POLITECNICO DI MILANO

Master of Science in Energy Engineering

Department of Energy

School of Industrial and Information Engineering

Design and operation of wind turbine for hybrid power plant application including P2X

Supervisor at Polimi:

Prof. Paolo Silva

Supervisors at DTU:

Prof. Kaushik Das

Prof. Athanasious Barlas

Soheil Thahernejad Ledari

10597759

Academic Year 2020-2021

Acknowledgement

Most of all, I would like to express my sincere gratitude to my supervisors, Researcher Kaushik Das, Senior Researcher Athanasios Barlas not only for their guidance, support, and involvement but also for inspiring me by their knowledge and professionality, and professor Paolo Silva for warm hearting support, extensive care, and providing me the opportunity to fulfill this thesis.

I would particularly like to thank Sareh Jafari for her compassion, patience, and caring during this study. I should thank Ph.D. Hadi Mirgolbabaee for his delightful support and advice. I would like to thanks Ing. Safaee and Ing. Tahavori for their insightful ideas and support during this work. Last but not least, I would like to thank my family profoundly and sincerely, who always supported me in all aspects. It would be impossible for me to do any of this without their love, support, and patience.

Abstract

Renewable energies are introducing the most promising path to a cleaner future by producing decarbonized electricity. Among all renewable technologies, wind energy and solar PV are fast-growing due to high availability and declining cost in recent years. The principal objective of this project was to chose optimal design parameters for a wind turbine working in a Hybrid power plant by considering a strategy for maximizing the NPV. Additionally, two configurations for the Hybrid power plant, wind turbine+ battery storage and wind turbine + PEM electrolyzer, have been considered. In order to achieve the main goal of this study, a set of design parameters has been selected, and by utilizing the WISDEM library in Python, the wind turbine design has been implemented. Afterward, by considering an electricity price time series and cost of HPP elements, an economic study was performed to find the maximum NPV. Furthermore, in order to maximize the NPV for configured Hybrid power plants, a mathematical model for battery and electrolyzer optimization has been proposed. Besides, a comparison between the design strategy as it is today and the strategy with market objective has been accomplished. Finally, in order to find the competitive scenario for the battery and electrolyzer, a sensitivity analysis has been carried out.

Executive Summary

Background & limitation After two decades of this century, it is more evident now that climate change should be the most primary concern with medium- and long-term priorities. Although the COVID-19 pandemic takes many lives and cause social and economic crises since last year, it should not be a reason to forget a more significant concern that may cause a crisis on a greater scale. The first worldwide challenge in the 21^{st} century is global warming and, consequently, climate change. Accordingly, a considerable number of studies represent that the main reason for climate change is anthropogenic greenhouse gas (GHG) emissions, which result in global warming. In addition, International Energy Agency (IEA) predicts that the worldwide energy demand by 2030 experience an increase of more than 50%, and the reason is emerging of developing countries, mainly in Asia and South America. Therefore, a cleaner path for near-future energy generation is imperative. The second challenge is related to energy availability and security for countries with no access to fossil fuel sources such as oil, coal, or natural gas.

In order to tackle these challenges, in 2020, IRENA introduced the Transforming Energy Scenario, an effective solution to keep global temperature growth below 2°C, set in the Paris Agreement. This scenario offers a reduction of CO2 emission by 3.8% per year, and it becomes reachable by transforming the fossil fuel-based energy sector into a renewable one in combination with energy efficiency improvement by 2050. Not only do renewables offer a more secure and sustainable energy source as an alternative for fossil fuels, but they also positively affect GDP, job opportunities, and other economic indicators by playing a role in the local energy market. However, among all renewable technologies, solar and wind are the most promising ones to accomplish the decarbonization target for 2050. Today, the share of low-carbon energy generation is dominated by Hydro and Nuclear power; however, their primary limitation is available capacity and safety, respectively. Consequently, Wind and Solar PV have become a more reliable alternative.

Although wind and solar PV are the primary energy supplier in the near future, they have an issue in terms of natural resource variability. This is the main reason for the low availability and low profitability of these kinds of energy sources. In consequence, most wind and solar PV power plants are built with either feed-in-tariffs or power purchase agreements to be as competitive as fossil fuels power plants. However, in the near future, renewables should be more economically efficient to dominate electricity generation share until mid-century. Therefore, combining some wind and solar PV technologies with energy storage systems to create Hybrid Power Plants (HPP) may be the solution to have a more flexible,dispatchable, and profitable power plant that can provide electricity as a reliable source.

Purpose The primary goal of this study is to design a wind turbine working in Hybrid power plants by considering the maximum Net Present Value (NPV) strategy. It is noteworthy to mention the fact that today's wind turbine designs are based on lowering the Levelized Cost Of Energy (LCOE). However, this strategy is a logical and secure path for companies to develop their wind turbine, but it does take their independence from any supportive regulations, such as feed-in tariff or power purchase agreement. Therefore, what is interesting in order to fulfill this study is to find a new design methodology based on NPV maximization for the future wind turbine. In addition, battery storage with the arbitrage strategy coupling with a wind turbine was the first motivation of this study. Afterward, due to the significantly fast-growing market for Hydrogen production, a Hybrid power plant including an electrolyzer for 2030 becomes an area of interest in this study. In a more explicit manner, the following question presents the main aim of this study:

- How to define the wind turbine design parameters in order to achieve the highest NPV by considering different markets?
- Is the BESS a profitable solution by considering the cost projection in 2030 in order to be utilized in the HPP? if the answer is no, how much the cost of BESS should be reduced in order to have a profitable business?
- Is the HPP, including the wind turbine and Hydrogen production system, a profitable configuration by considering today's electricity prices and WT and PEM electrolyzer cost for 2030? if the answer is no, in which price of Hydrogen or cost reduction of electrolyzer it becomes a profitable business?

- Does the BESS and PEM electrolyzer affect the design of the wind turbine in order to charge/ discharge the battery storage or generate Hydrogen?

- Will the wind turbine design parameters be different by considering minimum LCOE as the objective function compared to the maximum NPV strategy?

Assumptions In the procedure of performing the study, some simplified assumptions were made due to the lack of sufficient data or difficulty to obtain them. Those critical assumptions are listed as follows:

- **Electricity price:** An electricity price time series with an hourly resolution has been generated for the year 2019. Due to the complexity of generating the electricity price for a wind turbine's whole lifetime, an extrapolation for 25 years has been taken into account.

- **Wind speed:** Similar to the electricity price, an hourly wind time series for selected locations have been generated by CorRES, which is a Technical University of Denmark (DTU) tool. Also, the generated time series is considered constant each year for the selected location during the wind turbine's lifetime.

- **HPP components costs:** Since this study is looking for future wind turbines working in hybrid power plants, all costs are projected to 2030. Consequently, a projected cost of the battery storage has been utilized from Danish Energy Agency (DEA). Additionally, a cost projection from International Renewable Energy Agency (IRENA) has been selected for the PEM electrolyzer. In order to find the cost of the wind turbine in 2030, first, by performing the Wind-Plant Integrated System Design and Engineering Model (WISDEM), the cost for 2010 has been evaluated; afterward, a linear extrapolation was accomplished.

- **Hydrogen price:** The study in the part of Hydrogen has been simplified significantly. A constant hourly price for whole life time of HPP has been considered. Therefore, a sensitivity analysis is carried out to assess the robustness of the model.

- **Hydrogen storing and transportation:** In this study, the transportation or storing cost of Hydrogen has not been taken into account. Besides, ample storage has been assumed where other utilities of Hydrogen are constant using.

- **Market impact:** In the case of coupling BESS for all wind turbines competing in an electricity market with an arbitrage strategy, the electricity price would be a constant value for each hour. Therefore, it is considered that the designed HPP in this study is the first mover to the market with the proposed strategy.

- **Locations:** In this study, three locations, Denmark, Italy, and the Netherlands, have been chosen to implant the designed HPP in order to examine the accuracy and comprehensivity.

Structure The overall structure of the study takes the form of five chapters. **Chapter 1** It begins by introducing the work, presenting a vision of background in this field of study, marking the existing problem at present and those limitations that may remain in the future, and finally, pointing those questions that will be answered in this study. **Chapter 2** will consider both the sources and methods of study proposed by other authors until now and, additionally, an illustration of a utilized method in the current study. The **3$^{\text{rd}}$ chapter** is concerned with the methodology employed for this study. **Chapter 4** presents all results and a brief discussion about them. Finally, the **last chapter** concludes the study and proposes a desirable direction for future study.

Methodology & implementation In chapter 3, a detailed description of wind turbine design, either working as a single component in wind power plants or cooperating with other HPP components, has been explained. Additionally, an HPP plant with two different scenarios, one with a battery storage system and the other one with Hydrogen generation technology, has been described. Figure 1 presents different configurations of hybrid power plants that their design procedures will be explained in this section. The first designed configuration is a single wind turbine connected to the grid. However, a single wind turbine can not be a Hybrid power plant, but it is the first step in designing a hybrid power plant anyway.

Additionally, to understand the effect of hybridization, a zero state is needed to be compared with different hybrid power plant configurations. The second and third scenarios are a wind turbine in contribution with battery storage and a PEM electrolyzer, respectively. As depicted in the figure, the power plants are connected at a single point to the grid, which is a definition for hybrid systems. Additionally, in the case of wind turbine and battery storage, there is a 2-way key to ensure that charge/discharge is not happening simultaneously. Similarly, in wind turbine and electrolyzer case, the switch grantee that the electricity has a single direction after the HPP, either toward grid or hybrid power plant.

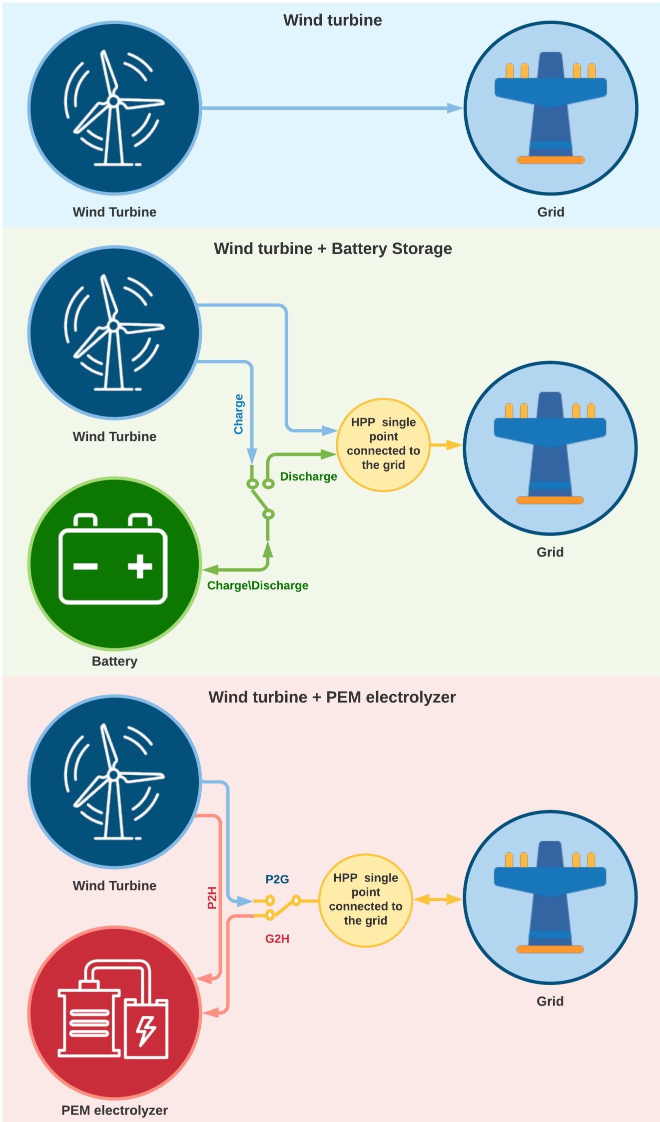


Figure 1: Different Hybrid power plant configuration

Figure 2 briefly shows the flow strategy designed to find the configuration of HPP with the highest NPV. It is understandable from the graph that the procedure can be divided into two main parts. The first is to choose a characteristic design for HPP's components and optimize it to generate the highest revenue. Moreover, the second one is to iteratively change the chosen characteristic design of HPP's elements in order to find the one with maximum NPV (outer block diagram).

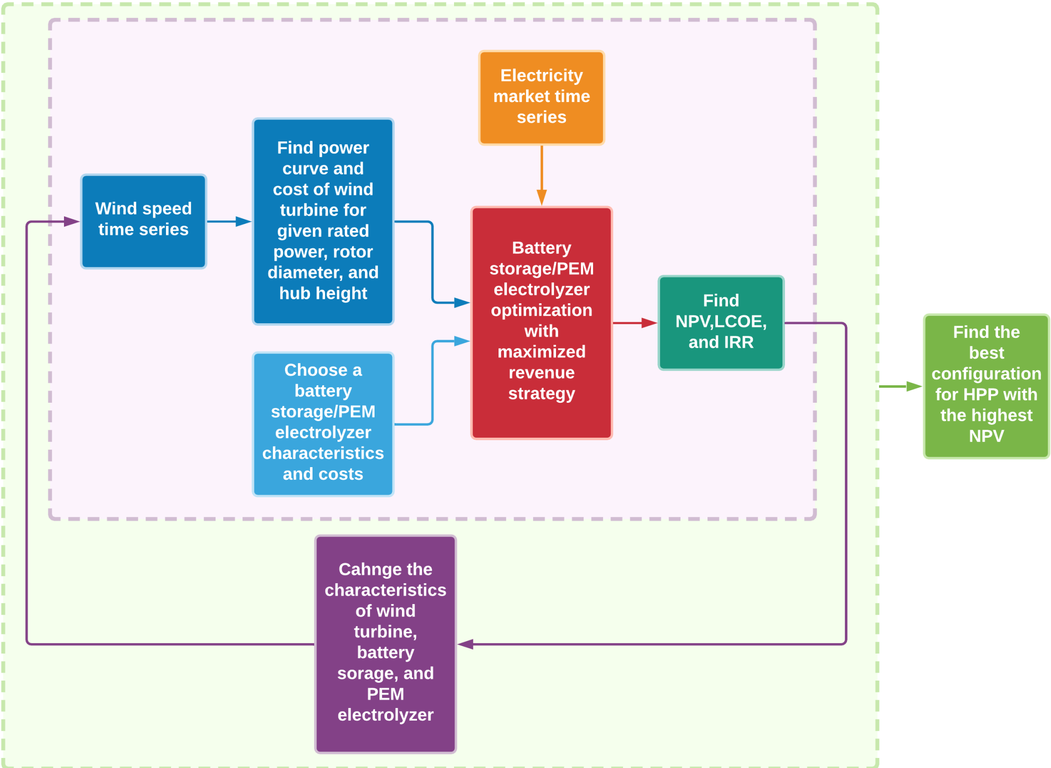


Figure 2: Methodology block diagram

In the design procedure of three main components, there are two categories of input data. First, the fixed input data, which are those data assumed once and until the end procedure, will be fixed, and second, the design parameters that are variable input data. For example, a set of rated power will be tested in order to maximize the NPV. However, the cut-in and cut-out wind speeds are considered as fixed input data. A detailed list of input data and design parameters has been reported in chapter 3.

Afterward, by considering the explained configurations, strategy and block diagram presented, fixed input data, and design parameters, it is possible to begin the design procedure that is including finding power curve, capital cost (CAPEX), and operational cost (OPEX) for the wind turbine, and battery storage and PEM electrolyzer optimization. In order to find the power curve, CAPEX and OPEX, a model introduced by IRENA in 2006, WISDEM, has been put into practice. By importing the fixed input data for the design of the wind turbine into the WISDEM Python library, it is possible to compute the power curve ($P(MW) - V(m/s)$). Therefore to find the power related to wind speed in selected locations and linear interpolation has been accomplished. Additionally, In this model, the cost of the wind turbine is evaluated by summation of numerous elements, which is reported in chapter 3. As an example, the cost of the rotor blade and tower has been explained in detail. Although this model is a very detailed one in order to compute the cost of the wind turbine, it is capable of computing the cost of the wind turbine until 2010. Therefore, an extrapolation has been performed in order to project the CAPEX to the year 2030. It is noteworthy to mention that the WISDEM is proficient in evaluating the cost of two different types of blade, bedplate, and tower by considering different materials. Therefore, the design of wind turbine for working in HPP is performed into two scenarios as "Baseline" and "Advanced" turbine.

The implementation of battery storage and PEM electrolyzer is almost identical. After selecting a characteristic design for both battery and electrolyzer, a mathematical model for optimization in cooperation of wind turbine has been proposed. After finishing the procedure by finding technical and economic indicators, the characteristic of components will vary until the desirable design for HPP with the highest NPV results iteratively.

Results & Analysis In the HPP design procedure, there are numerous design parameters in order to achieve to a maximized power plant. In addition, A methodology for advancing wind turbine by advancing the blade, bedplate, and tower has been considered during this procedure. The list below shows all design parameters for HPP's components:

- *Rated power:* 3.0-6.0 [MW]
- *Rotor diameter:* 100-200 [m]
- *Hub height:* 90-150 [m]
- A choice for advancing blade, bedplate, and/or tower.
- *Battery storage:* 3.0-6.0 [MW]
- *C-rate^{-1}:* 1-10 [MWh/MW]
- *Electrolyzer rated power:* 3.0-10.0 [MW]

		Denmark		Italy		Netherlands	
	Unit	Base	Adv	Base	Adv	Base	Adv
Rated power	MW	6	6	3	3	6	6
Rotor diameter	m	160	170	120	130	180	190
Hub height	m	150	150	150	150	150	150
AEP	GWh	24.58	26.24	6.24	7.03	30.02	31.43
Capacity factor	%	46.91	50.06	23.81	26.85	57.28	59.97
Annual Revenue	M€	0.95	1.01	0.33	0.37	1.53	1.61
Total Revenue	M€	10.10	10.79	3.51	3.96	16.36	17.16
Specific cost of Turbine	$/kW	1,605	1,555	1,584	1,556	1,975	1,903
Capex	M€	6.96	6.74	3.43	3.37	8.56	8.25
Opex	M€	0.06	0.06	0.03	0.03	0.06	0.06
Total expenditure	M€	7.60	7.38	3.75	3.69	9.20	8.89
NPV	M€	2.51	3.41	-0.236	0.266	7.16	8.27
LCOE	€/MWh	28.96	26.36	56.36	49.18	26.26	24.23
Average electricity price	€/MWh	38.69		52.35		52.52	
IRR	%	12.00	13.51	7.18	8.91	16.85	18.49

Table 1: Best wind turbine design based on the highest NPV in selected locations

It is striking interesting from table 1 that by advancing the wind turbine, not only the specific cost of the wind turbine fell drastically, but also a bigger rotor can be utilized to generate more revenue. Additionally, table 1 shows that the highest-rated power solution for Denmark and Netherlands due to very high average wind speed, 6.96 $\frac{m}{s}$ and 7.44 $\frac{m}{s}$ respectively has been chosen. On the other hand, due to low average wind speed in Italy, 4.69 $\frac{m}{s}$, there is not sufficient wind energy to exploit, so the smallest corner solution has been generated by design model. Even though the least rated power has been chosen for Italy, a negative NPV has resulted as a best case. However, by advancing wind turbine, the NPV becomes a positive value, but still, it is negligible.

Although the primary goal of this study is that to design a wind turbine with the highest NPV and not minimizing the LCOE, it is understandable from table 1 that higher deviation between LCOE and average electricity price in the Netherlands ensure the higher NPV generation in comparison to other locations. It is essential to mention that this study focuses on designing future wind turbines without any feed-in tariff or power purchase agreement. Therefore, the only solution to make a profit via wind power plant is to increase revenue production while choosing a wind turbine with considerably low cost, which results in maximum NPV. In the case of Italy, however, the average electricity price is a comparable number, but there is not sufficient wind energy to produce.

Since the output data related to the Netherlands are very interesting, therefore, the data related to the Netherlands has been presented in this section. However, all results in detail can be found in chapter 4.

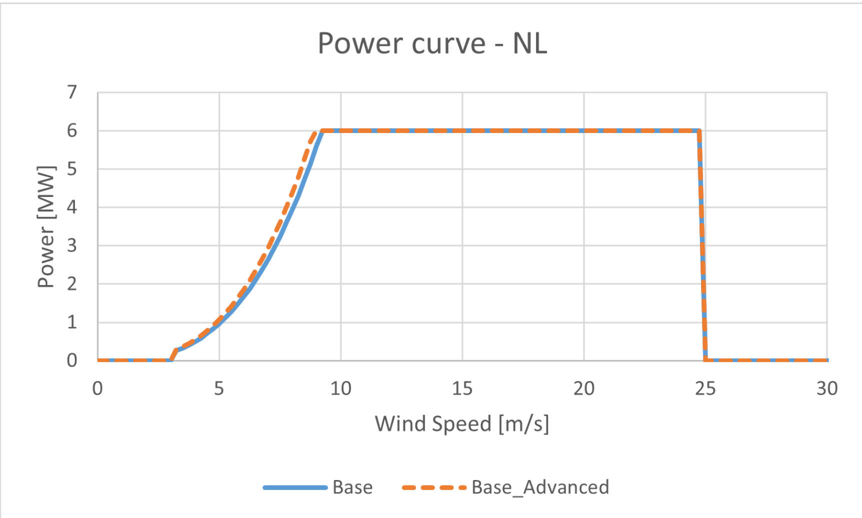


Figure 3: Designed Power curves in case of Baseline and Advanced wind turbine

Figure 3 shows the characteristic power curve of Baseline and Advanced wind turbine. What is interesting about the generated power curves in this figure is that By advancing blade, bedplate, and tower, the wind turbine's rated speed becomes a lower value, and it is able to work in rated power in a broader range of wind speed.

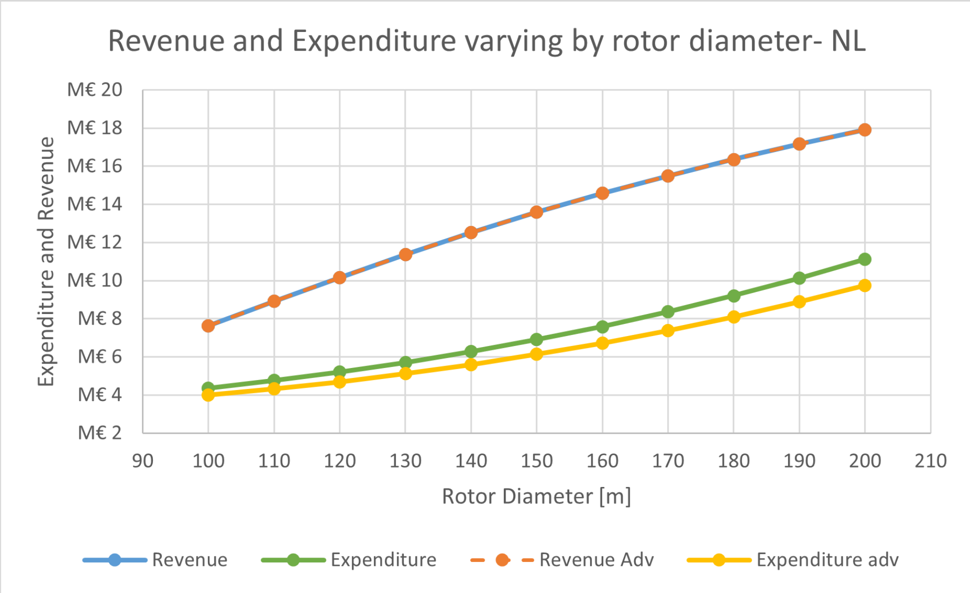


Figure 4: Rotor diameter variation effect on the revenue and the expenditure in Netherlands

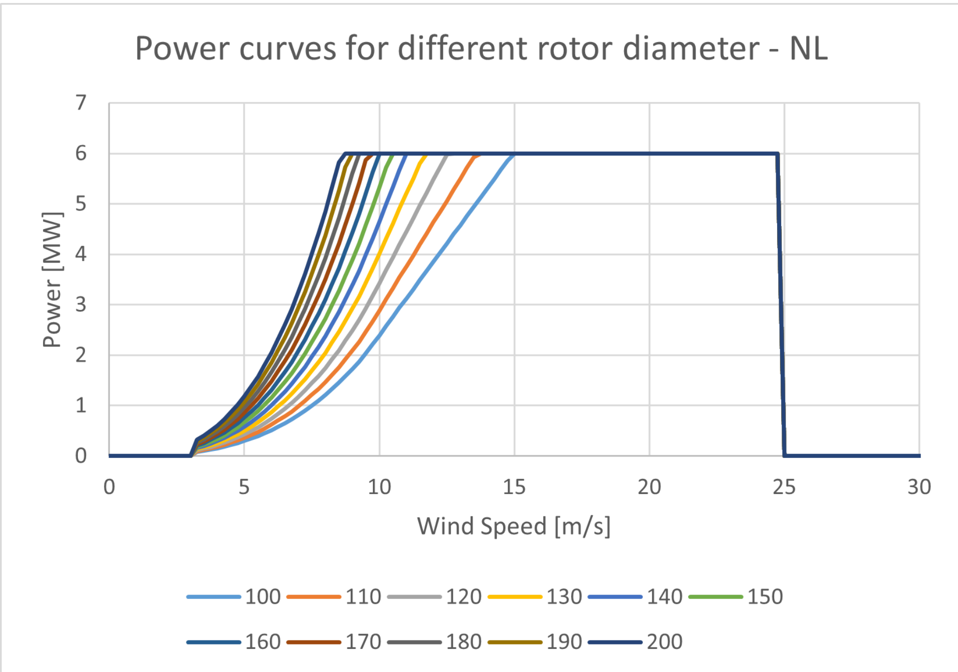


Figure 5: Power curves variation by differentiating rotor diameter in Netherlands

Since the design of rotor diameter as presented in table 1 does not result in a corner solution, therefore it is essential to go into detail and examine the reason of rotor diameter selection by model. Figure 4 represents the revenue and the expenditure in M€ evolution by varying the rotor diameter. From graph it is understandable that at $D = 180[m]$ for baseline wind turbine the highest deviation between revenue and expenditure occurs, and therefore the highest NPV. However, for the Advanced wind turbine the highest NPV is achievable at $D = 190[m]$. An explanation for the different increasing behavior of the revenue and the expenditure in figure 4 is that the revenue is related to the produced power and consequently to the second order of diameter ($P = \frac{1}{2}\rho C_P A V^3$) whereas, the expenditure increases in a order between two and three.

