

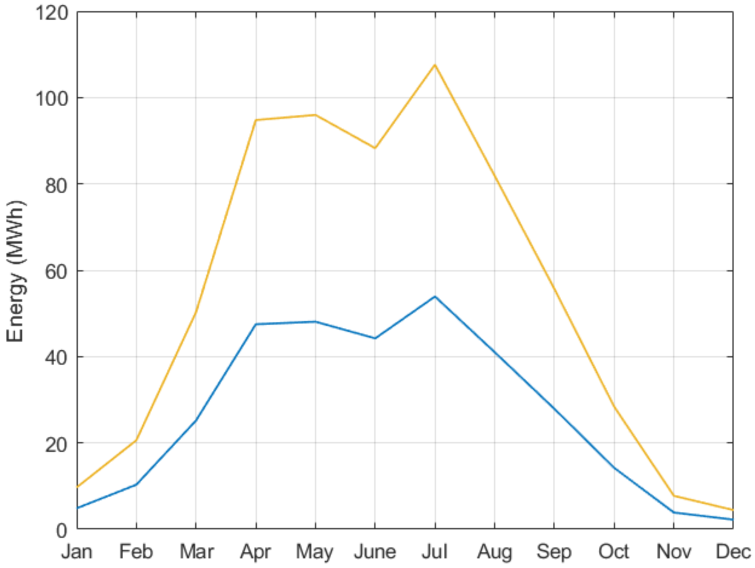


Figure 11: Monthly Solar Energy Production Grimstad Cluster

7.1.2 Wind Capacity

Moving to the Wind Capacity, three wind turbines have been selected and described with their power curves as well, in the previous section.

Each of them provides a different share of the total demand for the cluster, which will be similar to the total renewable share, since the solar production is limited due to the low irradiation potential. Moreover, each of the turbines works with a total yearly capacity factor which is the average of the monthly capacity factor.

As visible in figure 12, there is a consistent difference between the low renewable penetration scenario and the high renewable penetration scenario, also clearly visible in table 5, where the total energy produced for one year is reported as well as the capacity factor. The capacity factor for operational wind farms in Norway varies between 14% and 48%; the generation-weighted average capacity factor is around 33% [35].

Regarding the cluster performance, the biggest turbine has a slightly beyond average capacity factor, while the other two have below average performances but still acceptable. As already mentioned previously this depends mainly on the availability of wind, the swept area of the rotor and the size of the generator. In fact the higher the tower, the wider the rotor and the stronger the wind and then the more wind energy harvested.

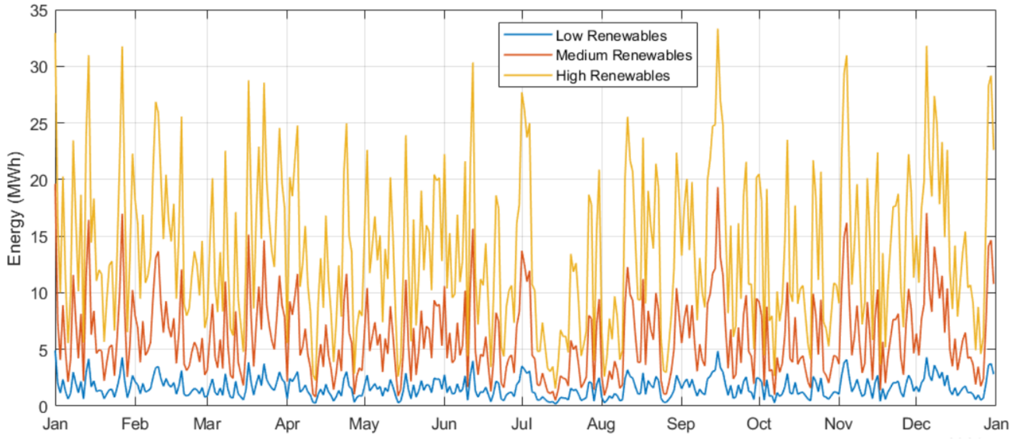


Figure 12: Daily Wind Energy Production Grimstad Cluster

Model name	Installed Power	Total Energy Produced (% of demand)	Yearly Capacity Factor (%)
Vestas V27/225	225 kW	596,2 MWh (10,5%)	19,3
GE 900S	900 kW	2,22 GWh (38,9%)	24,5
GE 1.5 xle	1,5 MW	5 GWh (87,9%)	34,9

Table 5: Wind Generation Performance for Grimstad Cluster

In the end, as indicated in section 6, the renewable power plants for the three clusters are made of both solar and wind capacity, and as such the total renewable production is the sum of the two capacity generation outputs. This is visualized in figure 13, where the three generation outputs, one for each penetration scenario are combined with the energy demand for the cluster.

What is interesting to notice also, is that only medium and high share of renewable scenarios are able to fulfill the energy demand for some days, whilst a low renewable integration is never able to meet the daily demand for the cluster's FCS, requiring energy off-takes from the grid. In addition, a storage system is required both for an high and medium share of renewable energy is planned to be installed.

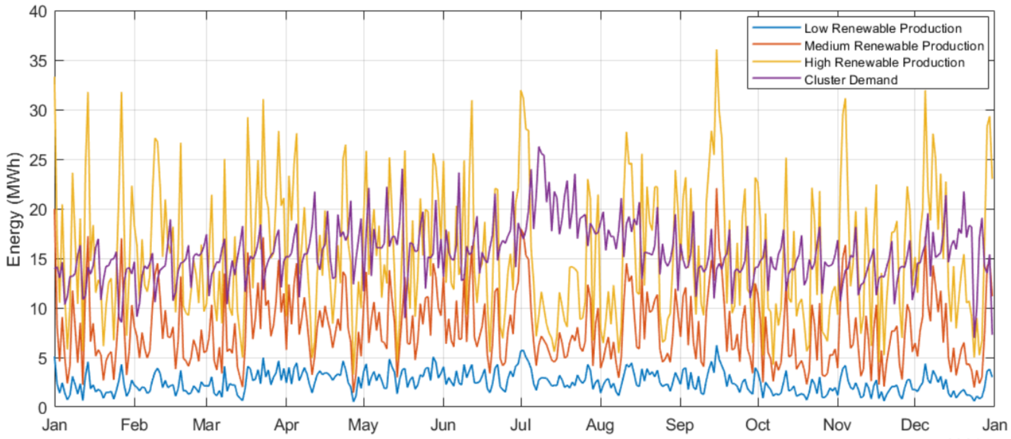


Figure 13: Renewable Energy Generation and Demand Grimstad Cluster

All in all, table 6 shows the solar and wind energy generation with the correspondent share of the energy demand, and also the relative percentage referring to the renewable total generation output.

	Solar Energy Production (% of Renewables)	Wind Energy Production (% of Renewables)	Total Energy Produced (% of Demand)
Low Renewables	323,3 MWh (35,2%)	596,2 MWh (64,8%)	919,5 MWh (16,2%)
Medium Renewables	645,3 MWh (22,5%)	2,22 GWh (77,5%)	2,865 GWh (50,2%)
High Renewables	645,3 MWh (12,9%)	5 GWh (87,1%)	5,6453 GWh (99,2%)

Table 6: Renewable Generation Performance for Grimstad Cluster

7.1.3 Storage Capacity

After evaluating thoroughly the demand and renewable supply, the dimensioning of a storage system has to be conducted. As already explained in the previous section, we evaluated that the worst day of renewable production, with the lowest generation for the cluster, is the 27th of April 2019. By applying equation 6, we found out the following storage requirements, grouped in table 7.

