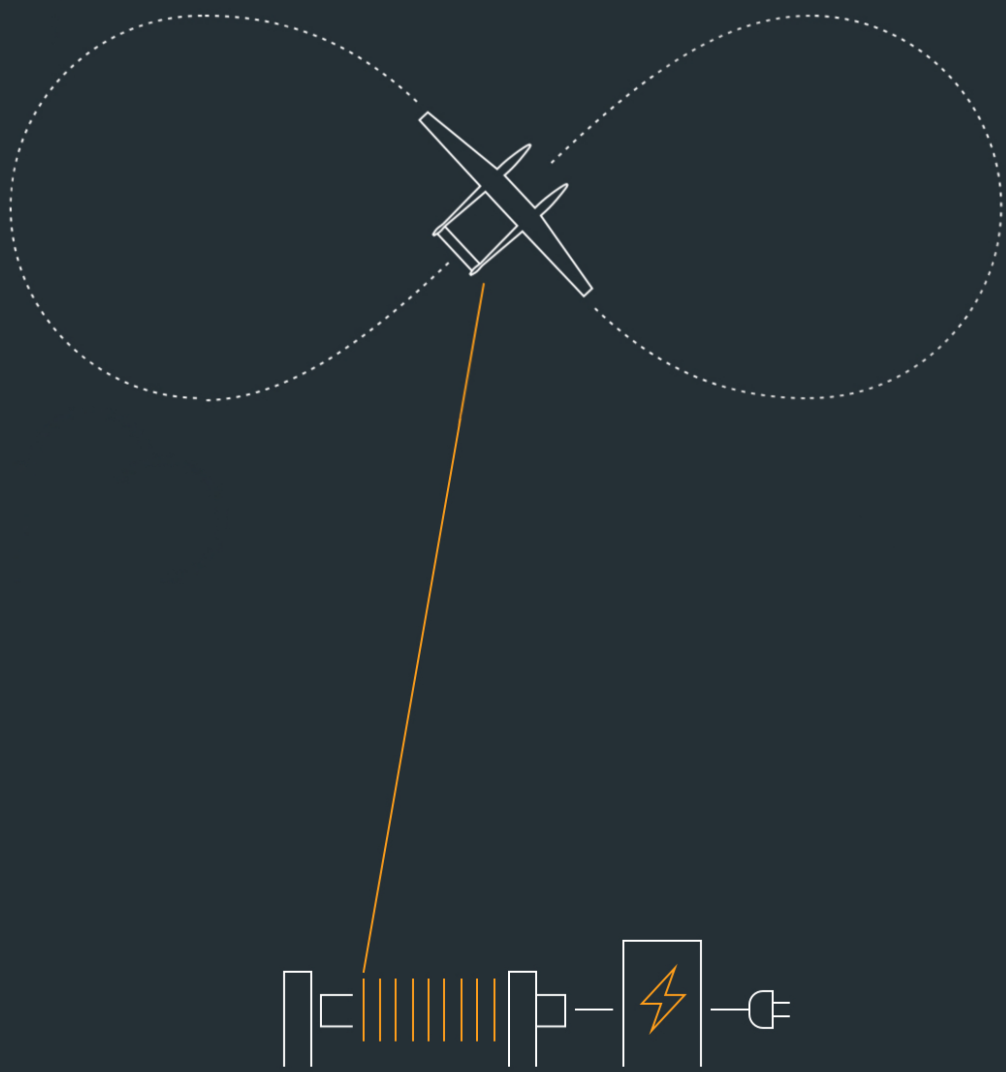
Influence of the European Electricity Market on the System Design of Airborne Wind Energy

A method to quantify the merit order effect of wind power on the revenue generation of the systems

Rishikesh Joshi



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Cover image: Ampyx Power B.V.

Delft University of Technology

Influence of the European Electricity Market on the System Design of Airborne Wind Energy

A method to quantify the merit order effect of wind power on the revenue generation of the systems

by

Rishikesh Joshi

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Thesis committee

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"The greatest threat to our planet is the belief that someone else will save it"

- Robert Swan

Preface

This report marks the culmination of my masters degree in Sustainable Energy Technology from TU Delft. Looking back, I can confidently say that the last two years have made a significant positive impact on my professional as well as personal development. I was introduced to airborne wind energy through one of the university courses in my first year and was immediately intrigued by the concept. I was able to acquire an internship at Ampyx Power B.V, one of the leading companies involved in developing the technology. This internship became a stepping stone for my master thesis. At the end of my internship, we were able to formulate a research topic which was an intersection of the research opportunities at the company and my area of interest. I am happy to publish this work which is a collaborative effort of the company, my supervisors and myself.

I would like to thank Ir. Yannan Zhang, data & BI analyst at Ampyx Power, for her guidance throughout my thesis. I would like to thank Dr. Michiel Kruijff, the CTO of Ampyx Power and Dr.-Ing Roland Schmehl, an associate professor at TU Delft for supervising over my thesis. Their insights and valuable feedback helped me shape my research. I would like to thank my colleagues at Ampyx Power for being so welcoming and friendly since the day I started. I enjoyed the interesting conversations we had at the coffee machine and as well as during the lunch hours. Kudos to the team for working on such a radical innovation.

I would like to thank Dr. Michiel Zaayer, Dr. Dominic von Terzi and Ir. Mihir Mehta of the wind energy group of TU Delft for their valuable insights which helped me steer my thesis in the right direction.

I would like to thank all my friends in Delft and especially my housemates without whom my life in Delft would certainly have been difficult. I am grateful for all the fun and the intellectual conversations that we had. I would also like to thank my friends from India with whom I share a special bond despite being so far away. Special thanks to Vaishnavi for constantly supporting me and always being there for me.

Finally, but most importantly, I would like to thank my mother, Mugdha Joshi and my father, Shirish Joshi for always believing in me and motivating me to pursue my dreams. These two years would have been impossible without their emotional and financial support. I cannot thank them enough for everything that they have done for me.

Rishikesh Joshi
Delft, September 2020

Abstract

Airborne wind energy (AWE) is a new generation of wind energy technology which uses tethered kites to reach the stronger and steadier high altitude wind resource. Research and development of AWE has been accelerated in the last two decades. Around 40 institutions around the world are working on their own concepts and architectures of the technology. This research has been collaborated with Ampyx Power B.V, a Dutch company involved in development of one of the concepts of AWE. No company has yet been able to prove the commercial viability of their technology. A successful market diffusion is possible when there is a perfect product-market fit i.e. the technology development should be aligned with the market requirements. Economies of scale and maturing of technology is continuously reducing the cost of utility scale variable renewable energy sources (VRES) like wind and solar PV. Anticipating a subsidy free future, utility scale VRES will be dependent on the day-ahead electricity market (DAM) for their revenue generation. The electricity prices from the market are dynamic and are dependent on the supply and demand characteristics of the country. Higher influx of VRES in the grid depress the DAM prices, this effect is known as the merit-order effect of VRES. Therefore, the value of electricity depends on the time at which it is produced. This indicates to investigate if there is a need to shift from cost driven system design to value driven system design for VRES.

Energy production and revenue generation of AWE at a certain time, depends on the wind speed and the energy price at that particular time. A data driven statistical model has been developed in MATLAB environment to identify and quantify the merit order effect of wind power by estimating the correlation of DAM prices and wind speeds. A decision support tool for the system design of AWE is developed by integrating the correlation model with a revenue model and the existing cost model of Ampyx Power. Correlation model results for different locations in Europe confirms that there exists a negative correlation between the DAM prices and wind speeds. Among the tested locations, the German DAM prices drop by around 1.2€/MWh, the Danish by around 0.9€/MWh and the Dutch by around 0.6€/MWh per 1m/s increase in wind speed. Different locations in different European markets have different strengths of the correlation depending on their wind climate and their energy mix. A case study based on three different locations in Germany has been analyzed using the developed tool to understand the influence of the merit order effect on the system design of AWE. The results show that in a DAM based revenue generation scenario, value driven optimization leads to a different system configuration than cost driven optimization. It leads to systems which perform better at lower wind speeds.

Keywords: Airborne wind energy (AWE), variable renewable energy sources (VRES), merit-order effect, day-ahead market (DAM), wind speeds, correlation, revenue, cost, system design.

Contents

Nomenclature

Abbreviations

AEP	Annual energy production
AP-0	Ampyx Power's 0^{th} gen prototype: Proof of principle for positive power generation
AP-1	Ampyx Power's 1^{st} gen prototype: Proof of principle for autonomous power generation
AP-2	Ampyx Power's 2^{nd} gen prototype: Algorithm test bed for future prototypes
AP-3	Ampyx Power's 3^{rd} gen prototype: Safety and autonomy demonstrator
AP-4	Ampyx Power's 4^{th} gen prototype: First commercial demonstrator
AWE	Airborne wind energy
AWES	Airborne wind energy systems
AWESCO	Airborne wind energy system modelling, control and optimisation
BoP	Balance of plant
BRP	Balance responsible party
CAPex	Capital expenditure
CDS	Climate data store
CfD	Contract for difference
DAM	Day-ahead market
DCF	Discounted cash flow
DEVex	Development expenditure
ECMWF	European centre for medium-range weather forecasts
ECN	Energy research center of the Netherlands
EEZ	Exclusive economic zone
ENTSOE-E	European network of transmission system operators for electricity
EPEX	European power exchange
FGAWES	Fly generation airborne wind energy systems
FIP	Feed-in-premium
FIT	Feed-in-tariff
GGAWES	Ground generation airborne wind energy systems
IRENA	International renewable energy agency
LCoE	Levelised cost of energy
LLA	Launch and land apparatus

LRoE	Levelized revenue of energy
MCP	Market clearing price
MCV	Market clearing volume
MV	Market value
MW	Mega watt
MWh	Mega watt hours
NaN	Not a number
NPV	Net present value
OLS	Ordinary least squares
OPex	Operational expenditure
OTC	Over-the-counter
PGA	Power generation apparatus
PKGS	Pumping kite generating systems
PMC	Product/Market combinations
PPA	Power purchase agreements
RES	Renewable energy sources
RPA	Remotely piloted aircraft
SSE	Sum of squared error
TNO	Netherlands organisation for applied scientific research
TSO	Transmission system operator
TT	Tether tension
VF	Value factor
VRES	Variable renewable energy sources
WA	Wing area
WACC	Weighted average cost of capital

Greek symbols

α	Y intercept of the fit line in regression analysis
β	Slope of the fit line in regression analysis
ϵ_i	Error for the i^{th} estimation in regression analysis
$\hat{\alpha}$	Y intercept of the best fit line in regression analysis
$\hat{\beta}$	Slope of the best fit line in regression analysis
μ	Mean
σ	Standard Deviation
$\sum$	Summation

Latin symbols

$cov(X,Y)$	Covariance of random variables X and Y
E	Energy produced
$f(u)$	Probability of wind speeds
H_a	Alternate hypothesis
H_o	Null hypothesis
N	Sample size of random variable
P	P-value in statistical significance testing
p	Energy price
$P(u)$	Power function of a system as a function of wind speeds
$p(u)$	Energy price as a function of wind speeds
R	Pearson correlation coefficient
r	Discount rate
T	Economic lifetime of project
t	Time instant
$var(X)$	Variance of random variable X
$var(Y)$	Variance of random variable Y
X	Random variable
X_i	i^{th} datapoint of variable X
X_m	Mean of variable X
Y	Random variable
Y_i	i^{th} datapoint of variable Y
Y_m	Mean of variable Y

List of Tables

List of Figures

1

INTRODUCTION

1.1. BACKGROUND

The history of wind power development has shown continuous increase in the wind turbine height and the size of blades essentially to unlock the stronger and steadier wind resource present at higher altitudes. The average height of conventional wind turbines has been steadily increasing from around 70 meters at the start of the 21st century to around 130 meters in 2019. The mass of the tower and the foundation also increases significantly with an increase in the hub height of a wind turbine. Over the past few years, the hub height of wind turbines has been stabilizing, indicating that a further increase in the height of wind turbines will require additional technology innovations and significant cost reductions [12–14].

Airborne wind energy (AWE) is potentially a game-changing concept of wind energy technology which is able to tap the currently inaccessible high altitude wind resource. Airborne wind energy systems (AWES) are mainly made of three components, a kite, a tether and a ground station. A kite (sometimes also referred as an aircraft or a wing) is mechanically connected to a ground station with the help of a tether (sometimes also referred as a rope) [3]. Figure 1.1 shows the analogy between the conventional wind turbines and the AWES followed by the main advantages and challenges recognized by the AWE industry compared to wind turbines.