Figure 5 illustrates how rotor diameter variation affects power curves. It is also mentionable that other parameters are kept constant as noted in table 1. Since revenue is proportionally related to power ($Revenue = \sum_{i=1}^{8760} Power \times ElectricityPrice$) , by increasing the rotor diameter, the wind turbine can work in a broader range of rated power and so the revenue generation will rise. On the other hand, in the direction to a higher value of rotor diameter, the power lines gap becomes narrower. This decrease is the reason for a negative second-order derivative of revenue evolution in figure 4.

As a brief conclusion for the wind turbine design, the choice of the rated power is correlated with average wind velocity and available wind energy in the selected location. As shown before in table 1, the highest-rated power for Denmark and Netherlands and the lowest-rated power for Italy is the best design. On the other hand, the largest or tiniest rotor diameter is not perpetually the best design to reach the highest NPV. In order to find the best design for rotor diameter, it needs a cost and benefits analysis procedure as presented in graph 4. A beneficial design methodology for the future wind turbine is to go toward installing a wind turbine in a higher average altitude in comparison to today's wind turbine hub height working area. Finally, in all methodologies and strategies presented so far, advancing the blade, bedplate and tower is a positively effective solution to declining expenditure.

Afterward, the optimization of wind turbine + battery storage and wind turbine + PEM electrolyzer for a whole year has been performed. The same framework illustrated in the wind turbine section has been put into practice, which can be found in chapter 4, in order to present the technical and economic outputs. The result shows that by adding an energy storage system, the design of the wind turbine in selected locations does not change. Additionally, the NPV in both cases is lower than the single wind turbine; therefore, the smallest battery storage and PEM electrolyzer has been chosen in contribution with the wind turbine.

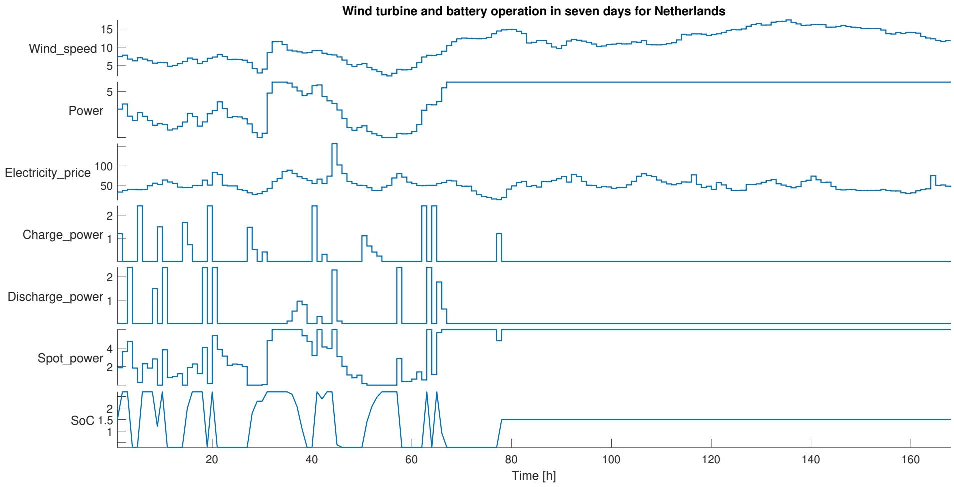


Figure 6: WT+BESS optimized operation for seven days in Netherlands

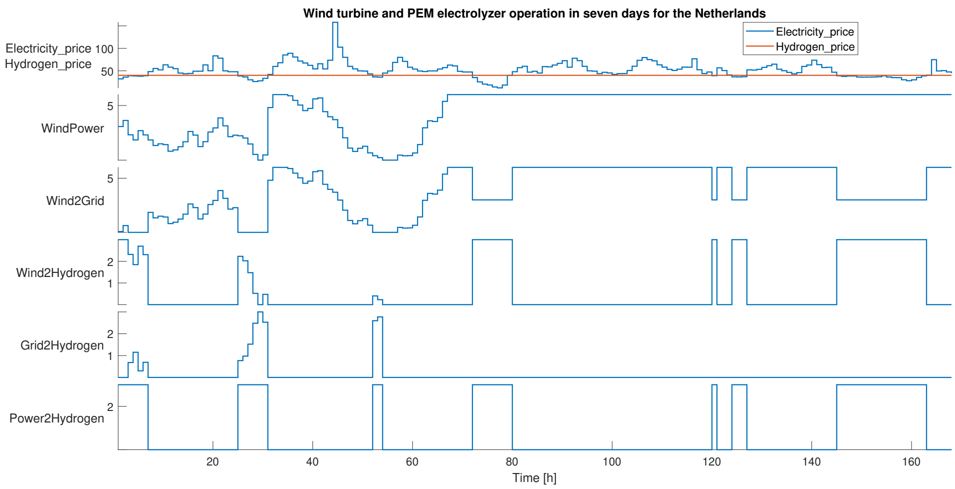


Figure 7: WT+PEM electrolyzer optimized operation for seven days in Netherlands

Figure 6 represents the wind speed, wind turbine power output, charge and discharge power of the battery, spot power which will be sold to the grid, Electricity price in each hour, and finally, the battery's State of Charge. In this graph, as an example, week 11, which has the highest electricity deviation, has been selected in order to depict the accuracy of the optimization model. As mentioned before, battery storage can store the wind turbine's produced energy when the electricity price is pretty low and send it to the grid when the electricity price is significantly high. Therefore, by going into detail of this graph, it is crystal clear that when the electricity price is low, the model accurately saves the energy and sells it in the time of high electricity price. It is noteworthy to mention that it is predicted that a battery storage system can operate more effectively in a location where the electricity price's fluctuation is considerable. As the figure shows, the electricity price's fluctuation in the Netherlands is negligible; therefore, the battery contribution would be uninfluential in this location.

Figure 7 similarly shows the wind turbine + PEM electrolyzer system working for seven days in the selected location. With the same explanation in the wind turbine + battery storage system, a similar choice for representing week has been chosen. From the graph, it is understandable that whenever the electricity price exceeds the Hydrogen price line, the model sells the power to the grid. On the contrary, when Hydrogen has a profitable business, the model sends as much as possible power to generate Hydrogen. In conclusion, it is comprehensible that due to the high price of the electrolyzer and the low price of Hydrogen, there is not a considerably practical value to install a PEM electrolyzer as a participating element in HPP.

In this study, the main strategy to find the best desirable design for the wind turbine working in a hybrid power plant is to maximize the NPV. As a logical strategy, today's objective function for the design of the wind turbine is based on lowering the LCOE. However, in this thesis, it has been revealed that considering the market as a primary goal to generate as much as possible revenue and proportionally NPV is a considerably profitable strategy for future wind turbine design. Table 2 presents a comparison between the design of a wind turbine as it is today and a wind turbine for market purposes. The first sticking interesting result is that, by changing the strategy from minimizing LCOE to maximizing NPV, the design of wind turbine has been changed. On the contrary, considering a component in contribution with wind turbine does not affect the wind turbine design. Afterward, by analyzing a single wind turbine in two different explained strategies, it is clear that minimum LCOE wind turbine has a higher IRR value which means lesser risk in terms of economic stability in the selected location. Although it seems more logical to chose a wind turbine with a higher IRR and lower LCOE, it is a conservative and inefficient strategy for the future wind turbine. For example, by sacrificing less than 5% of IRR, NPV can grow more than doubled its value.

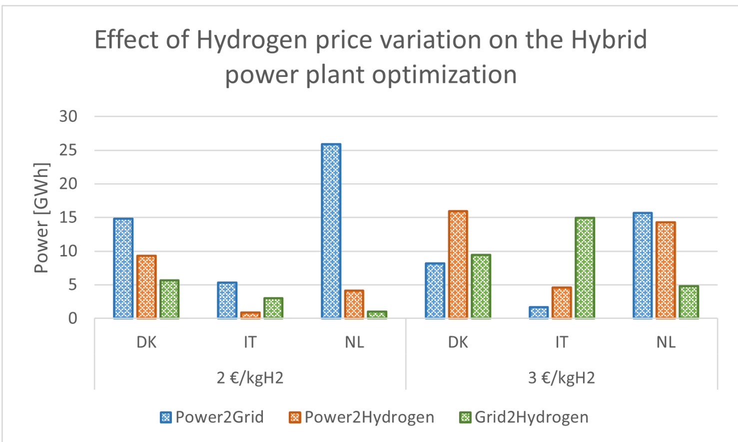
Netherlands					
		min LCOE	max NPV		
	Unit	WT	WT	WT+BESS	WT+PEM
Rated power	MW	3	6	6	6
Rotor diameter	m	100	180	180	180
Hub height	m	150	150	150	150
Battery storage	MW	-	-	3	-
Battery capacity	MWh	-	-	3	-
Electrolyzer rated power	MW	-	-	-	3
AEP	GWh	11.7	30.02	30.02	30.02
Capacity factor	%	44.69	57.28	57.28	57.28
Total Revenue	M€	6.34	16.36	16.7	16.73
Total expenditure	M€	2.92	9.2	10	11.3
NPV	M€	3.42	7.16	6.70	5.42
LCOE	€/MWh	21.36	26.26	31.21	35.27
Average electricity price	€/MWh	52.52			
IRR	%	21.52	16.85	15.65	13.54

Table 2: comparison of the wind turbine as it is designed today and designed for market objective in the Netherlands

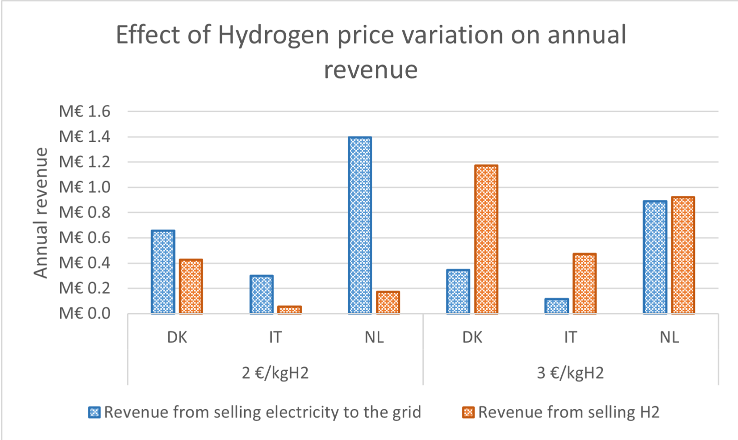
From the table, it is apparent that the battery storage and PEM electrolyzer have no profitable business in the Netherlands. The reason is mainly because of the significantly high installation price of these kinds of technologies. In order to understand that in which price they can be a competitive alternative, a sensitivity analysis on the cost of battery storage and PEM electrolyzer and Hydrogen price has been performed in chapter 4.

In **BESS CAPEX** sensitivity analysis section, It is mentionable that by reducing BESS CAPEX up to 40%, no change has been observed in the design of the wind turbine or battery storage. Afterward, from 50% to 90%, it does not affect the design of the wind turbine, but battery storage and capacity gradually increased. Although the maximum C-rate^{-1} could reach a 10-hour battery, in the case of 90% CAPEX reduction, surprisingly model chose a 7-hour battery. The reason is that a battery storage system needs a fluctuating market to be a practical option working in an HPP.

In **Hydrogen price** sensitivity analysis section, Figure 8 presents the effect of change in the Hydrogen price on power optimization and revenue earned by different markets. Graph 8a compare the variation of the power decision made in order to maximize the revenue in two different Hydrogen prices. By increasing the price share of power sent to the electrolyzer and consequently revenue produced by selling Hydrogen has been increased, see 8b. In the case of Italy, almost three times more than power produced by the wind turbine, power has been bought from the grid in order to generate Hydrogen. In the Netherlands, there is sufficient power produced from the wind turbine for both grid and Hydrogen production. Therefore there is an equal amount of revenue production from both markets.



(a) Annual power optimization for different Hydrogen price



(b) Annual share of earned revenue for different Hydrogen price

Figure 8: Wind turbine + PEM electrolyzer HPP annual share of power and revenue earned for different Hydrogen price

In **PEM electrolyzer CAPEX** sensitivity analysis section, the same analogy as the battery storage section has been implemented in order to perform a sensitivity analysis. Similarly, the reduction in the CAPEX does not affect the design of the wind turbine. Results present that by reducing the cost of electrolyzer, the NPV increased in all locations as is predicted. In addition, at one point, CAPEX reduction (34% for Denmark, 89% for Italy, and 83% for the Netherlands), the design of the electrolyzer has been changed from the lowest to the highest amount of rated power in each location. Since the Hydrogen price is low in Italy and the Netherlands, it needs more reduction in the cost of electrolyzer to be a profitable business.

Conclusion The purpose of the current study was to design a wind turbine in order to be utilized in a hybrid power plant by maximizing NPV as an objective function. However, the design of the wind turbine by lowering the cost (as it is today a common strategy to design) seems a safe and secure solution for companies in the wind turbine industry, but looking towards a more ambitious and profitable design strategy is essential for the near future of the wind turbine market. Accordingly, the results of this research support the maximized NPV strategy as a primary solution for future wind turbines. For example, in the case of the Netherlands, by changing the strategy from design a wind turbine with the minimum LCOE to maximum NPV, the profit would be more than doubled (an increase from3.42 M€ to 7.16 M€). Although the IRR decreased around 4% in the Netherlands by strategy variation, the economic stability in this location could reduce the risk of money worth alteration.

In addition, in order to find optimal design parameters suits to each electricity market, a design procedure for the wind turbine has been proposed. A trustworthy strategy for the future wind turbine is to go toward a higher hub height. The finding of this study illustrates that in all selected locations with a different strategy and design configuration, a hub height equal to 150m, which was the maximum value in the design set, has been chosen. However, finding the best-rated power and rotor diameter is more location-dependent.

The research has also shown that the BESS needs a cost reduction of more than 50% than the price predicted for 2030 to be a competitive solution. However, in the case of Denmark and the Netherlands, the NPV generated by WT+BESS is considerably higher than the NPV generated by today's wind turbine.

Additionally, the study depicts that the PEM electrolyzer is not a profitable solution by considering projected cost in 2025 and a Hydrogen price equal to 2 €/kgH2. By increasing 1 €/kgH2 to the Hydrogen price, the result would be a significantly profitable market for almost all locations. For example, in the case of Denmark, the NPV has been grown around 15 M€.

Returning to the question posed at the beginning of this study, it is now possible to state that the size and cost of the battery and PEM electrolyzer do not affect the wind turbine design. However, by changing the methodology from minimum LCOE to maximum NPV, the design of the wind turbine would be different. Finally, the maximized NPV methodology is a reliable path for future wind turbines.

Abbreviations

AEP	Annual Energy Production
ALK	Alkaline
BESS	Battery Energy Storage Systems
BoS	Balance of System
CAPEX	Capital Expenditure
CF	Capacity Factor
CSM	Cost and Scaling Model
ESS	Energy Storage Systems
GDP	Gross Domestic Product
GHG	Green House Gas
HESS	Hydrogen-Based Energy Storage System
HPP	Hybrid Power Plant
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
LCOE	Levelized Cost Of Energy
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OPEX	Operating Expense
PEM	Polymer Electrolyte Membrane
PV	Photovoltaics
RES	Renewable Energy Sources
SoC	State of Charge
WISDEM	Wind-Plant Integrated System Design and Engineering Model
WT	Wind Turbine

Nomenclature

η	Maximum efficiency of rotor and drivetrain at rated power
λ	Maximum tip ratio
ω	Rotational speed
ρ	Air density
C_P	Power coefficient
C_T	Thrust coefficient
D	Rotor diameter
H	Hub height
k	Variable-speed torque constant
P	Power
Q	Torque
r	Discount rate
T	Thrust
V	Wind speed

List of Figures

List of Tables

Contents

Chapter 1

Introduction

1.1 Background and motivation

After two decades of this century, it is more evident now that climate change should be the most primary concern. Although the COVID-19 pandemic takes many lives and cause social and economic crises since last year, it should not be a reason to forget a more significant concern that may cause a crisis on a greater scale [17]. A considerable number of studies represent that the main reason for climate change is anthropogenic greenhouse gas(GHG) emissions, which results in global warming [30]. Figure 1.1 illustrates the drastic augmentation of GHG emission from 1970 to 2010 which the share of CO2 emission from fossil fuel combustion and industrial processes is around 78%. Therefore, a reduction in CO2 generation would result in a decrease in GHG emission, and thus the changing climate behavior would slow down. In 2020 IRENA introduced the Transforming Energy Scenario, an effective solution to keep global temperature growth below 2°C, set in the Paris Agreement. This scenario offers a reduction of CO2 emission by 3.8% per year, and it becomes reachable by transforming the fossil fuel-based energy sector into a renewable one in combination with energy efficiency improvement [17].

Another challenging problem raised by fossil fuels is that countries heavily dependent on imported fossil fuels suffering from a lack of energy security and sustainability[17][11]. Not only renewables offer a more secure and sustainable energy source as an alternative for fossil fuels, but they also positively affect GDP, job opportunities, and other economic indicators by playing a role in the local energy market [17].

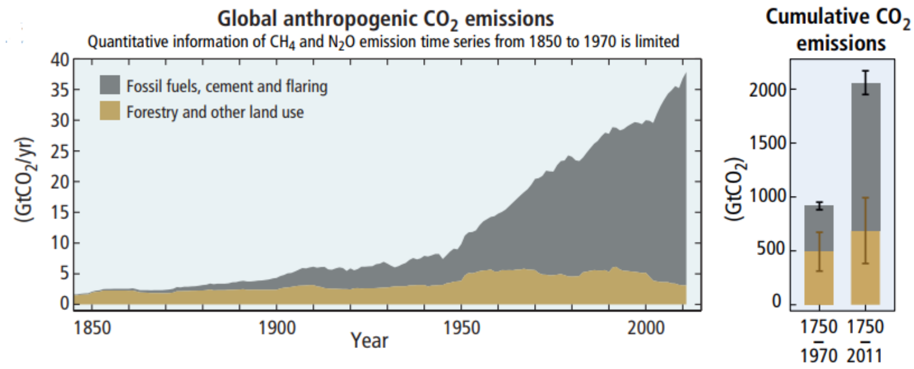


Figure 1.1: Global anthropogenic CO2 emissions from forestry and other land use as well as from burning of fossil fuel,cement production and flaring [30]

1.1.1 Renewable technologies

Although renewables are the key to a cleaner future, most of them have limitations in terms of available capacity, very high installation and maintenance cost, etc., which make them unusable and ineffectual. However, Among all renewable technologies, solar and wind are the most promising ones to accomplish the decarbonization target for 2050 [31]. Even though solar PV and wind share for electricity production were undoubtedly increased in past decades, 3% and 8% respectively [15][6], yet they are far from dominating 60% share of electricity production meet the target for mid-century [17][15]. As figure 1.2 represent, Although hydro and nuclear energy nowadays plays the significant role in producing the electricity among all low-carbon technologies, As mentioned before, both have some limitation in terms of available capacity and safety respectively. Consequently, Wind and Solar PV as an alternative seem more reliable sources.

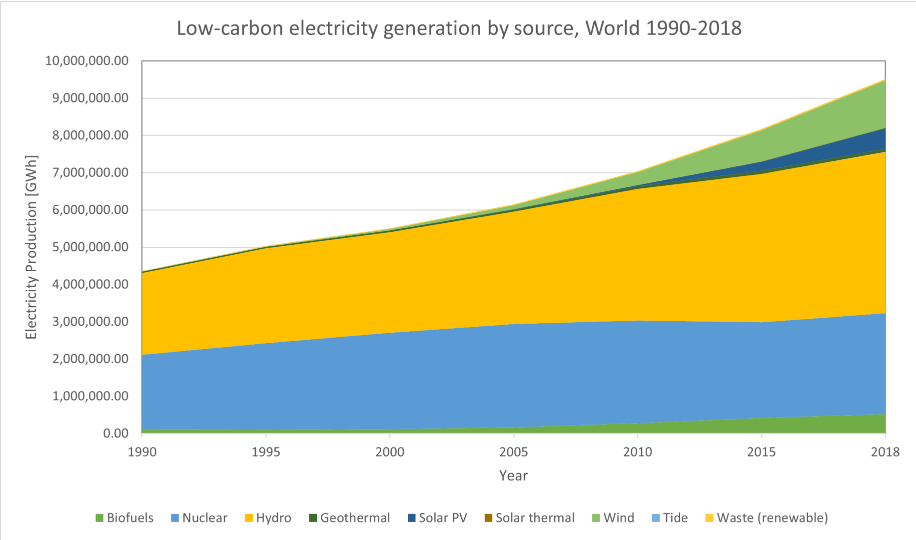


Figure 1.2: Electricity generation from low-carbon resource in world scale, 1990-2018

1.1.2 Hybrid Power Plants

The primary challenge for wind and solar PV technologies is natural resource variability. Today, most of these technologies are built with either feed-in-tariffs or power purchase agreements to be as competitive as fossil fuels power plants. However, in the near future, renewables should be more economically efficient to dominate electricity generation share until mid-century. Therefore, combining some renewable technologies with energy storage systems may be the solution to have a more flexible and dispatchable power plant that can provide electricity as a reliable source[11].

1.1.3 Wind energy

From recorded history about human civilization, between 500 and 900 B.C, Persians utilized wind energy to produce food via windmills for the first time. Until last century and Betz's novel study about wind energy and its aerodynamics, all wind turbines were drag-driven based and producing a meager amount of energy. In 1926, a revolutionary development for a new generation of a wind turbine had been developed [7], and during WWII, the largest wind turbine with 1.25 MW rated power has been installed. However, after the oil crisis in 1970, the necessity to wind energy and, in general, renewable energy became more evident than ever, and numerous studies and research have been done.

In the last 50 years, both technological development and an extensive increase in wind energy research cause a remarkable power production growth via wind turbines and a striking decrease in Levelized cost of energy(LCOE) yearly [41], see figure 1.3.In 2019 in Europe, the share of electricity demand covered by Wind Power reached to 15% (15.4 GW), including 11.7 GW onshore and 3.6 GW off-shore conventional Wind Turbines [35]. Even though Wind Power Technologies experienced a rapid expansion in the past few years and occupied a considerable share of the electricity market, it still does not reach its maximum capacity exploitation. The incredible worldwide available capacity and very low LCOE for wind energy is a motivation for this project.

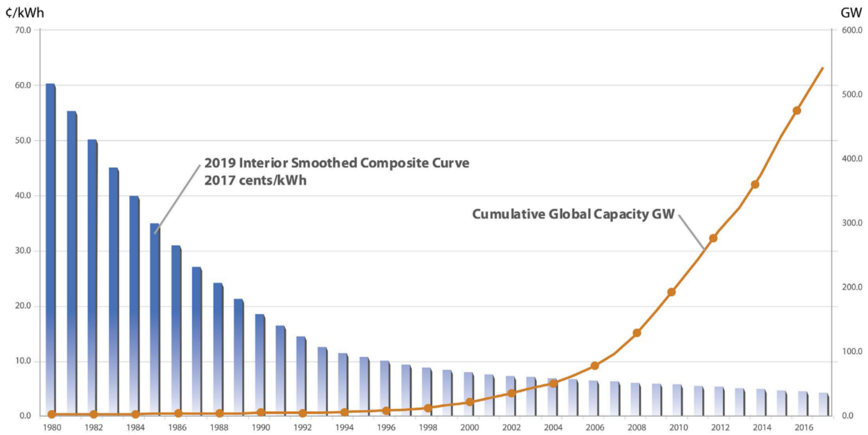


Figure 1.3: Global cumulative installed capacity (GW) for wind energy and estimated LCOE for the U.S. interior region (cents/kWh) from 1980 to the present [41]

1.1.4 Energy Storage Technologies

Energy storage systems (ESS) may be a solution to tackle renewables' problems caused by natural source variability. By absorbing and controlling the excess power output and store it via an ESS when it is more than demand, and return it to the grid from the ESS in the time of imbalance of power produced and demand, they can play a supportive role in increasing their electricity market participation [12]. Here, there are two principal methodologies in returning the stored electricity to the grid:

- ***Peak Shaving:*** The primary goal in this method is to decline, as much as possible, the power produced fluctuation from renewables. To achieve this goal, the ESS stores the electricity produced when it is higher than the proximity average of power produced within a specific time duration, and instead, it sends back the stored electricity when the production is lower than average.