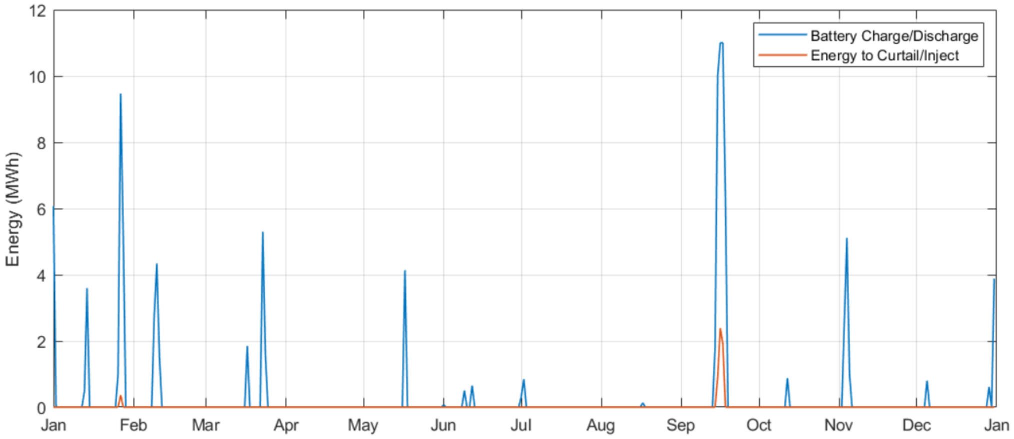
As can be seen the storage capacity required is fairly big and it will have an impact in the total cost of the renewable installation. Moreover, the higher the renewable power installed, the lower the size of the storage system, which is straightforward to understand, since the difference between the lowest production and the demand will be lower the more renewable capacity is installed.

Although, by observing the daily renewable generation for the low production scenario and the energy demand of the cluster, we realized that the former is always lower than the latter, leading to the conclusion that no storage is required. Anyway, the grid can always act as a storage system if unpredicted spikes of production occur. As such, we didn't consider any storage capacity for the low production scenario for the cluster.

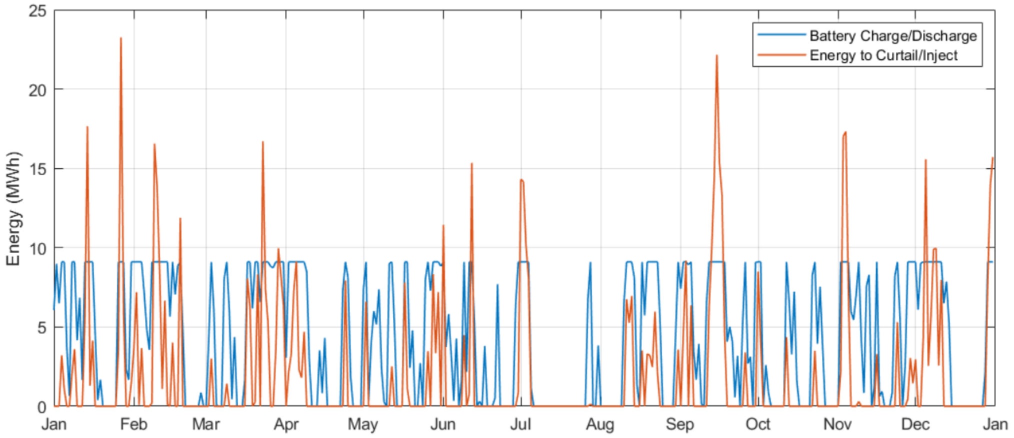
	Storage System Size (MWh)
Low Renewables	0
Medium Renewables	11
High Renewables	9,1

Table 7: Storage System Size for Grimstad Cluster

Moreover in Figure 14, it is shown how the behaviour of the storage system in term of charge and discharge of the batteries pack (in blue) and the consequent energy to curtail or inject into the grid (in orange). The high production scenario sub-figure b shows perfectly how the battery pack charges to its maximum capacity when the blue line flattens and the orange line spikes are all in the same time locations when the battery is fully charged and thus the excess energy has to be dealt with differently, indeed by curtailment or injection into the grid.



(a) Medium Renewable Production



(b) High Renewable Production

Figure 14: Grimstad Storage and Curtailment/Injection

7.2 Sandefjord Cluster

Similarly to the first cluster, the solar field and wind farm are described more in details for the central cluster of Sandefjord, showing relevant figures and facts to better reflect on the performance achieved.

7.2.1 Solar Capacity

Regarding the solar capacity installed, the technology installed is the same as the Grimstad Cluster, so monocrystalline silicon, as well as the parameters of the solar field, like efficiency, tilt angle, tracking system and so on.
In figure 15, it is possible to see the monthly solar production for the Sandefjord Cluster for each renewable penetration scenario. The lines have a similar trend due to the same meteorological conditions applying for all the renewable production scenarios. Also, medium and high renewable penetration overlap because the same capacity is planned for both.

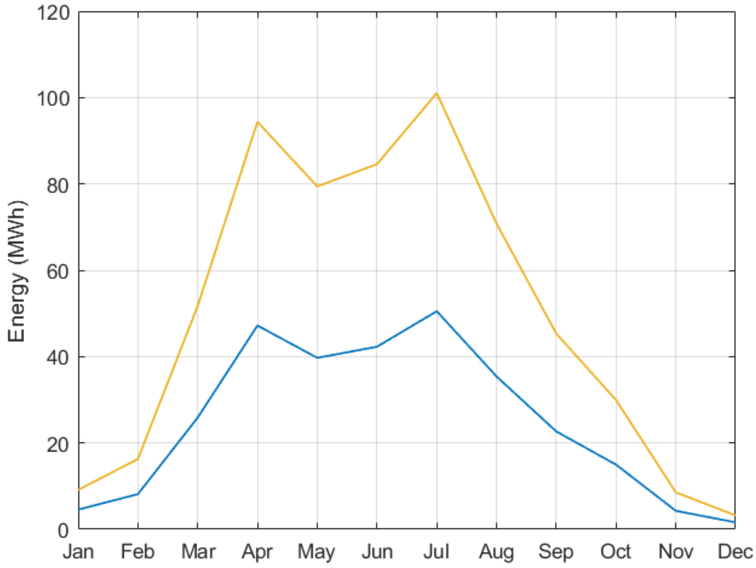


Figure 15: Monthly Solar Energy Production Sandefjord Cluster

7.2.2 Wind Capacity

Considering the Wind Capacity, two wind turbines are the same selected for Grimstad Cluster, while one bigger is planned for the high renewable scenario.

Each of them provides a different share of the total demand for the cluster, which will be similar to the total renewable share, since the solar production is further limited due to the lower irradiation potential because of the norther latitude of the cluster with respect to Grimstad Cluster.

As visible in figure 16, the high renewable penetration scenario implies a high power turbine installed which clearly leads to big amount of wind energy produced, even though the capacity factor is lower than for the Grimstad Cluster, mainly because the wind conditions are less favourable, as already mentioned in section 5.1. Nevertheless, the performance remains acceptable, even though not optimal. In table 8, the total yearly energy produced is reported as well as the capacity factor.

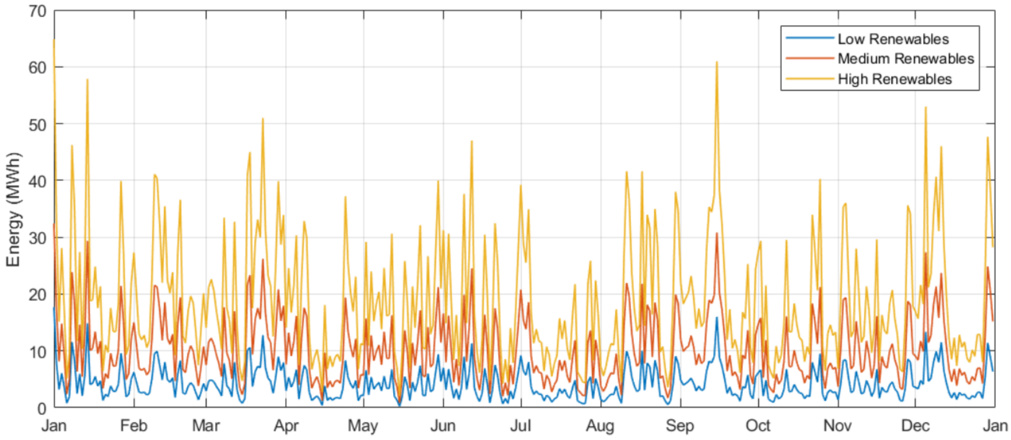


Figure 16: Daily Wind Energy Production Sandefjord Cluster

Model name	**Installed Power**	**Total Energy Produced (% of demand)**	**Yearly Capacity Factor (%)**
GE 900S	900 kW	1,54 GWh (18,2%)	16,3
GE 1.5 xle	1,5 MW	3,7 GWh (43,6%)	23,8
Siemens SWT 3.0-101	3 MW	6,93 GWh (81,8%)	25,1

Table 8: Wind Generation Performance for Sandefjord Cluster

In figure 17, it is possible to see the three renewable generation outputs, one for each penetration scenario combined with the energy demand for the cluster.