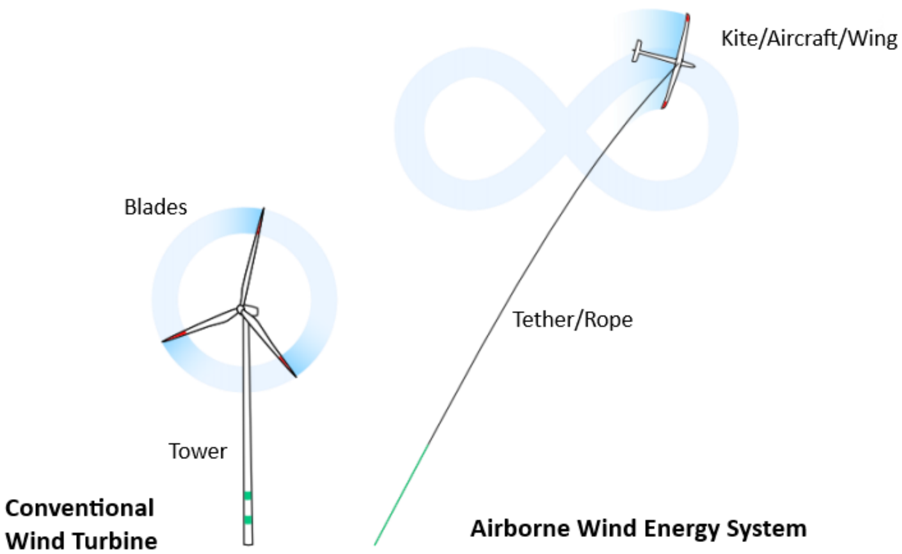


Figure 1.1: Analogy of AWES with conventional wind turbines [2]

ADVANTAGES OF AWES OVER CONVENTIONAL WIND TURBINES

1. AWES have higher and adjustable operating altitude which leads to higher utilization factors.
2. Low wind speed locations which may not be suitable for conventional wind turbines can potentially be suitable to AWES.
3. Overall lesser material and small foundation leads to lower capital costs and lesser carbon emissions for similar sized systems. Comparatively more suitable for far-offshore floating installations.
4. Higher mobility due to lesser material makes it suitable for off-grid, remote locations which are difficult to reach.

CHALLENGES FACED BY THE TECHNOLOGY DEVELOPERS

1. Requires cutting-edge control systems and high performance materials (i.e high strength low cost) for components like the kite and the tether.
2. Different regulatory barriers exist which are not yet clear to the technology developers.
3. Convergence in terms of concepts and technology choices is not yet seen in the AWE community, making it difficult for the development of a supply chain for the industry.
4. Measured or modelled wind data to estimate the energy production at higher altitudes is limited.

ORIGIN OF AWE AS AN ENGINEERING BRANCH

In 1980, Miles L. Loyd [15], an American engineer working at Lawrence Livermore National Laboratory, published the fundamentals of crosswind kite power which today is comprehensively known as AWE. In crosswind flight, the motion of the tethered kite is approximately perpendicular to the direction of the wind. This is analogous to the motion of conventional wind turbine blades moving perpendicular to the direction of wind. He was the first to mathematically model and publish the fundamental concepts of AWE. In his paper on crosswind kite power, he compared the pulling power of the kite that is moving in a single direction, with the pulling power of a kite that is performing crosswind patterns. He proved that crosswind kites harness more energy than kites flying in a single direction.

The work of Miles Loyd inspired many engineers and scientist within the last decade of the 20^{th} century to explore crosswind kite power which eventually led to the foundation of the AWE community existing today. The AWE community is small as compared to the conventional wind industry but is growing continuously. First decade of the 21^{st} century saw a worldwide accelerating growth in the number of institutions and companies involved in research and development of AWE [3].

Two of the highly researched concepts till date are the ones first described by Miles Loyd in 1980, shown in Figure 1.2. Both these concepts differ on the basis of the method of electricity generation, but both of the concepts are based on the same crosswind flight operation.

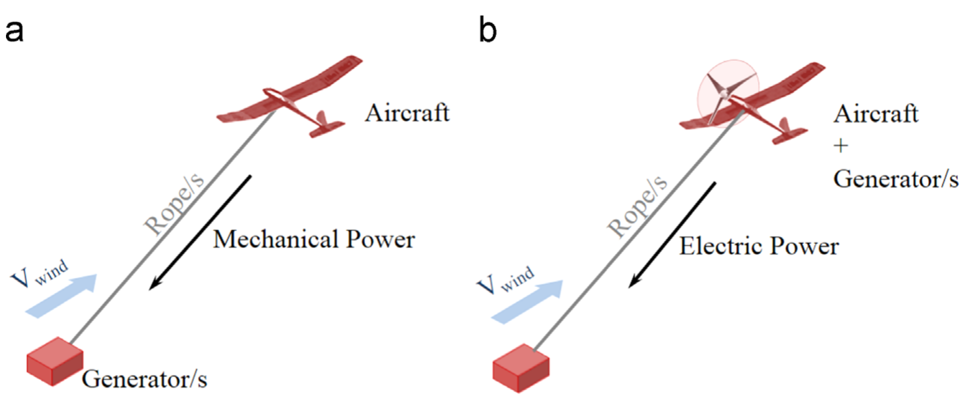


Figure 1.2: AWE concepts described by Miles Loyd in his paper about crosswind kite power in 1980 [3]

(a) Ground generation airborne wind energy system (GGAWES): In this concept of AWE, a tethered kite performs crosswind flight patterns while unwinding from a ground stationed winch. The mechanical power produced due to the rotating winch during the unwinding phase is converted into electrical power by coupling the winch to a electric generator. After the tether has reached its limit during unwinding, the kite glides back to its original position and this cycle continues. Due to these reel-out and reel-in phases, they are also known as the pumping kite generation system (PKGS).

(b) Fly generation airborne wind energy system (FGAWES): In this concept of AWE, a tethered kite moving crosswind has on-board electric generator(s) which directly convert(s) the aerodynamic energy to mechanical energy and consequently into electrical energy. This energy is then transported to the ground via a conductive tether. This type of a system does not have reel-out and reel-in phases and hence gives a comparatively stable power output than the PKGS.

Figure 1.3, shows the currently pursued concepts of AWES by different companies around the world. The different concepts of AWE are primarily categorized based on the method of electricity generation and further, based on the nature of the flight operation. This information has been compiled by Dr. Roland Schmehl and published under the doctoral training network AWESCO (Airborne wind energy system modelling, control and optimisation) [16].

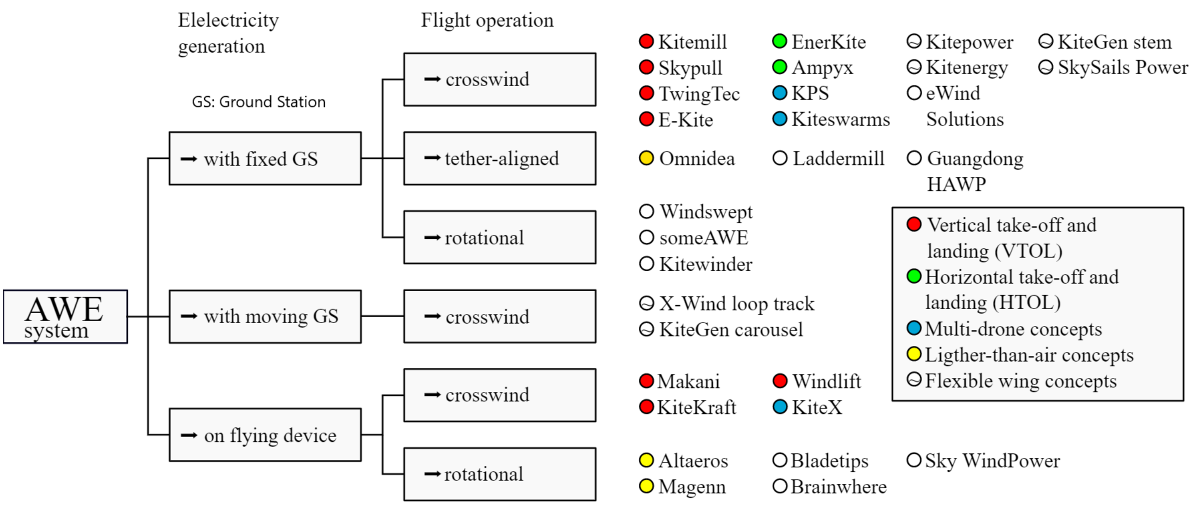


Figure 1.3: Classification of AWE concepts and the respective companies involved in their development till date [4]

At the end of the last decade of the 20th century, Dr. Wubbo Ockels, a TU Delft professor, worked on a concept based on a cable loop, which was driven by kites attached at regular intervals. The mechanical net pulling power in the loop was to be converted into electricity on the ground. His work lead to the establishment of a research group at TU Delft in 2004 and led to the foundation of two pioneering companies, Ampyx Power (2008) [5] and Kitepower (2016) [4, 17]. Both of the companies are working on the GGAWES concept with crosswind flight operation, but, Ampyx Power's technology consists of a rigid wing aircraft whereas Kitepower's technology consists of soft wing kite.

This research is carried in collaboration with Ampyx Power B.V. Following section gives information about the company and its developments relevant to this research.

ABOUT THE RESEARCH PARTNER

Ampyx Power B.V is a TU Delft spin-off and was founded in 2008. It is based in The Hague, Netherlands with a subsidiary in Australia. Ampyx Power's technology is based on the concept of GGAWES. The company is currently developing their third generation of prototype known as the AP-3, which will demonstrate safety and autonomy. Their fourth generation of AWES known as the AP-4 will be optimized for cost and is proposed to be their first product for market entry [5].

THE TECHNOLOGY

A schematic of the Ampyx Power technology is shown in Figure 1.4. "A tethered wing is connected to a generator on the ground. It flies crosswind in repetitive patterns, pulling the tether that drives the generator. After this reel-out phase during which electricity is generated, the wing glides back towards the generator and the process is repeated. The aircraft launches and lands automatically from a platform" [5].

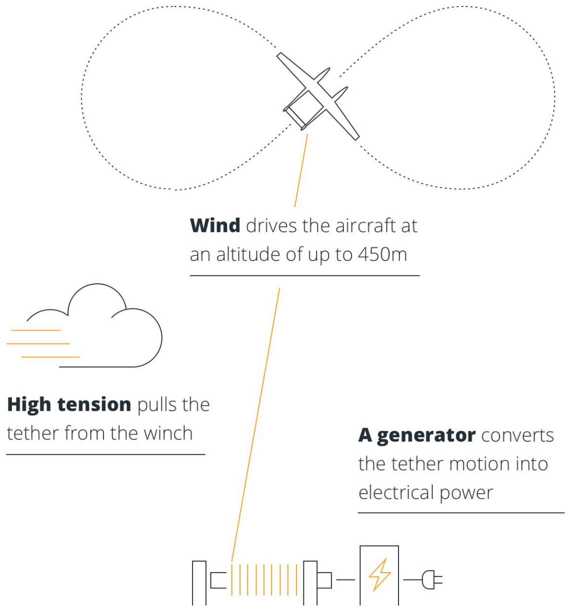


Figure 1.4: Technology schematic of Ampyx Power technology (Rigid wing aircraft with crosswind flight operation and ground based electricity generation) [5]

GENERATIONS OF PROTOTYPES

Figure 1.5 shows the aircraft generations from 2009 till present. Each generation of prototype is developed with a particular purpose. Neither of the currently developed prototypes have been optimized for cost.

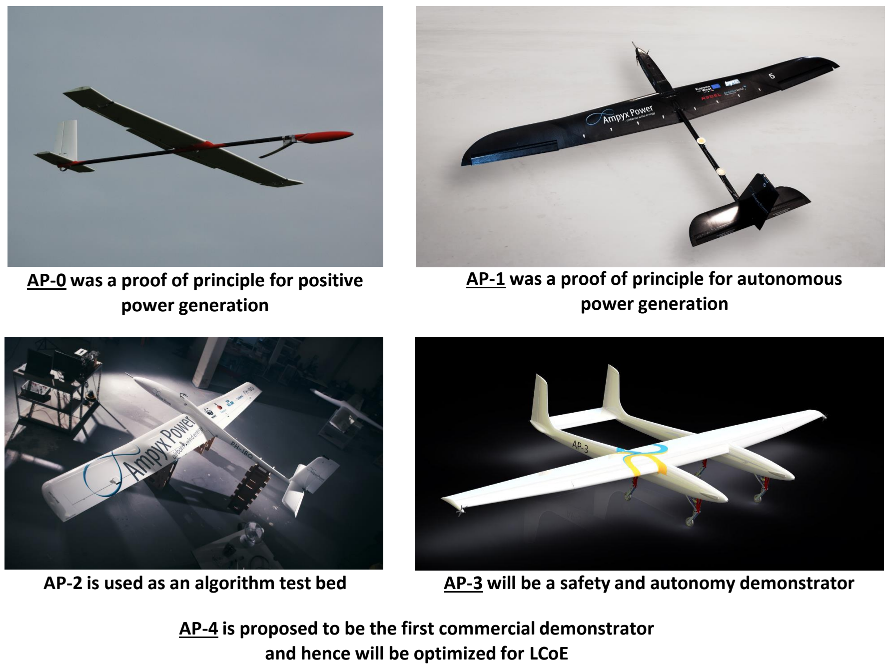


Figure 1.5: Ampyx Power prototype generations (2009 - present)

Development of AP-0 to AP-3 have proved to be vital learning steps for the company in terms of developing their technology. AP-0 and AP-1 were developed to demonstrate the proof of principle for positive power generation and autonomous power generation respectively. AP-2 was developed upon the knowledge and the experience gained from AP-0 and AP-1. The objective of developing AP-2 was to use it as a test bed to test the flight control algorithms which are currently being developed for the pre-commercial demonstrator (AP-3) and the commercial demonstrator (AP-4). Currently, AP-2 is successfully being used to test the flight control algorithms at a test facility developed by the company in Kraggenburg, Netherlands.

AP-3 is an aircraft with a wing area of $12\mathrm{m}^2$ and is capable of generating 150kW electrical power. It is the pre-commercial demonstrator, which is mainly developed to demonstrate safety and autonomy of the company's technology. It is currently been manufactured at the company's main facility in the Hague, Netherlands. Low wind speed tests are planned to begin at the end of 2020 at a facility which is currently being developed at Breda, Netherlands. High wind speed tests and autonomous power generation along with power grid integration will be demonstrated at a test site which is currently being developed in collaboration with RWE Renewables (an international, private energy supplier based in Essen, Germany) in Ireland.