- ***Arbitrage:*** In this method, the purpose is to maximize the revenue and simultaneously decrease the Levelized cost of the electricity. Since the electricity price in the market is not a constant value during a day, it is possible to store the produced energy when the electricity prices are low, during the night, for example, and sell it when it has a higher price. This methodology also is the central aim of this thesis.

In this research two most trending technologies of ESS have been investigated:

Battery Energy Storage System (BESS)

BESS can store the produced energy from a power plant in the form of electrochemical energy and return it to the network either for necessity or economic purposes. In this project, the Lithium-ion battery (Li-ion) is gain attention since it is the most used energy storage in the market [12].

Hydrogen-based Energy Storage System (HESS)

Nowadays, it is a fast-growing energy storage technology and attracts many studies and projects. Hydrogen as a clean energy source can be utilized in the form of fuel either directly in the automotive industry or in fuel cells to generate electricity. It is worth mentioning that Hydrogen can be produced in many different ways, but in this project, a PEM electrolyzer contributing to wind tribune is a chosen technology to produce Hydrogen [12].

1.2 Indicating a problem and limitation

So far, the significance of relying on wind turbine has been emphasized, and some global problem such as climate change due to excessive consumption of fossil fuels and energy sustainability and security for countries heavily dependent on fossil fuels has been pointed. By 2050, wind energy needs to be the global primary energy supplier, but it needs more technological enhancement and economic development to achieve this goal. As mentioned before, today's wind turbines are constructed either with feed-in-tariffs or power purchase agreements to be competitive in the comparison of other technologies; however, in the future, wind turbines must be maximized in power production simultaneously minimized in cost, besides sustaining and improving their flexibility and reliability. Finally, all enhancement, development, and improvement in wind turbines' design and operation result in a higher value of annual revenue production and NPV, which is an essential term for future wind turbines' independence.

A practical method in enhancing future wind turbines, increasing at least one among rated power, rotor diameter, or hub height, is essential. However, by enlarging the wind turbine, there will always be some limitation in design parameter due to safety issue, such as maximum tip speed and rotor acceptable thrust [41]. Additionally, considering an Energy Storage Systems(ESS) would be useful to overcome the lack of flexibility and reliability. Even though today, the cost of ESS is considerably high, predictions promise an effective decrease in the price of both battery storage and electrolyzers for Hydrogen production by the end of current decade.

It is noteworthy to mention the fact that today's wind turbine designs are based on lowering the LCOE. However, this strategy is a logical and secure path for companies to develop their wind turbine, but it does take their independence from any supportive regulations, such as feed-in tariff or power purchase agreement. Therefore, what is interesting in order to fulfill this study is to find a new design methodology based on NPV maximization for the future wind turbine. In addition, battery storage with the arbitrage strategy coupling with a wind turbine was the first motivation of this study. Afterward, due to the significantly fast-growing market for Hydrogen production, HPP, including an electrolyzer for 2030, becomes an area of interest in this study.

1.3 Assumption

In the procedure of performing the study, some simplified assumptions were made due to the lack of sufficient data or difficulty to obtain them. Those critical assumptions are listed as follows:

- **Electricity price:** An electricity price time series with an hourly resolution has been generated for the year 2019. Due to the complexity of generating the electricity price for a wind turbine's whole lifetime, an extrapolation for 25 years has been taken into account. An electricity price time series from the Nordpool website for Denmark and The Netherlands have been generated [1]. In addition, for Italy, from the GSM website, data for electricity price has been gathered [2].

- **Wind speed:** Similar to the electricity price, an hourly wind time series for selected locations have been generated by CorRES, which is a DTU tool [21]. Also, the generated time series is considered constant each year for the selected location during the wind turbine's lifetime.

- **HPP components costs:** Since this study is looking for future wind turbines working in hybrid power plants, all costs are projected to 2030. Consequently, a projected cost of the battery storage has been utilized from Danish Energy Agency (DEA) [3]. Additionally, a cost projection from IRENA [18] has been selected for the PEM electrolyzer. In order to find the cost of the wind turbine in 2030, first, by performing the WISDEM model, the cost for 2010 has been evaluated; afterward, a linear extrapolation was accomplished.

- **Hydrogen price:** The study in the part of Hydrogen has been simplified significantly. A constant hourly price for whole life time of HPP has been considered. Therefore, a sensitivity analysis is carried out to assess the robustness of the model.

- **Hydrogen storing and transportation:** In this study, the transportation or storing cost of Hydrogen has not been taken into account. Besides, ample storage has been assumed where other utilities of Hydrogen are constant using.

- **Market impact:** In the case of coupling BESS for all wind turbines competing in an electricity market with an arbitrage strategy, the electricity price would be a constant value for each hour. Therefore, it is considered that the designed HPP in this study is the first mover to the market with the proposed strategy.

1.4 Aim of the project

The main aim of this thesis's report is to address following research questions:

- How to define the wind turbine design parameters in order to achieve the highest NPV by considering different markets?

- Is the BESS a profitable solution by considering the cost projection in 2030 in order to be utilized in the HPP? if the answer is no, how much the cost of

BESS should be reduced in order to have a profitable business?

- Is the HPP, including the wind turbine and Hydrogen production system, a profitable configuration by considering today's electricity prices and WT and PEM electrolyzer cost for 2030? if the answer is no, in which price of Hydrogen or cost reduction of electrolyzer it becomes a profitable business?
- Does the BESS and PEM electrolyzer affect the design of the wind turbine in order to charge/ discharge the battery storage or generate Hydrogen?
- Will the wind turbine design parameters be different by considering minimum LCOE as the objective function compared to the maximum NPV strategy?

1.5 Report structure

The overall structure of the study takes the form of five chapters. It begins by introducing the work, presenting a vision of background in this field of study, marking the existing problem at present and those limitations that may remain in the future, and finally, pointing those questions that will be answered in this study. Chapter 2 will consider both the sources and methods of study proposed by other authors until now and, additionally, an illustration of a utilized method in the current study. The third chapter is concerned with the methodology employed for this study. Chapter 4 present all results and a brief discussion about obtained them. Finally, the last chapter concludes the study and proposes a desirable direction for future study.

Chapter 2

Literature Review

In the previous chapter, the necessity of renewable energy and specifically wind energy has been emphasized. Additionally, all advantages and disadvantages of today's wind turbines have been accounted, and some trended solution such as hybrid power plants has been pointed. In this chapter, however, numerous studies on the subject of wind energy enhancement since 1970, hybrid power plant, battery storage system, and hydrogen energy system will be reviewed.

2.1 Wind energy

In the past half-century, wind energy has experienced very impressive technological enhancements and economic improvements. From 1982 which the first three-blade wind turbine (22 kW) had been installed, until 2019, just in Europe, the share of electricity demand covered by wind energy reached 15% (15.4 GW), including 11.7 GW onshore and 3.6 GW off-shore Wind Turbines [35]. Even though Wind Power Technologies experienced a rapid expansion, especially in the last decade, and occupied a considerable share of the electricity market, it still does not reach its maximum capacity exploitation. To understand how it is possible to exploit the wind's mechanical energy with a lower cost of energy (COE), it is better to look at equation 2.1 which is the fundamental relation for producing power from the wind turbine.

$$P = 1/2\rho C_P A V^3 \tag{2.1}$$

In the equation 2.1 c_P is the power coefficient of the wind turbine, ρ is the air density, A stands for the rotor area, and finally, V is the velocity of wind incidence with the turbine's blade. To reduce the specific cost of a Wind Turbine, from the equation 2.1, an increase in rated power, hub height and rotor diameter is essential. Wind speeds are greater in magnitude and more uniform in direction at higher elevations, so much higher power is produced since the relation between wind speed and power generation is cubic. Similarly, an increase in rotor diameter would enlarge the blade's contact area and blowing wind; therefore, it can capture more energy. By increasing the size of either hub height or rotor diameter, a single component's cost rises while the power production increases more effectively, and so annual revenue. Moreover, to have higher rated power in constant C_P, a large generator capacity supported by power electronics is necessary. The outcome would be a machine with the capability of variable-speed operation, which can operate at max C_P to capture more energy in a broader range of wind speed. Notably, the rotor and generator's size is usually increased relatively; consequently, the machine reaches rated power at lower wind speed, which the wind frequency is high. In conclusion, all enhancement results in upgrades in wind turbines, which absorb more energy per turbine, so the installation and capital cost (CAPEX), balance-of-system(BoS) cost, and operation and maintenance cost (OPEX) would decrease significantly [41].

2.1.1 Trends

Technological trend

Figure 2.1 From IRENA report [16] present the global trend of rated power and rotor diameter since 2000 and an expectation for future wind turbine design parameters. As same as the parametric studies reveal, this graph shows the pathway of future wind turbine crosses in a higher rated power and more extensive rotor diameter.

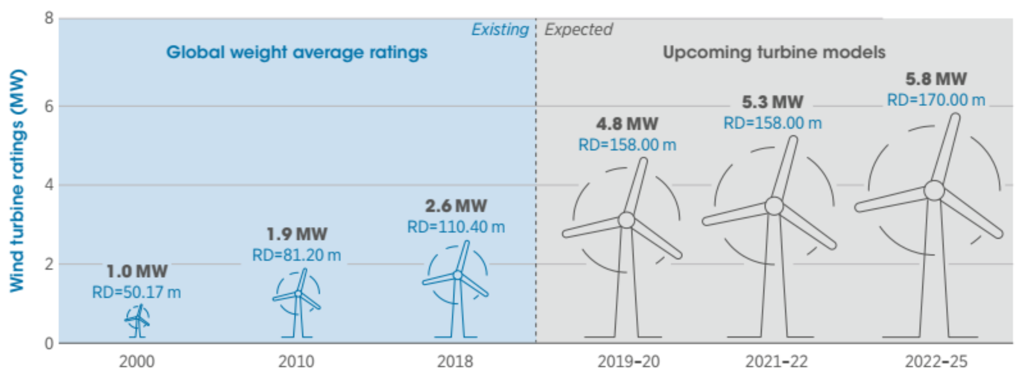


Figure 2.1: Wind turbine technological innovation and enhancement in enlarging the rated power and rotor diameter since 2000, in addition to a prediction for future wind turbine [16]

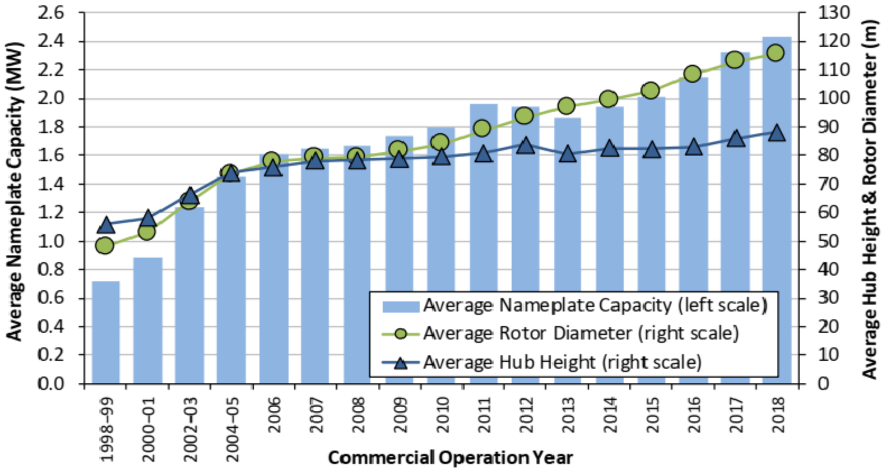


Figure 2.2: Enhancements for wind turbine in last two decades in USA [40]

As well as figure 2.1, figure 2.2 present the wind turbine technological enhancement in the USA between 1998 until 2018. In this graph, in addition to rated power and rotor diameter, a trend for hub height has been depicted. Both figures identically mention that until 2018 the average rated power was around 2.6 [MW], average rotor diameter was approximately around 120 [m], and average hub height was close to 90 [m]. Consequently, in this thesis, by inspiring by previous articles about the future trend of the wind turbine, a detailed study on wind turbines with rated power between 3-6 [MW], rotor diameter from 100 [m] to 200 [m], and hub height from 90 [m] to 150 [m] has been done [40].

Economic trend

As depicted in figure 1.3, the LCOE has been decreased significantly since 1980 [41]. Today both LCOE and specific cost of a wind turbine have become lower two orders in magnitude in comparison with 1980, and the reason for this breakthrough is significant technology improvement, specialization and standardization, broader and more competitive supply chains, economies of scale, competitive procurement and a broad base of experienced, internationally active project developers [16]. In the report [16], it is mentioned that the total installation cost of a wind turbine in 2018 was approximately 1500 $/kW, and it will continue to decrease in the next three decades, by 2030 an average between 800 $/kW and 1350 $/kW, and by 2050 an average between 650 $/kW and 1000 $/kW are expected.

On the contrary to the previous report from IRENA, which depicted a decreasing historical trend for wind turbine specific cost, in the report [40] it mentioned that in the USA, the specific cost of a wind turbine was rising from 800 $/kW to more than 1600 $/kW until 2008 [28]. The reason for this increase in cost came from several factors, for example, a raised cost of materials, energy, and labor; a general increase in turbine manufacturer profitability due in part to strong demand growth; and increased costs for turbine warranty provisions [40] [28]. However, after 2008, some of the mentioned parameters acted reversely. Besides, growth in competition among wind turbine manufacturers and a significant decline in cost by wind turbine and their parts suppliers became more evident. These transitions result in a steep declined in the specific price for wind turbines after 2008 until today. Finally, it is understandable that the wind turbine cost could experience more reduction in the future by growing both demand and manufacturers participation in wind turbine production and installation; therefore, the cost could lessen than the predicted price for 2050.

2.1.2 LowWind generation of wind turbine

A mentioned in the first chapter, a fundamental problem for a grid connection entirely dependent on the wind turbine is that there is a lack of electricity production in the low wind, and in the high velocity of wind, a significant portion of unexploited wind energy. Although a solution to fix this problem is either to utilize an energy storage system or other flexible power supply systems, from the wind power production side, the LowWind generation of the wind turbine is introduced to contribute as much as possible in the system integration.

Two main differences between this kind of wind turbine and the traditional one are the specific power production and cut-in and cut-out wind turbine speed. In task 26 of IEA [5], it is found that the specific power of 250 W/m^2 is the stabilized scenario until 2030. However, in the LowWind study, a 100 W/m^2 wind turbine that works in the range of 2 m/s to 13 m/s has been investigated. The study [23], in addition to the design of the LowWind type of wind turbine, represents a comparison between a 3.4 MW wind turbine with a 208 m rotor diameter as LowWind and a 130 m rotor diameter as a conventional wind turbine [8].

Advantages and disadvantages

The first advantage of this new generation of the Wind Turbine is higher AEP (40-45%) compared to the conventional one, which proceeds to higher annual revenue due to higher AEP and higher electricity price at low wind speed [24]. Another benefit of this kind of Wind Turbine is that while conventional WT reaches their rated power and enough power has been generated, it shut down. However, to produce 3.4MW with a LowWind, the rotor size is considered 208m (102m blade length). It raises another problem regarding installation and transportation costs as the blade and rotor are oversized [23].

In this study, in order to reach the best design of wind turbine in contribution with an energy storage system, a broad range of specific power production will be examined.

2.1.3 WISDEM

The Wind-Plant Integrated System Design and Engineering Model (WISDEM) is a set of models for assessing overall wind plant cost of energy (COE). WISDEM model is written in Python using OpenMDAO, and it includes several sub-models, from physical to cost models, in order to analyze and optimize a wind power plant. However, all sub-models can be utilized independently, but they are required to use the overall WISDEM turbine design capability. All WISDEM models are steady-state, and computational efficiency has always represented an important goal during the development of WISDEM to support wide explorations of the solution space [39] [37] [38].

NREL CSM

It is a mass and cost model contributing to evaluating the primary components of a wind turbine and resulting in overall capital cost (CAPEX). The NREL Cost and Scaling Model (CSM) dated from 2006 [22], and it is the outcome of project work between 2002 to 2005 in Wind Partnerships for Advanced Component Technology (WindPACT) and relatively the University of Sunderland model in 1993 [13]. First, the University of Sunderland model has been developed considering all components of a wind turbine consisting: blade, hub system (hub, pitch system, and nose cone), nacelle (low-speed shaft, main bearings, gearbox, the high-speed shaft/mechanical brake, generator, variable speed electronics, electrical cabling, mainframe (bedplate, platforms and railings, base hardware, and crane), HVAC system, controls, and nacelle cover), and tower. This model was based on a set of semi-empirical models for each component that estimated design loads at the rotor, propagated these loads through the entire system, and used the loads to estimate the size of each component calibrated to data on actual turbines in the field during that time. Cost estimates were then made on a per weight basis using a multiplier again based on field data or industry sources [38] [13]. Afterward, WindPACT examines several cases with Sunderland's model and update it by changing some cost coefficient and, in several cases, the entire cost equation [25]. Finally, the NREL CSM model in 2006 was developed based on the WindPACT model while it was modified compared to Sunderland's model. In this study, the model *nrel_csm_orig* is presented in WISDEM documentation as an open-source Python script has been deployed in order to calculate the power produced by designed wind turbines and their CAPEX and OPEX.

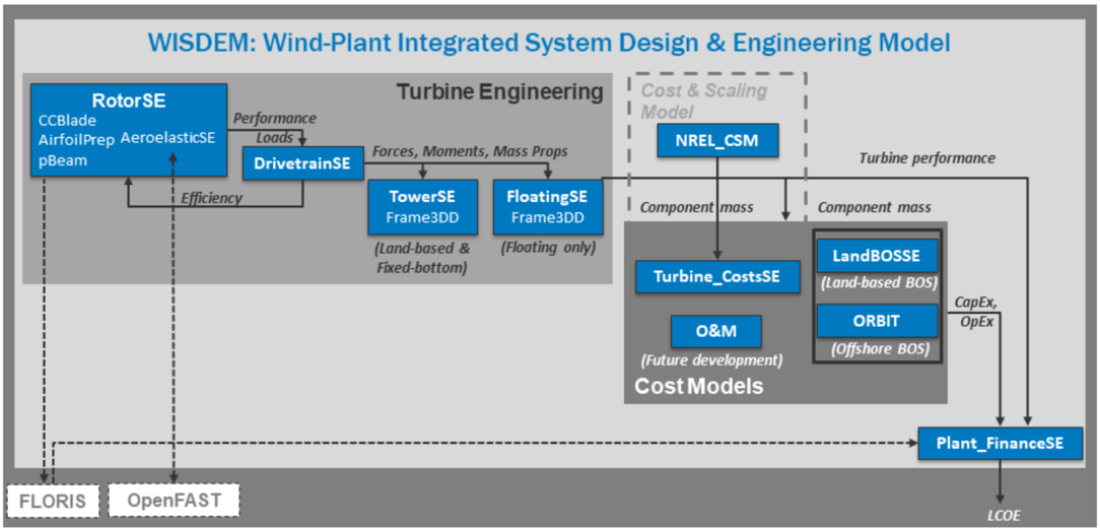


Figure 2.3: Map of WISDEM model blocks [38]

Limitation

As a limitation of the WISDEM model and especially *nrel_csm_orig*, it is not able to evaluate the CAPEX and OPEX variation in the desired year, and the possible prediction is until 2010. Although in 2015, they updated the mass and cost model by the name of *nrel_csm_mass_2015* and *nrel_csm_cost_2015*, they were not as flexible as the original code. Therefore in this study, the original model has been utilized with an escalation factor in order to update the specific cost of a wind turbine.

2.2 Hybrid power plant

2.2.1 Hybrid Definition

There are many different definitions for Hybrid Power plants and Hybrid Sources. The terms of HPP in [26] are described as combining renewable technologies or conventional power generation modules with or without storage. However, in [31], a Hybrid Source is explained as incorporating various energy generation technologies that offer a single resource behind the point of interconnection. In view of all that has been mentioned so far, one may suppose that all technologies accounted for in the HPP have connected to one single connection point. In this paper, the HPP contains a wind turbine contributing to Lithium-ion battery storage in one case, and in the other case, the wind turbine provides power for the Hydrogen electrolyzer.

2.2.2 Advantages

There are significant superiorities for hybrid energy in terms of reliability, flexibility, and dispatchability; however, this kind of technology's main advantage is that it can participate more actively in the daily market and generate more revenue thanks to storage. A fully renewable dependent grid may also experience either a shortage or surplus in providing electricity in daily operation. However, on the other hand, a hybrid dependent base grid that gains benefits from diverse energy sources supported by storage is more reliable in terms of safety and economics [11].
in [31] the motivations behind hybrid power plant are mentioned:

- Optimize the network usage
- Higher yearly capacity factor, more stable power output over time with less ramping issues and
- HPPs can be advantageous in terms of dispatching power in the market. It is notable that the basis of this study is to store wind energy when the electricity price is not beneficial and earn revenue when the electricity price is considerably high.
- Reduces investment cost since it needs to be set up via a single connection for the entire HPP.

- Reduced balancing costs and less renewable energy sources (RES) curtailment
- Acceleration of rural electrification

In [10] a detailed study qualitatively and quantitatively has been done to depict the advantages of a wind-based hybrid power plant (HPP) in comparison to a single wind/PV power plant. In this paper, a list of advantages was emphasized that is reported below:

- **Increase in capacity factor:** for a power plant, it is happening in case of limited evacuation factor and overplanting scenario.
- **Reduction in variability:** the variable nature of wind/PV energy generation based on weather condition and not the grid demand, impose additional stress on the electrical grid, curtailment of renewable generators, and low or even negative power prices.
- **Increase in availability:** instead of curtailment of excess energy, it can be stored in an energy storage system to increase AEP and CF.
- **Cost reduction and revenue increase:** combining different technology behind a single point that is connected to the grid by utilizing the same electrical infrastructure is the reason to decline the capital cost (CAPEX) and operational cost (OPEX) of Hybrid power plants.
- **Increase in ancillary service capability:** since the value of subsidies for wind power plant has decreased in the last few years, it is crucial for this source of energy to provide ancillary service to earn more revenue. in papers [32][33][27] detailed study has been done, and several strategies have been proposed.
- **Increase of lifetime of the wind turbine:** it is possible to decrease the wind turbine load by diverting it to other elements in Hybrid power plants, namely battery storage or PV, see [20].

2.2.3 Limitation

A very basic challenge related to Hybrid Power Plants (HPPs) is to find a suitable location where all components of HPPs can operate in their best functionality. Additionally, as mentioned in [31] for the best design and operation of HPPs with a profitable business, it requires a profound understanding of electrical infrastructure, site condition, grid restrictions, local regulation, etc. For example, this report suggests, "developers must be flexible to size and agree with the local authorities the grid connection capacity based on the optimized generation output of the HPP, driving a profitable business case for the project."

2.3 Battery storage system

2.3.1 Background, advantages, and disadvantages

In integrating energy production and energy storage systems to create a hybrid power system, battery storage is the steeply growing used component. In the comparison of two primary energy storage systems, pump hydro storage and battery storage, the superiority of battery storage in terms of sizing and geographical flexibility is significantly evident [19]. Battery storage capacity from a few MWh to hundreds of MWh can be easily deployed in the desired location at the most suitable sizing in cooperation with other elements in hybrid power plants. From the technological point of view, there are many different battery technologies such as lithium-ion (Li-ion), sodium-sulfur, and lead-acid batteries. From the IEA report in 2017 (figure 2.4), among all existed technology, Li-ion accounted for nearly 90% of large-scale battery storage additions [4].

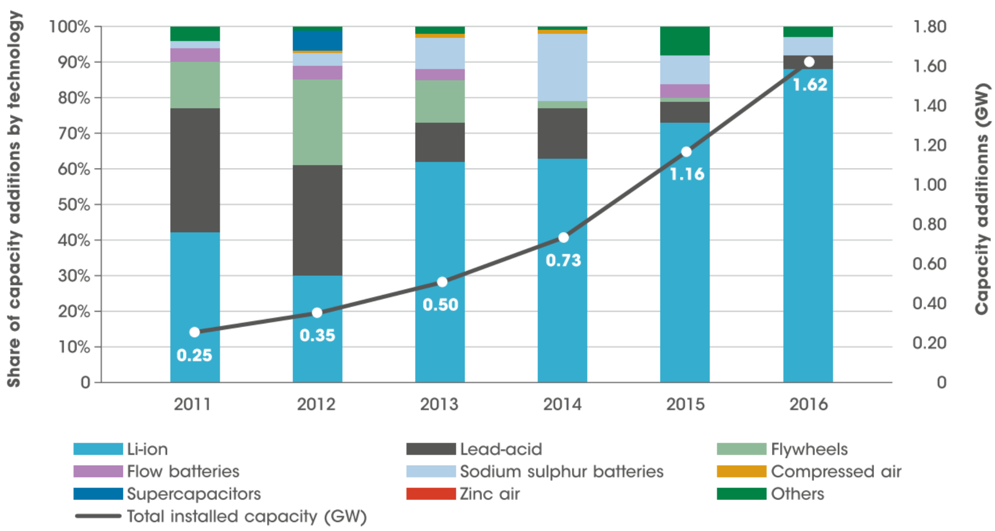


Figure 2.4: Increasing share of Li-ion in annual battery storage capacity additions globally Share [4]

The list below shows three main advantages of utility-scale battery storage, which has been reported in [19]:

1. **Frequency regulation:** The imbalance between power supply and demand may result in grid frequency fluctuation more than its specified range and, consequently, damage to grid infrastructures. In contrast to conventional power plants, batteries can reduce this risk by responding to system operators' instructions within a millisecond.