Again only medium and high share of renewable scenarios are able to fulfill the energy demand for some days and storage strategies are still required if an high share of renewable energy is planned to be installed. Similarly, low renewable integration is never able to meet the daily demand for the cluster's FCS, requiring energy off takes from the grid.

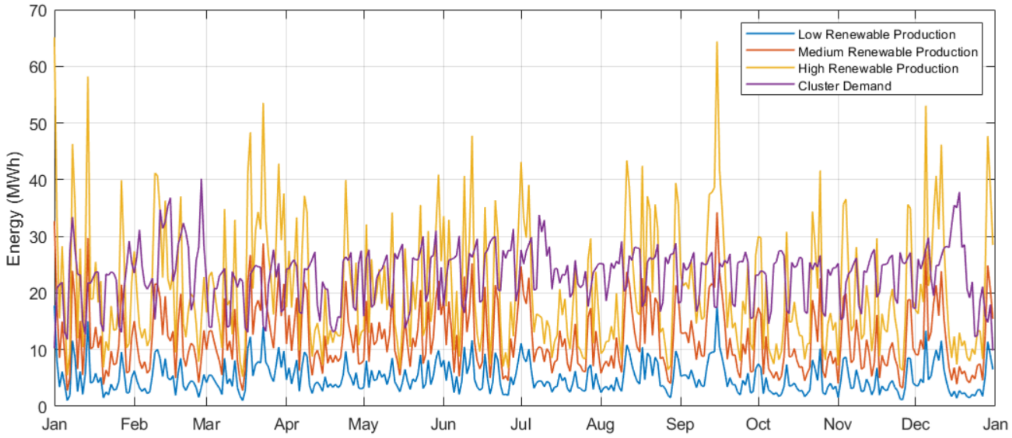


Figure 17: Renewable Energy Generation and Demand Sandefjord Cluster

All in all, table 10 shows the solar and wind energy generation with the correspondent share of the energy demand, and also the relative percentage referring to the renewable total generation output.

	Solar Energy Production (% of Renewables)	Wind Energy Production (% of Renewables)	Total Energy Produced (% of Demand)
Low Renewables	317,8 MWh (17,1%)	1,54 GWh (82,9%)	1,8578 GWh (22,35%)
Medium Renewables	636,9 MWh (14,7%)	3,7 GWh (85,3%)	4,3369 GWh (50,1%)
High Renewables	636,9 MWh (8,4%)	6,93 GWh (91,6%)	7,5669 GWh (89,3%)

Table 9: Renewable Generation Performance for Sandefjord Cluster

7.2.3 Storage Capacity

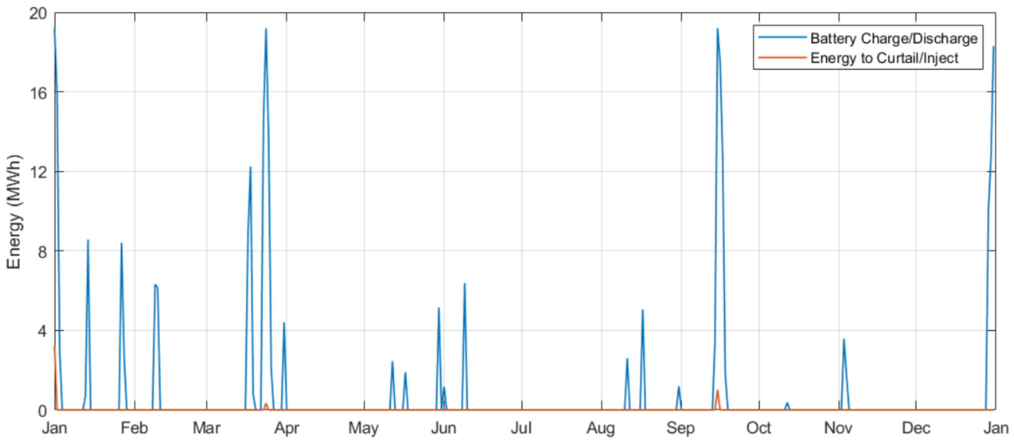
Again, the storage system sizing is conducted in the same way as the previous cluster, leading to the results grouped in table 10. This time though for the medium and high renewable scenarios, the worst day for renewable generation is the 15th of March, while the worst for the lowest renewable penetration occurs the 1st of June. This may seem weird, but in reality it is closely depending on the wind turbine and solar field installed. Indeed for the wind conditions on the two days mentioned, one turbine is performing worse on one day, while the other two on the other day.

Similarly to Grimstad Cluster, in the lowest renewable production scenario, the planned capacity obtained with the methodology explained in the previous section, is overestimated and the maximum energy recharged is roughly 7,5 MWh, thus a capacity of 7,6 MWh is enough to fulfill the scenario's renewable production.

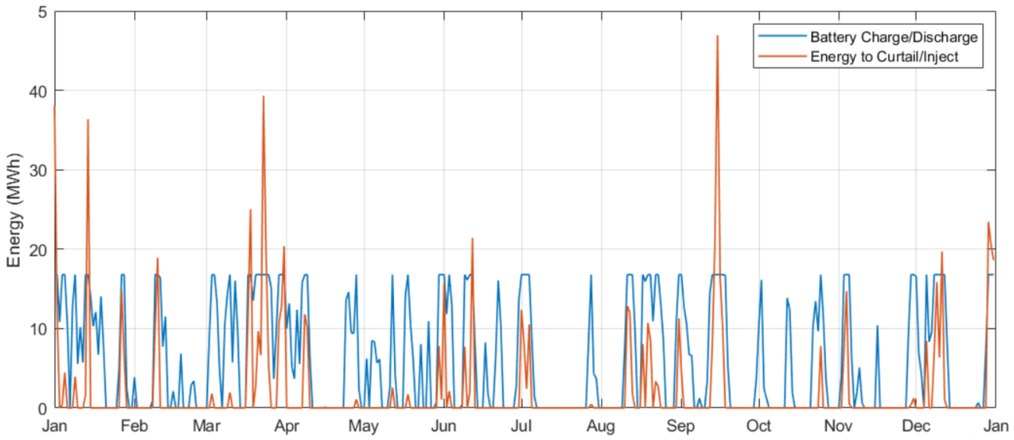
	Storage System Size (MWh)
Low Renewables	7,6
Medium Renewables	19,2
High Renewables	16,8

Table 10: Storage System Size for Sandefjord Cluster

In addition, figure 18 again depicts the storage capacity behaviour along the year considered. Similarly, the excess energy to manage with curtailment or injection into the grid occurs on the days when the battery pack is completely charged and thus cannot receive additional energy. This phenomena is more visible in the High Renewable Production Scenario, whilst in the medium renewable is almost not happening.



(a) Medium Renewable Production



(b) High Renewable Production

Figure 18: Sandefjord Storage and Curtailment/Injection

7.3 Oslo Cluster

All in all, the renewable generation performance for the third and norther cluster of Oslo.

7.3.1 Solar Capacity

The solar capacity installed is the same as the one installed in the other two clusters and the characteristics and parameters as well.
In figure 19, it is possible to see the monthly solar production for the Oslo Cluster for each renewable penetration scenario. The trend is similar to the one of the previous clusters with the curve dipping a little bit in may and then rising up again in summer months.