AP-4 is planned to be a mega-watt rated system and will be the first commercial demonstrator of the company. De-risking activities for the AP-4 project have already began and the company will soon enter a transition phase of transferring majority of its resources from AP-3 project to the AP-4 project [18].

Most of the current studies related to the AP-4 project are in the sphere of understanding the level 0 requirements of the AP-4, this particular study being one of them. Motivation and aim of this research is discussed in the following section.

1.2. MOTIVATION AND AIM

Ampyx Power and almost all other companies involved in developing their concepts of AWE are more or less in the 'valley of death' phase of their lifetime. 'Valley of death' refers to the period in the life of a startup in which it is operational but not generating any revenue [19]. Research and development of AWE has been accelerating since the last decade, but no company or an institution has yet been able to demonstrate commercial viability.

The road to market is long and is uncertain. A successful market entry is possible when there is a product-market fit. Product-market fit is an intersection of 'what the product can deliver?' and 'what does the market offer?'. The first part refers to the bottom-up aspect i.e. technology development and the latter refers to the top-down aspect i.e. understanding the market and its drivers. Bottom-up approach in developing the product refers to cost driven decision making which is entirely dependent on the product and top-down approach in developing the product refers to value driven decision making which is dependent on the market in which the product is introduced.

For a successful market entry of AWE, the technology development should be aligned with the market requirements. There is a need to develop a framework which captures the cost driven and as well as the value driven aspects to assist in the system design of utility scale AWE. This need, forms the motivation of this research.

The aim of this research is to assess the influence of the European electricity market on the system design of utility scale AWE. Detailed problem analysis leading to the formulation of a research question and the approach is carried out after performing the literature review. The required background for this research has two aspects - understanding the European electricity market and understanding the economics of AWE. Therefore, the literature review is carried out in these two spheres.

The focus of this study is entirely on the utility scale electricity market in Europe. Utility scale refers to the systems which are directly connected to the nation's transmission system (national grid). Remote area markets such as micro-grids/hybrid applications and other small scale private markets do not form the scope of this study.

1.3. METHODOLOGY AND OUTLINE

Figure 1.6 shows the adopted methodology for this research followed by the thesis outline. Research area and the scope has been defined in Section 1.2 .

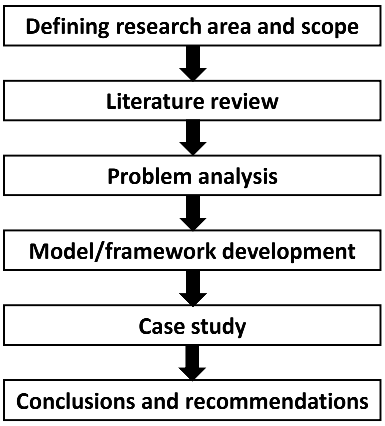


Figure 1.6: Research methodology

THESIS OUTLINE

- **Chapter 2** is the 'Literature review'. It documents the background knowledge required for this research, identifies the gaps in the current research and presents the detailed problem analysis.
- **Chapter 3** is about the framework of the developed tool to answer the research question
- **Chapter 4** is about the application of the developed tool to answer the research question. It presents a case study and its results.
- **Chapter 5** is 'Conclusions and recommendations'. It discusses the overall conclusions, reflections and provides some future work recommendations from the research.

2

Literature Review

A thematic structure for writing the literature review was chosen considering the multidimensional nature of this research. The aim of this literature review was threefold:

1. To explore and summarize the background knowledge required for this research.
2. To critically evaluate and identify the areas not covered by the present research.
3. To formulate the research question and the approach to answer the research question.

As indicated in the motivation section, section 2.1 gives information about the European electricity market and its various aspects, section 2.2 discusses the economics behind airborne wind energy (AWE) and finally, section 2.3 summarizes the knowledge gained from the literature and formulates the research question and the approach to answer the research question.

2.1. The European electricity market

The electricity market is one of the principal drivers for diffusion of AWE in the energy sector. Subsection 2.1.1 explains the market framework, subsection 2.1.2 discusses the merit order effect and subsection 2.1.3 explains the concept of market value of wind power.

2.1.1. Market framework

The liberalization process of the European electricity market began almost around 20 years ago. Different areas of the electricity market are now controlled by different actors. Figure 2.1 shows the conceptual framework of the Dutch electricity market which is an appropriate representation of a typical liberalized electricity market in Europe [6].

In Figure 2.1, the physical layer represents the actual flow of electricity in the physical network and the institutional layer represents the actors responsible for each segment of the physical layer. The power plant owners form the supply side of the market and the large consumers and retail companies form the demand side of the market. Matching the supply and demand of electricity is regulated by the wholesale market. Power trading is facilitated by the power exchanges and the transmission and distribution is controlled by the transmission system operator (TSO). TSOs are also responsible for the safety and reliability of the network. Following are some of the actors of the Dutch electricity market:

Electricity producers	:	Vattenfall [20], Engie [21], Eneco [22] etc.
Power exchange	:	epexspot [7], Nord Pool [23]
Retail companies	:	Eneco [22], Vattenfall [20] etc.
Small consumers	:	Apartments, residential complexes etc.
Large consumers	:	Industries with large power requirements etc.
Transmission system operator	:	TenneT [24]

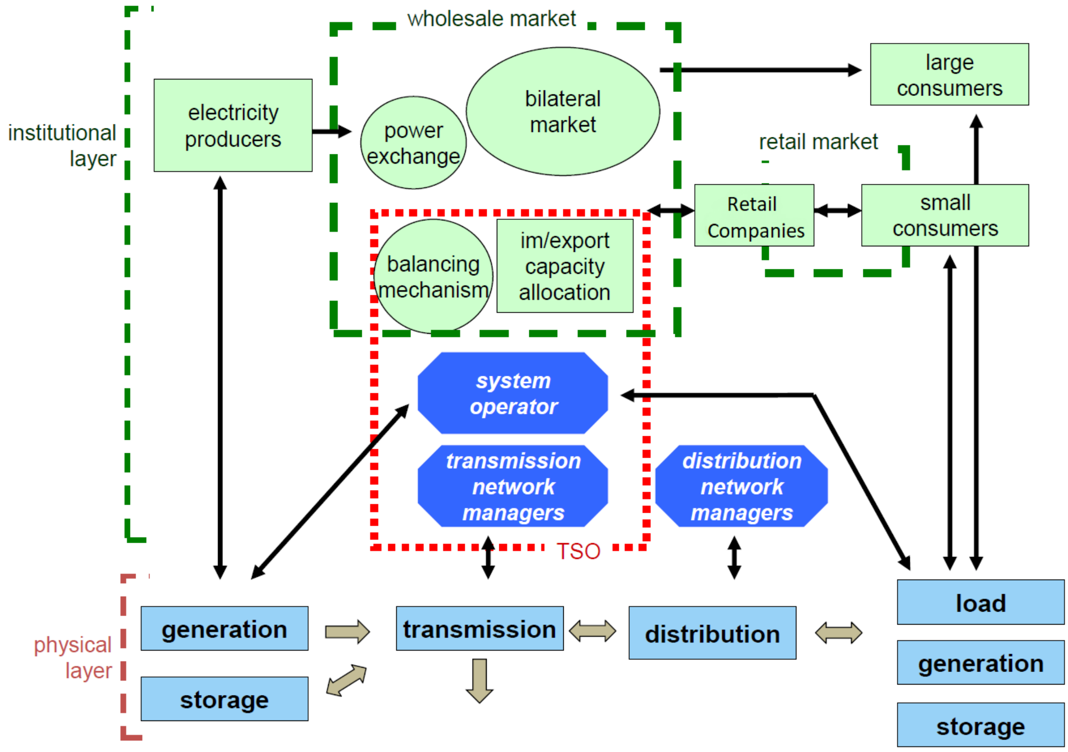


Figure 2.1: EU electricity market framework [6]

Currently, the market in Europe is mainly an energy only market, which means that producers are paid for generated electricity. If producers were paid for their generation capacity, it would have been a capacity based market. Electricity is a commodity which has to be produced at the moment when it can be consumed. Large scale electricity storage are not yet commercially viable. The supply and demand has to be matched continuously in time. Therefore, to maintain the grid balance, different types of markets cover different periods in time. This is essential to maintain the overall security and reliability of electricity supply in the market [25, 26].

Different types of markets, depending on different periods that they cover in time, combinely form the European electricity market. Following are different types of electricity markets introduced sequentially based on their moment of delivery (from years to minutes) [25, 26].

TYPES OF ELECTRICITY MARKETS

1. Forward and Future market: This market runs from years before to day before the delivery time. Contracts to supply and consume a certain amount of electricity at a certain time in the future are agreed upon beforehand. 'Future' contracts are standardized and can be further traded in power exchanges. 'Forward' contracts are not standardized and provide flexibility to the parties involved. They are mainly agreed bilaterally (over-the-counter trading) and further trading in power exchanges does not happen. These types of contracts reduce vulnerability for both parties. The supplier is protected from risks against his revenues and the consumer is protected against the uncertainty of the electricity price.

2. Day-ahead market (DAM): In the DAM, electricity is traded one day before the moment of delivery. It is based on an auction based mechanism which takes place once a day, everyday. Power plant owners submit their generation capacity at their acceptable price for each hour of the following day and the consumers submit their power requirement and their willingness to pay for each hour of the following day. All the 24 hours of the following day are traded in this auction. Figure 2.2 shows a representation of the auction for a certain hour of the day. The bids must be entered by all the market participants into the trading platform before 12.00 pm CET which is the market clearance time of the day. Market clearing price (MCP) is the result of the intersection of the supply and demand curves. The electricity price for each hour is set by the most expensive producer required at that hour. This is also known as

the economic dispatch of power plants. Market clearing volume (MCV) is the legally binding volume of electricity that needs to be supplied by the winning suppliers and which needs to be bought by the winning buyers at the MCP [7].

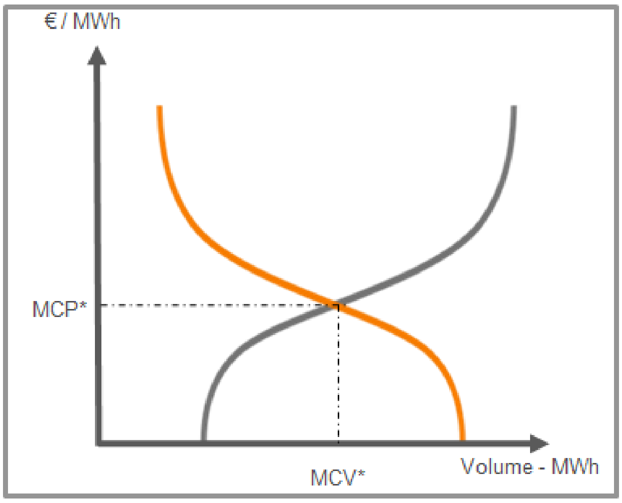


Figure 2.2: Representation of DAM clearance for a certain hour of the day [7]

3. Intra-day market: Intraday market is the market which runs 24 hours of the day and is mostly used for immediate and/or urgent consumption, or balancing. This market mainly enables the market participants to correct for their commitments due to unexpected power plant outages, drop in demand, better forecasts for variable renewable energy sources (VRES) etc. As and when the orders of a buyer and a seller match, the trade is executed immediately. Electricity can be traded up to 5 minutes before delivery and through hourly, half-hourly or quarter-hourly contracts. This gives very high flexibility to the members to do last minute adjustments to balance their positions closer to real time [7].

4. Balancing market: To maintain the grid balance and the instantaneous frequency to avoid grid failure, generation must exactly match the consumption. Energy trade always takes place before real time. Contracts are never fully accurate due to various unexpected and unaccounted factors. It is almost impossible to accurately forecast the demand and supply of electricity at every moment of the contract in future. To avoid grid failure, the final responsibility for maintaining the instantaneous generation and consumption lies with the TSO. Balance responsible parties (BoPs) are private legal entities that take up the responsibility of balancing generation and consumption over a period of quarter hour. A BRP is an administrative entity which maintains a portfolio of generators and consumers which are used to manage this imbalance. Sometimes BRPs obtain a power plant on the verge of decommissioning to act as a reserve for imbalance management. Sometimes, energy storage technologies like pumped hydro storage or large battery storage are also used to manage imbalances. Therefore, this market is also known as the reserves market.

2.1.2. MERIT ORDER EFFECT

This phenomenon is associated with the DAM of countries with sufficient penetration of VRES in their grid. When there is a need to generate electricity, generators are dispatched in an order ranging from the lowest to the highest price. This order of dispatch is known as the merit order. Renewable energy sources like the wind and solar have the lowest operating costs and hence they are dispatched first before any other types of generators like coal or natural gas. Merit order of VRES is higher than other electricity generators.

Figure 2.3 represents a typical DAM clearing instant in a typical European market. As seen in the figure, for a constant demand (say at a certain hour of the day), increase of renewable power supply in the grid would reduce the MCP for that hour. Further, renewable energy sources are weather dependent, therefore this drop in electricity price becomes more and more uncertain with increase in the share of VRES in the energy mix of a country. This depression in price due to the merit order of dispatch is popularly known as the 'merit order effect'. This phenomenon has been identified and addressed in multiple articles and journals over the past decade [8, 27, 28].