2. **Flexible ramping:** Batteries are able to neutralize the dramatic change of renewables' load curve and thus acquire a flatted ramp.

3. **Black start services:** In the time of grid failure, batteries as same as traditional diesel generators, can provide restoration of generation plants that requires power to start up again (referred to as "black start").

Apart from the technical drawbacks of Li-ion batteries mentioned in [12], their cost needs to decrease more than the predicted value to ensure a profitable and independent HPP from any feed-in tariff or power purchase agreement.

2.3.2 Optimization and sizing

In [34] the optimal size of large scale battery storage in cooperating with wind farm connected to the grid has been discussed. They found that the optimal size of the battery decrease by adding more battery in BESS. Additionally, they have proposed a constraint-based monotonic charge/discharge strategy of individual batteries of BESS with optimal capacity each. Likewise, in the [14] another strategy for charging/discharging battery storage has been proposed. This paper's primary goal is to limit the power fluctuation between the two adjacent 5-min by suggested strategy for BESS. The proposed strategy performs better and more effectively than the simple strategy in coordinating energy storage systems and wind power due to considering the potential contributions of BESS charging/discharging to future time intervals.

Previous studies proposed an optimal strategy for charging and discharging the battery in best synergy with the wind turbine. Although they were a very detailed study, they did not take into account battery profitability in contribution with the wind turbine. Therefore, in [11] a comprehensive charging/discharging approach has been revealed by considering bidding optimization and balancing methodology to control battery storage in wind-storage HPP optimally. In this study also a battery optimization strategy based on what is proposed in [11] will be deployed.

2.4 Hydrogen generation system

2.4.1 Background, advantages, and disadvantages

Hydrogen produced by renewable energy is achievable through electrolyzers. Furthermore, an electrolyzer is a device to produce Hydrogen by cracking the water molecule into Hydrogen (H_2) and Oxygen (O). Moreover, there are two main types of electrolysis technology at chimerical state. The first kind of electrolyzer operating in the industry since 1920 is the Alkaline electrolyzer. A younger generation of electrolyzer, which was invented in 1970, is the Polymer Electrolyte Membrane (PEM) electrolyzer. Therefore, the Hydrogen produced by the electrolyzer would either be stored in a different kind of storage or sent by pipeline to be utilized in industry. However, the secondary process on the Hydrogen, such as Hydrogen storage or transmission, is not the area of interest of this study. In this study, the PEM electrolyzer has been chosen to be coupled with the wind turbine in the HPP. In order to achieve a suitable selection of electrolyzer in cooperation with the wind turbine, it is necessary to compare the two major type of them [18],[12]. Table 2.1 shows a comparison between Alkaline and PEM electrolyzer.

Technology		**ALK**		**PEM**	
	Unit	2017	2025	2017	2025
Efficiency	kWh/kgH2	51	49	58	52
Efficiency (LHV)	%	65	68	57	64
Lifetime stack	Operating hours	80,000 h	90,000 h	40,000 h	50,000 h
CAPEX	€/kW	750	480	1200	700
OPEX	% of initial CAPEX/y	2	2	2	2
lifetime	Years	20		20	

Table 2.1: ALK and PEM electrolyzers comparison [18]

As it is observable from the above table, the ALK electrolyzer cost is lower, and it has higher efficiency. However, from the state of the art point of view, the PEM electrolyzer is more flexible in daily operation. In addition, since renewable technologies have a limitation in terms of resource variability, the PEM electrolyzer promises a reliable device in order to produce clean Hydrogen.

2.4.2 Optimization and sizing

One of the detailed studies about optimizing electrolyzer in cooperation with the wind turbine has been introduced by *S.Carr* [9]. In this study, an optimization algorithm in order to find the optimal performance of a Hydrogen refueling station in an electricity market has been proposed. However, in this study, the primary goal was to reduce as much as possible the curtailment of wind turbine power produced by sending the excess power to the Hydrogen generation station. In this study, the main aim is to design a WT+PEM electrolyzer HPP connected at a single point to the grid in order to achieve the highest NPV by the end of its lifetime. Hence, an algorithm has been proposed to optimize the HPP in order to earn the most benefits from the electricity and Hydrogen market.

Chapter 3

Methodology

3.1 Overview

In this chapter, a detailed description of wind turbine design, either working as a single component in wind power plants or cooperating with other HPP components, has been explained. Additionally, an HPP plant with two different scenarios, one with a battery storage system and the other one with Hydrogen generation technology, has been described. Figure 3.1 present different configurations of hybrid power plants that their design procedures will be explained in this section. The first designed configuration is a single wind turbine connected to the grid. However, a single wind turbine can not be a Hybrid power plant, but it is the first step in designing a hybrid power plant anyway.

Additionally, to understand the effect of hybridization, a zero state is needed to be compared with different hybrid power plant configurations. The second and third scenarios are a wind turbine in contribution with battery storage and a PEM electrolyzer, respectively. As depicted in the figure, the power plants are connected at a single point to the grid, which is a definition for hybrid systems. Additionally, in the case of wind and battery, there is a 2-way key to ensure that charge/discharge is not happening simultaneously. Similarly, in wind and electrolyzer cases, the switch grantee that the electricity has a single direction after the HPP, either toward grid or hybrid power plant.

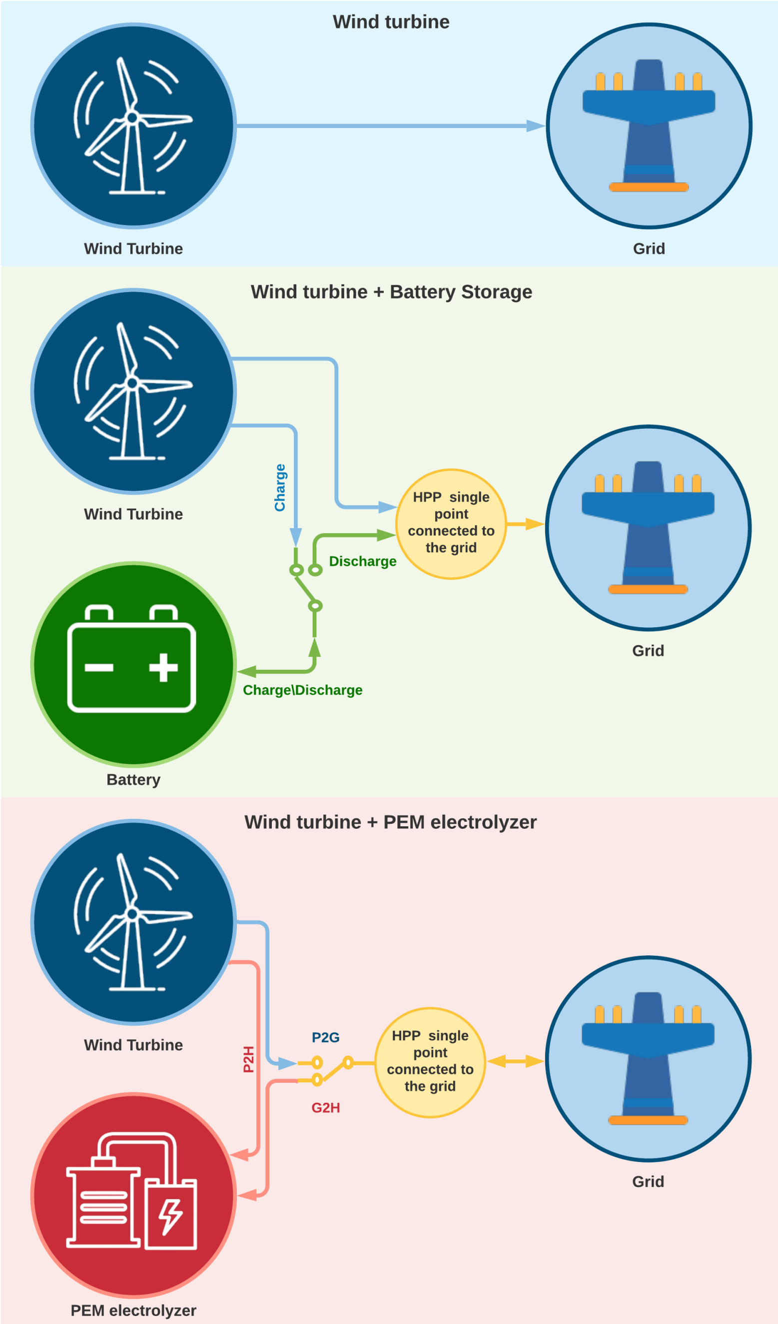


Figure 3.1: Different Hybrid power plant configuration

In this section, First, the design theory behind the three main elements will be explained. Thus, the implementation methodology will be expressed. In the design procedure of three main components, there are two categories of input data. First, the fixed input data, which are those data assumed once and until the end procedure, will be fixed, and second, the design parameters that are variable input data. For example, a set of rated power will be tested in order to maximize the NPV. The list below depicts the fixed and variable input (design parameters) data.

- **Fixed input data**
  - Fixed input for the wind turbine
    * Wind speed hourly time series for one year
    * Cut-in wind speed
    * Cut-out wind speed
    * Maximum speed at blade tip
    * Maximum power coefficient - C_P
    * Maximum tip ratio - λ
    * Maximum efficiency of rotor and drivetrain at rated power - η
    * Thrust coefficient - C_T
    * Altitude of wind site
  - Fixed input for the battery storage
    * Capital cost of battery storage and capacity - EUR/MW & EUR/kWh
    * Fixed annual maintenance and operational cost - EUR
  - Fixed input for the PEM electrolyzer
    * Capital cost of electrolyzer - EUR/MW
    * Cost of Hydrogen - $EUR/kgH2$
    * Efficiency of electrolyzer - $MWh/kgH2$
  - Economic fixed input
    * Electricity price hourly time series for one year
    * Discount rate - r
    * Exchange rate of EUR and $
- **Design parameters**
  - Design parameters for the wind turbine
    * Rated power - P_{rated}
    * Rotor diameter - R
    * Hub height - H
    * Advanced turbine

- Design parameters for the battery storage
  - Battery storage - MW
  - Battery capacity - MWh
- Design parameters for the PEM electrolyzer
  - Electrolyzer rated power - MW

3.2 Design of wind turbine

In this Thesis, all wind turbines based on NREL study [22] and the WISDEM Python library will be designed. The procedure divided into three main part:

1. Find the power curve
2. Find the capital cost of the wind turbine - CAPEX
3. Operational and maintenance cost - OPEX

3.2.1 Power curve

In the procedure of calculating the power curve, the first step is to calculate the air density (ρ) in the site as reported in [22].

$$\rho = \frac{101300 \cdot \left[1 - \left(\frac{0.0065 \cdot altitude}{288}\right)^{\frac{9.80665}{0.0065 \times 287.15}}\right]}{287.15 \cdot (288 - 0.0065 \cdot altitude)} \tag{3.1}$$

In the procedure of defining power curve, a basic method is that to divide power curve into four main region as shown below:

i : $P = 0$ $\quad$ $0 < V < V_{cut-in}$

ii : $P = \frac{1}{2}\rho\frac{\pi D^2}{4}V^3 C_P$ $\quad$ $V_{cut-in} < V < V_{rated}$

iii : $P = \frac{1}{2}\rho\frac{\pi D^2}{4}V_{rated}^3 C_P$ $\quad$ $V_{cut-in} < V < V_{rated}$

iv : $P = 0,$ $\quad$ $V_{cut-out} < V$

As it is clear from the equations in the list above, it is straightforward to find the third region of the power curve since all data are available as input data. Therefore it could be the starting point to find the power curve in region two. To have an even more straightforward approach, the NREL suggests that the second region can be divided into two parts itself. Although they take into account different intersection points at first, the mid-point of region two was their final choice due to more convincing results. However, before finding the second region of the power curve, some preliminary steps are essential. So the second step after calculating air density is to find the rated hub power, which is the hub power when the turbine is at rated power, indicating a different kind of losses. Maximum rotor efficiency at rated power is deviated from unity by indicating three losses: the one is independent to the power level, the one changing linearly with power, and the one changing by the second-order in relation to power [22]. However, in this study, the maximum efficiency of the rotor is as an input data, so the rated power is:

$$P_{hub,rated} = \frac{P_{rated}}{\eta} \tag{3.2}$$

$$\omega_M = \frac{Maximum\ speed\ at\ blade\ tip}{D/2} \tag{3.3}$$

$$\omega_0 = \frac{\omega_M}{1 + slope} \tag{3.4}$$

$$Q_M = \frac{P_{hub,rated}}{\omega_M} \tag{3.5}$$

Equation 3.3 present how the rated rotor speed is calculated. In equation 3.4, ω_0 is rotor speed at which region two hits zero torque, and the *slope* shows the slope at mid-point in the second region. Finally, the preliminary steps toward finding the second region of power curve by presenting equation 3.5 will be done. In this equation Q_M is the rated torque of rotor.

As It is illustrated in equation 3.7, power in the first part in region 2 has a cubic relation with rotor speed, whereas the second part linearly intersects region 3. Before preform, the power curve calculation in region 2, the variable-speed torque constant (k) has to be introduced.

$$k = \frac{\pi \rho D^5 C_P}{64 \lambda^3} \tag{3.6}$$

And finally, power equations for the second region:

$$P_{2nd\ region} : \begin{cases} k\left(\frac{V\lambda}{0.5D}\right)^3 & V < V_{\omega_t} \\ \frac{P_{hub,rated} - P_{\omega_t}}{V_{rated} - V_{\omega_t}}(V - V_{\omega_t}) + P_{\omega_t} & V_{\omega_t} < V \end{cases} \tag{3.7}$$

ω_t is the rotor speed at the mid-point of the second region, and it is derived from the quadratic equation:

$$\omega_t = -\frac{-b - \sqrt{b^2 - 4ac}}{2a} \quad (3.8)$$

Where:

$$a = k$$
$$b = -\frac{Q_M}{\omega_M - \omega_0} \quad (3.9)$$
$$c = \frac{Q_M \omega_0}{\omega_M - \omega_0}$$

It is noteworthy to mention that, if $\Delta > 0$ in quadratic equation, it presents the second region of the power curve. In other cases of Δ, such as 0 or a negative value, the power curve is considered in the third region. Therefore by taking into account the $\Delta > 0$ condition and the velocity conditions established in equation 3.7, the power curve in the second region can be depicted.

One of the major difficulties in finding the power curve is the rated wind speed calculation. However, the NREL study [22] made an assumption for the rated wind speed, but in the WISDEM model and relatively *nrel_csm_orig* script, there is a calculative function to compute the rated wind speed. Finally, this section reaches its end by finding maximum rotor thrust, which is essential to find the cost of the wind turbine.

$$T_{rotor} = \rho C_T \pi D^2 \frac{V_{rated}^2}{8} \quad (3.10)$$

3.2.2 Capital Cost of wind turbine

The NREL study and proportionally WISDEM model are utilized to find the capital cost of the wind turbine in this study. The reason is that the NREL study is very detail and comprehensive for the sake of preliminary study. In addition to that, the WISDEM is scripted as Python libraries that are easy to work and effectively time-saving. The following list presents primary cost elements tracked in the WISDEM model.

- Rotor
    - Blades
    - Hub
    - Pitch mechanisms and bearings

  - Spinner, nose cone

- Drive train, nacelle

  - Low-speed shaft
  - Bearings
  - Gearbox
  - Mechanical brake, high-speed coupling, and associated components
  - Generator
  - Variable-speed electronics
  - Yaw drive and bearing
  - Main frame
  - Electrical connections
  - Hydraulic and cooling systems
  - Nacelle cover

- Control, safety system, and condition monitoring

- Tower

- Balance of station

  - Foundation/support structure
  - Transportation
  - Roads, civil work
  - Assembly and installation
  - Electrical interface/connections
  - Engineering permits

In the NREL study [22] the detail of all mentioned elements' capital cost calculations is reported. Additionally, to obtain the capital cost of wind turbines, in the WISDEM model a precise Python library has been developed [name the input data]. Since the blade and tower cost are the center of attention of this study, their theory behind the capital cost calculation will be briefly explained.

Rotor blade cost

The blade cost model that has been deployed in the WISDEM model is base on the TPI blade cost scaling report [29]. In this study, the cost of material and labor assumed 72% of the total cost, and what is remaining is related to profit, overhead, tooling, and transportation. Additionally, two types of rotor blades with different materials have been investigated in the TPI study. Table 3.1 shows blade materials composition for baseline and advanced blade.

Material	Baseline blade	Advanced blade
Fiberglass fabric (NAICS Code 3272123)	60%	61%
Vinyl type adhesives (NAICS Code 32552044)	23%	27%
Other externally threaded metal fasteners, including studs (NAICS Code 332722489)	8%	3%
Urethane and other foam products (NAICS Code 326150P)	9%	9%

Table 3.1: Material composition of baseline and advanced blade

In contrary to the material composition, the labor cost scale is assumed to be the same for the baseline blade and the advanced blade. Finally, the outcome of the NREL study is an experimental function to calculate the rotor blade's cost. Equations 3.11 3.12 present the cost per blade. The basic theory to find these equations is $cost = {}^{(material\ cost + labor\ cost)}\!/_{0.72}$.

$$Baseline: \ cost = \frac{(0.4019R^3 - 955.24) \times BCE + 2.7445R^{2.5025} \times GDPE}{0.72} \tag{3.11}$$

$$Advanced: \ cost = \frac{(0.4019R^3 - 21051) \times BCE + 2.7445R^{2.5025} \times GDPE}{0.72} \tag{3.12}$$

In these equations, R is the rotor radius,BCE is blade material cost escalator, and $GDPE$ represents labor cost escalator. The cost methodology escalator also can be found in the NREL documentation [29] [22]. Graph 3.2 shows comparing the previous study cost escalation model with the NREL one.

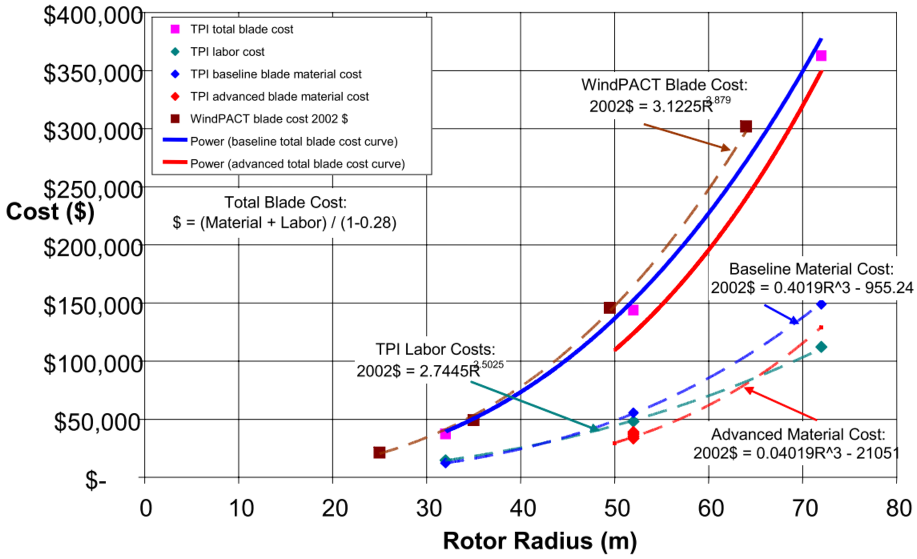


Figure 3.2: Blade cost scaling relationship per blade [22]

Tower cost

Based on the WindPACT reports [36],[25] the tower's cost calculate with a relationship between mass and cost. First tower's mass will scaled up with tower's volume ($swept\ area \times hub\ height$) and then the cost will be computed by driving a linear relation with mass.

$$Baseline:\ mass = 0.3973 \times swept\ area \times hub\ height - 1414 \tag{3.13}$$

$$Advanced:\ mass = 0.2694 \times swept\ area \times hub\ height + 1779 \tag{3.14}$$

By knowing the cost of the steel ($\$1.5/kg$) which reported in WindPACT, the tower's cost will be computed:

$$tower\ cost = mass \times \$1.5/kg \tag{3.15}$$

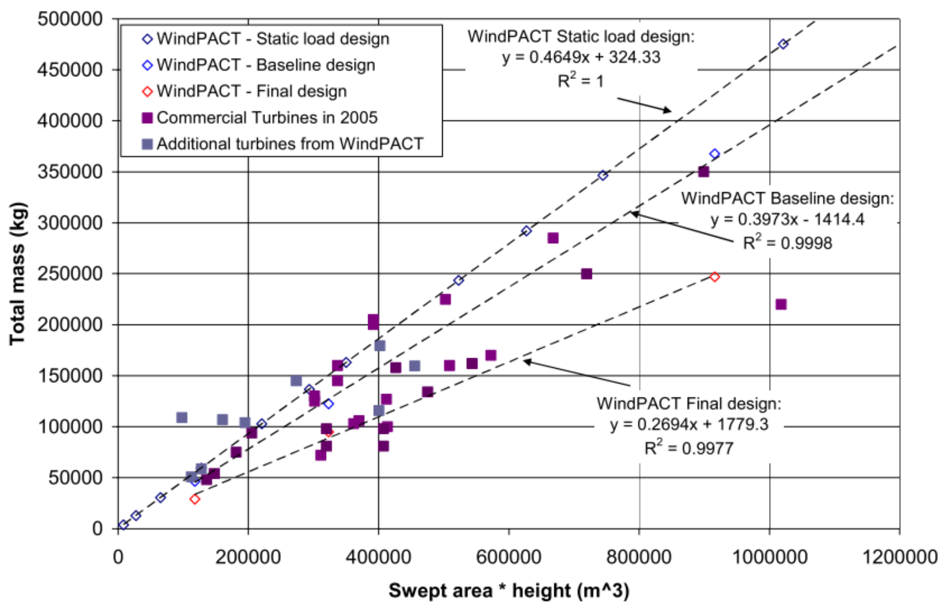


Figure 3.3: Tower cost scaling relationship [22]

3.3 Design of the battery storage

In this study, the design of battery storage is divided into two major parts. First, a charge/discharge strategy will be implemented by setting necessary conditions to achieve the highest annual revenue. Afterward, based on the highest NPV, a size for the battery storage will be selected.

3.3.1 Charge/discharge strategy

The approach to reaching the highest annual revenue is to absorb electricity that wind turbine produced, charge the battery storage when the electricity price is not beneficial, and then discharge it to the grid when the electricity price is considerably high. Based on study [11], it is achievable by implementing the following equations:

$$max\ OF = \sum \left(Electricity\ Price \times P^{spot}\right)_t \tag{3.16}$$

$$P_t^{spot} = P_t^{WT} + P_t^{dis} - P_t^{cha} \tag{3.17}$$

$$\left|P_t^{spot}\right| \leq P_{max}^{HPP} \tag{3.18}$$

$$P_t^{dis} \leq P_{max}^{BESS} \cdot (1 - switch_t) \tag{3.19}$$

$$P_t^{cha} \leq P_{max}^{BESS} \cdot switch_t \tag{3.20}$$

$$0 \leq P_t^{dis} \tag{3.21}$$

$$0 \leq P_t^{cha} \tag{3.22}$$

$$SOC_{min} \leq SOC_t \leq SOC_{max} \tag{3.23}$$

$$SOC_{t+1} = SOC_t + P_t^{cha} \cdot \Delta t - P_t^{dis} \cdot \Delta t \tag{3.24}$$

Equation 3.16 is the objective function in order to maximize the revenue. P_t^{spot} is the hourly power of HPP that participating in bidding, see equation 3.17. Additionally, P_t^{cha} and P_t^{dis} are charging and discharging power of battery storage. Equation 3.18 make sure that HPP is not producing more than its rated capacity. Since there is no possibility to charge and discharge the battery storage at the same time, equations 3.21 and 3.22 grant this condition by a *switch* which is a binary variable. P_{max}^{BESS} in these equations is the rated power of the battery storage. Afterward, to ensure that the charged and discharged power is in the range of battery capacity in each hour, equation 3.23 has been applied to the *SOC* boundaries. Finally, equation 3.24 present the next hour battery's state of charge (*SOC*).

3.3.2 Sizing

To find the optimum size of the battery storage in cooperating with the wind turbine in HPP to produce the highest NPV, a set of the feasible size of battery storage has been chosen. Afterward, to find the Highest NPV, all established configurations for the wind turbine and the battery storage have been tested cooperatively.