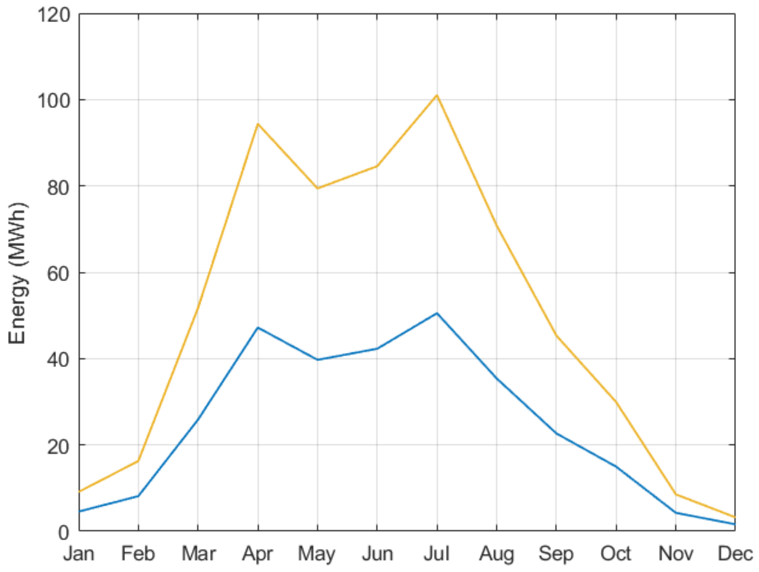


Figure 19: Monthly Solar Energy Production Oslo Cluster

7.3.2 Wind Capacity

The Wind Capacity installed is the same for the first two renewable penetration scenarios (low and medium) with respect to Sandefjord Cluster, implying the same turbine model selected. Nevertheless the capacity factor is getting worse than the previous cluster for lower wind availability in the area, as already commented in section 5.1 which also depends on the fact, that the biggest city of the country is nearby the planted installation site, flattening the potential of the wind (roughness index increase).

In figure 20, the daily wind energy production reflects the same observations done previously, namely a high production scenario leading to the storage problematic, which will be dealt in the economical section.

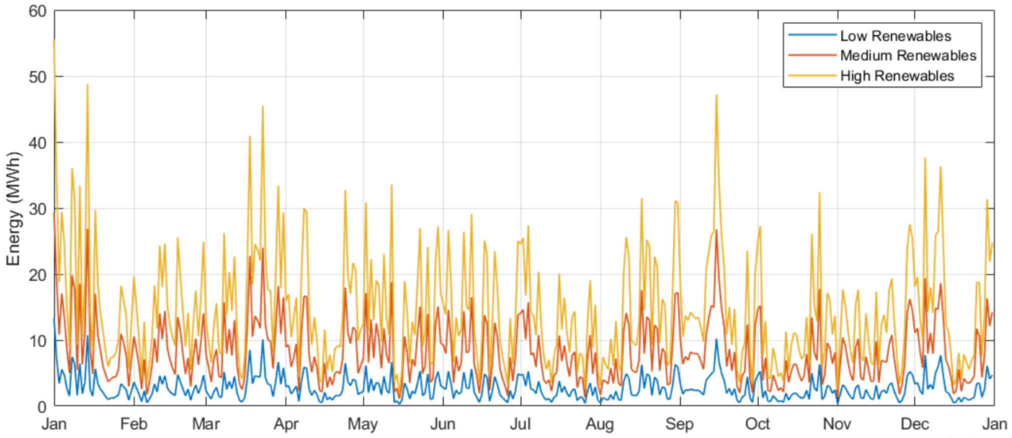


Figure 20: Daily Wind Energy Production Oslo Cluster

Model name	Installed Power	Total Energy Produced (% of demand)	Yearly Capacity Factor (%)
GE 900S	900 kW	999,302 MWh (16%)	14,6
GE 1.5 xle	1,5 MW	3,026 GWh (48,6%)	19,6
GE 2.75-103	2,75 MW	5,382 GWh (86,3%)	23,6

Table 11: Wind Generation Performance for Oslo Cluster

In figure 21, the three renewable generation outputs are shown, one for each penetration scenario combined with the energy demand for the cluster.

Once again only medium and high share of renewable scenarios are able to meet the energy demand for some days and storage strategies are still required if an high share of renewable energy is planned to be installed. Similarly, low renewable integration is never able to meet the daily demand for the cluster's FCS, requiring energy off-takes from the grid.

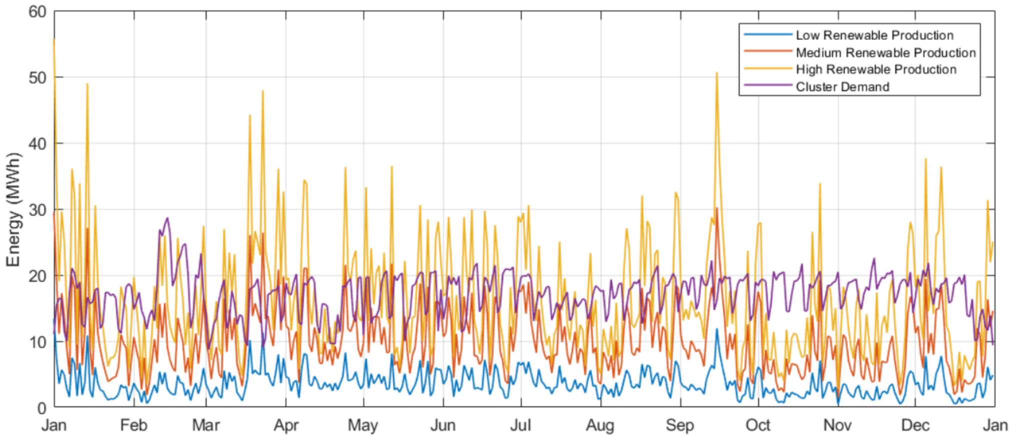


Figure 21: Renewable Energy Generation and Demand Oslo Cluster

All in all, table 12 shows the solar and wind energy generation with the correspondent share of the energy demand, and also the relative percentage referring to the renewable total generation output.

	Solar Energy Production (% of Renewables)	Wind Energy Production (% of Renewables)	Total Energy Produced (% of Demand)
Low Renewables	297,2 MWh (22,9%)	999,302 MWh (77,1%)	1,296 GWh (20,8%)
Medium Renewables	594,3 MWh (16,4%)	3,026 GWh (83,6%)	3,62 GWh (58,1%)
High Renewables	594,3 MWh (9,9%)	5,382 GWh (90,1%)	5,976 GWh (95,9%)

Table 12: Renewable Energy Generation and Demand for Oslo Cluster

7.3.3 Storage Capacity

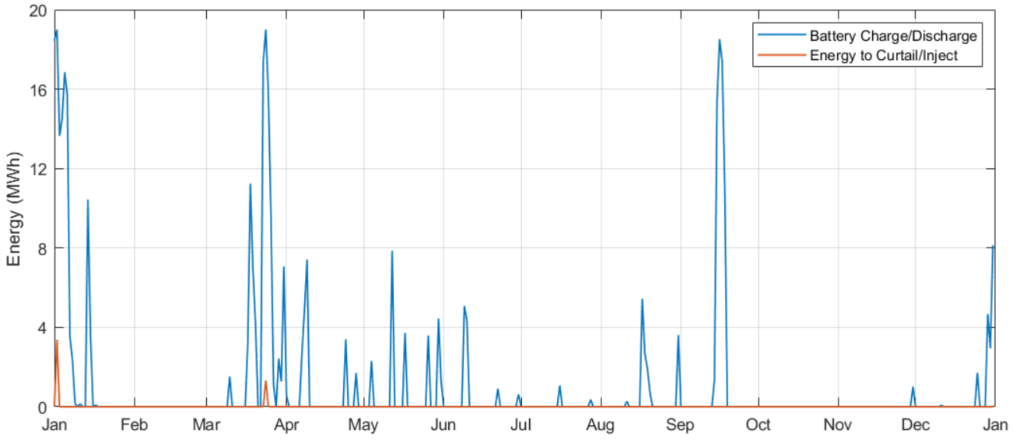
Oslo storage system requirements are obtained as the previous cluster and top the capacity required with the highest values among the clusters, grouped in table 13. This will mean a more costly investment and thus a lower profitability, as will be seen in the Economical Section.