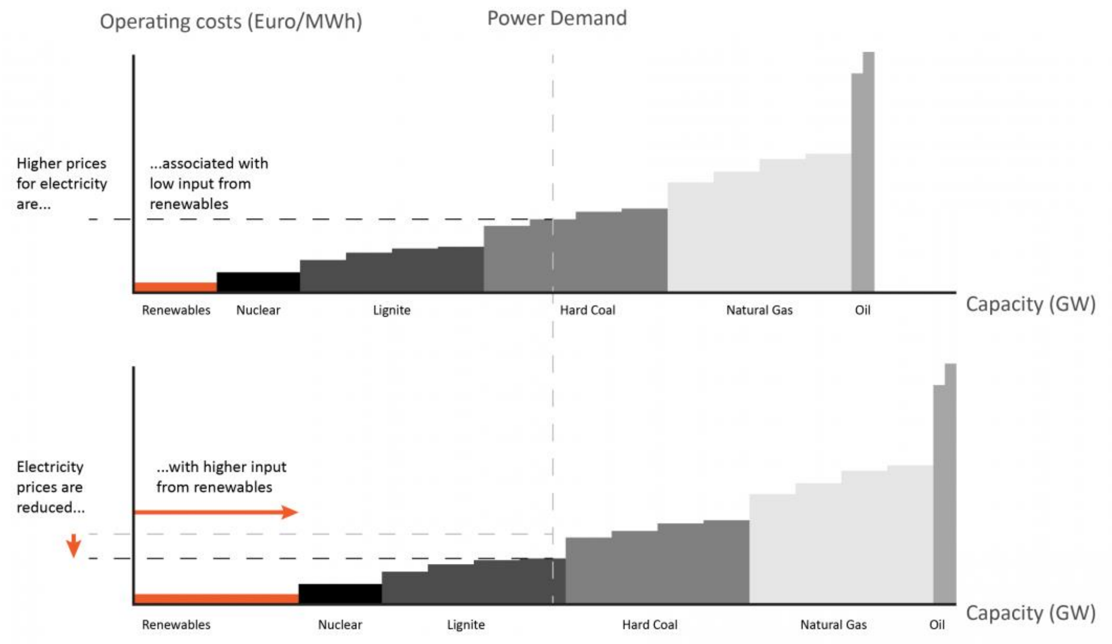


Figure 2.3: Merit order effect in the European electricity market [8]

Electricity generation by VRES in the European market is dominated by wind power. Around 40% of the renewable energy share is wind, around 20% is solar PV and around 40% is hydro [29]. Weihao Hu et al. [30] in 2010 carried out a study about the relation between electricity price and wind power generation in Danish electricity markets. The wind power penetration in Denmark's electricity generation was around 20%. The study shows the negative relation between the two, proving the merit order effect in the then Danish market. The authors chose Denmark since it was one of the countries with higher wind energy penetration hence could be a representative of future European electricity market with overall increased wind penetration. In recent years, there have been similar studies on the German, Spanish, Dutch, Australian and US markets.

Janina C. Ketterer [31] in 2014 investigated the relationship between wind power production and electricity prices in Germany using a GARCH (Generalized AutoRegressive Conditional Heteroskedasticity) model. He confirmed the negative correlation between the daily wind power feed-in and the German spot electricity prices. He stated that regulatory changes have been able to stabilize the electricity prices, but such policy implications should be continuously revisited for better integration of VRES into the grid in future. Alexander Zipp [32] in 2017 investigated the merit-order effect in the German-Austrian electricity market with a multi-variate regression model. For his analysis, he used the electricity market data available from EPEX (European Power Exchange) Spot day-ahead market. He showed that there has been a decline in the average revenues earned by wind farm owners from a 2011 to 2013 and he further predicted similar decline till 2016.

Liliana Gelabert et al. [33] in 2011 published an empirical analysis based on the introduction of renewable electricity sources on wholesale electricity prices. They used data of hourly resolution from 2005 to 2009 in Spain. They used a multivariate regression model which resulted in an estimation that a marginal increase of 1GWh electricity generated with VRES causes a reduction of almost 2 €/MWh in electricity prices. This comes to around 4% of the average price during that period.

ECN (Energy Research Centre of the Netherlands) [34] in 2013 published a report assessing the impact of wind power production on the day-ahead electricity prices in the Dutch market for over the period from 2006 to 2009. The timeseries of wind power forecast was compared with the timeseries of the day-ahead electricity market for the same period. The analysis implied that over this period, wind power has reduced the the average day ahead market price by about 5% than if the wind production was absent. Further, it also states that in long run, there will be sufficient changes in regulations and market structure to suppress this effect.

Zsuzsanna Csereklyei et al. [35] in 2019 investigated the effect of utility scale wind and solar electricity generation on the wholesale electricity prices in Australia for years from 2010 to 2018. The authors used ARDL (Autoregressive distributed lag) models to decompose the merit order effect of the two VRES over time and across states. They calculated that an increase of 1GW of wind power decreased the wholesale electricity price by 11 Australian dollars/MWh at the time of generation. They found out that the merit order effect is indeed pronounced in the Australian market, but despite of this, the wholesale electricity prices have been increasing which is driven by an increase in the natural gas prices.

Javier López Prol et al. [36] in 2019 performed a timeseries econometric analysis using hourly data from the day-ahead wholesale electricity market in California for the period of 2013 to 2017. The authors explained the merit order effect with a term known as the 'self-cannibalizing effect', which means that the power plant owners based on VRES are decreasing their own revenues by injecting more renewable energy into the power grid. Quint and Dahlke [37] in 2018 developed a series of econometric models using the midcontinent independent system operator (MISO) market data for the period from 2008 to 2016. The results estimated a decrease of around 0.2USD/MWh for each 0.1MWh of additional wind power production. It was seen that this effect has declined overtime which is most likely associated with the structural changes made by MISO in order to better integrate VRES in their power grid.

The same volume of stakeholders which have been responsible for reducing the cost of wind energy and increasing the share of wind energy in a country have become responsible for reducing their own revenues. In dramatic terms, this outcome is also recognized as the 'self-cannibalization effect'. Such studies provide insights and indicate the challenges in large scale integration VRES in the national grid.

Installed wind capacity of a country is not the only factor responsible for this effect to be evident, but the share of wind power in the electricity mix and the type of base-load plants(e.g. coal or natural gas) also play a key role. If the electricity mix of the country is dominated by a high cost fuel (e.g natural gas), then the merit order effect due to wind power is almost negligible.

2.1.3. MARKET VALUE OF WIND POWER

VRES are maturing and becoming more and more affordable over the years due to the economies of scale. Fewer subsidies are required by the wind farm developers to build and operate new wind farms. Subsidy free wind power is rapidly growing in the European market since the introduction of competitive auctions for VRES [38, 39].

In subsidy free future scenarios, the revenue generated by the wind farm will be dependent on the European electricity market. The merit order effect (explained in section 2.1.2) will significantly affect the revenues generated by the power plant owners. A unit of power produced by a wind farm will be more valuable if it is produced when the demand is high and/or its competitors are not producing at that time.

Lion Hirth [40] in 2013 presented a concept of Market value (MV). It is the ratio of revenues that power plant owners can generate through the market without any subsidies to the total energy produced by the generator. It is nothing but the average revenue per unit of wind power produced. It is expressed in €/MWh.

$$Market\ Value = \frac{Total\ lifetime\ revenue\ generation\ through\ the\ DAM}{Total\ lifetime\ energy\ production} \tag{2.1}$$

$$MV = \frac{\sum_{t=1}^{T} p_t E_t}{\sum_{t=1}^{T} E_t} \tag{2.2}$$

where,

MV	:	Market value
t	:	Time instant
T	:	Economic lifetime of the project
p	:	Energy price
E	:	Energy produced

For clarity in comparison between different wind power technologies, MV can be normalized with the average DAM price. This normalized MV is known as the Value factor (VF). When the VF of a wind farm is greater than one, it can be inferred that the wind farm is generating more revenue than the average revenue earned by the wind farms in the market. Lower the VF, lower is the revenue as compared to the average revenue earned by other wind farms in the same market.

$$Value\ Factor = \frac{Market\ Value}{Average\ DAM\ price} \tag{2.3}$$

$$VF = \frac{MV}{p_{avg}} \tag{2.4}$$

where,

VF	:	Value factor
MV	:	Market value
p_{avg}	:	Average energy price

Lion Hirth [40] has conducted extensive analysis regarding the value factors of wind and solar technologies in different European countries. The variability of wind and solar radiation affects the electricity price that the power plant owners receive. For shorter timescales, i.e. during windy and sunny days, the electricity price drops reducing the revenues as compared to the revenue generated during normal weather. This can be captured in the VF. On a seasonal timescale, the installed capacity of the VRES affects their own average VF.

In 2013, Lion compiled quantitative evidence from published studies, regression of market data, and using a calibrated European electricity market model EMMA [41]. He found out that the value factor of wind power dropped from 1.1 to 0.5-0.8 as wind penetration increased from zero to 30%. In 2016, on behalf of EFORIS (a research program on electricity market design), he extended published his study on the market value of wind power using the EMMA model. He stated that mostly the drop in value factor is observed for countries dominated by thermal power plants, such as Germany. He also stated that drop in value factor in countries dominated by hydropower is relatively low. Figure 2.4 shows the drop in value factors for Denmark, Sweden and Germany. Germany has the lowest amount of hydropower. Sweden has an hydro share of 50%, and Denmark does not have hydropower but is slightly interconnected to Sweden and Norway [9].

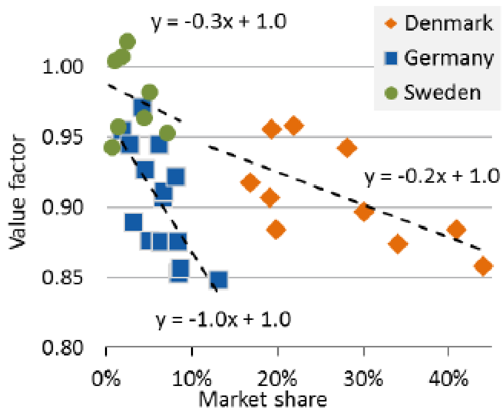


Figure 2.4: Drop in VF of wind power in Germany, Sweden, Denmark from 2001 to 2015 [9]

THE SILENT WIND REVOLUTION

To counter this effect of drop in the value factor, a silent revolution began in the wind industry since the last decade. One of the counter measures taken by the wind industry was to lower the specific power of the turbines by increasing the size of the rotor for the same generator size. The outcome is that these turbines can produce energy at lower wind speeds and overall capacity factor of such turbines also higher. This market driven shift in the wind turbine technology throughout the globe is known as the 'silent wind revolution'. US, one of the biggest liberalized electricity market saw a decline in specific power from around 400 W/m^2 in the year 2000 to around 200 W/m^2 in the year 2017 [42].

2.2. ECONOMICS OF AIRBORNE WIND ENERGY

The motivation for the actors of the AWE industry lies in their vision of being economically profitable as compared to the conventional wind turbines. The economics of AWE or any other VRES is dependent on four factors: the available resource potential, the performance of the system , the cost of the system and the value that can be derived from the system. Figure 2.5 shows the factors influencing the economics of AWE. Icon credits to the 'Noun project' [43].

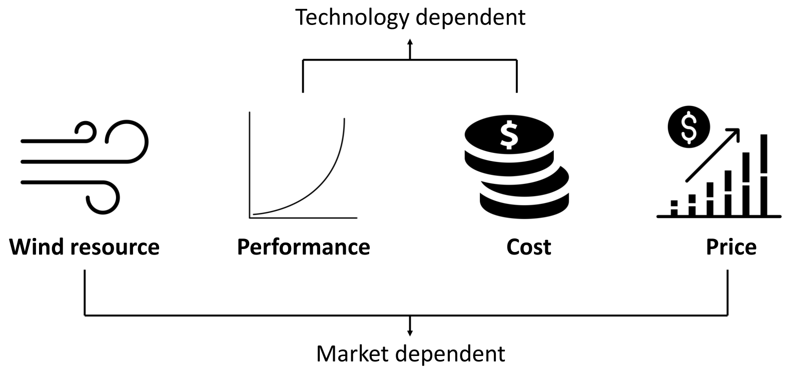


Figure 2.5: Factors influencing economics of AWE

To maximize the economic value of an AWES, all the four factors must be optimized. It should be installed in a location with higher wind resource, it should have high performance characteristics in low costs and it should be able to maximize the revenue generation. Out of the four factors, performance and cost are technology based factors whereas wind resource and price are market based factors.

AWE is an emerging field, therefore the literature available on the economic assessment of AWE is limited. Philip Bechtle et. al. in 2019 [44] published a paper on airborne wind energy resource analysis in which the authors compared the available wind resource for AWES and conventional wind turbines for western and central Europe. The wind data was used from the ERA5 renalysis dataset with a temporal coverage of 7 years and a resolution of 1 hour. The ERA5 reanalysis dataset has a surface resolution of 31km X 31km and a vertical resolution of 37 pressure levels [45]. The authors concluded that the available wind power density at a fixed hub height of conventional wind turbines increases by a factor of two for AWES. Mark Schelbergen et al. in 2020 [46] published a novel method of estimating energy production of AWES by clustering wind profile shapes. The authors used wind data from DOWA (Dutch Offshore Wind Atlas) [47] and the ERA5 reanalysis dataset [45] for their analysis. These studies show that, modelled datasets like ERA5 and DOWA can be used for wind resource assessment related to AWE due to their suitable geographic, spatial and temporal resolutions.