3.4 Design of PEM electrolyzer

As same as battery storage, the design of the PEM electrolyzer is divided into two parts. First, optimize the Hydrogen generation to contribute to the wind turbine and grid connection to reach the highest NPV. Afterward, Finding the best-rated power size of the electrolyzer in cooperation with the wind turbine achieves the primary goal of this study. Additionally, in order to find the optimum size of the PEM electrolyzer, a strategy as same as the one utilized in the battery storage has been implemented.

3.4.1 Optimization algorithm

In this section, the goal is to find an optimal solution between selling power to the grid or producing Hydrogen to make the business profitable as much as possible. Additionally, there is a possibility to buy power from the grid in case of a lack of power produced by the wind turbine. Therefore a comprehensive strategy is needed first to make a decision to sell the power to the grid or send it to the electrolyzer and second to determine that it is profitable to buy electricity to produce Hydrogen or not. Hence, in this study, a strategy has been proposed in order to optimize the cooperation between wind turbine, PEM electrolyzer, and the grid. The following equations present the suggested algorithm:

$$\begin{aligned} max\ OF = \sum (&P2G \times Electricity\ Price + P2H \times H_2\ Price \\ &+ G2H \times (H_2\ Price - Electricity\ Price))_t \end{aligned} \tag{3.25}$$

$$P2G + P2H \leq P_{Wind} \tag{3.26}$$

$$G2H + P2H \leq P_{Electrolyzer} \tag{3.27}$$

$$0 \leq P2G \leq switch \cdot P_{Wind} \tag{3.28}$$

$$0 \leq G2H \leq (1 - switch) \cdot P_{Electrolyzer} \tag{3.29}$$

$$0 \leq P2H \tag{3.30}$$

In the equation 3.25, *OF* present the objective function in order to maximize the annual revenue, *P2G* is the power sold to the grid, *P2H* present the power sent to the electrolyzer, and *G2H* is the power bought from the grid to produce Hydrogen.

Equation 3.26 ensure that the power sent to the grid and Hydrogen in not exceed the maximum power produced by wind turbine hourly. Equation 3.27 constrain the power that has been sent to the electrolyzer. In equation 3.28 and 3.30 a *switch* binary variable considered, as same as for the battery, to ensure that in a single point, the hybrid plant is connected to the grid. Specifically, It is not possible to sell the power to the grid and buy electricity to produce Hydrogen.

3.5 Technical and economic assessment

3.5.1 Technical performance

AEP

It is the Annual Energy Production of the wind turbine either in kWh or MWh. In this study, since the hourly power is available, AEP calculates by summation of hourly power in a year. Equation 3.31 shows how the AEP was calculated.

$$AEP = \sum_{i=1}^{8760} P_i \times \Delta t_i \tag{3.31}$$

In this equation, P_i is the power produced by the wind turbine in each hour, and Δt_i is equal to 1 hour.

Capacity factor

Capacity factor (CF) is the ratio between the amount of energy produced by the wind turbine in a time period and the amount of energy when the wind turbine work at rated power in the same time period. Therefore, the numerator in this equation would be AEP, and the denominator includes the summation of rated power in a year.

$$CF = \frac{AEP}{P_{rated} \times 8760} \tag{3.32}$$

3.5.2 Economic analysis

Revenue

Revenue is the profit that a power plant can earn by doing regular activity. For example, in the wind turbine case, it is the benefit earned by selling electricity to the grid, and in the case of wind turbine and PEM electrolyzer, the gained money from selling H2 or electricity to the grid. Equation 3.33 shows the hourly revenue in wind turbine and wind turbine-battery storage hybrid power plant, and equation 3.34 presents the calculation of revenue in the case of the wind turbine-PEM electrolyzer.

$$Revenue_t = P_t \times Electricity\ Price_t \tag{3.33}$$

$$\begin{aligned} Revenue_t = P2G_t \times Electricity\ Price_t + P2H_t \times H_2\ Price_t \\ + G2H_t \times (H_2\ Price_t - Electricity\ Price_t) \end{aligned} \tag{3.34}$$

A summation on hourly revenue result in revenue in a year; see equation 3.35. As mentioned before, the electricity price and wind speed times series assumed would be without any change during wind plant lifetime. Consequently, by considering the same annual revenue for 25 years (wind power plant lifetime), the total revenue can be calculated as shown in equation 3.36. Since the worth of money would be different during the power plant lifetime, a discount rate has been considered in order to take into account the differentiation of the earned revenue in each year.

$$Annual\ revenue = \sum_{t=1}^{8760} Revenue_t \tag{3.35}$$

$$Total\ revenue = \sum_{i=1}^{25} \frac{Annual\ revenue}{(1+r)^i} \tag{3.36}$$

Expenditure

In this study, expenditure includes the capital cost (CAPEX) of the wind turbine, battery storage, and PEM electrolyzer. Additionally, a yearly operation and maintenance cost (OPEX) for wind turbines and battery storage has been considered. Equation 3.37 illustrate the expenditure during the wind power plant lifetime.

$$Total\ expenditures = CAPEX + \sum_{i=1}^{25} \frac{OPEX}{(1+r)^i} \tag{3.37}$$

NPV

Maximization of the net present value is the fundamental goal of this study in the design procedure. The NPV is calculated by subtracting the total revenue and total expenditure. A positive value presents that the power plant economically is beneficial, and a negative amount means the net loss.

$$NPV = total\ revenue - total\ expenditures \tag{3.38}$$
$$= -CAPEX + \sum_{i=1}^{25} \frac{Annual\ revenue - OPEX}{(1+r)^i}$$

LCOE

The Levelized Cost Of Electricity is the ratio of the total expenditure to the lifetime energy production. It presents the cost of one unit of energy in EUR/MWh over the lifetime of the power plant. Additionally, it shows the minimum selling price of energy in order to make the project profitable. For example, in the case of an LCOE higher than electricity price, the total revenue would be lower than the expenditure and thus negative NPV. Equation 3.39 shows how the LCOE can be calculated.

$$LCOE = \frac{Total\ expenditures}{\sum_{i=1}^{25} \frac{AEP_i}{(1+r)^i}} \tag{3.39}$$

IRR

The Internal Rate of Return corresponds to the value of the discount rate when the NPV becomes equal to 0; see equation 3.40. It is the annual rate of growth a power plant is expected to generate. The positive subtraction of IRR and discount rate ensure the project profitability. Since it is not possible to calculate the IRR analytically, a Matlab toolbox has been utilized.

$$NPV = -CAPEX + \sum_{i=1}^{25} \frac{Annual\ revenue - OPEX}{(1+IRR)^i} = 0$$

3.6 Implementation

3.6.1 Wind turbine

In order to implement the theory explained for the design of the wind turbine, a Matlab code has been scripted. In the first step, all technical and economical fixed input data and design parameters related to the wind turbine have been imported to the main script in Matlab. By having all the necessary data to find the power curve, a function in Python has been developed and called in Matlab in order to export the wind speed and power curves (V on x-axis-P on y-axis) for different design parameters. Since the WISDEM library makes an array of wind speeds and finds the power curve based on that, interpolation is needed to find hourly power produced based on wind speed time series for each location. After finding the power curve, the capital cost of the wind turbine can be calculated. It is noteworthy to mention that, in order to find the power curve by the WISDEM model, *nrel_csm_orig_* library has been utilized. This library is capable of accomplishing numerous objectives related to the cost and technical assessment of the wind turbine. However, among all functions, three of them have been utilized in order to find the power curve (used function: *aero_csm*), capital cost (*tcc_csm*), and operational and maintenance cost of the wind turbine (*nrelopex*). Finally, with a power hourly time series, electricity price, CAPEX, and OPEX, all technical and economic assessments can be performed. By integrating a "for" loop, the explained procedure has to be repeated for all design parameters in order to find the maximum NPV. Figure 3.4 shows the flow diagram in design procedure.

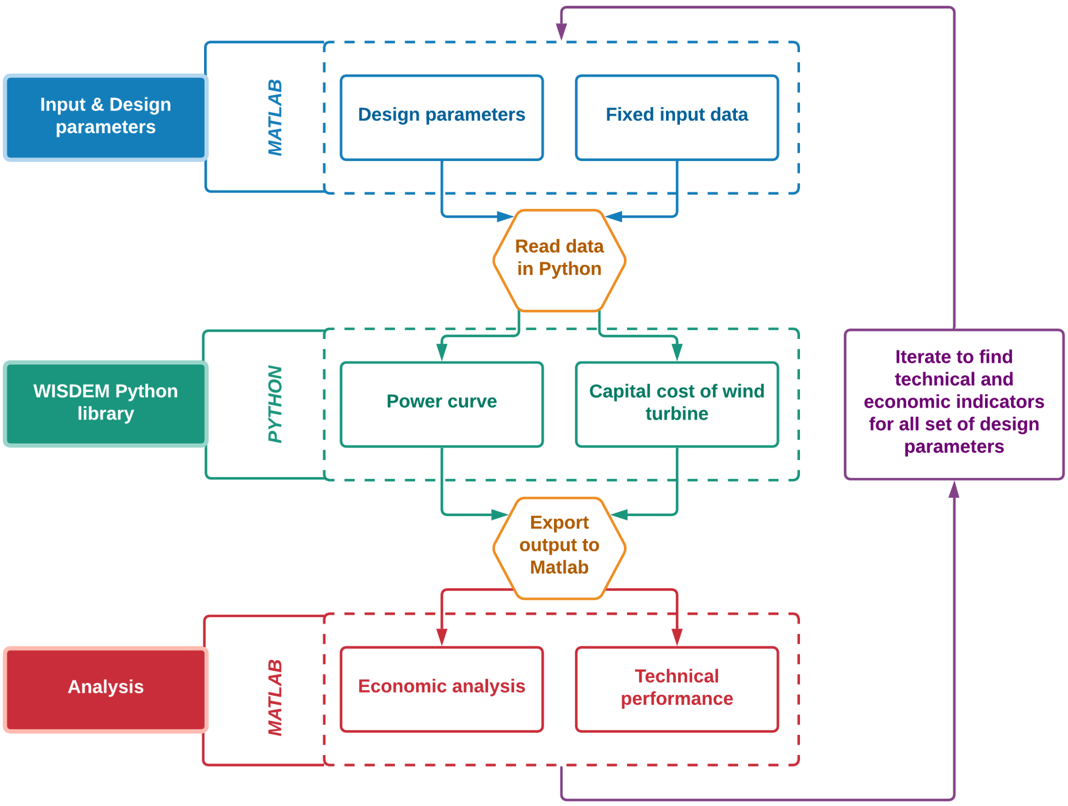


Figure 3.4: Flow chart of design of wind turbine

3.6.2 Wind turbine+ battery storage

All procedures for the design of the wind turbine and technical and economic analysis are the same as in the previous section. The difference in this section is to optimize the charge/discharge battery in order to find the highest yearly revenue. Therefore, the *intlinprog* (Mixed-integer linear programming solver) from the optimization toolbox of Matlab has been applied. As an assumption, the optimization will be done weekly. It means the code attempts to start with 50% SOC at the start of 1^{st} hour and finish the optimization with the same amount of SOC by the end of 167^{th} hour. Thus, there are 52 weeks to be optimized to the highest value of revenue. A weekly decision for charge/discharge battery has been made by considering the mentioned objective function, and an array of power sold to the grid has been generated. By having the new array of wind power bidding to the grid, electricity price, CAPEX, and OPEX one more time, all technical and economic assessments can be performed. Graph 3.5 illustrate the design procedure of wind turbine + battery storage as an HPP.

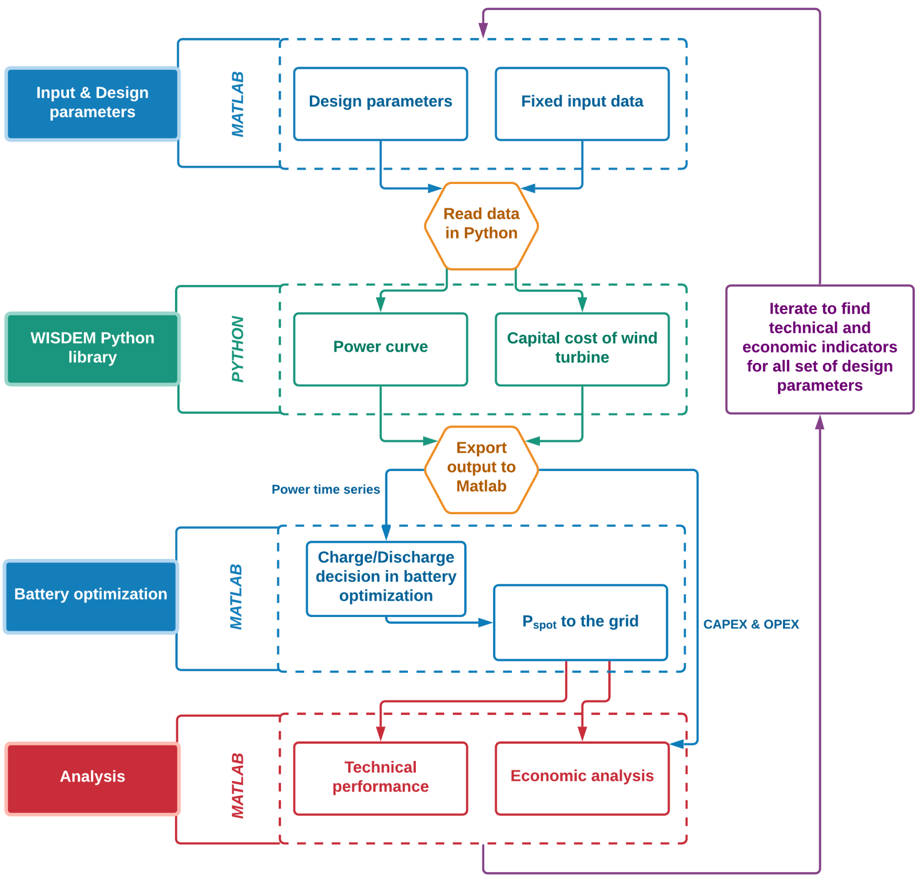


Figure 3.5: Flow chart of design of wind turbine + battery storage

3.6.3 Wind turbine+ PEM electrolyzer

As it is mentioned, the same procedure has been implemented in order to find the power curve and cost of the wind turbine. In this section, however, a decision has to be made either sell the electricity to the grid or send it to the electrolyzer in order to produce Hydrogen. Additionally, in the case of the profitable business of Hydrogen generation, a decision has to be made whether to buy electricity to produce Hydrogen or not. To perform the optimization between grid and configured hybrid power plant, a Matlab function has been characterized. Once more, the same Matlab toolbox and function (*intlinprog*) has been utilized. By running the optimization code, arrays of P2G (power sold to the grid), P2H (power sent to electrolyzer), and G2H (bought electricity from the grid to electrolyzer) have been generated. Therefore the annual revenue by considering electricity price and Hydrogen price can be evaluated.

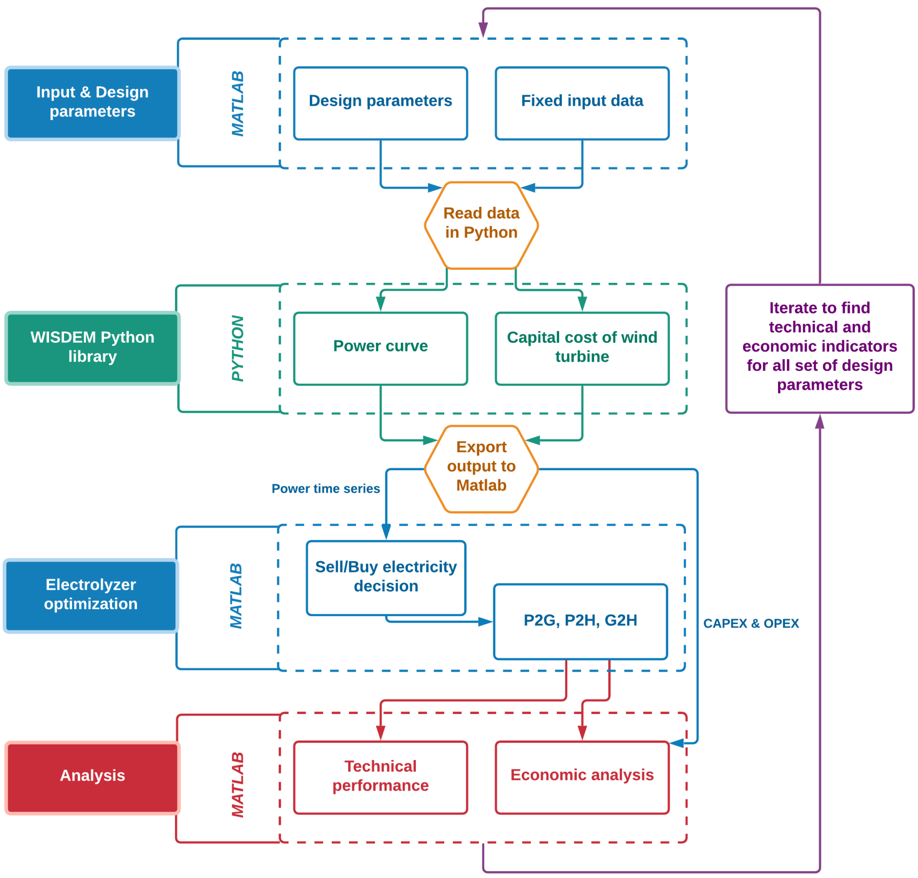


Figure 3.6: Flow chart of design of wind turbine + PEM electrolyzer

Chapter 4

Results

In this chapter, all outputs and result data for three cases with a single wind turbine, wind turbine + battery storage, and wind turbine + PEM electrolyzer in three locations will be illustrated. As mentioned before, the main aim of this study is to design a wind turbine in cooperation of a Hybrid power plant, which results in the highest NPV.

4.1 Wind turbine

In the wind turbine design procedure, rated power, rotor diameter, and hub height as three main design parameters varied in order to result in the highest NPV for each location. In addition, A methodology for advancing wind turbine by advancing the blade, bedplate, and tower has been considered. Variable design parameters are listed as below:

- *Rated power:* 3.0-6.0 [MW]
- *Rotor diameter:* 100-200 [m]
- *Hub height:* 90-150 [m]
- A choice for advancing blade, bedplate, and/or tower.

By implementing the methodology which has been explained in chapter 3, A preliminary result for each location will be generated. Accordingly, the table 4.2 represents design output for a wind turbine and a related economic study for all locations in two different scenarios, with and without advanced blade, bedplate, tower. In this table, "Base" represent the baseline turbine technology, and"Adv" stands for an advanced wind turbine consisting of an advanced blade, bedplate, and tower.

Besides these design parameters there are other fixed input data listed in the table below. During Design of wind turbine in all location these input data will kept constant.

Technical			
Cut-in wind speed [m/s]	3	Max power coefficient	0.5
Cut-out wind speed [m/s]	25	Tip speed ratio	8.15
Shear Exponent	0.2	Max efficiency	0.9
Max tip speed [m/s]	80	Thrust coefficient	0.8
Economic			
Discount rate [%]	8	$ to € exchange rate	0.85

Table 4.1: Fixed design parameter for wind turbine

It is striking interesting from table 4.2 that by advancing the wind turbine, not only the specific cost of the wind turbine fell drastically, but also a bigger rotor can be utilized to generate more revenue. Additionally, table 4.2 shows that the highest-rated power solution for Denmark and Netherlands due to very high average wind speed, 6.96 $\frac{m}{s}$ and 7.44 $\frac{m}{s}$ respectively. On the other hand, due to not significant average wind speed in Italy, 4.69 $\frac{m}{s}$, there is not sufficient wind energy to exploit, so the smallest corner solution has been generated by design model. Even though the least rated power has been chosen for Italy, a negative NPV has resulted as a best case. However, by advancing wind turbine, the NPV becomes a positive value, but still, it is negligible.

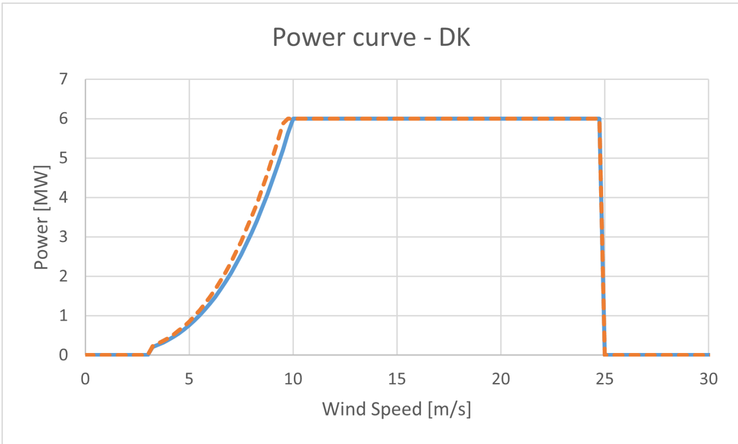
Although the primary goal of this study is that to design a wind turbine with the highest NPV and not minimizing the LCOE, it is understandable from table 4.2 that higher deviation between LCOE and average electricity price in the Netherlands ensure the higher NPV generation in comparison to other location. It is essential to mention that this study focusing on designing future wind turbines without any feed-in tariff or power purchase agreement. Therefore, the only solution to make a profit via wind power plant is to increase revenue production and at the same time decrease expenditure as much as possible.

		Denmark		Italy		Netherlands	
	Unit	Base	Adv	Base	Adv	Base	Adv
Rated power	MW	6	6	3	3	6	6
Rotor diameter	m	160	170	120	130	180	190
Hub height	m	150	150	150	150	150	150
AEP	GWh	24.58	26.24	6.24	7.03	30.02	31.43
Capacity factor	%	46.91	50.06	23.81	26.85	57.28	59.97
Annual Revenue	M€	0.95	1.01	0.33	0.37	1.53	1.61
Total Revenue	M€	10.10	10.79	3.51	3.96	16.36	17.16
Specific cost of Turbine	$/kW	1,605	1,555	1,584	1,556	1,975	1,903
Capex	M€	6.96	6.74	3.43	3.37	8.56	8.25
Opex	M€	0.06	0.06	0.03	0.03	0.06	0.06
Total expenditure	M€	7.60	7.38	3.75	3.69	9.20	8.89
NPV	M€	2.51	3.41	-0.236	0.266	7.16	8.27
LCOE	€/MWh	28.96	26.36	56.36	49.18	26.26	24.23
Average electricity price	€/MWh	38.69		52.35		52.52	
IRR	%	12.00	13.51	7.18	8.91	16.85	18.49

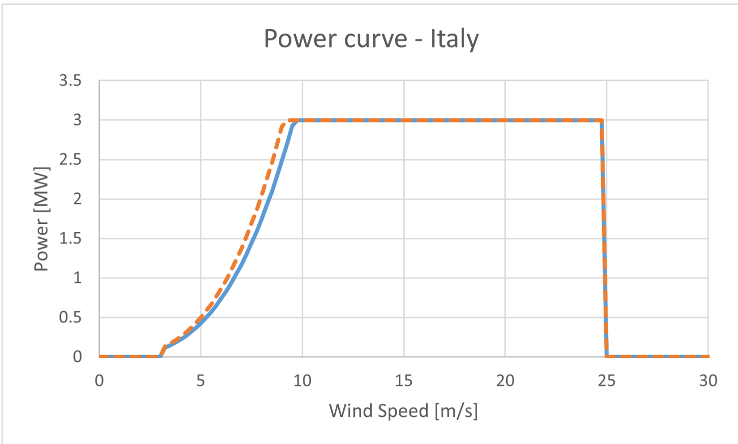
Table 4.2: Best wind turbine design based on the highest NPV

4.1.1 Power curve for designed wind turbine

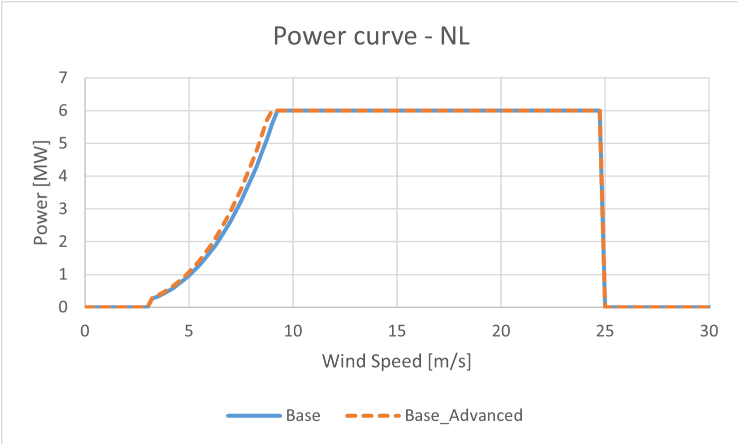
In figure 4.1, the characteristic power curve related to each location has been represented. As mentioned before, a 6 MW wind turbine for Denmark and Netherlands and a 3 MW wind turbine for Italy result in maximum NPV. What is interesting about the generated power curves in this figure is that By advancing blade, bedplate, and tower, the wind turbine's rated speed becomes a lower value, and it is able to work in rated power in a broader range of wind speed.