	Storage System Size (MWh)
Low Renewables	2,4
Medium Renewables	19
High Renewables	18

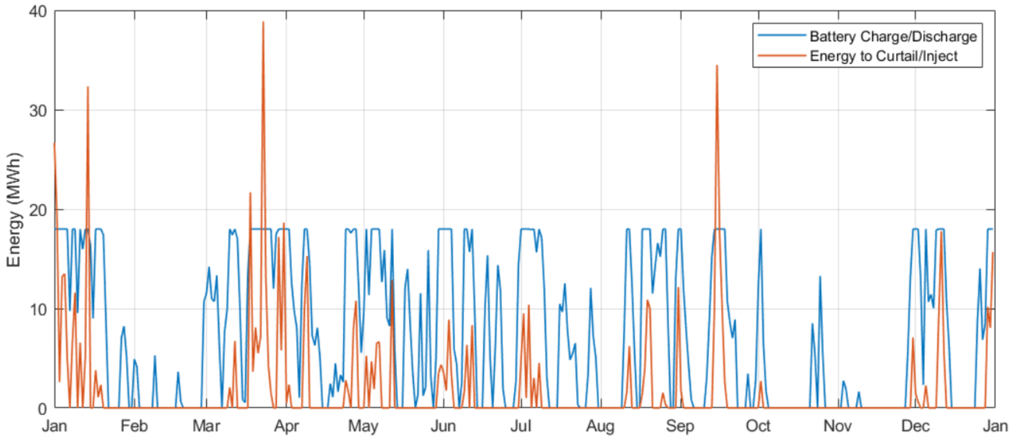
Table 13: Storage System Size for Oslo Cluster

In addition, figure 22 shows the storage capacity charge and discharge behaviour for the Oslo Cluster.

The behaviour is similar to the other two clusters already described, so no further comments will be given, leaving to the reader just the plots. Again, the low scenario storage capacity was overestimated and has been set at 2,4 MWh.



(a) Medium Renewable Production



(b) High Renewable Production

Figure 22: Oslo Storage and Curtailment/Injection

8 Economical & Environmental Impact

As every new planned renewable capacity installation, a deep economical analysis has to be performed, in order to show the feasibility of the project and attract potential investors.

The economical section will first focus on the description of the investment and operation and maintenance costs or CAPEX and OPEX, which are the main cost components for every new planned installation. Moreover, the profitability of the project needs to be evaluated through some indicators relying on the cash flow generated by the renewable energy production, the opportunity cost and so on.

The economical analysis will be followed by an environmental analysis to compare both and assess the feasibility and attractiveness of the project.

8.1 Investment Cost or CAPEX

Capital expenditures (CAPEX) or investment costs are expenditures required to achieve commercial operation in a given year [36].

The total investment cost of every renewable cluster project is the sum of the solar and wind capacity investment plus the cost of the storage system:

- The investment costs for new wind capacity includes the cost of wind turbines, foundations, internal grid, external grid connection, land acquisition, civil works, and project development [37];
- The investment costs for new solar capacity includes the cost of hardware, module supply, power electronics, wiring materials, balance of system, land acquisition and project development as well [36];
- The cost of the storage system include the battery pack and the inverter.

The investment cost for new wind capacity in Norway has been estimated equal to 1592 €/kW [37], even though is set to decrease further in the following years. On the other hand, the investment cost for new solar capacity has been considered to be roughly 820 €/kW, considering the EU average price [38]. Finally, the average cost for storage systems based on lithium-ion technology has been considered to be 113 €/kWh [39].

It is straightforward to calculate then the CAPEX for each renewable penetration scenario and for each cluster, just by applying equation 7.

$$CAPEX = (SC * CXS) + (WC * CXW) + 2 * SSC \tag{7}$$

where: SC is solar capacity in kW, WC is wind capacity in kW, CXS is capex for solar in €/kW and CXW is capex for wind in €/kW, while SSC is the storage system cost, which is multiplied by 2, because it needs to be substituted with a new one after ten years, thus having half the lifetime of the rest of solar and wind capacity, as will be explained in the Profitability Indexes section (see 8.4).

The yearly results are then grouped in table 14.

It is easy to understand that the investment cost is directly proportional to the size of the wind turbine and solar field, and it is interesting to notice how the highest generating plant (Sandefjord, high renewables) is almost ten times more expensive than the less

	Grimstad Cluster	**Sandefjord Cluster**	**Oslo Cluster**
Low Renewables	563.200 €	3.355.400 €	2.180.200 €
Medium Renewables	4.328.800 €	7.137.200 €	7.092.000 €
High Renewables	4.854.600 €	8.982.800 €	8.856.000 €

Table 14: CAPEX for Renewable Installation for each Cluster and Scenario

generating one (Grimstad, low renewables). In general the higher production scenarios are almost double the cost than the medium renewables ones.

8.2 Operation & Maintenance

The Operation & Maintenance costs or OPEX (Operation Expenditures) is a cash expenditure that occurs every year and can be divided into fixed O&M costs like insurance, administration, fixed grid access fees and service contracts for scheduled maintenance and variable O&M costs, which typically include scheduled and unscheduled maintenance not covered by fixed contracts, as well as replacement parts and materials, and other labour costs. Although, operational costs for renewable energy power plants are mainly due to three component, some already mentioned: service agreements, grid access tariffs, and balancing costs.

The service agreements refers to scheduled and unscheduled maintenance as well as additional services which are planned before operation starts between the different parties or stakeholders involved in the power plant [40]. Grid access tariff is a cost accounted for having a cost-based compensation for renewable energy producers, providing price certainty and long-term contracts that help finance renewable energy investments [41]. All in all, balancing fees are paid to the system operator for the balancing ancillary services required for the injection of renewable power that can cause frequency oscillation or in general imbalance in the grid. Usually those costs are limited in Europe, due to the robustness of the grid.

Therefore, the OPEX for solar energy has been fixed at 8,2 €/kW [38], so a as a fixed cost depending on the capacity, the OPEX for wind energy has been set at 20 €/MWh [37], so as a variable cost depending on the energy produced by the generator, while the one for the storage system have calculated both with a fixed part (8,5 €/MW), depending on the power rate of the battery, and a variable part (2,5 €/MWh) [42], depending on the energy stored.

In table 15, the yearly OPEX are collected for each scenario and cluster.

	Grimstad Cluster	**Sandefjord Cluster**	**Oslo Cluster**
Low Renewables	13.997,84 €	32.882,34 €	22.060,38 €
Medium Renewables	48.662,10 €	78.484,77 €	65.038,58 €
High Renewables	106.436,45 €	144.059,80 €	113.490,19 €

Table 15: OPEX for Renewable Installation for each Cluster and Scenario

Again the most producing scenario at Sandefjord cluster is ten times more costly than the lowest producing at Grimstad.

8.3 Revenues and Incentives

Renewable energy transition needs a support from the market to actually make it viable and possible.

The EU Renewable Energy Directive (2009/28/EC) [5] aims to promote the use of energy from renewable sources, by establishing the electricity certificate scheme or green certificates scheme. This is a market-based support scheme [6], where producers of renewable electricity receive one certificate per MWh of electricity they produce for a period of up to 15 years. Moreover, the scheme is technology-neutral, meaning that all forms of renewable electricity production qualify for these certificates.The establishment of the joint Norwegian-Swedish market was contingent on the possibility of meeting a quota obligation in Sweden these purchasing Norwegian electricity certificates, and vice versa.

Electricity suppliers and some categories of end users have an obligation to purchase electricity certificates corresponding to a proportion of their consumption, which is called quota obligation. Those are imposed by the Norwegian and Swedish governments who made aggregates their obligations to create a demand for electricity certificates. Nevertheless, the market determines their price and which projects are carried out. Producers of renewable electricity gain an income from the sale of electricity certificates, in addition to their earnings from electricity sales, while end-users contribute to this scheme through their electricity bills. The average price of one certificate is approximately 20 €/MWh produced, based on the average spot price of certificates [37].