Miles Loyd [15] in 1980 published his work on the basic principles of power generation using kites. All the companies and the universities working on AWE are based on the fundamentals laid down by Loyd. Roland Schmehl et al. [48] in 2013 published a paper on traction power generation using tethered kites. Companies working on performance modelling of their concept of AWE have not published their work. On a fundamental level, it is known that the surface area and the maximum tension that can be carried by the tether are two of the main factors defining the amount of power that can be extracted from the available wind resource. Higher wing areas coupled with higher tension tethers ideally would lead to higher power harvesting factors. Bigger systems will perform better than smaller systems, but performance alone does not influence the economics of AWE. Along with performance, costs also scale with increase in wing area and tether tension.

Heilmann and Houle [49] in 2013 provided a method for economic assessment of ground station based kite power systems based on conventional wind turbines. The article explains all the factors influencing the economic viability of conventional wind turbines and relates it to ground station based kite power systems in reasonable depth. The study relates the wind turbine scaling laws to ground station based kite power systems which are based on the assumption that cost scales with mass which in turn scales with volume. Nominal power was identified as the main cost driver of the system. But, in reality the AWES have many subsystems with diverse characteristics and complexities depending on the system architecture (e.g. ground station based generation or on-board generation). These type of assumptions are helpful in determining approximately the order of costs for the AWES, but from a commercial point of view the analysis needs to be more extensive and detail. The article also notes that the influence of electricity prices on the economic viability of the system cannot be determined easily as the prices vary significantly.

Faggiani and Schmehl [50] in 2018 performed a study on the economic potential of a ground station based kite power technology with a leading edge inflatable tube kite under real wind conditions and in a park configuration. This analysis is based on the study by Heilmann and Houle [49] which was described earlier. The article acknowledges that calculating the LCoE of a project requires in-depth knowledge of the system performance, site characteristics and the costs associated with it. This article gives a detail theoretical framework and the methodology adopted for choosing the design parameters of a ground station based kite power system. A cost model which uses parametric relations with different components in the system is used to assess the economic performance.

Ampyx Power has developed a cost model [51] that can be used for three types of business cases: offshore re-powering, offshore floating and onshore. The current cost assumptions are based on supplier quotes, industrial standards, empirical numbers and the experience gained by the company. Ampyx Power has also performed joint studies with ECN part of TNO for understanding the offshore installation and maintenance costs. Offshore floating costs are based on a joint study with Mocean Offshore B.V. Detailed information about the cost model is presented in subsection 2.3.1.

Generalized cost modelling framework for AWE is an impractical task due to the diverse architecture choices in the industry. Every company/institution could develop their own cost model based on their own architecture but which can't be translated to any other concept due to their dissimilarities.

Out of the four factors influencing the economics of AWE, wind resource, performance and the cost is captured in a single economic metric known as the Levelized cost of energy (LCoE).

LCoE is a metric that is used to compare different energy technologies. It is the average net present cost of electricity generation for a system or a plant over its entire economic lifetime. Following is the expression used to calculate LCoE of a wind energy energy technology stated by IRENA [52]. It is expressed in €/MWh.

$$Levelized\ Cost\ of\ Energy = \frac{Total\ lifetime\ costs}{Total\ lifetime\ energy\ production} \tag{2.5}$$

$$LCoE = \frac{\sum_{t=1}^{T} \frac{CAPex_t + OPex_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \tag{2.6}$$

where,

t	:	Time instant
$LCoE$	:	Levelized Cost of Energy
$CAPex$	:	Capital expenditure
$OPex$	:	Operations and maintenance expenditure
E	:	Energy produced
r	:	Discount rate
T	:	Economic lifetime of the project

Discount rate is the interest rate used in discounted cash-flow (DCF) analysis. DCF is a valuation method used to estimate the value of an investment based on its future cash flows. The value of future cash flows is lesser than present cash flows. The discount rate expresses the time value of money and is used to determine the present value of the future cash flows [53].

The factor which is not captured by LCoE is the price. For VRES, the price has been dependent on various economic support schemes provided by the European governments. Following are some of the common economic support schemes. Definitions are compiled from 'RES Legal Europe' [54].

Feed-in-tariff (FIT): A price-based policy instrument irrespective of the DAM price, whereby the eligible renewable energy generators are paid a fixed price at a guaranteed level for the electricity produced and fed into the grid [55].

Feed-in-premium (FIP) - fixed: A price-based policy instrument whereby the eligible renewable energy generators are paid a premium price of x€/MWh in addition to the DAM price [55].

Feed-in-premium (FIP) - floating: A price-based policy instrument whereby eligible renewable energy generators are paid a floating (changing) premium in addition to the DAM price. This premium is calculated as the difference between an average DAM price and previously defined guaranteed price. This effectively guarantees a minimum revenue to the electricity producers.

Contract for difference (CfD): This is similar to floating premium. But if the DAM prices rise above a set guaranteed price, the electricity producers are required to pay back the difference between the guaranteed price and the DAM price. End result is therefore same as a FIT.

But, in a subsidy free scenario, the price obtained by any VRES will be completely dependent on the European DAM. The dynamic nature of the DAM will increase the influence of the price component on the economics of AWE. Therefore, along with the LCoE of AWES, the revenue generated by the systems will also be an important factor in decision making. Influence of this economic factor on the system design of AWE is a lesser explored area in the literature.

2.3. PROBLEM ANALYSIS

Based on the performed literature review, this section presents the detailed problem analysis. Subsection 2.3.1 gives the state of the art of the system design framework of the company, subsection 2.3.2 explains the research element which is missing in the state of the art and finally, subsection 2.3.3 states the research question and the approach laid down to ultimately answer the research question.

2.3.1. STATE OF THE ART

Ampyx Power is currently performing studies to understand the level 0 requirements of their first commercial demonstrator, AP-4. Current framework for the system design of AP-4 is based on the optimization of LCoE. The current cost model developed by the company is a parametric model based on the known elements and the components of a full AP-4 facility. Figure 2.6 shows the breakdown of all the elements of the model.

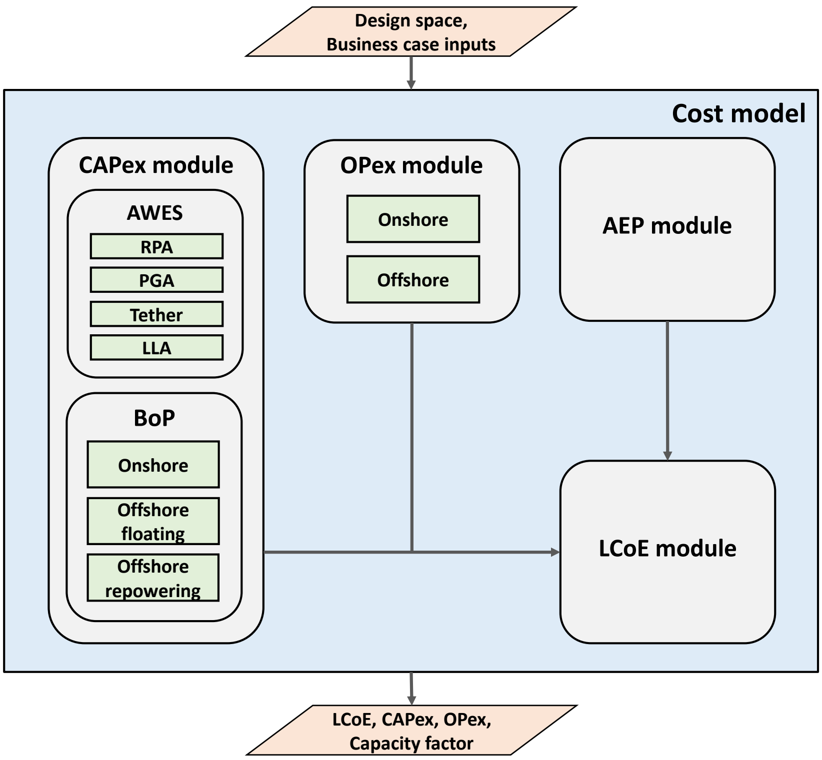


Figure 2.6: Current cost model of Ampyx Power AWES

The cost model is composed of four modules: CAPex, OPex, AEP and the LCoE module. The design space for AP-4 and the business case assumptions form the inputs to the cost model. The cost model calculates the costs for three different types of business cases - Offshore repowering, Offshore floating and Onshore.

Offshore repowering business case assumes to reuse the foundation and some of the site infrastructure of a decommissioned offshore wind farm. Offshore floating business case is based on installation of AWES in deep sea locations on floating platforms and the onshore business case is based on installation of AWES on the farmlands or open spaces on land.

CAPex module consists of AWES and balance of plant (BoP) components. Cost of AWES is divided into four main elements - RPA (remotely piloted aircraft), PGA (power generation apparatus), Tether, LLA (launch and land apparatus). Cost scaling of all the AWES components is based on knowledge gained by the company from their third generation of prototype, AP-3. BoP assumptions are based on literature and reference from conventional wind turbine farms. Ampyx Power carried out a joint study with Energy Research center of the Netherlands (ECN part of TNO) regarding the offshore installation and maintenance costs. Offshore floating costs are based on a joint study with Mocean Offshore B.V.

The cost model is being updated and extended continuously with recent studies and findings. The cost model outputs are not utilized for its absolute values which it gives, but instead are used to compare different configurations and business cases with each other. This is done to understand the scalability and system sizing of their technology. The aim is not to have accurate LCoE estimations but rather to compare LCoEs of different systems in different business cases.

2.3.2. RESEARCH GAP

The current decision-making framework for the system design of Ampyx AWES is based on optimization of LCoE (bottom-up approach). Anticipated subsidy free future for VRES would lead to volatility in the revenue generation of the systems. The merit order effect shows that the value of VRES depends on the time at which the energy is produced. Fewer and fewer subsidies will increase the dependency of VRES on the DAM for their revenue generation. This indicates to investigate if there is a need to shift from cost driven optimization to value driven optimization. This was found to be one of the lesser explored areas in the literature.

AWE is a wind energy technology and hence its direct competitors in the market are the conventional wind turbines. To be competitive in the wind energy market, AWE not only needs to be cost effective but also needs to derive more value than its competitors. In simpler terms, AWE should be able to earn more profit than its competitors. Merit order effect shows that the value of electricity produced by a wind power plant will be higher when its competitors are idle and not producing any power. Therefore, it is beneficial to study and quantify the effect of wind power production of a country on its DAM prices and further incorporate this phenomenon in value driven optimization for system design of AWE.

Summarizing from the literature study, we know that the effect of wind power production on the DAM of a country depends on the amount of wind power production at a certain time, and the wind power production depends on the wind speeds at that particular time. For a particular market, this indicates that there might exist a correlation between the DAM prices and wind speeds. Each market has a different demand for electricity, different energy mix, different fuel costs etc. Therefore the strength of this correlation should be different for different markets.

Since, the energy production and the energy price at a particular time, are both dependent on the wind conditions of that particular time, the correlation of the DAM price and wind speeds can be used in the value driven optimization for the system design of AWE,

$$Rev_t = E_t p_t \tag{2.7}$$

where,

t	:	Time instant
Rev	:	Revenue generated
E	:	Energy produced
p	:	Energy price

LEVELIZED REVENUE OF ENERGY (LROE)

In such a scenario when revenues of wind farms are not only based on fixed subsidies (fixed energy price per MWh) but are dynamic, different renewable energy technologies in the market will have different revenue generation rates (variable energy price per MWh). A revenue based metric analogous to LCoE which gives average net present revenue of electricity generation for a system or a plant over its entire economic lifetime can be used to compare technologies based on their capacity to generate revenue. It can be defined as follows:

$$Levelized\ Revenue\ of\ Energy = \frac{Total\ lifetime\ revenue}{Total\ lifetime\ energy\ production} \tag{2.8}$$

$$LRoE = \frac{\sum_{t=1}^{T} \frac{(p_t + Subsidy_t)E_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \tag{2.9}$$

where,

$LRoE$	:	Levelized Revenue of Energy
t	:	Time instant
T	:	Economic lifetime of the project
p	:	DAM price
$Subsidy$	:	Subsidy rate awarded by the Government
E	:	Energy production
r	:	Discount rate

Instead of using the LCoE to compare technologies, the LCoE and the LRoE can be used together to compare technologies based on their value. Since LCoE and LRoE are both discounted to account for the time value of money, they can be used to calculate the net present value of the project as shown below.

$$Net\ Present\ Value = E(LRoE - LCoE) \tag{2.10}$$

where,

E	:	Energy generation discounted for entire economic lifetime
$LRoE$	:	Levelized Revenue of Energy
$LCoE$	:	Levelized Cost of Energy

2.3.3. RESEARCH QUESTION AND THE APPROACH

Following research question is formulated after summarizing the information and the missing elements from the present research:

In a DAM based revenue generation scenario, is there a difference in the system design of utility scale AWE when 'optimizing for cost' vs 'optimizing for value'?

Following steps are formulated to answer the research question:

- Develop a correlation model of the DAM price and wind speeds to confirm and quantify the merit order effect of wind power in the European electricity markets.
- Develop and integrate a revenue model with the existing cost model of Ampyx Power.
- Integrate the correlation model of the DAM price and wind speeds with the revenue model.
- Shape the above framework into a decision support tool for the system design of AWE.
- Compare cost driven system design with value driven system design through a case-study using the developed tool.

3

Decision Support Tool for the System Design of Utility Scale AWE

This chapter explains the tool developed to answer the formulated research question. Section 3.1 explains the framework of the developed tool. Section 3.2 explains the correlation model of the day-ahead market (DAM) price and wind speeds. Section 3.3 explains the improved approach of value driven system design of utility scale airborne wind energy (AWE).