(a)



(b)



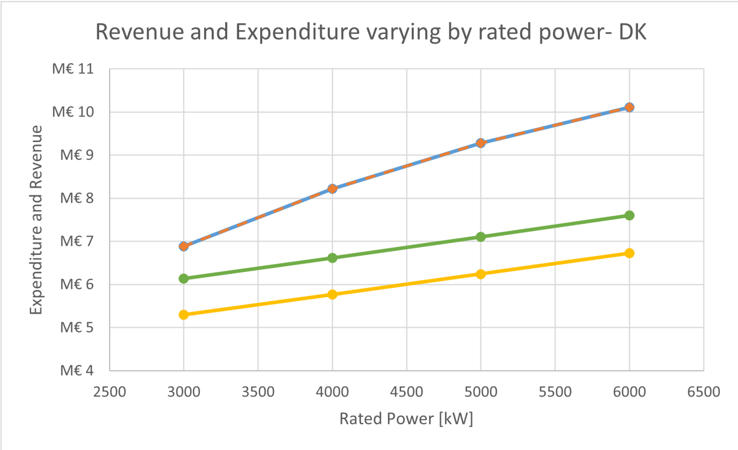
(c)

Figure 4.1: Designed Power curves for three locations

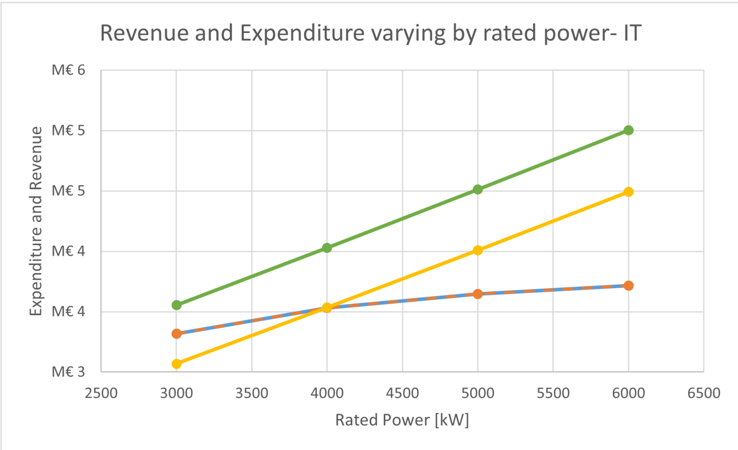
In the case of Italy, however, the average electricity price is a comparable number, but there is not sufficient wind energy to produce. Therefore, the NPV becomes a negative value.

4.1.2 Rated power analysis

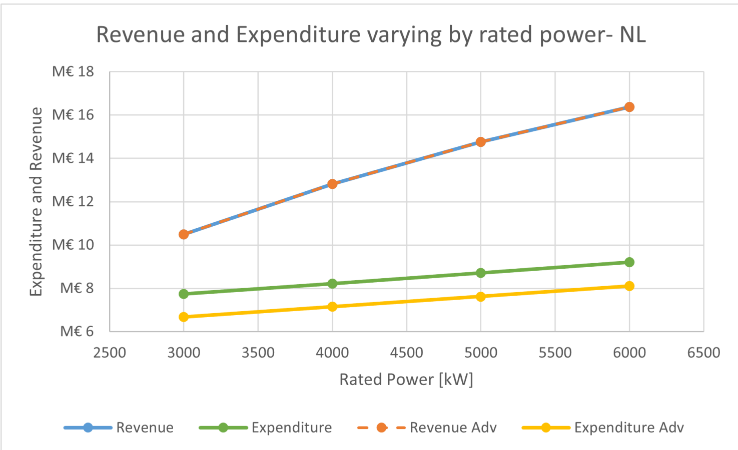
A sensitivity analysis on rated power has been done in figure 4.2 and simultaneously, other design parameters are kept constant as reported in the table 4.2 for each location. In this figure, the X-axis represents rated power in kW, and the Y-axis illustrates the revenue and expenditures in M€. Notably, In all locations, the expenditure increase linearly by increasing the rated power, and revenue relaxingly grows up. Additionally, this figure proves that advancing the wind turbine strategy is an effective solution to lessen expenditure. On the contrary, revenue does not experience any variation by advancing the wind turbine. However, as emphasized before, in Denmark and Netherlands, due to high average wind velocity, a 6MW wind turbine can generate more power and consequently more revenue, whereas in Italy with low average wind speed, a 3 MW wind turbine is the best solution to generate the highest NPV. It is crystal clear that a strategy that produces maximum revenue while expenditure is minimum is the one that can result in the highest NPV.



(a)



(b)

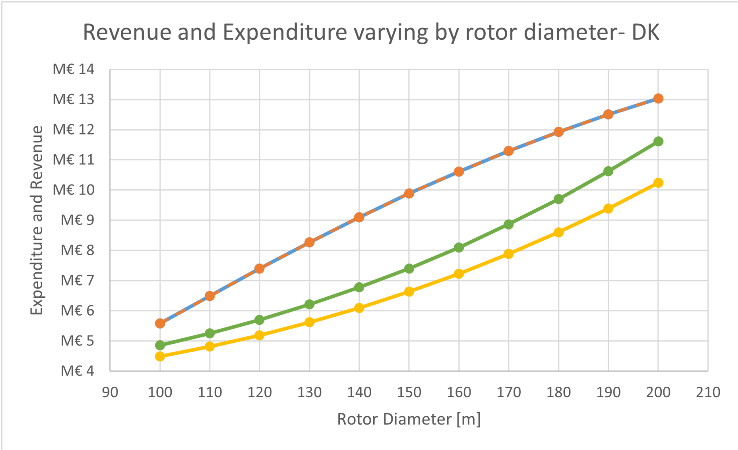


(c)

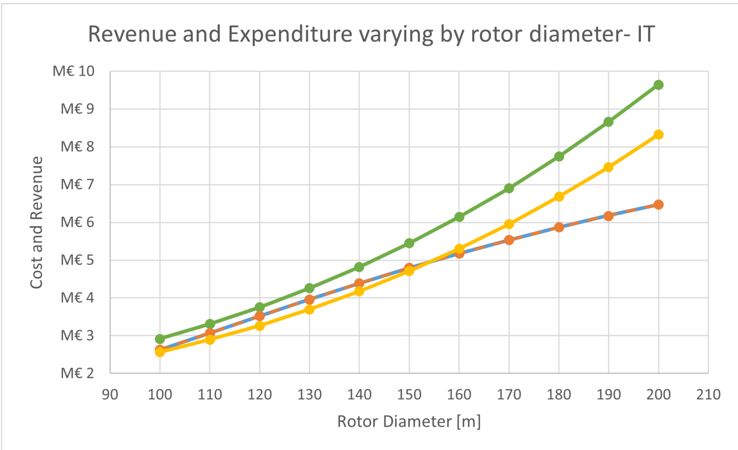
Figure 4.2: Rated power variation effect on the revenue and the expenditure

4.1.3 Rotor diameter analysis

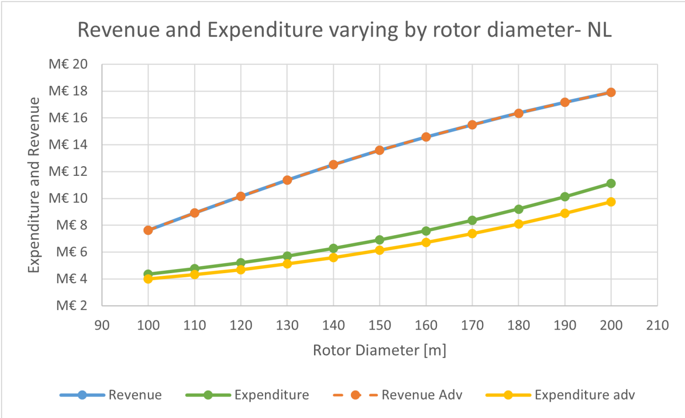
Figure 4.3 represents the revenue and the expenditure in M€ evolution by varying the rotor diameter. This figure illustrates that in opposite to figure 4.2, the largest wind turbine does not necessarily result in the highest NPV in the case of Denmark and the Netherlands. This study's promising outcome is that in the same rated power(6MW) and hub height (150m), the highest difference between the revenue and the expenditure occurs at 160m and 180m rotor diameter, respectively. Similarly, the best design of rotor diameter for Italy with 3 MW rated power and 150 m hub height would be 120 m.



(a)

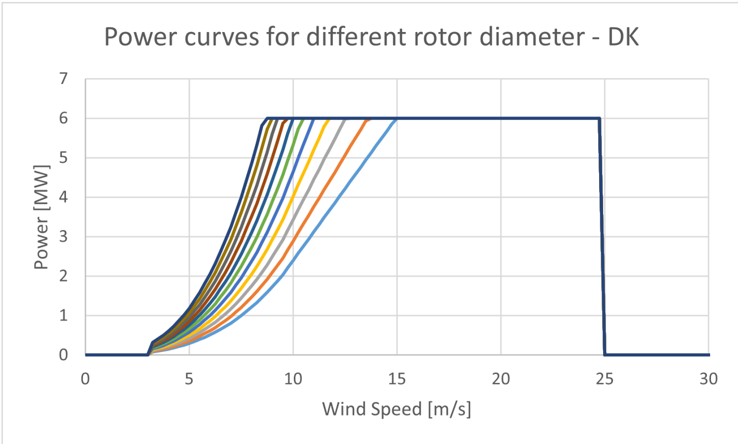


(b)

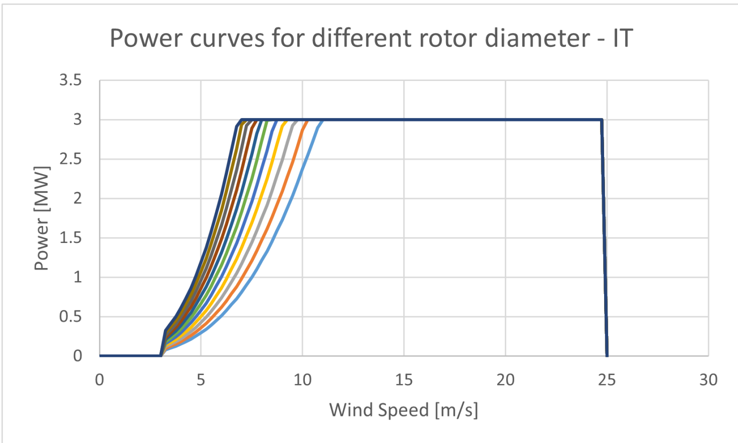


(c)

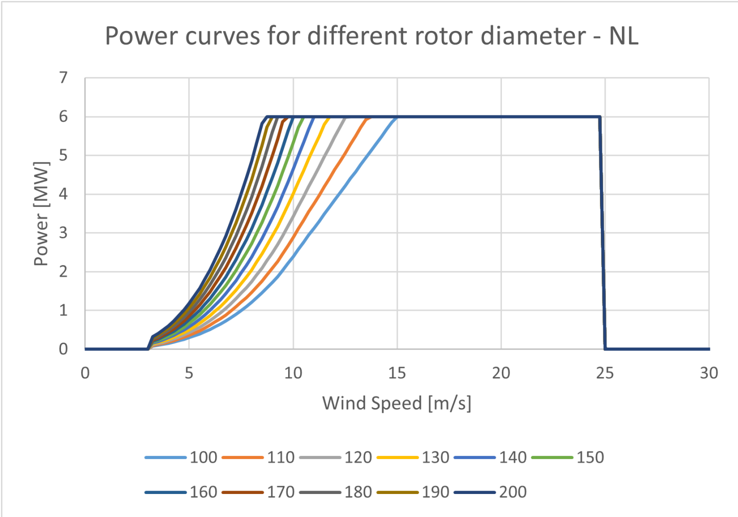
Figure 4.3: Rotor diameter variation effect on the revenue and the expenditure



(a)



(b)



(c)

Figure 4.4: Power curves variation by differentiating rotor diameter

An explanation for the different increasing behavior of the revenue and the expenditure in figure 4.3 is that the revenue is related to the produced power and consequently to the second order of diameter ($P = \frac{1}{2}\rho C_P A V^3$) whereas, the expenditure increases in a order between two and three.

Figure 4.4 illustrates how rotor diameter variation affects power curves. It is also mentionable that other parameters are kept constant as noted in table 4.2. Since revenue is proportionally related to power ($Revenue = \sum_{i=1}^{8760} Power \times ElectricityPrice$) , by increasing the rotor diameter, the wind turbine can work in a broader range of rated power and so the revenue generation will rise. On the other hand, in the direction to a higher value of rotor diameter, the power lines gap becomes narrower. This decrease is the reason for a negative second-order derivative of revenue evolution in figure 4.3.

4.1.4 Hub height analysis

Figure 4.5 shows how the revenue and the expenditure vary by increasing the hub height. What is interesting in this graph is that by adding a few amounts of expenditure, it is possible for a wind turbine to work at a higher altitude which the wind velocity has a more stable regime and a higher velocity.

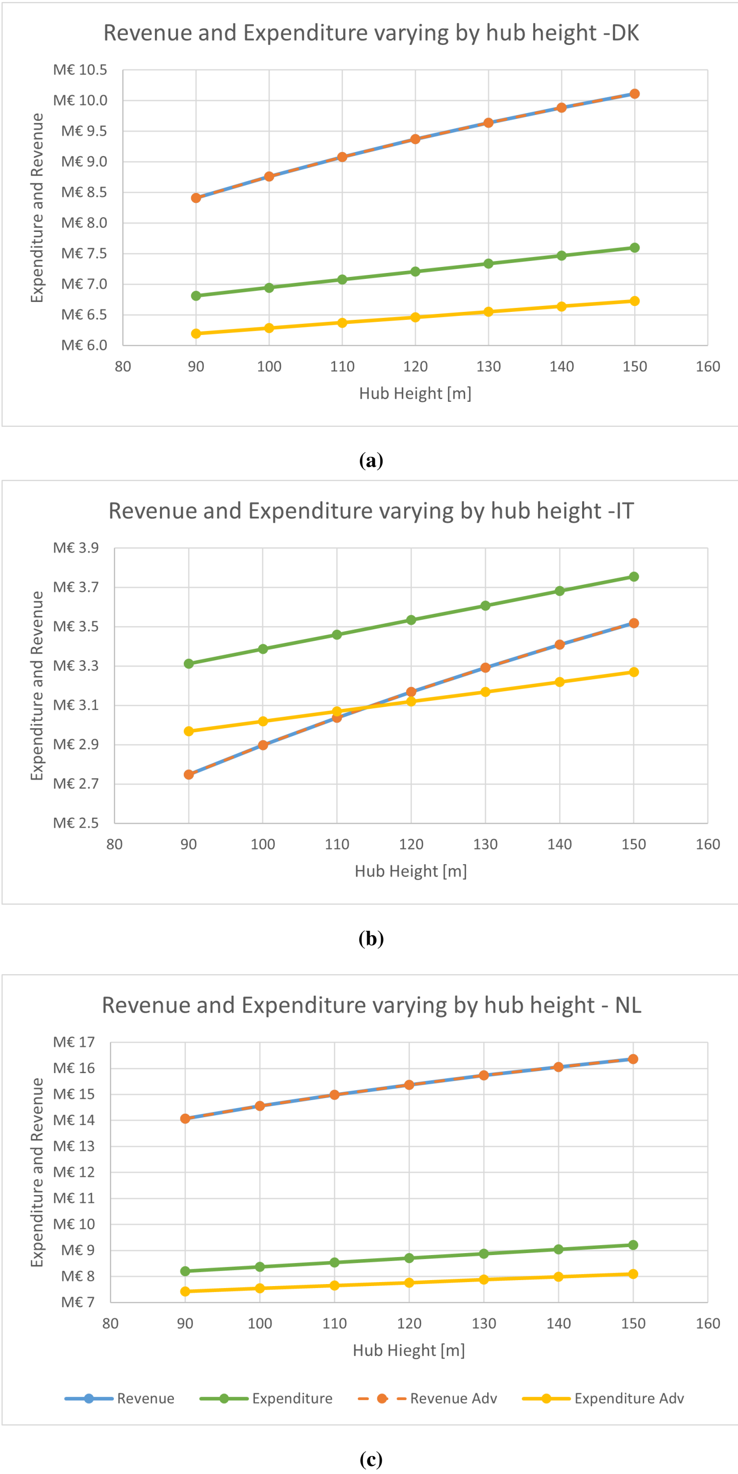


Figure 4.5: Hub height variation effect on the revenue and the expenditure

The result presented in figures 4.5 would be the same for all locations: impressive higher increasing slope for revenue than expenditure. This result can prove that an inevitable solution for future wind turbines toward independence from any supportive regulation is let wind turbines work at higher altitudes.

4.1.5 Conclusion on design of wind turbine

As a brief conclusion for the wind turbine design, the choice of the rated power is correlated with average wind velocity and available wind energy in the selected location. As shown before, a last number in the mentioned range for rated power for Denmark and Netherlands and least rated power in range for Italy is the best design. On the other hand, the largest or tiniest rotor diameter is not perpetually the best design to reach the highest NPV. In order to find the best design for rotor diameter, it needs a cost and benefits analysis procedure as presented in graph 4.3. A beneficial design methodology for the future wind turbine is to go toward installing a wind turbine in a higher average altitude in comparison to today's wind turbine hub height working area. In figure 4.5 it is clearly depicted that increasing the hub height has an effective influence on increasing revenue in exchange for a negligible amount of expenditure. Finally, in all methodologies and strategies presented so far, advancing the blade, bedplate and tower is a positively effective solution to declining expenditure.

4.2 Wind turbine + Battery storage

Similarly to the last section, the design procedure for a wind turbine in cooperation with battery storage has been implemented. The main difference in this section is how to design and optimize battery in a way to reach the highest NPV for a Hybrid system. By utilizing the methodology explained in chapter 3, a charge/discharge strategy have been developed in order to optimize the cooperation between battery storage and the wind turbine to achieve highest NPV. The list below presents designed parameters for wind turbine + battery storage.

- *Rated power:* 3.0-6.0 [MW]
- *Rotor diameter:* 100-200 [m]
- *Hub height:* 90-150 [m]
- *Battery storage:* 3.0-6.0 [MW]
- $Crate^{-1}$: 1-10 [MWh/MW]

In the procedure to design of wind turbine and battery storage, there were economic fixed parameters which has been listed in table 4.3.

Energy component [M€/MWh]	0.062	Other project costs [M€/MWh]	0.08
Capacity component [M€/MW]	0.16	Fixed O&M [k€2015/MW/y]	0.54

Table 4.3: Fixed economic parameters for battery storage

By utilizing a Matlab code script and a "for" loop, the desired result as the highest NPV can be obtained. Table 4.4 present the best design for the wind turbine and battery storage in addition to the financial result dedicated to selected locations. It is noteworthy to mention that all wind turbine fixed input data are kept constant as the same as the previous section.

The first understandable result from table 4.4 is that the wind turbine design has not changed compared to the previous scenario. It means the same wind turbine as the best system has been chosen by model once more, and this is true for both the baseline and the advanced wind turbine model. In order to find the highest NPV, the model has decided the lowest battery storage and capacity in all locations (3 MW and 3 MWh). However, the reason for this selection will be discussed in detail later in this section, but as a brief explanation, due to the very high price of battery storage and capacity, the model has decided to choose the minimum size of battery for all locations. By looking at total revenue and expenditure, it is clear that the revenue increased by installing battery storage, but the total expenditure has been increased significantly.

In addition, installing the battery storage has a negative impact economically in all locations. A lower amount of NPV and IRR and a higher value for the LCOE resulted from considering battery storage in cooperation with the wind turbine.

		Denmark		Italy		Netherlands	
	Unit	Base	Adv	Base	Adv	Base	Adv
Rated power	MW	6.0	6.0	6.0	6.0	6.0	6.0
Rotor diameter	m	160	170	120	130	180	190
Hub height	m	150	150	150	150	150	150
Battery storage	MW	3.0	3.0	3.0	3.0	3.0	3.0
Battery capacity	MWh	3.0	3.0	3.0	3.0	3.0	3.0
AEP	GWh	24.58	26.24	6.24	7.03	30.02	31.43
Capacity factor	%	46.91	50.06	23.81	26.85	57.28	59.97
Annual Revenue	M€	0.97	1.03	0.35	0.39	1.56	1.64
Total Revenue	M€	10.3	11	3.76	4.2	16.70	17.48
Specific cost of Turbine	$/kW	1605	1555	1585	1557	1976	1903
Capex	M€	7.75	7.54	4.23	4.17	9.36	9.19
Opex	M€	0.06	0.06	0.03	0.03	0.06	0.06
Total expenditure	M€	8.4	8.18	4.55	4.49	10.00	9.83
NPV	M€	1.94	2.82	-0.788	-0.285	6.70	7.66
LCOE	€/MWh	29.46	29.20	62.86	59.77	31.21	29.29
Average electricity price	€/MWh	38.69		52.35		52.52	
IRR	%	10.81	12.15	5.73	7.19	15.65	16.82

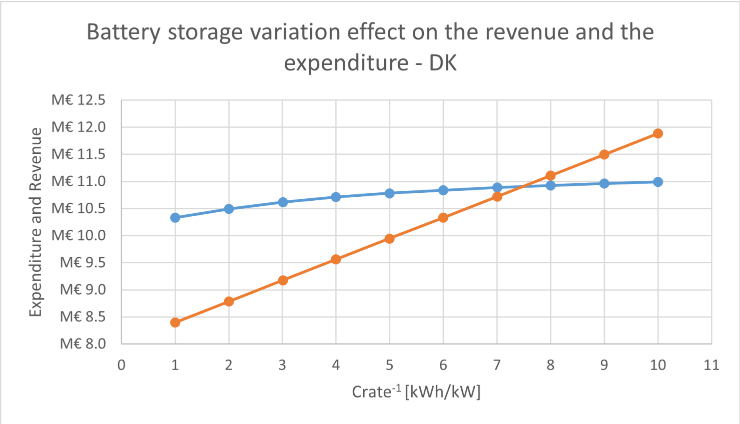
Table 4.4: Best wind turbine design and battery storage based on the highest NPV

4.2.1 Battery storage and capacity analysis

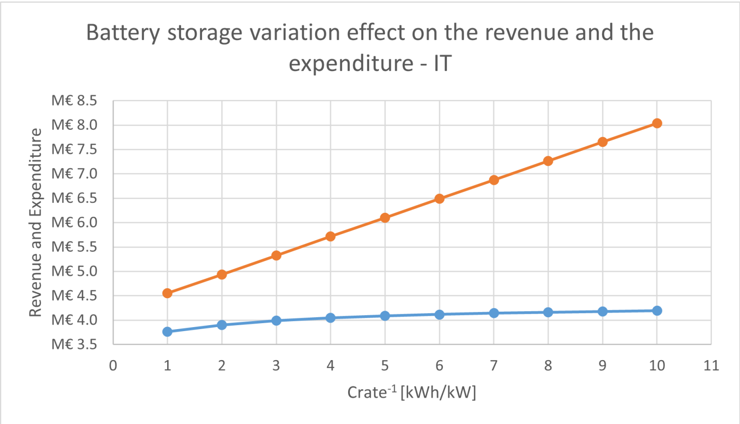
Figure 4.6 illustrates the alteration of revenue and expenditure by varying $Crate^{-1}$, representing the number of hours of battery storage. As it is crystal clear in all figures, by increasing the battery's size, expenses rise with a higher slope than revenue. Therefore, the outcome will be that the battery storage installment contribution with a wind turbine is not a practical solution to increase the revenue in all selected locations. It is noteworthy to mention that the project aims to increase as much as possible NPV and not lower the LCOE. In the implemented strategy, batteries can not be a desirable solution since the electricity fluctuation is not high enough in selected locations.

Figure 4.7 represents the wind turbine power output, charge and discharge power of the battery, spot power which will sell to the grid, Electricity price in each hour, battery's State of Charge, and finally, the wind speed. To have a comprehensive examination of the wind turbine and battery contribution, each location's electricity price, which has the most severe deviation, has been chosen. Accordingly, in Denmark, week 1, in Italy, week 51, and Netherlands, week 11 are represented in this figure. As mentioned before, battery storage can store the produced energy from the wind turbine when the electricity price is pretty low and send it to the grid when the electricity price is significantly high. Therefore, it is predicted that a battery storage system can operate more effectively in a location where the electricity price's fluctuation is considerable. As the figure shows, the electricity price's fluctuation in Denmark and Netherlands is negligible; therefore, the battery contribution would be uninfluential in these locations. On the other hand, in Italy, with an immensely fluctuated electricity price, the wind speed and consequently power production is not significantly high, so battery contribution is not a positive effect.