Therefore, the revenues from the power plants of the three clusters have been considered to come both from the green certificates scheme but clearly also from the savings of the energy not purchased from the grid as off-take to meet the FCS demand.

To calculate the energy savings the average electricity price of 2019 for Norway has been considered and by simply multiplying the energy produced and the average price of electricity, it is straightforward to obtain the monetary saving for the year considered. Although, this calculation must take into account the energy curtailed which is lost, or the energy injected which is rewarded a feed-in-tariff which has been set at 13,4 €/MWh [43], which clearly leads to a surplus earning from just considering the non purchased energy. Even so, the impact on the total revenues of the energy fed into the grid is almost irrelevant being just 0,4 % of the total revenues for the high renewable scenario. As such, it will be ignored among the sources of revenues depicted in figure 23.

Finally, while in the past decade the fast charging facilities have been free of charges for the users who wanted to recharge their electric vehicles, now with an increasing share of EV's with respect to the entire vehicle fleet, the FCS have been turned to a more profitable business model by asking a fixed tariff per kWh recharged. This has been set recently in Norway at the considerable high price of 0,82 €/kWh [4]. Clearly, this is a source of revenues that has to be split somehow between the renewable energy producer and the owner of the FCS facilities who bears the cost of installation of the recharge facilities, as well as the operation and maintenance costs and also the additional energy to be purchased from the grid to meet the recharge demand.

In this sense, the business model of the renewable power plants has been defined just as an energy provider to the FCS facility, who shares the recharging profits and bears the cost of the additional energy required. The share of profit coming from the recharging fee applied has been divided into two different share, taking into account the higher cost borne by the FCS stakeholder, even though in real life different agreements might be put in place. As such, the share of revenues have been defined with an assumption to be 75% for the FCS facilities and 25% for the renewable power producer.

Even though, the two different parties have been considered to be distinct, they may merge into one big party who would own both the power plant and the FCS connected, then clearly bearing all the cost as well as gaining all the revenues.

As can be seen from figure 23, the charging fee is the biggest source of revenues for both parties involved and in particular for the power plant owner.

The calculations of the revenues and savings are grouped in table 16, while on figure 23, it is possible to see the share between the three scenarios of the revenues gained, whether from the certificates mechanism, the energy not purchased or the charging fees applied at the FCS. As already mentioned, most of the revenues comes from the energy recharged at the FCS, under the payment of a fee per unit of energy.

	Grimstad Cluster	**Sandefjord Cluster**	**Oslo Cluster**
Low Renewables	454.049,10 €	917.381,64 €	639.964,80 €
Medium Renewables	1.413.595,94 €	2.140.621,63 €	1.786.591,15 €
High Renewables	2.636.835,67 €	3.579.683,77 €	2.812.889,36 €

Table 16: Revenues for each Cluster and Scenario

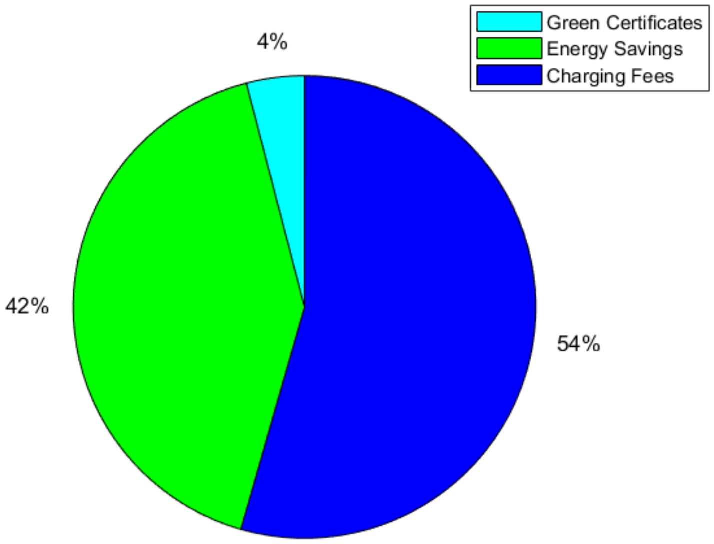


Figure 23: Renewable Plants Source of Revenues Share

8.4 Profitability Indexes

To assess the viability of the investment, the evaluation of some key economical indicators is required. In particular, the most important is the concept of return on investment which can be evaluated by analyzing different parameters, which now will be presented. Although, before jumping to the parameters some financial assumptions have to be made:

- The system lifetime is set to 20 years for the wind power plants and 30 years for the solar PV field [44], but for the sake of simplicity in the calculations 20 years is considered as investment lifetime for the PV, in order to consider the system (PV + wind) economical evaluation as a whole.

- The interest rate are now really low in order to stimulate growth during a period of economic decline and uncertainty, like the one we are living due to the COVID-19 pandemic, which means that borrowing costs become cheaper. As such, the outlook for the next years sets the interest rate at around 0.75-1%, but for the economical analysis the value of 1% will be used.

- The degradation rate for both technologies have to be included in the analysis, meaning that each year the generation capability is reduced of a small percentage: 0,7% less energy produced per year for PV solar [45] and around 1,6% for wind turbines [46]. In more details, every year the revenues calculated in the previous sub-section, will be proportionally reduced due to the degradation and the consequent reduction of the energy generation productivity and mathematically presented in the definition of the Simple Cash Flow.

With all due respect to the mentioned assumption, some economical indicators can be calculated and commented in the next paragraphs. Before so, in table 17, all the economical assumption and data necessary to the calculation are grouped.

Variable	Variable Name	Value Considered
C_y	Yearly Net Cash Flow	See Section 8.3
C_0	CAPEX	See Section 8.1
Y	System Lifetime	20 years
y	Interest Rate	1%
M	OPEX	See Section 8.1
d	Degradation Rate	0,7% (PV); 1,6% (Wind)

Table 17: Nomenclature and Values for Economical Variables

The first parameter is the NPV or net present value, which compares the present value of all cash inflows with the present value of all cash outflows associated with an investment project [47]. In order for the investment to be economically viable so that the investor can make a profit, it is necessary that the NPV is bigger than 0. While, if NPV is equal to 0, the investor will only break even but still the investment will be viable. However, if NPV is lower than 0, the investment will not be viable and thus profitable for the investor.

Equation 8 is the formula to calculate the NPV, where the variables have been already presented in table 17.

$$NPV = \sum_{y=1}^{Y} \frac{C_y}{(1+r)^y} - C_0 \tag{8}$$

The NPV takes the present value of the money into consideration and it is one of the most common method used to financially assess long-term projects. Nevertheless, it has a main drawback which is the need to assume an interest rate which can change the result significantly.

The amount of time required to repay the up-front cost is called Simple Payback Period or SPBP. The SPBP does not incorporate the time value of money, thus assumptions on discount or interest rates are not required. It is easy to understand, but on the other hand introduces an overly optimistic bias for long term investments, overestimating the value of future returns [48].

The Simple Payback Period formula is shown on equation 9:

$$SPBP = \frac{CAPEX}{SCF} \tag{9}$$

While, the meaning of CAPEX has already been explained in the previous sections and refers to the initial investment, SCF stands for Simple Cash Flow. To calculate this quantity equation 10 has been applied.

$$\begin{cases} SCF = \sum_{y=1}^{Y} C_y \\ C_y = R_y - O\&M_y \end{cases} \tag{10}$$

Where clearly R_y stands for yearly revenues and $O\&M_y$ are the yearly operation and maintenance costs, which have been presented in the last sub-section.
To include the degradation rate in the constant decrease of revenues, the simple degradation coefficient is included in the revenue factor as in equation 11, where R_0 are the revenues generated in the first year of operation of the renewable power plants.

$$R_y = (1 - y * r) * R_0 \tag{11}$$

The equation must be applied separately for each technology considered since the degradation rates are sensibly diverging one from the other.