3.1. Framework

The developed tool is an extension of the existing cost model of Ampyx Power which was introduced in subsection 2.3.1. The tool is developed in MATLAB environment and is modular. Figure 3.1 shows the inputs and the outputs of the tool. The tool has two main inputs - AWES specifications (complete design space to find the optimal from) and the Business case inputs for the three types of business cases as explained in subsection 2.3.1. The tool finds the optimal system configuration based on multiple economic indicators like the levelized cost of energy (LCoE), the levelized revenue of energy (LRoE) and the net present value (NPV).

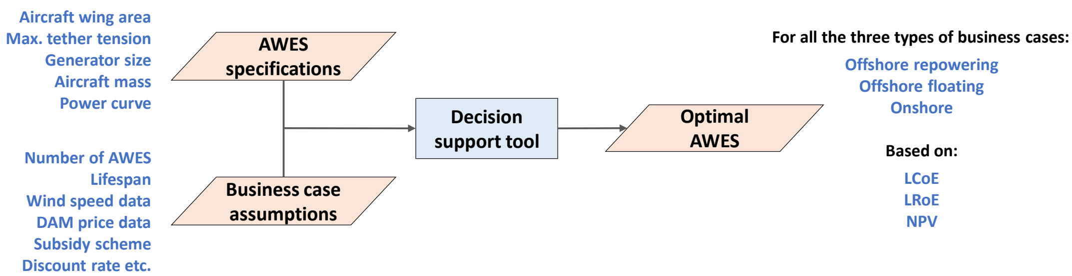


Figure 3.1: Framework of the developed decision support tool

The business case inputs are directly entered in the MATLAB script. To input the AWES specifications, the tool requires a MAT-file with all the specifications. A script has been written to generate this MAT-file from the company's analytical performance model. Ampyx Power has developed a low fidelity performance model based on analytical equations and educated assumptions instead of getting performance curves through simulations. The model focuses on modelling parametric losses from ideal behaviour and is suitable for sensitivity analysis due to its low computation time. This model is mainly used to explore the scalability of the systems and to understand generator sizing and power capping. Aircraft wing area, maximum tether tension and generator size are the main inputs to the model. The model calculates the mass associated with the particular AWES configuration and calculates its power curve. Discrete design space having a range for aircraft wing area, maximum tether tension and generator size can be generated using the model. Figure 3.2 shows a sample design space which can be used as an input to the developed tool.

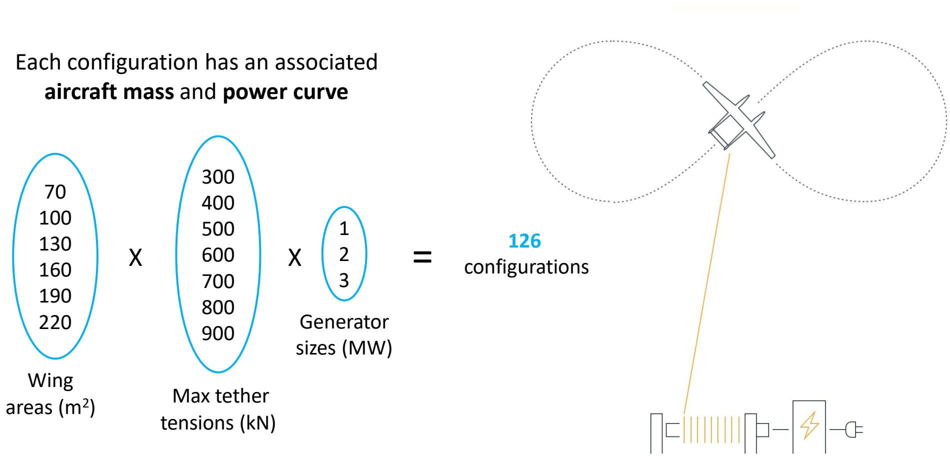


Figure 3.2: Sample design space generated from Ampyx Power's analytical performance model

Figure 3.3 shows three of the AWES configurations from the design space which are generated using the analytical performance model of the company. Aircraft mass is an output of mass dependencies of the structural components of a particular aircraft and the tether tension combination. Each combination can be coupled to a generator which will dictate and limit the power production of that particular AWES.

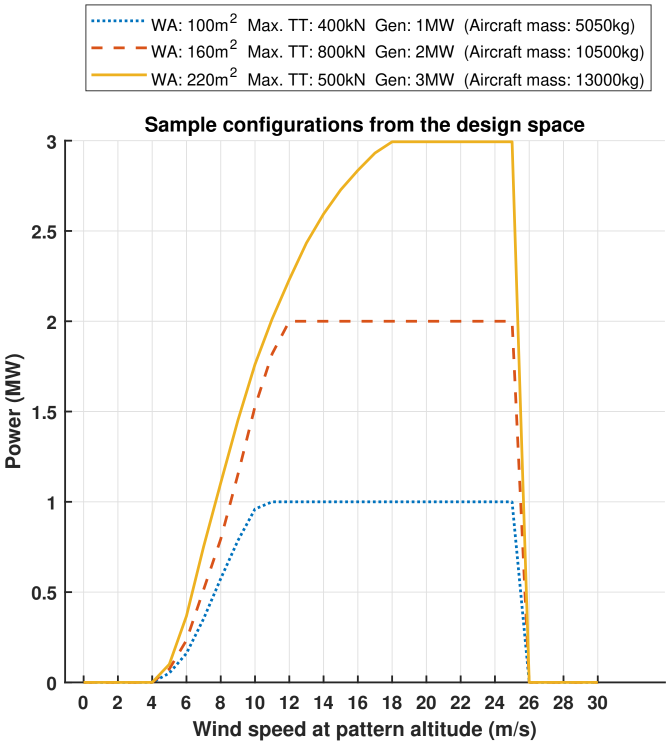


Figure 3.3: Sample AWES configurations from the generated design space

The developed tool is essentially an integration of three models - the existing cost model of Ampyx Power, the correlation model of DAM price and wind speeds and the value model. Following sections explain each of these developed models and their integration in the tool.

3.2. CORRELATION MODEL: DAM PRICE AND WIND SPEEDS

This section addresses the first step of the approach formulated to answer the research question. It explains the method to model the correlation between the DAM price and wind speeds. Flowchart in Figure 3.4 gives an overview of the method adopted to model the correlation. Data-driven statistical model has been developed using tools like the Pearson correlation and regression analysis.

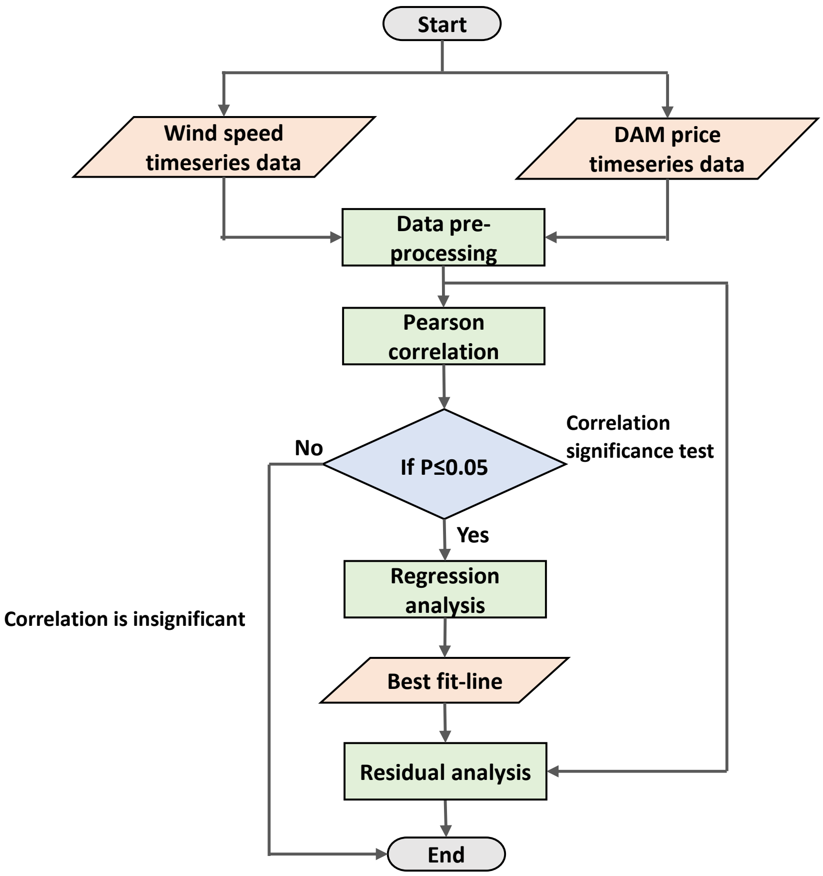


Figure 3.4: Flowchart of the correlation modelling method of DAM price and wind speeds

Majority of the available studies on the merit order effect in the European electricity market are based on empirical data. A data driven approach was considered suitable for modelling the correlation because of the availability of DAM price and wind speeds data of same temporal coverage and resolution. Also, both the datasets are available with sufficient geographical coverage. Following subsections explain each of the intermediate steps involved in modelling the correlation.

3.2.1. DATA PRE-PROCESSING

A timeseries dataset from Germany is used to explain the modelling method. Timeseries is a series of datapoints recorded sequentially in time. The temporal coverage of the timeseries data used is 5 years and the resolution is 1 hour. Table 3.1 gives information of the sample data set used for explaining the modelling method. The wind speed data is from an offshore location in the exclusive economic zone (EEZ) of Germany in the north sea. The global co-ordinates of the location are 54°North and 7°East.

Table 3.1: Wind speed and DAM price dataset from Germany used to explain the correlation modelling method

Description	Wind speed (m/s)	Day ahead electricity price (€/MWh)
Source	ERA5 Reanalysis data	ENTSOE-E Transparency Platform
Temporal resolution	1 hour	1 hour
Surface resolution	31km X 31km	Fixed for the bidding zone of a country
Temporal coverage	2015 : 2019	2015 : 2019
Location	DE North Sea (Wind farm: Nordsee one)	DE

ERA5 REANALYSIS DATA

The wind speed timeseries data is obtained from the ERA5 reanalysis dataset. ERA5 is a modelled dataset with global coverage from 1979 (soon to be updated from 1950) to near real-time. It is produced by the European centre for medium-range weather forecasts (ECMWF). It provides hourly data for number of atmospheric, land and sea state parameters. For the wind speed data, the surface resolution based on the latitude and longitudinal grid on the earth's surface is 0.25°x 0.25 °which translates to around 31km X 31km and the vertical resolution is of 37 pressure levels in the atmosphere. The modelling method is based on combining model data and actual observations from around the globe to produce a consistent dataset using the laws of physics [45]. The data can be downloaded through the Copernicus climate change service (C3S) climate data store (CDS) [56].

ENTSOE-E TRANSPARENCY PLATFORM

The DAM price timeseries data has been obtained from ENTSOE-E Transparency platform. ENTSO-E is the European network of transmission system operators for electricity. It represents 42 transmission system operators from 35 countries across Europe. It is a transparent platform responsible for collection and publication of data related to electricity generation, transmission and consumption in the European market [57].

Figure 3.5 shows the original timeseries data of the two variables. Mean DAM price is 35 €/MWh and the mean wind speed is 10m/s. The wind speed values are at 323m (pressure level of 975hPa) altitude.

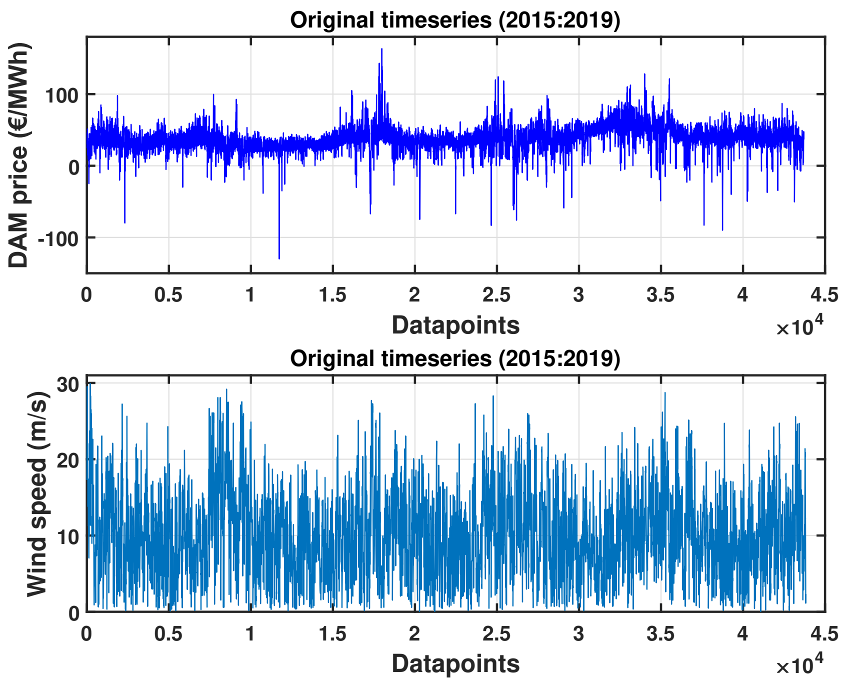


Figure 3.5: Original timeseries datasets of DAM price and wind speeds from an offshore location in Germany

DATA CLEANING

A clean and consistent dataset is necessary when working with timeseries, but the available data may not always be complete and consistent. Following checks are performed to clean the data:

1. Consistency check: Both the datasets are checked for missing timestamps and data points with inconsistent timestamps are parallelly removed from both datasets.
2. 'Not a number' (NaN) check: Both the datasets are checked for NaN values and data points with NaN values are parallelly removed from both datasets.