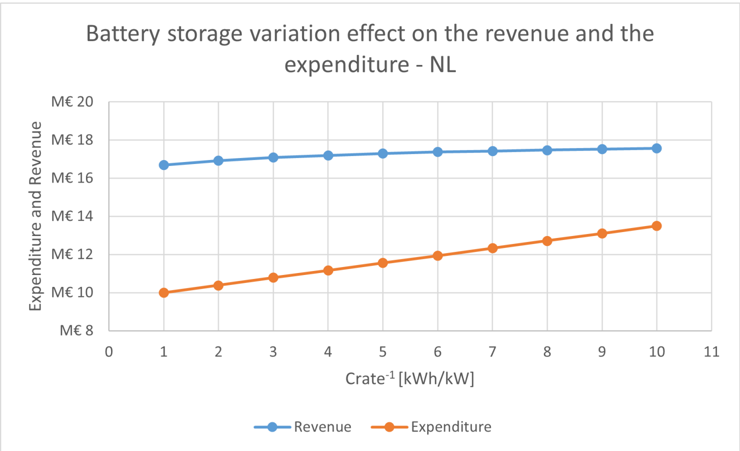
Figure 4.8 present the duration curve for the electricity price in the selected locations. It is understandable from graph, the higher decreasing slope shows the more fluctuation in the electricity price. In consequence, as mentioned before, it is obvious that in Denmark and Netherlands electricity price has not a significant fluctuation and so the battery is not effective solution to increase NPV.



(a)

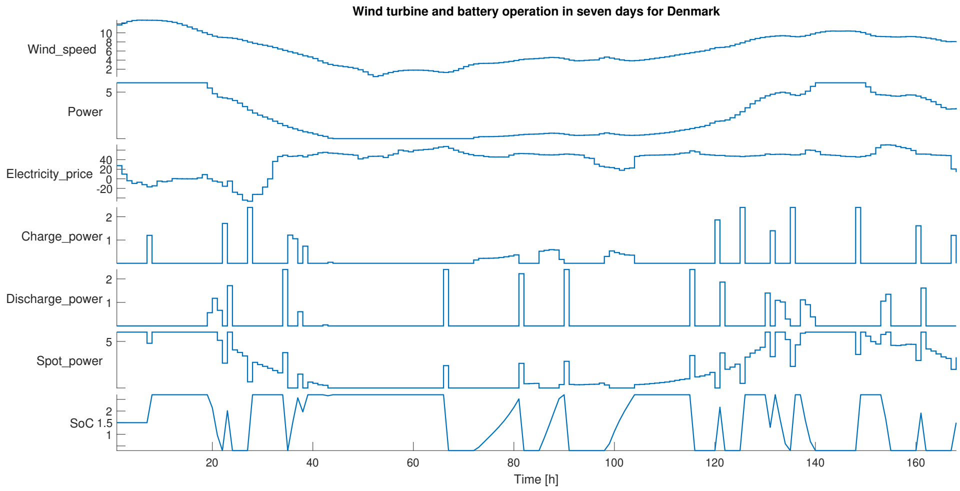


(b)

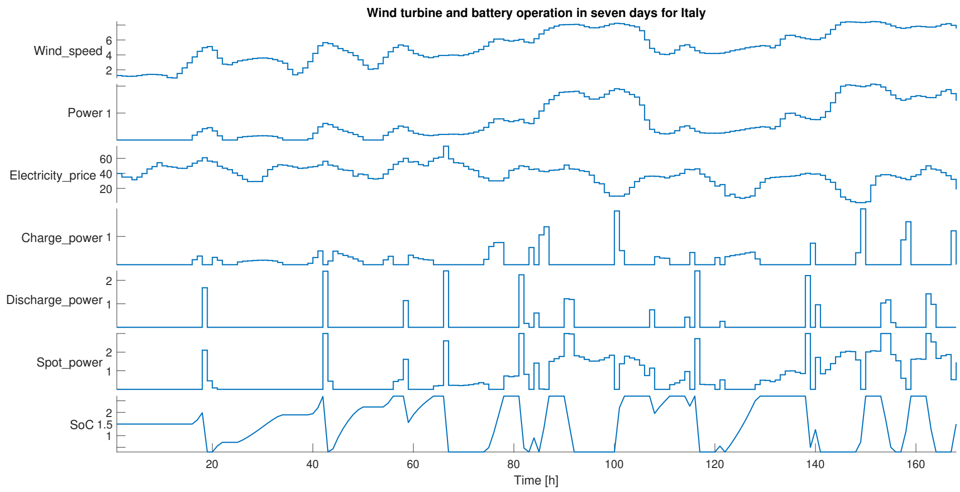


(c)

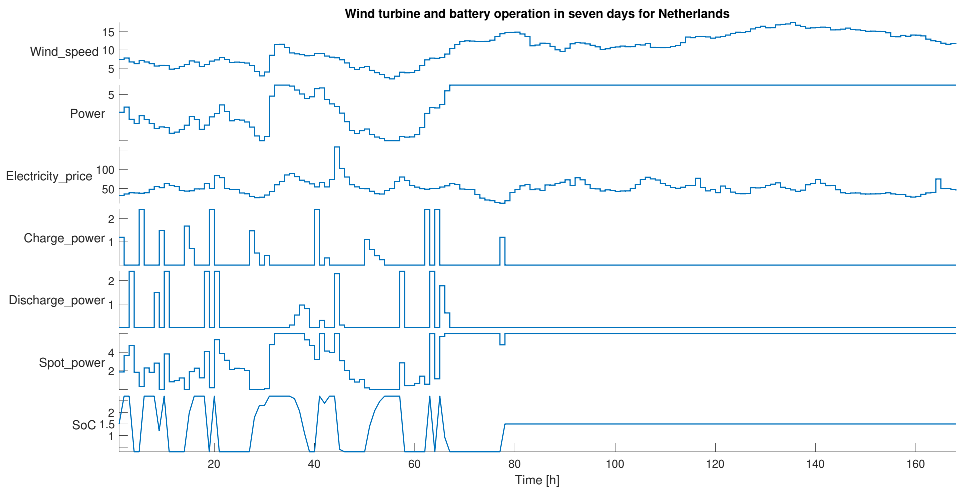
Figure 4.6: $Crate^{-1}$ variation effect on the revenue and the expenditure



(a)



(b)



(c)

Figure 4.7

Figure 4.8: Price duration plot

4.3 Wind turbine + PEM electrolyzer

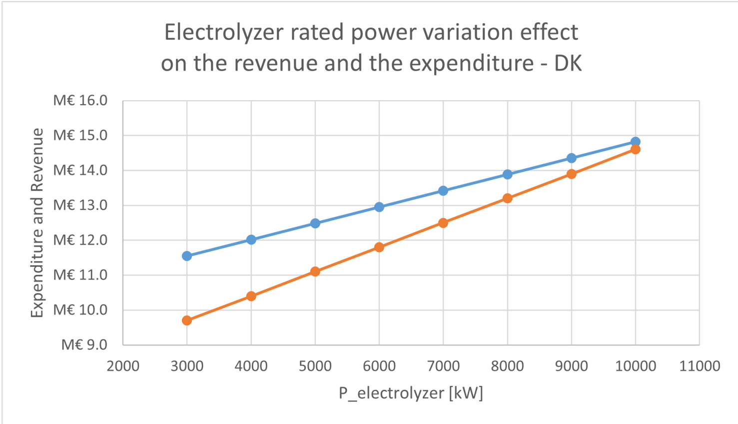
This section will present the final result related to wind turbine + PEM electrolyzer design and optimization. In the procedure of finding the highest NPV, a set of design variables has been chosen for both wind turbine and PEM electrolyzer. The list below shows the design parameters:

- **Design parameters**
  - *Rated power:* 3.0-6.0 [MW]
  - *Rotor diameter:* 100-200 [m]
  - *Hub height:* 90-150 [m]
  - *Electrolyzer rated power:* 3.0-10.0 [MW]
- **Fixed input data**
  - *Capital cost of electrolyzer:* 700 [EUR/MW]
  - *Cost of Hydrogen:* 2 [EUR/kgH2]
  - *Efficiency of electrolyzer:* 50 [MWh/kgH2]

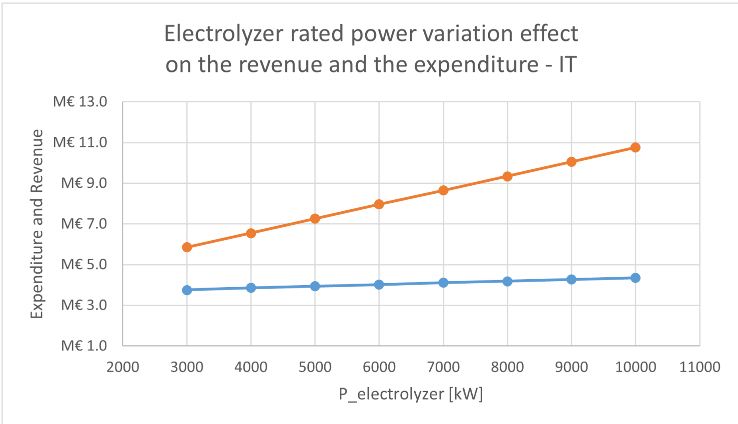
After integrating the theory and implementation process explained in chapter 3, The best design result is presented in table 4.5. One more time, the same result as in the wind turbine + battery storage section has been generated for the design of rated power, rotor diameter, and hub height. In addition, due to the considerably high amount of CAPEX, the lowest PEM electrolyzer rated power has been considered in cooperation with the wind turbine in the hybrid power plant. The low price of Hydrogen, in addition to the high cost of PEM electrolyzer, are the main reasons to make this business not profitable in comparison to a single wind turbine.

		Denmark		Italy		Netherlands	
	Unit	Base	Adv	Base	Adv	Base	Adv
Rated power	MW	6	6	3	3	6	6
Rotor diameter	m	160	170	120	130	180	190
Hub height	m	150	150	150	150	150	150
Electrolyzer rated power	MW	3	3	3	3	3	3
AEP	GWh	24.58	26.24	6.24	70.38	30.02	31.43
Capacity factor	%	46.91	50.06	23.81	26.85	57.28	59.97
Annual Revenue	M€	1.08	1.15	0.35	0.39	1.57	1.64
Total Revenue	M€	11.55	12.23	3.77	4.21	16.73	17.53
Specific cost of Turbine	$/kW	1605	1555	1585	1557	1976	1903
Capex	M€	9.06	8.84	5.53	5.47	10.66	10.35
Opex	M€	0.06	0.06	0.03	0.03	0.06	0.06
Total expenditure	M€	9.7	9.48	5.85	5.79	11.31	10.99
NPV	M€	1.85	2.75	-2.08	-1.58	5.42	6.54
LCOE	€/MWh	36.96	33.86	87.88	77.13	35.27	32.76
Average electricity price	€/MWh	38.69		52.35		52.52	
IRR	%	10.31	11.47	3.15	4.38	13.54	14.8

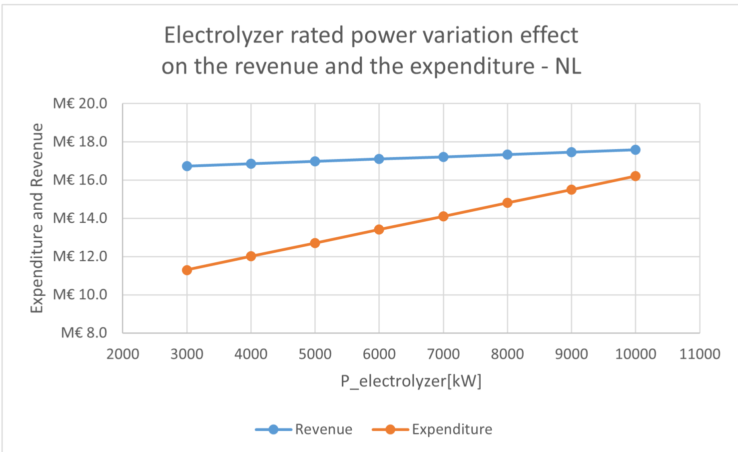
Table 4.5: Best wind turbine + PEM electrolyzer design based on the highest NPV



(a)



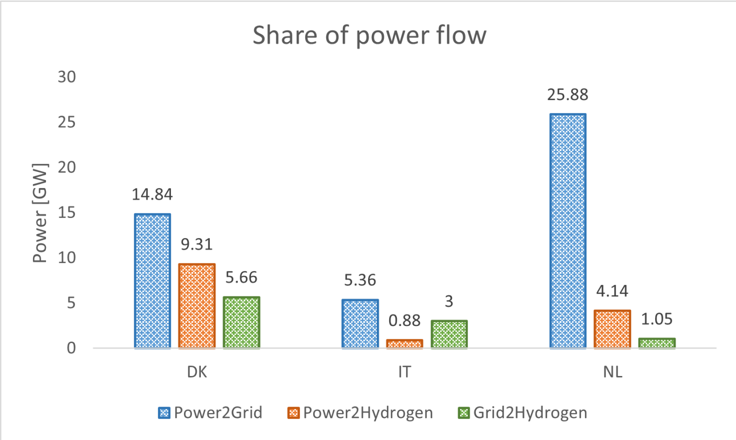
(b)



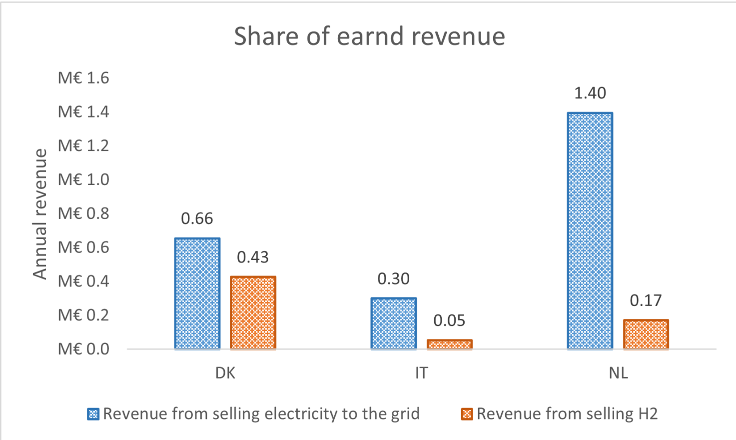
(c)

Figure 4.9: PEM electrolyzer rated power variation effect on the revenue and the expenditure

Figures 4.9 present the electrolyzer-rated power variation on the x-axis and revenue and expenditure value on the y-axis. As it is understandable, an increase in revenue by raising the size of electrolyzer is not favorable. Unlike Denmark, in Italy and Netherlands, a change in the electrolyzer's size has no significant effect on the revenue.



(a) Annual share of power sent to the grid and the electrolyzer or bought from the grid



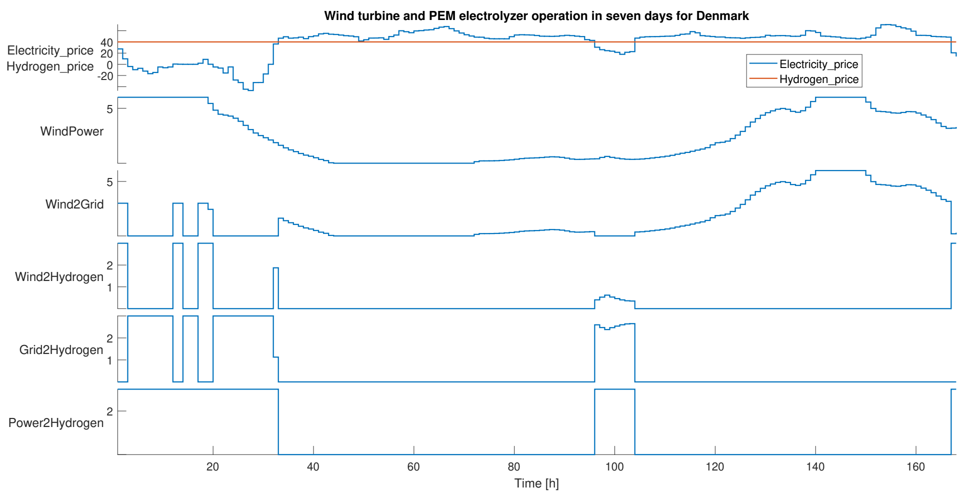
(b) Annual share of earned revenue by selling electricity to the grid or selling Hydrogen

Figure 4.10: Wind turbine + PEM electrolyzer HPP annual share of power and revenue earned

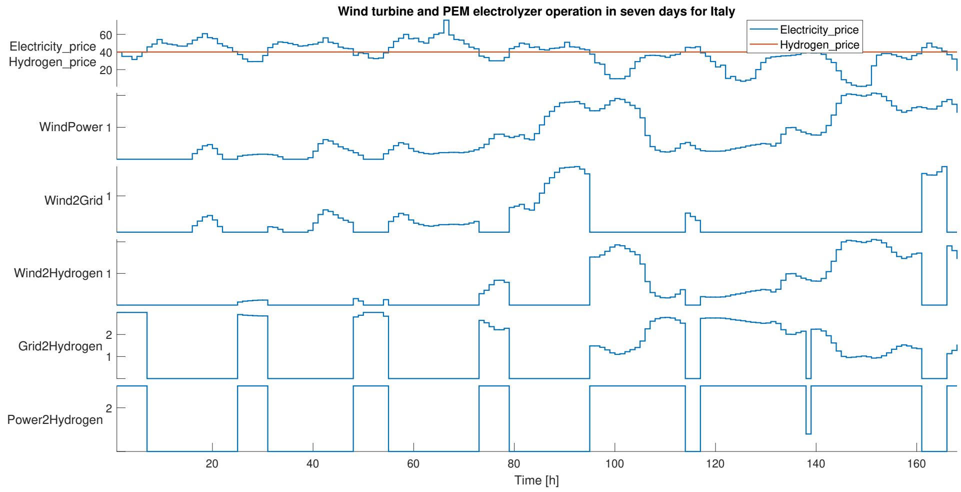
As mentioned before, a rise in the size of electrolyzer has no effect on revenue in Italy and Netherlands. A closer inspection of the figure shows that, in Italy and the Netherlands, the slope of revenue is almost equal to 1. The reason is that, by assuming the Hydrogen price equal to 2EUR/kg and an efficiency of 50 kWh/kgH2, the selling price of hydrogen will be 40 EUR/MWh, which is lower than the electricity price in Italy and Netherlands (52.3 and 52.7 respectively). Therefore, since the Hydrogen price exceeds the electricity price very few times in a year, the model decides to sell the power to the grid. Consequently, increasing the size of electrolyzer in the case of Italy and the Netherlands is not a rational decision. However, in Denmark, the average electricity price is 38 EUR/MWh, and so electrolyzer can contribute to revenue production.

Figure 4.10 show the reason explained above in a more explicit way. Figure 4.10a present the share of annual power sold to the grid (P2G), sent to the electrolyzer (P2H), and the electricity bought from gird in order to produce Hydrogen (G2H) in selected locations. As it is noticeable, in Italy and Netherlands, most of the power has been sold to the grid due to the low price of Hydrogen. However, In Denmark, the share of power is distributed more equally. It means that Hydrogen has a considerable profitable business in comparison to selling electricity to the grid in Denmark. Figure 4.10b illustrate the participation of the PEM electrolyzer in the HPP from an economic point of view. As it could be predicted, unlike Denmark, revenue generated from selling Hydrogen in Italy and Netherlands is a negligible value.

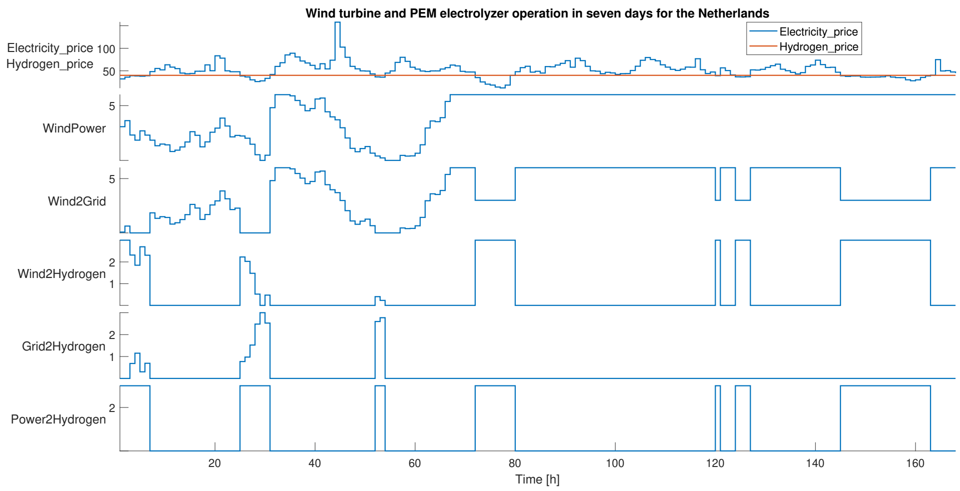
After running the optimization for one year, figure 4.11 as an example, shows the wind turbine + PEM electrolyzer system working for seven days in selected locations. With the same explanation in the wind turbine + battery storage system, a similar choice for representing week in each location has been chosen. From the graph, it is understandable that whenever the electricity price exceeds the Hydrogen price line, the model sells the power to the grid. On the contrary, when Hydrogen has a profitable business, the model sends as much as possible power to generate Hydrogen. In conclusion, it is comprehensible that due to the high price of the electrolyzer and the low price of Hydrogen, there is not a considerably practical value to install a PEM electrolyzer as a participating element in HPP.



(a)



(b)



(c)

Figure 4.11

4.4 HPP Configurations comparison

In this study, the main strategy to find the best desirable design for the wind turbine working in a hybrid power plant is to maximize the NPV. As a logical strategy, today's objective function for the design of the wind turbine is based on lowering the LCOE. However, in this thesis, it has been revealed that considering the market as a primary goal to generate as much as possible revenue and proportionally NPV is a considerably profitable strategy for future wind turbine design. Tables 4.6,4.7, and 4.8 present compassion between the design of wind turbine as it is today and for the market purposes.

To have comprehensive compassion between what is presented in these tables, the design of wind turbine, in addition to three economic indicators (NPV, LCOE, and IRR), has to be taken into account. Additionally, the case of Denmark and the Netherlands with the same output has been explained first, and Italy with different performance accounted afterward. '

Denmark and Netherlands

The first sticking interesting result is that, by changing the strategy from minimizing LCOE to maximizing NPV, the design of wind turbine would change. However, considering an element in contribution with wind turbine does not affect its design. Additionally, In compassion of today's wind turbine with lowering LCOE strategy and future's wind turbines with market objective, it is crystal clear that the LCOE for today's wind turbine has a lower value. Afterward, by analyzing a single wind turbine in two different explained strategies, it is clear that minimum LCOE wind turbine has a higher IRR value which means lesser risk in terms of economic stability in each location. However, it seems more logical to chose a wind turbine with a higher IRR and lower LCOE, but it is a conservative and inefficient strategy for the future wind turbine. For example, by sacrificing 1% of IRR, NPV can grow more than 1 million EUR in Denmark, and in the case of the Netherlands, the NPV would be doubled by decreasing IRR less than 5%.

Italy

In the case of Italy, since there is no significant power production from the wind turbine, changing the strategy does not affect wind turbine design. As the table 4.7 shows, the exact same design for minimum LCOE and maximum NPV strategy has been chosen.

From tables, it is apparent that the battery storage and PEM electrolyzer have no profitable business in non of selected location. The reason is mainly because of the significantly high installation price of these kinds of technologies. In order to understand that in which price they can be a competitive alternative, a sensitivity analysis has been performed.

Denmark					
		min LCOE	max NPV		
	Unit	WT	WT	WT+BESS	WT+PEM
Rated power	MW	3	6	6	6
Rotor diameter	m	100	160	160	160
Hub height	m	150	150	150	150
Battery storage	MW	-	-	3	-
Battery capacity	MWh	-	-	3	-
Electrolyzer rated power	MW	-	-	-	3
AEP	GWh	10.59	24.58	24.58	24.58
Capacity factor	%	40.4	46.91%	46.91%	46.91%
Total Revenue	M€	4.36	10.1	10.3	11.55
Total expenditure	M€	2.28	7.6	8.4	9.7
NPV	M€	1.44	2.51	1.94	1.85
LCOE	€/MWh	25.84	28.96	29.46	36.96
Average electricity price	€/MWh	38.69			
IRR	%	13.00	12.00	10.81	10.31

Table 4.6: comparison of the wind turbine as it is designed today and designed for market objective in Denmark

Italy					
		min LCOE	max NPV		
	Unit	WT	WT	WT+BESS	WT+PEM
Rated power	MW	3	3	3	3
Rotor diameter	m	120	120	120	120
Hub height	m	150	150	150	150
Battery storage	MW	-	-	3	-
Battery capacity	MWh	-	-	3	-
Electrolyzer rated power	MW	-	-	-	3
AEP	GWh	6.24	6.24	6.24	6.24
Capacity factor	%	23.81	23.81	23.81	23.81
Total Revenue	M€	3.51	3.51	3.76	3.77
Total expenditure	M€	3.75	3.75	4.55	5.85
NPV	M€	-0.236	-0.236	-0.788	-2.08
LCOE	€/MWh	56.36	56.36	62.86	87.88
Average electricity price	€/MWh	52.35			
IRR	%	7.18	7.18	5.73	3.15

Table 4.7: comparison of the wind turbine as it is designed today and designed for market objective in Italy

Netherlands					
		min LCOE	max NPV		
	Unit	WT	WT	WT+BESS	WT+PEM
Rated power	MW	3	6	6	6
Rotor diameter	m	100	180	180	180
Hub height	m	150	150	150	150
Battery storage	MW	-	-	3	-
Battery capacity	MWh	-	-	3	-
Electrolyzer rated power	MW	-	-	-	3
AEP	GWh	11.7	30.02	30.02	30.02
Capacity factor	%	44.69	57.28	57.28	57.28
Total Revenue	M€	6.34	16.36	16.7	16.73
Total expenditure	M€	2.92	9.2	10	11.3
NPV	M€	3.42	7.16	6.70	5.42
LCOE	€/MWh	21.36	26.26	31.21	35.27
Average electricity price	€/MWh	52.52			
IRR	%	21.52	16.85	15.65	13.54

Table 4.8: comparison of the wind turbine as it is designed today and designed for market objective in the Netherlands

4.5 Sensitivity analysis

There are many driven which can do a better business for the battery storage. For example, an electricity market with considerable price fluctuation during optimization, an electricity market with a higher average of electricity price, the minimum cost of battery storage and capacity, etc., can be mentioned as practical elements in the BESS business. Among all driven, the BESS CAPEX is the one that can be minimized by technological development in this industry in the future to reach a competitive and profitable business.