Although, considering the Discounted Payback Period allows to have a more realistic overview of the time to repay the initial investment by simply replacing the simple cash flow with a discounted cash flow, which takes into account that the value of the future revenues is lower than the value of the present ones. Equation 10 is updated as shown in equation 12 by adding the interest rate component.

$$DCF_y = \frac{SCF_y}{(1+r)^y} \tag{12}$$

Finally, to calculated the Discounted Payback Time or DPBT, it is enough to replace the SCF in equation 9 with the DCF just calculated.

Moreover, the Profitability Index (PI) indicates how much profit or loss the project is able to generate in a certain period of time. It is calculated as straightforwardly shown in equation 13. There is a breakeven when PI is equal to 1, indeed NPV equal to 0 is associated to the breakeven point, while the profit is doubled if PI is equal to 2.

$$PI = \frac{NPV}{CAPEX} + 1 \tag{13}$$

Finally, in table 18, all the results for each scenario and cluster are grouped.

	DPBP (years)			**IRR**			**PI**		
	Grimstad	Sandefjord	Oslo	Grimstad	Sandefjord	Oslo	Grimstad	Sandefjord	Oslo
Low Renewables	~ 3	~ 8	10	76%	24%	26%	6,39	2,41	2
Medium Renewables	~ 5	~ 6	$\sim 7,5$	29%	27%	22%	3,85	3,41	2,71
High Renewables	~ 3	~ 4	$5,5$	50%	36%	28%	6,96	4,80	3,64

Table 18: Profitability Indexes Results

The values collected in table show how much the investment in the proposed renewable capacity is profitable. Indeed, the pay back times are all minor or equal than 10 years, with the record value of roughly 3 years both for the high capacity and low capacity power plants of Grimstad Cluster. The high economical performance of this cluster for the considered scenarios is reflected also in the other indexes like the PI and the IRR which scores the highest values of more than 6 and 76% and 50%.

On the other hand, the worst performing cluster is Oslo for a low renewable penetration scenario which has the highest payback time of 10 years and the lowest IRR and PI as well. Even though, the cluster is still profitable, it is clearly less performing than the other ones, in particular Grimstad one, previously commented.

To conclude this section, the economical performance of every investment scenario is strictly connected to the resource availability and thus the capacity factor of the wind turbine which is the main voice in the capital expenditure but also for the solar capacity, even though it has a lower impact in the indexes, without forgetting the storage capacity and availability.

8.5 Environmental Impact

As a last section for the Renewable integration Feasibility Study, we performed an environmental analysis considering the life-cycle greenhouse gas emissions of the energy sources for electricity generation in Norway [7], as well as the storage capacity environmental impact [49], which is incredibly higher than the others because it includes emissions from mining, refining and so on. It is to mention that we considered second-life batteries which are usable for stationary applications like the one object of study which have a reduced environmental impact with respect to a new battery of about 75% [50]

All the results are collected in figure 24, where we can see three different groups, one for each renewable generation impact with the comparison between a renewable generation life-cycle CO_2 emissions and the same amount of energy generated by following the generation mix of Norway. Indeed, just to recall it from the Preliminary Analysis section (3), Norway generation mix is composed of hydro-power which accounts for 93% of the total production, while the rest is shared by wind generation (4%) and thermal generation (3%).

To obtain the results collected in figure 24, we have considered the life-cycle greenhouse gas emissions or CO_2 equivalent associated to each generation technology reported in Table 19.

Energy Source	**g CO_2 eq/kWh (kW-bat)**
Wind Onshore	11
Thermal	600
Hydro-Power	24
Solar (Utility)	48
Lithium-Ion Batteries (Recycled)	6000

Table 19: Life-cycle greenhouse gas emissions per Energy Source

	Grimstad	**Sandefjord**	**Oslo**
Low Renewables	-41%	-42%	-45%
Medium Renewables	-38%	-43%	-39%
High Renewables	-55%	-57%	-53%

Table 20: Percentage of Emissions Reduction

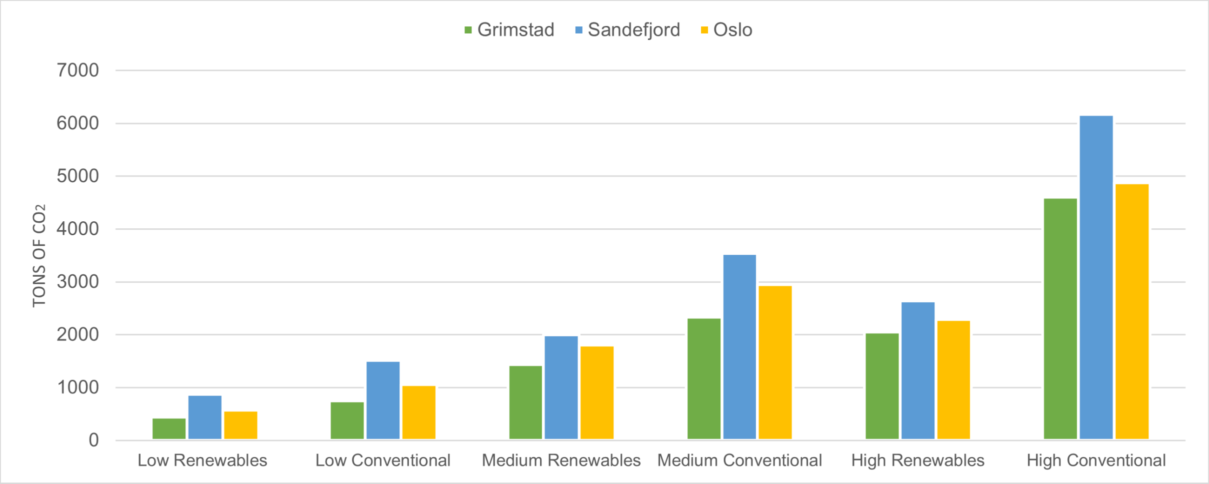


Figure 24: Emissions Levels Comparison for each Generation Scenario

Commenting figure 24, the higher the energy produced with renewable sources, the higher the amount of CO_2 saved. Indeed, the more energy is produced with wind and solar, the less with thermal energy technology which is an order of magnitude more polluting. Although, the environmental performance of renewable generation is lowered by the storage capacity which has an high impact even if recycled. Nevertheless, it is a one time emission when changing the batteries pack (kW-bat), which in our analysis has been considered every ten years so two times during the lifetime of the investment, and no emissions are considered during the working time of the batteries.

It is interesting to see that even in a lower renewable integration scenario, Grimstad cluster performs quite good, confirming that the cluster is a good investment even in environmental terms. However, the best performance in term of emission reduction is achieved at Sandefjord Cluster because the size of the renewable plant is the biggest and as a consequence more energy is harvested and not emitted with conventional generation technology. Moreover, the cluster of Oslo has a surprisingly good performance for the lowest renewable generation scenario, probably due to the fact that the storage requirement is less than for Sandefjord with the same generation scenario with the same renewable capacity installed. Thus, here lies the small difference visible between the two clusters.

Finally, all the emission reduction percentages are collected in table 20.

9 Cost of the Project

The cost for realizing this project was limited because all the resources deployed, a part from the cost of labor, were open source and free of charges.

Indeed, the cost of labor was divided between the cost of an engineer, represented by me, and the cost of an external consultant, represented my supervisor and the co-supervisor. The former have been assigned a monetary value of 30 €/hour, while the latter a value of 45 €/hour. The number of hours I worked on the project has been roughly 750, as supposed to be for a thesis worth 30 ECTS, while the hours of external consultancy has been set at 20 and equally divided between my supervisor and co-supervisor. All the labor cost are grouped in table 21.

All in all, the cost of materials are considered to be really limited, since the computer used was mine and have been assigned a depreciated cost of 100 €. In addition, an internet connection worthy 50 €/month was included, for 4 months of work, resulting in 200 €.