Data cleaning resulted in removal of 0.2% of datapoints from the original timeseries data. This indicates that there is no significant loss of datapoints and the quality of the original dataset is reasonable.

DETRENDING THE DATASETS

In statistics, a spurious correlation refers to a relationship between two variables which appears to be causal, but is not. These relations just appear to be correlated [58]. Two random unrelated variables increasing or decreasing in time could be misinterpreted as correlated. Figure 3.6 shows few examples of spurious correlations published in a article by Harward Business Review [10].

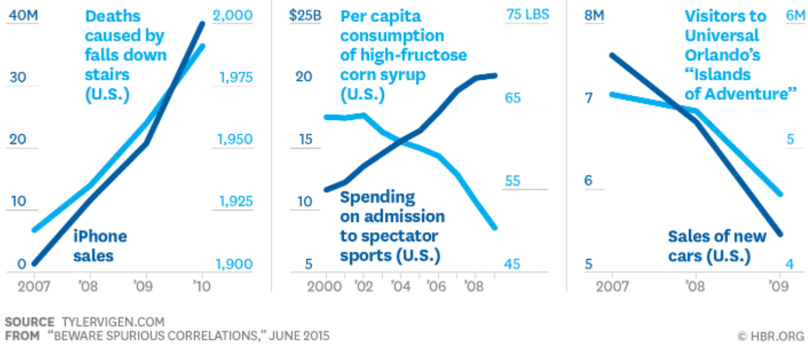


Figure 3.6: Examples of spurious correlations [10]

In each of the three graphs, both the datasets seem highly correlated with each other, but in fact, this correlation is misleading. The two datasets seem correlated due to the inherent trends present in the individual datasets. There cannot be a real correlation between these datasets (e.g. Iphone sales and Deaths caused by falling down from stairs cannot be correlated with one another). These examples are quite straightforward and easy to understand, but it indicates that it is important to check for spurious correlations when dealing with any kind of timeseries data.

A timeseries consists of following three components [59]:

1. Trend: A systematic upward or downward component which may or may not be linear and which does not repeat over time.
2. Seasonal: Systematic upward or downward fluctuations which may or may not be linear and which repeat over time.
3. Irregular: A non-systematic component that is nor trend nor seasonality within the data.

Spurious correlations are usually misinterpreted as correlations due to the trend component of the timeseries. Variables having a similar trend component in their timeseries data could be misleading. Therefore, it is important to detrend the timeseries data before exploring relationship between the variables.

Figure 3.7 shows an example of detrending a timeseries data. The sample dataset used in this example are the daily stock market prices. An overall upward trend is seen in the original dataset. Linear detrending is removing the best straight fit-line from the data. The leftover dataset is without any inherent trend which could lead to a spurious correlation.

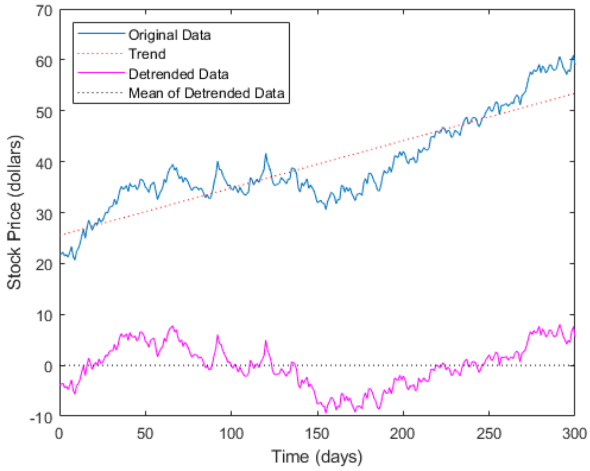


Figure 3.7: Example of detrending a timeseries

Same detrending process is performed on the DAM price and the wind speed timeseries data to avoid spurious correlations.

OUTLIER REMOVAL

In statistcs, an outlier is a datapoint which differs significantly from other datapoints in the dataset. Such aberrant datapoints should be removed so as to avoid their influence in the statistical model. In large data samplings which are normally distributed, datapoints further away from the mean could be considered unreasonable.

Figure 3.8 shows the distribution of DAM prices of Germany from 2015 to 2019. It is a normal distribution with a mean of 35 €/MWh and a standard deviation of 14 €/MWh. The datapoints which are three standard deviations apart are categorized as outliers and have been removed.

Since the wind speeds timeseries is a 'modelled dataset' from ERA5 and is not a measured dataset, no datapoints have been categorized as outliers. However, timestamps from the DAM price which were categorized as outliers have been removed from the wind speeds timeseries to maintain consistency.

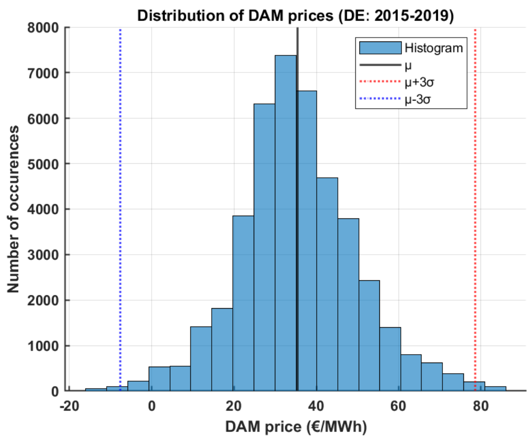


Figure 3.8: Distribution of DAM prices of Germany (2015-2019)

The outlier removal process resulted in the removal of 1.1% of the datapoints.

PROCESSED TIMESERIES DATASETS

Ideally each dataset should have had 43824 datapoints (considering 2016 was a leap year). Data pre-processing removed 627 timestamps, which is around 1.4% of the original dataset. Figure 3.9 and Figure 3.10 show the difference between the original timeseries and the processed timeseries for the DAM prices and the wind speeds respectively. The negative wind speed values in the processed timeseries are the result of detrending the data. The processed timeseries are used to explore correlation between the variables.

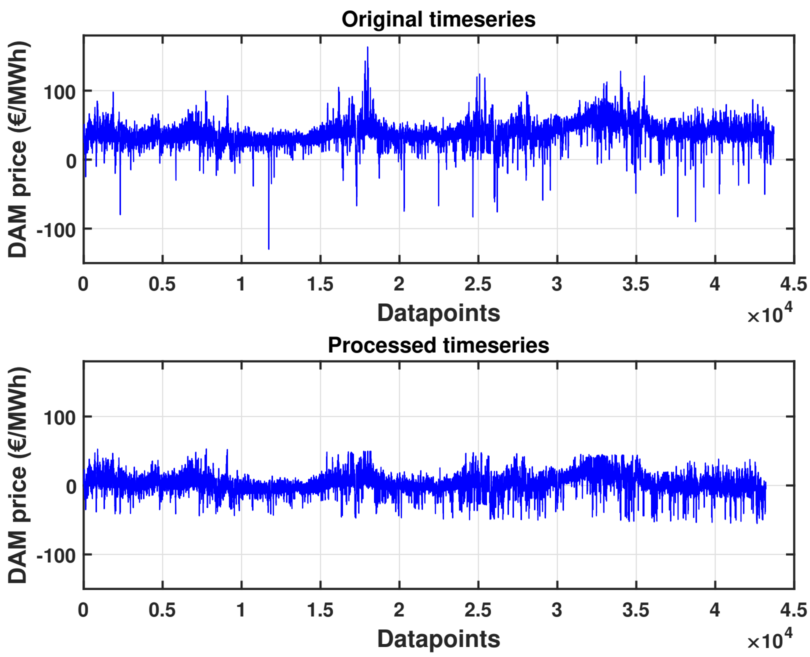


Figure 3.9: Original vs processed DAM price timeseries from Germany (2015:2019)

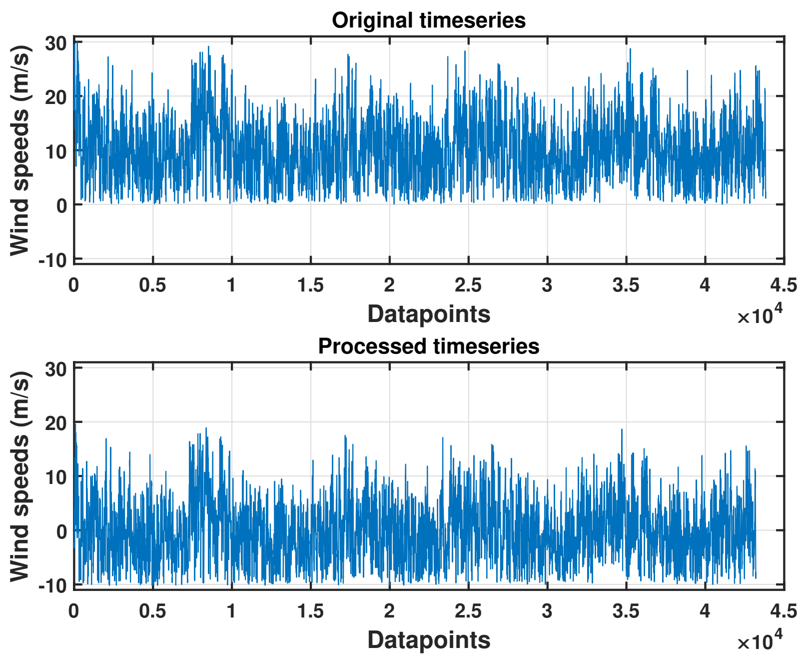


Figure 3.10: Original vs processed wind speeds timeseries from Germany (2015:2019)

3.2.2. PEARSON CORRELATION

In statistics, correlation is a measure to indicate if two variables have a linear relationship between them. Variance and covariance of the datasets form the basis for correlation analysis. Variance measures the spread of a dataset around its mean value. Larger variance means that larger is the distance between the datapoints and the mean. Conversely, smaller variance means that the datapoints are closer to the mean. Covariance is the measure of joint variability of the two variables. Positive covariance represents positive relationship and negative covariance represents negative relationship, but the covariance does not tell about the strength of the relationship. [60].

Consider two random variable datasets 'X' and 'Y' having 'N' number of datapoints. Variance and covariance of datasets are calculated as follows:

$$var(X) = \frac{\sum_{i=1}^{i=N}(x_i - x_m)^2}{N} \tag{3.1}$$

$$var(Y) = \frac{\sum_{i=1}^{i=N}(y_i - y_m)^2}{N} \tag{3.2}$$

$$cov(X,Y) = \frac{\sum_{i=1}^{i=N}(x_i - x_m)(y_i - y_m)}{N} \tag{3.3}$$

where,

X	:	Variable 1
Y	:	Variable 2
$var(X)$	:	Variance of x
$var(Y)$	:	Variance of y
$cov(X,Y)$	:	Covariance of the two datasets
x_i	:	i^{th} datapoint of variable X
x_m	:	Mean of X
y_i	:	i^{th} datapoint of variable Y
y_m	:	Mean of Y
N	:	Size of the datasets

Correlation coefficients not only indicate the direction of the relationship, but also indicate the strength. There are four types of correlations: Pearson correlation, Kendall rank correlation, Spearman correlation, and the Point-Biserial correlation. The most commonly used correlation is the Pearson correlation.

To have a valid correlation analysis, the datasets of the two variables should satisfy the following four assumptions [1]:

1. The two variables should be continuous
2. The relationship is linear
3. There are no significant outliers
4. The variables must be approximately normally distributed

The DAM price and the wind speed dataset from Germany are timeseries of hourly resolution. Which means that the datapoints lie at continuous intervals and hence the first assumption is satisfied. Second assumption is confirmed during regression analysis in subsection 3.2.3. Outliers have been removed in data preprocessing and hence the third assumption is satisfied. Figure 3.8 shows that the DAM price is normally distributed. The wind speeds have a Weibull distribution, but the scale and shape factor of the weibull distribution of the wind speeds are such that it is almost similar to a normal distribution. This assumption is mainly to confirm that the relationship between the two variables is linear.

The Pearson correlation coefficient is a number denoted by 'R' and ranges between -1 and 1, both inclusive. It indicates whether a linear relationship exists between the two continuous variables, the strength of the linear relationship and the direction of the relationship (if it exists) [61]:

- If $R = 0$: No relationship exists between the two variables
- If $R = 1$: Perfectly positive relationship exists between the two variables
- If $R = -1$: Perfectly negative relationship exists between the two variables

'R' is calculated as follows:

$$R_{xy} = \frac{cov(X,Y)}{\sqrt{var(X)var(Y)}} \tag{3.4}$$

where,

R	:	Pearson correlation coefficient
$var(X)$	:	Variance of X
$var(Y)$	:	Variance of Y
$cov(X,Y)$	:	Covariance of X and Y

Table 3.2 gives the correlation strength scale.

Table 3.2: Pearson correlation strength scale [1]

Strength	**Positive**	**Negative**
Weak	0.1 to 0.3	-0.1 to -0.3
Moderate	0.31 to 0.6	-0.31 to -0.6
Strong	0.61 to 1.0	-0.61 to -1.0

Table 3.3 shows the correlation coefficients for the sample dataset from Germany. From Table 3.2, we can infer that there is a negative correlation of weak to moderate strength between the DAM price and wind speeds for the chosen location.