4.5.1 A sensitivity analysis on BESS CAPEX

In this section, a sensitivity analysis only in the case of the Netherlands has been performed. The reason is mainly that, from a power production and market point of view, BESS has more opportunity to be a competitive technology. In addition, the process of reducing BESS CAPEX to find technical and economic parameters has needed considerable time for running the code and evaluating design parameters. It is notable that the same set of design parameters and fixed input data as considered in part of WT+BESS design have been chosen.

Netherlands							
Battery storage and capacity CAPEX reduction	%	0-40	50	60	70	80	90
Rated Power	MW	6	6	6	6	6	6
Rotor diameter	m	180	180	180	180	180	180
Hub height	m	150	150	150	150	150	150
Battery storage	MW	3	3	3	4	5	6
Battery capacity	MWh	3	6	9	12	20	42

Table 4.9: BESS CAPEX reduction effect on design of wind turbine + BESS

Table 4.9 present the effect of cost reduction of battery storage and capacity on the design of WT + BESS. It is mentionable that by reducing BESS CAPEX up to 40%, no change has been observed. Afterward, from 50% to 90%, it does not affect the design of the wind turbine, but battery storage and capacity gradually increased.

Although the maximum C_{rate}^{-1} could reach a 10-hour battery, in the case of 90% CAPEX reduction, surprisingly model chose a 7-hour battery. The reason is that a battery storage system needs a fluctuating market to be a practical option working in an HPP.

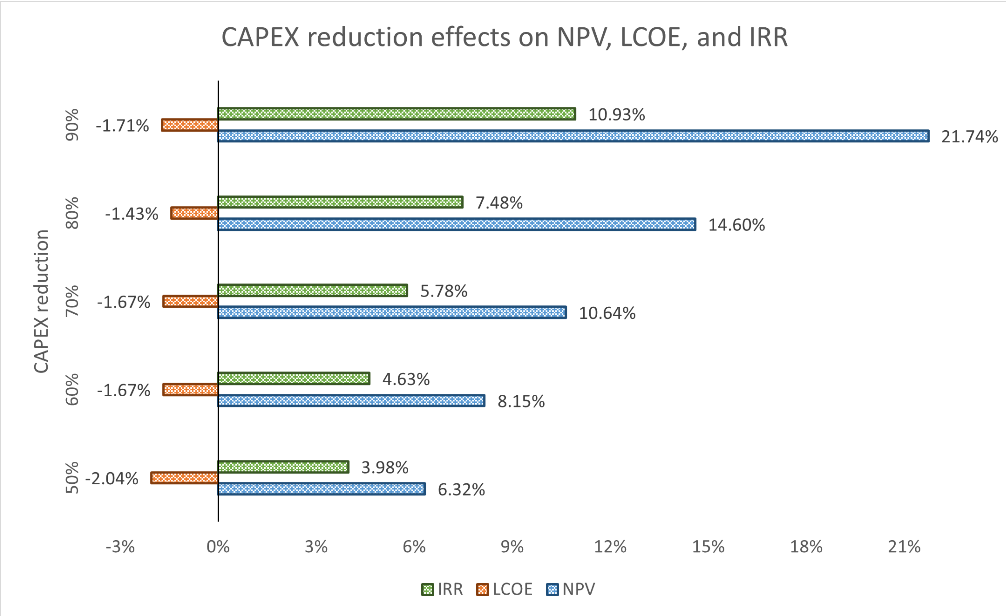


Figure 4.12: BESS CAPEX reduction effect on NPV,LCOE, and IRR

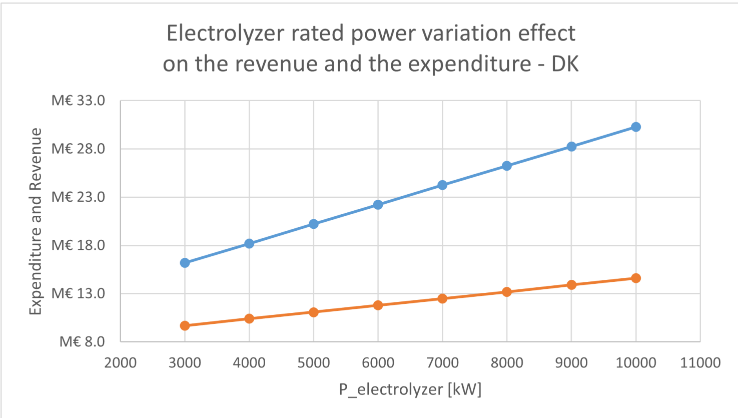
Graph 4.12 illustrates NPV, LCOE, and IRR change in percentage by reducing BESS CAPEX in the Netherlands. A detailed inspection in this figure reveals that, by reducing the BESS CAPEX by more than 60%, the NPV in the case of WT+BESS would be higher than a single WT. It is observable that by reducing the cost of battery storage from 50% to 90%, the LCOE is paradoxically increasing. It is mainly because the size of battery storage and capacity gradually increasing by reducing BESS CAPEX. As same as NPV and LCOE, IRR will be improved, and in maximum reduction, it can be 3% lower than the case of minimum LCOE.

4.5.2 A sensitivity analysis on WT+PEM electrolyzer

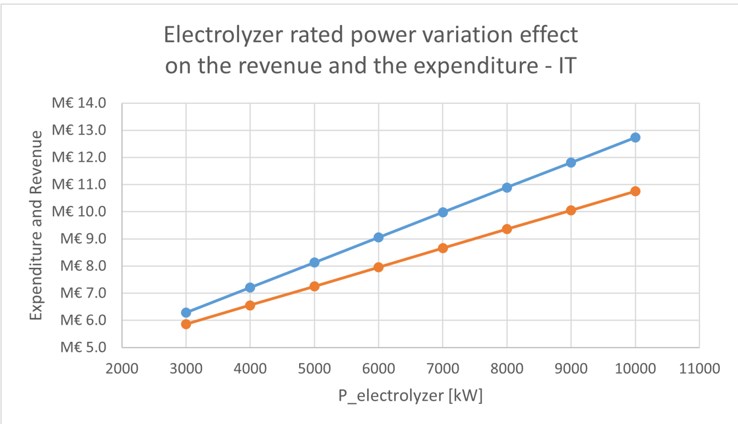
In order to have a profitable business for the PEM electrolyzer, it is possible to vary the assumption that has been made for the Hydrogen price and cost of the PEM electrolyzer.

sensitivity analysis on the Hydrogen price

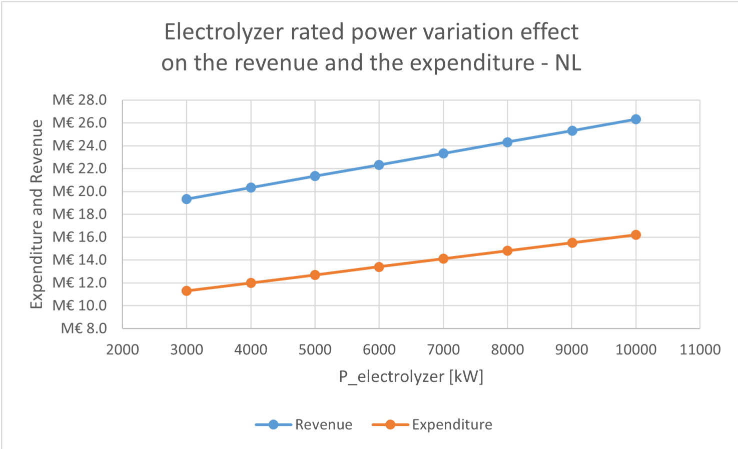
By changing the Hydrogen price up to 10 EUR/kgH_2, it does not affect the design of the wind turbine. However, by increasing the price from 2 to 3 EUR/kgH_2, the model chose the largest rated power for electrolyzer in order to produce Hydrogen. Figure 4.13 presents the influence of electrolyzer rated power variation on the revenue and expenditure. The main difference between this graph the Hydrogen price considered equal to 3 EUR/kgH_2 and in the graph 4.9 it was 2 EUR/kgH_2. What stands out in the figure is in all locations, by the size of the electrolyzer, the revenue experience higher growth. The reason is that a change of price from 2 to 3 EUR/kgH_2 is equal to a change from 40 EUR/MWh to 60 EUR/MWh. Consequently, the Hydrogen price would be higher than the average electricity price in all locations and result in a better business.



(a)



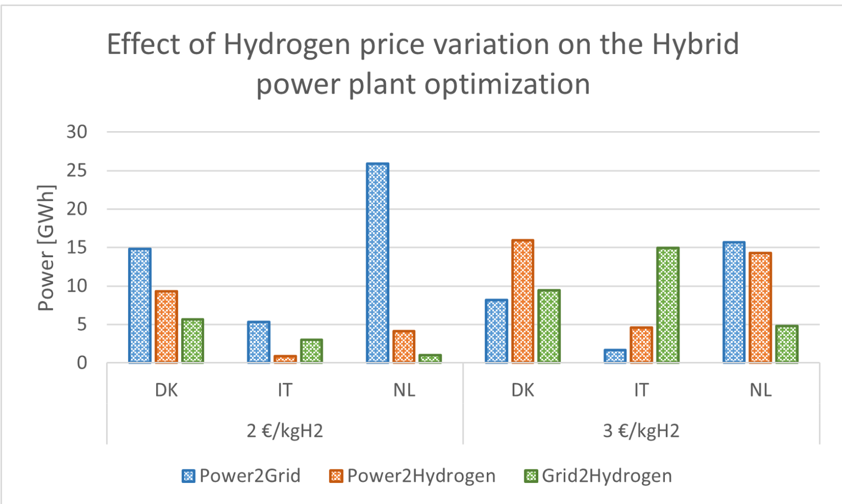
(b)



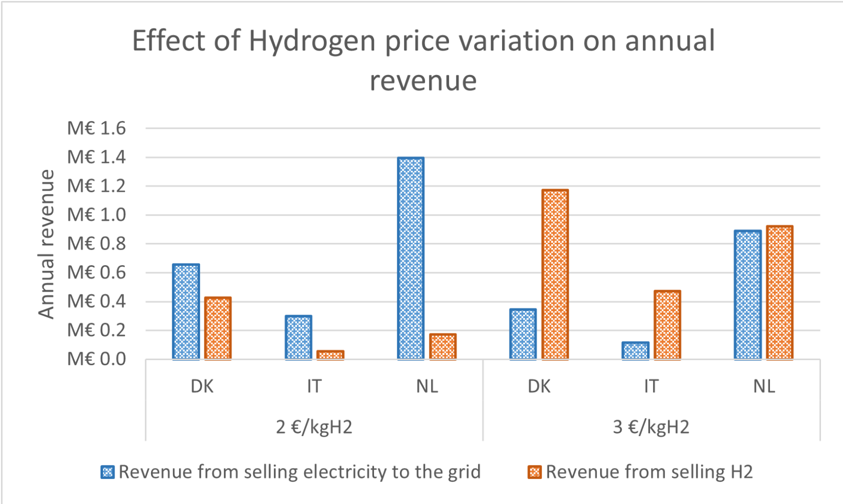
(c)

Figure 4.13: Effect of electrolyzer rated power variation on the revenue and the expenditure

Figure 4.14 present the effect of change in the Hydrogen price on power optimization and revenue earned by different markets. Graph 4.14a compare the variation of the power decision made in order to maximize the revenue in two different Hydrogen prices. By increasing the price share of power sent to the electrolyzer and consequently revenue produced by selling Hydrogen has been increased, see 4.14b. In the case of Italy, almost three times more than power produced by the wind turbine, power has been bought from the grid in order to generate Hydrogen. In the Netherlands, there is sufficient power produced from the wind turbine for both grid and Hydrogen production. Therefore there is an equal amount of revenue production from both markets.



(a) Annual power optimization for different Hydrogen price



(b) Annual share of earned revenue for different Hydrogen price

Figure 4.14: Wind turbine + PEM electrolyzer HPP annual share of power and revenue earned for different Hydrogen price

Finally, the sensitivity analysis on Hydrogen price depicts that, by changing 1 EUR/kgH_2, the design of the electrolyzer has been changed from lowest to highest rated power. In addition, The highest NPV in comparison to other scenarios (WT min LCOE, WT max NPV, and WT+BESS max NPV) have been obtainable. Table 4.10 shows the NPV, LCOE, and IRR briefly in selected locations after increasing the Hydrogen price. It is shockingly interesting that the NPV in Denmark becomes a higher value in comparison to the Netherlands. Additionally, in the best scenario, the NPV in Denmark reached 2.5 M€, but by increasing the Hydrogen price, it turned to the highest NPV among all scenarios in all locations that have been analyzed so far in this study.

Economic indicators	Unit	Denmark	Italy	Netherlands
NPV	M€	15.68	1.98	10.11
LCOE	€/MWh	55.63	161.43	50.56
IRR	%	19.66	10.15	14.98

Table 4.10: Best design economic indicators in selected locations

sensitivity analysis on CAPEX

The same analogy as the previous section has been implemented in order to perform a sensitivity analysis on PEM electrolyzer CAPEX. Similarly, the reduction in the

CAPEX does not affect the design of the wind turbine. Figure 4.15 shows that by reducing the cost of electrolyzer, the NPV increased in all locations as is predicted. In addition, it is highlighted in the graph as a point, the design of the electrolyzer has been changed from the lowest to the highest amount of rated power in each location. Since the Hydrogen price is low in Italy and the Netherlands, it needs more reduction in the cost of electrolyzer to be a profitable business.

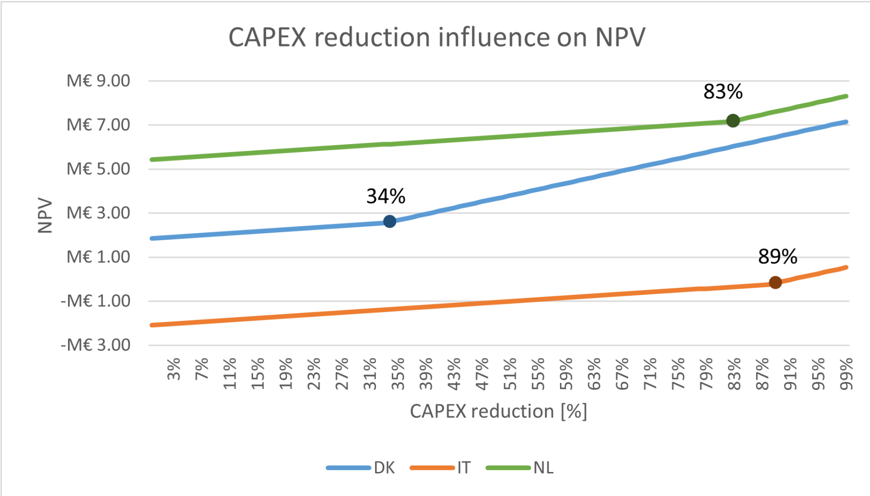


Figure 4.15: PEM electrolyzer cost reduction effect on NPV

Chapter 5

Conclusion

The purpose of the current study was to design a wind turbine in order to be utilized in a hybrid power plant by maximizing NPV as an objective function. However, the design of the wind turbine by lowering the cost (as it is today a common strategy to design) seems a safe and secure solution for companies in the wind turbine industry, but looking toward a more ambitious and profitable design strategy is essential for the near future of the wind turbine market. Accordingly, The results of this research support the maximized NPV strategy as a primary solution for future wind turbines. For example, in the case of the Netherlands, by changing the strategy from design a wind turbine with the minimum LCOE to maximum NPV, the profit would be more than doubled (an increase from3.42 M€ to 7.16 M€). Although the IRR decreased around 4% in the Netherlands by strategy variation, the economic stability in this location could reduce the risk of money worth alteration.

In addition, in order to find optimal design parameters suits to each electricity market, a design procedure for the wind turbine has been proposed. A trustworthy strategy for the future wind turbine is to go toward a higher hub height. The finding of this study illustrates that in all selected locations with a different strategy and design configuration, a hub height equal to 150m, which was the maximum value in the design set, has been chosen. However, finding the best-rated power and rotor diameter is more location-dependent.

The research has also shown that the BESS needs a cost reduction of more than 50% than the price predicted for 2030 to be a competitive solution. However, in the case of Denmark and the Netherlands, the NPV generated by WT+BESS is considerably higher than the NPV generated by today's wind turbine.

Additionally, the study depicts that the PEM electrolyzer is not a profitable solution by considering projected cost in 2025 and a Hydrogen price equal to 2 €/kgH2. By increasing 1 €/kgH2 to the Hydrogen price, the result would be a significantly profitable market for almost all locations. For example, in the case of Denmark, the NPV has been grown around 15 M€.

Returning to the question posed at the beginning of this study, it is now possible to state that the size and cost of the battery and PEM electrolyzer do not affect the wind turbine design. However, by changing the methodology from minimum LCOE to maximum NPV, the design of the wind turbine would be different. Finally, the maximized NPV methodology is a reliable path for future wind turbines.

Bibliography

[1] URL: https://www.nordpoolgroup.com/Market-data1/Regulating-Power1/Regulating-Prices1/DK-1/Denmark/?view=table.

[2] URL: https://mercatoelettrico.org/it/Mercati/MercatoElettrico/MPE.aspx.

[3] URL: https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-energy-storage.

[4] International Energy Agency. *Energy Storage: Tracking Clean Energy Progress*. Tech. rep. 2018.

[5] Aisma Vītiņa Alberto Dalla Riva János Hethey. *IEA Wind TCP Task 26 on the System Value of Wind in Europe*. Tech. rep. 2017.

[6] European Court of Auditors. *Electricity production from wind and solar photovoltaic power in the EU Background paper*. Tech. rep. 2018.

[7] Albert Betz. *Wind-Energie und ihre ausnutzung durch Windmühlen*. Göttingen, Vandenhoeck, 1926.

[8] Pietro Bortolotti et al. *IEA Wind TCP Task 37: Systems Engineering in Wind Energy-WP2.1 Reference Wind Turbines*. English. National Renewable Energy Laboratory (NREL), 2019. DOI: 10.2172/1529216.

[9] Stephen Carr et al. "Optimal operation of a hydrogen refuelling station combined with wind power in the electricity market". In: *International Journal of Hydrogen Energy* 41.46 (2016), pp. 21057–21066. DOI: 10.1016/j.ijhydene.2016.09.073. URL: http://dx.doi.org/10.1016/j.ijhydene.2016.09.073.

[10] Kaushik Das et al. "Enhanced Features of Wind-Based Hybrid Power Plants". In: *4th International Hybrid Power Systems Workshop* May (2019).

[11] Kaushik Das et al. "Optimal battery operation for revenue maximization of wind-storage hybrid power plant". In: *Electric Power Systems Research* 189 (2020). DOI: 10.1016/j.epsr.2020.106631. URL: https://doi.org/10.1016/j.epsr.2020.106631.

[12] Francisco Díaz-González et al. "A review of energy storage technologies for wind power applications". In: *Renewable and Sustainable Energy Reviews* 16.4 (2012), pp. 2154–2171. DOI: 10.1016/j.rser.2012.01.029. URL: http://dx.doi.org/10.1016/j.rser.2012.01.029.

[13] L Fingersh, M Hand, and A Laxson. *Wind Turbine Design Cost and Scaling Model*. Tech. rep. 2006, pp. 1–43.

[14] Tingting Hou et al. "Charge-discharge strategy for battery energy storage to smooth power fluctuations from wind farms". In: *China International Conference on Electricity Distribution, CICED* (2016), pp. 10–13. DOI: 10.1109/CICED.2016.7576001.

[15] IEA et al. *Tracking SDG 7: The Energy Progress Report*. Tech. rep. 2020. URL: https://trackingsdg7.esmap.org/.

[16] IRENA. *Future of Wind: Deployment, investment, technology, grid integration and socio-economic aspects*. Tech. rep. 2019, pp. 1–88. URL: www.irena.org/publications.

[17] IRENA. *Global Renewables Outlook: Energy transformation 2050*. Tech. rep. 2020.

[18] IRENA. *Hydrogen From Renewable Power: Technology outlook for the energy transition*. Tech. rep. September. 2018, pp. 1–52. URL: www.irena.org.

[19] IRENA. *Utility-Scale Batteries*. Tech. rep. 2019.

[20] Jonas Kazda. "Multi-objective Wind Farm Control". English. PhD thesis. Denmark, 2019. DOI: 10.11581/dtu:00000044.

[21] Matti Juhani Koivisto et al. "Using time series simulation tool for assessing the effects of variable renewable energy generation on power and energy systems". In: *Wiley Interdisciplinary Reviews: Energy and Environment* 8.3 (2019). ISSN: 2041-8396. DOI: 10.1002/wene.329.

[22] A. Laxson L. Fingersh M. Hand. "Wind turbine design cost and scaling model". In: (2005).

[23] H. Aa Madsen et al. “Initial performance and load analysis of the LowWind turbine in comparison with a conventional turbine”. In: *Journal of Physics: Conference Series* 1618 (2020). DOI: 10.1088/1742-6596/1618/3/032011.

[24] Helge Madsen et al. “The LowWind turbine concept for optimal system integration”. In: (July 2019). DOI: 10.13140/RG.2.2.15478.65604.

[25] D J Malcolm and A C Hansen. “WindPACT Turbine Rotor Design Study: June 2000–June 2002 (Revised)”. In: (Apr. 2006). DOI: 10.2172/15000964. URL: https://www.osti.gov/biblio/15000964.

[26] Jeffrey Plew Mark Ahlstrom Andrew Gelston and Lorenzo Kristov. “Hybrid Power Plants-Flexible Resources to Simplify Markets and Support Grid Operations”. In: (2019), pp. 1–12.

[27] S U B Mis. *14th wind Integration workshop*. Tech. rep. October. 2018.

[28] Christopher Moné et al. *2015 Cost of Wind Energy. Review NREL/TP-6A20-66861*. Tech. rep. May. 2017.

[29] CA-OWEE. *Offshore Wind Energy Ready to Power a Sustainable Europe*. Tech. rep. December. 2001, p. 289. URL: http://www.emu-consult.dk/includes/totalfinalreport.pdf.

[30] R.K. Pachauri, L.A. Meyer, and Core Writing Team. *Climate Change 2014, Synthesis Report Summary Chapter for Policymakers*. Tech. rep. 2014.

[31] Pérez, Ashley Santamaria, and E. Karina Operario. *Renewable Hybrid Power Plants*. Tech. rep. 2019.

[32] Lennart Petersen et al. “Vestas Power Plant Solutions Integrating Wind, Solar PV and Energy Storage”. In: *3rd International Hybrid Power Systems Workshop* May (2018), pp. 2–9.

[33] Daniel Vazquez Pombo. “Coordinated Frequency and Active Power Control of Hybrid Power Plants”. PhD thesis. 2018.

[34] Andrey V. Savkin, Muhammad Khalid, and Vassilios G. Agelidis. “Optimal size of battery energy storage and monotonic charging/discharging strategies for wind farms”. In: *2014 IEEE Conference on Control Applications, CCA 2014* (2014), pp. 1372–1376. DOI: 10.1109/CCA.2014.6981515.

[35] E. Sesto and N. H. Lipman. *Wind energy in Europe*. Tech. rep. 2019.

[36] Kevin Smith. *WindPACT Turbine Design Scaling Studies Technical Area 2: Turbine, Rotor, and Blade Logistics*. Tech. rep. June. 2001. URL: http://nrel.gov/docs/fy01osti/29439.pdf.

[37] NREL WISDEM Team. *WISDEM*. URL: https://github.com/WISDEM/WISDEM.

[38] NREL WISDEM Team. *WISDEM Documentation*. Tech. rep. 2020.

[39] NREL WISDEM Team. *WISDEM Documentation*. URL: https://wisdem.readthedocs.io/en/master/index.html#.

[40] U.S. Department of Energy. *2018 Wind Technologies Market Report*. Tech. rep. June. 2018, pp. 1–98. URL: http://www.windpoweringamerica.gov/pdfs/2010%7B%5C_%7Dannual%7B%5C_%7Dwind%7B%5C_%7Dmarket%7B%5C_%7Dreport.pdf.

[41] Paul Veers et al. "Grand challenges in the science of wind energy". In: (2019). DOI: 10.1126/science.aau2027.