Clearly, if we want to increase the level of accuracy of the analysis, more labor may be needed as well as a more accurate resource assessment for renewable generation, more powerful software and hardware indeed associated with a cost, but this was an academic investigation and thus connected with a low cost analysis. The total cost has then been added with a VAT set at 21%.

A brief summary of the total cost of the project is included in table 21.

Cost of Labor	**Hourly Cost (€/hour)**	**Number of Hours**	**Total Cost (€)**
Engineer (Student)	30	750	22.500
Consultant (Professor)	45	20	900
			23.400
Computer Cost	-	-	100
Wi-fi and others	-	-	200
Total without VAT			23.700
VAT			4.977
Total with VAT			28.677

Table 21: Cost of the project components

10 Conclusion

The integration of renewable capacity to boost in a greener way the electrification of E18 highway in Norway has been investigated in this master thesis and some interesting results have been obtained.

The energy demand of the FCS has been simulated starting from the traffic flow randomly characterized and once obtained was aggregated in three groups as described in the methodology section (see 2) to simplify the analysis and the dimensioning of the power plants.

Then, the new renewable capacity was accordingly dimensioned aiming to supply three different shares of the total demand, depending on the case scenario considered (2), leading to three different power plants for each cluster. Every plant is composed of a solar field and a wind turbine, with a shared storage system.

After this, the generation performance of the proposed capacity is studied, as well as the storage behaviour which may be adjusted if there is an over-estimation of the battery size needed (7.1.3, 7.2.3, 7.3.3)

Then, the economical section with the cost and revenues analysis together with some profitability KPIs. As reported in the results table 18, the discounted pay back times are all minor or equal than 10 years, with the record value of roughly 3 years both for the high capacity and low capacity power plants of Grimstad Cluster, which occurs to be highly profitable by looking also at the other indexes evaluated like the PI and the IRR with the highest values of more than 6 and 76%, 50%.

All in all, an estimate of the environmental impact of the new renewable capacity is compared with the business as usual generation mix of Norway (see table 20). The environmental performance of renewable generation is lowered by the storage capacity which has an high impact even if recycled. Nevertheless, Grimstad cluster performs again quite good, confirming to have a good impact even for environment. However, the best performance in term of emission reduction is achieved at Sandefjord Cluster because more green energy is produced saving emissions from conventional generation technology.

All in all, by joining the two impact assessment (economical and environmental), the two clusters which are a more interesting investment result to be Grimstad and Sandefjord, each one with a better penetration scenario: Grimstad with low or high renewables and Sandefjord with high renewables.

Clearly, this master thesis was the first assessment of the feasibility of renewable generation to boost the electrification of roads' infrastructure and more in general of the transportation sector.

Nevertheless, further investigation can be made on how to improve the charging strategy of EV's to better suit with the smart grid operation and renewables intermittent generation, but also to have a better picture of what could be the best investment both for the environment and on an economical point of view.

A Appendix

A.1 Fast-Charging Stations

Fast charging is also known as rapid charging or quick charging and aims to recharge EV batteries within a short period similar to that for gasoline refuelling of conventional vehicles [51]. The time necessary for fast charging is about 20 minutes for charging up 80% capacity. Thus, the total travelling distance of EV's can be greatly extended, provided that there are sufficient fast charging stations on the way. The key to fast charging stations is the charging module which can have a power of 35 kW or even higher, with corresponding voltage and current ratings of 45–450 V and 20–200 A, respectively. As both power and current ratings are so high, such recharging facilities have to be installed in supervised stations or service centres. Even though fast charging enables EVs to have a driving range similar to that of conventional vehicles, it can create adverse impacts on the power system, like harmonic contamination.

For fast-charging stations a strong grid access is necessary [52]. The required connecting power is not available everywhere, which causes extra investments for the grid infrastructure. Furthermore, a chicken-or-egg problem exists: Either a fast-charging infrastructure is needed before the vehicles can be used, or vehicles capable of fast charging have to exist before the infrastructure is built.

The introduction of fast-charging technology strongly depends on the user acceptance seeing the new technology as an opportunity. In fact, car drivers are used to the nearly unlimited driving range of their internal combustion engine (ICE) vehicles. The same feeling could be replicate by providing drivers with fast-charging stations.

Fast charging might be an interesting and worthy option for urban bus traffic and vehicle fleets such as cabs and delivery vehicles. As a matter of fact, these vehicles drive more kilometers per day and the duration of their trips are easier to plan. In this way, the batteries size can be greatly reduced, when the bus can be fast-recharged multiple times per day.

However, the infrastructure required for fast charging is fairly expensive. The costs are mainly for the grid access, power electronics, and connectors of the charging station. In addition, EV's drivers may make use of fast charging facilities option once a year or so, for vacation or traveling over the holidays. This would require an infrastructure designed for these extreme peak loads for a very few days in a year, increasing the overall cost.

A.2 Electrification of the Road Transportation Sector

The electrification of the transportation sector is deeply investigated in literature and in this appendix section a brief overview will be given to the reader to better understand the technologies behind it.
This could, for example, be achieved by:

- Electric vehicles with static charging at home or fast/super charging in public places;
- ERS or Electric Road Systems;
- The use of electricity to produce a fuel, such as hydrogen or synthetic hydrocarbons;

There is no clear single solution for the road transport sector, and each of the listed alternatives has its own advantages and disadvantages [53].
Electric Road Systems (ERS) can be defined as roads supporting dynamic power transfer to the vehicles from the roads they are driving on [15]. An ERS could be deployed on highways and more in general in the road network allowing the travelling fleet to be driven on external electric power instead of using fossil fuels. The propulsion in the non-electrified sections outside the ERS network could either be based on internal combustion engine (ICE), or on energy stored in small, on-board batteries optimized for smaller routes. With this solution, both the costs and the weight of the batteries can be kept small. In addition, the time of recharge of classic plug-in vehicle would be saved.
Theoretically, ERS could be based on energy transmission to the vehicle from above, from the side, or from under the vehicles. The idea of transmitting energy from above is the most mature technology, it has been used in e.g. trolley buses for many decades. Such a solution is suitable for the heavy transport segment but it excludes passenger vehicles since the current collector would be unrealistically long. Transmitting energy from the side of the road would be suitable for most kinds of vehicles but the potential number of lanes to be electrified would be limited. Electricity transferred from the roadside would also cause increased danger to vehicles in an accident or to people and

animals on the side of the road.

Instead, the solution of transmitting energy from the road below the vehicle could have a high potential, as it could be viable for both heavy duty and passenger vehicles and thus sharing infrastructure costs. Furthermore, there are different ways to transmit energy from an ERS to the vehicles and two of the more commonly discussed solutions are conductively and inductively.

In a conductive system, energy is transferred by establishing a physical contact between the vehicle and a conductor built into the road. Consequently, the technology requires a current collector, also known as a pick-up, which follows the electrified road and acts as the interface between the road and the vehicle. With the flexible highway vehicles, unlike trains that are bound to follow the rails, the pick-up needs to be active and capable of following the ERS with the ability to connect and disconnect depending on the driving behaviour and road conditions.

On the other hand, with inductive technology, the energy is transferred wireless through a magnetic field and no physical connection between the road and the vehicle is required. Instead of rails in the road, a conductor (comparable to the primary side of a transformer) inside the road generates a magnetic field that can be obtained in the vehicle and converted into electrical current. To enable the transmission also this solution requires a type of pick-up, corresponding to the second side of the transformer. To ensure high energy efficiency, the transmission distance and flexibility to follow the road collector are important issues.

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Friends are part of your family and that's the case also for me. I was scared to leave, thinking that I would have lost my lifetime friendship, but those that really mattered have just been reinforced. I'm talking about my friends from my hometown Castenaso and Bologna: Riccardo, Luca V, Elena, Ilaria and Andrea but also Alberto, Luca M, Stefano, Riccardo (Paips), Bobby, Ale, Beppe and many more that have shared a part of their life with me. What I wanted to say to all of you is that you have always made me feel home and like nothing has changed between us, which is something I really appreciated. With each of you I have a bond which I hope will always be as strong and beautiful.

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