Table 3.3: Correlation coefficients: Sample dataset (Germany - 2015:2019)

	Wind speed	**DAM price**
Wind speed	1	-0.33
DAM price	-0.33	1

STATISTICAL SIGNIFICANCE TESTING

In statistics, significance testing is done to provide evidence supporting or rejecting the obtained results. It is used to prove that the obtained results are not just an outcome of chance. If the sample size of the dataset is large, there is a high chance that the results obtained are statistically significant. Referring to a certain correlation analysis, there is a possibility that even if the correlation analysis results in a strong correlation, the results probably would be statistically insignificant, or vice-versa.

Hypothesis testing is a method used for statistical significance testing and sometimes is also known as confirmatory data analysis. In this research, a statistical hypothesis test is performed to verify and provide evidence for the correlation analysis performed earlier. A hypothesis test examines two opposing hypothesis about a population of data. In this analysis, the two hypothesis are as follows:

The null hypothesis (H_o)	:	There is no significant correlation between the variables
The alternate hypothesis (H_a)	:	The correlation is significant

The null hypothesis is the hypothesis being tested. A concept of P-value is used in the hypothesis testing to accept or reject the null hypothesis. P-value is the probability of an event in the sample dataset which is atleast as strong as the claim in the null hypothesis. In terms of the correlation analysis, it is the probability of an event in which the sample dataset has no correlation or a positive correlation.

If the P-value is less than the significance level (usually denoted as α), then the null hypothesis is rejected. The commonly accepted significance level is 5%. If P-value is less than or equal to 5% then it indicates statistical proof that the correlation is indeed significant [62].

For the performed correlation analysis, the P-value for the statistical hypothesis testing came out to be '0'. Since the P-values is less than the significance level (P value < 0.05), the null hypothesis is rejected and it can be concluded that the correlation is indeed significant.

For the sample dataset from Germany, it is concluded that the correlation between the DAM price and the wind speeds is weak, but is statistically significant. Following section aims at modelling the relationship between the two variables using regression analysis.

3.2.3. REGRESSION ANALYSIS

In statistical modelling, regression analysis is a form of predictive modelling technique which estimates the relationship between a dependent variable and independent variable(s). This modelling method is used for predictions, forecasting, timeseries modelling and finding causal relationships between variables.

ORDINARY LEAST SQUARES METHOD

Ordinary least squares (OLS) regression is the most common type of regression analysis which estimates the linear relationship between the dependent and the independent variable using a best fit straight line [63].

Consider the example in Figure 3.11. The dependent variable is illustrated on the Y-axis whereas the independent variable is illustrated on the X-axis. Based on the assumption that the relationship between the two variables is linear, a fit line can be expressed by the following expression:

$$y_i = \alpha + \beta x_i + \epsilon_i \tag{3.5}$$

where,

y_i	:	i^{th} datapoint of the dependent variable
x_i	:	i^{th} datapoint of the independent variable
α	:	Y intercept of the fit line
β	:	Slope of the fit line
ϵ_i	:	Error for the i^{th} estimation

Error is the difference between the actual and estimated value. The idea behind OLS is to find the parameters α and β when the error term is minimized for all datapoints. Since the error can be positive or negative depending on the observed datapoints, the sum of squared errors (SSE) is minimized to avoid compensation of positive and negative errors. Such a fit line with which the SSE is minimized is termed as the 'Best fit line' [64].

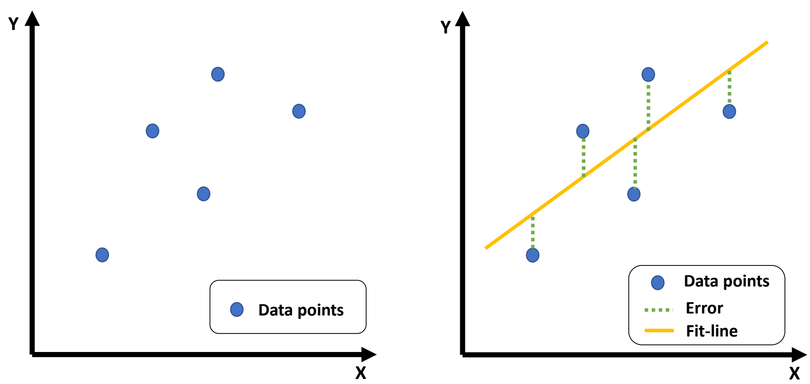


Figure 3.11: Representation of Ordinary Least Squares method for linear regression analysis

Minimizing for SSE is an optimization problem which can be solved using calculus. The values for α and β for which the SSE is minimized are termed as the least squares coefficients or as ordinary least squares coefficients or OLS coefficients. The best fit line is then expressed as:

$$y = \hat{\alpha} + \hat{\beta}x \tag{3.6}$$

where,

y	:	Dependent variable
x	:	Independent variable
$\hat{\beta}$	:	Slope of the best fit line
$\hat{\alpha}$	:	Y-intercept of the best fit line

This equation can be further used to estimate the values for the dependent variable for any given values of the independent variable.

For the sample dataset from Germany, Figure 3.12 shows regression analysis results for the DAM prices and wind speeds

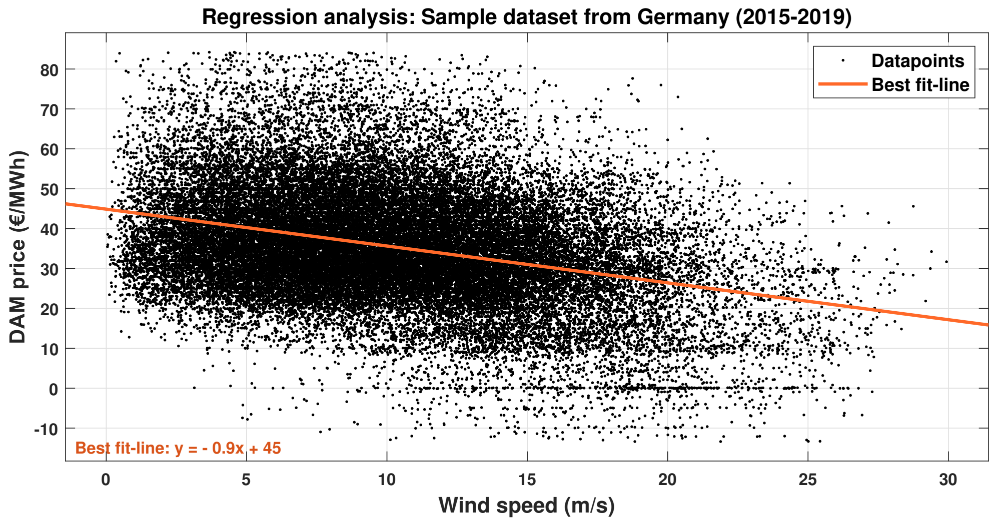


Figure 3.12: Regression analysis results for the DAM prices and wind speeds from the sample dataset from Germany (2015:2019)

After regression analysis, it is essential to perform residual analysis to validate the model. Following section addresses this analysis and is the last segment of the correlation analysis.

RESIDUAL ANALYSIS

Residual is the difference between the observed value and the estimated value from the regression model. Therefore, they have the same unit as that of the dependent variable. Residual analysis is a way to interpret the results of regression analysis and used to validate the assumptions of the OLS regression model. A residuals plot illustrates the residuals on the Y axis and the independent variable on the X axis.

$$\text{Residual} = \text{Observed value - Estimated value}$$

There are two main conditions to validate the OLS regression analysis [65, 66]:

1. The residuals must be randomly scattered around 0 for the entire range of the dataset
2. The residuals should follow a normal distribution with the mean of 0

Figure 3.13 shows the residuals plot for the performed regression analysis. It shows that the residuals are randomly scattered around 0, hence satisfying the first condition. Figure 3.14 shows that the residuals are normally distributed with a mean of 0, hence satisfying the second condition.

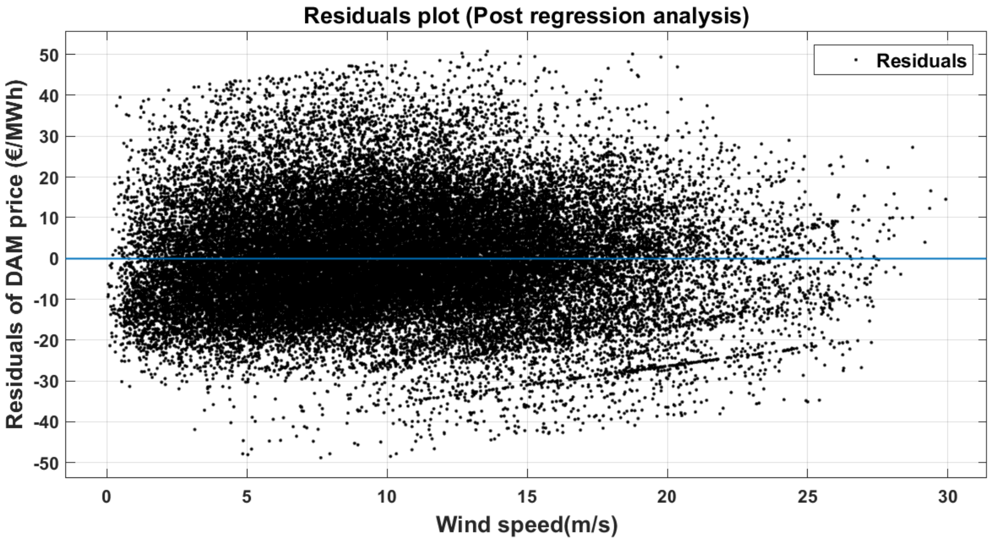


Figure 3.13: Residuals plot: Regression analysis results of the sample dataset from Germany (2015:2019)

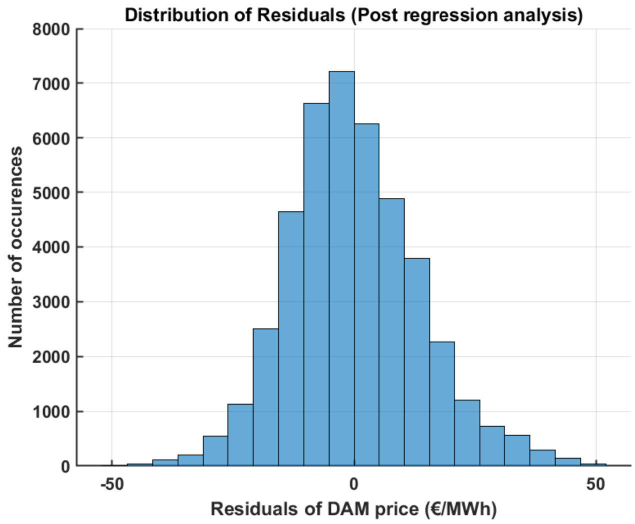


Figure 3.14: Residuals distribution from regression analysis of the sample dataset from Germany

Residual analysis validates the regression analysis performed on the DAM price and wind speeds from the sample dataset of Germany.

Following subsection explains the use of the correlation model to estimate the correlation of DAM price and wind speeds in different locations in Europe.

3.2.4. CASE STUDY AND INFERENCES

Subsections 3.2.1, 3.2.2 and 3.2.3 described in detail the modelling method developed for analyzing the correlation between the DAM price and wind speeds. This model helps to identify and quantify the merit order effect of wind power in the European market which was explored in the literature review.

The developed model was explained with the help of a sample dataset from an offshore location in the German North sea. Results of the correlation analysis for the sample dataset indicate a weak to moderate negative correlation between the DAM price and wind speeds. In simple terms, it means that the DAM price is usually high when the wind speeds are low and vice-versa.

Further, this model is used to find the correlation of DAM price and wind speeds for three different locations from Netherlands, Denmark and Germany. Table 3.4 shows the case study locations.

Table 3.4: Case study locations for estimating the correlation of DAM price and wind speeds

Case study	Country	Location	Coordinates	Mean DAM price (€/MWh)	Mean wind speed at 300m (m/s)
1	Netherlands	West-North sea	52.5°N 4.25°E	40	9.8
2	Denmark	West-North sea	55°N 8°E	32	10.6
3	Germany	North east onshore	53°N 12°E	35	8

The temporal coverage for both the datasets is 5 years, ranging from 2015 to 2019 with a resolution of 1 hour. Similar to the sample dataset used to explain the modelling method, the wind speed timeseries data has been obtained from ERA5 reanalysis dataset and the DAM price data has been obtained from ENTSOE-E Transparency platform.

Table 3.5 shows the results obtained from the correlation model for the case study locations. The correlation coefficients for all the locations are negative. This indicates that these locations have a negative correlation between the DAM price and wind speeds. Location from Netherlands has a weaker correlation as compared to the other two locations. Strongest correlation is observed in Denmark followed by Germany. The P values of all the correlation analysis are zero, indicating that all correlations are statistically significant. Therefore, a regression analysis can be performed on the datasets. The slope of the best fit-line indicates the drop in the DAM price with increase in wind speed. For the location in Netherlands, the value of the slope indicates that for every 1 m/s increase of wind speed, the DAM price will drop by 0.4 €/MWh and similarly for the other two locations. Location in Germany has the highest drop in DAM price with increase in wind speed followed by Denmark and then by the Netherlands.

Table 3.5: Correlation model results for the case study locations

Case study	Correlation coefficient	P value	Slope of the best fit-line
1	-0.15	0	-0.4
2	-0.38	0	-0.9
3	-0.32	0	-1.2

Figure 3.15 shows results of the regression analysis performed on the datasets after the correlation analysis. Results infer that the energy sold during low wind speeds will earn more than the energy sold during high wind speeds. This indicates there is a scope for a trade-off between designing a system better suitable for low wind speeds vs designing a system better suitable for high wind speeds. Usually, the system design framework is based on cost driven optimization, but such a scenario indicates the need to investigate a shift to a framework based on value driven optimization.

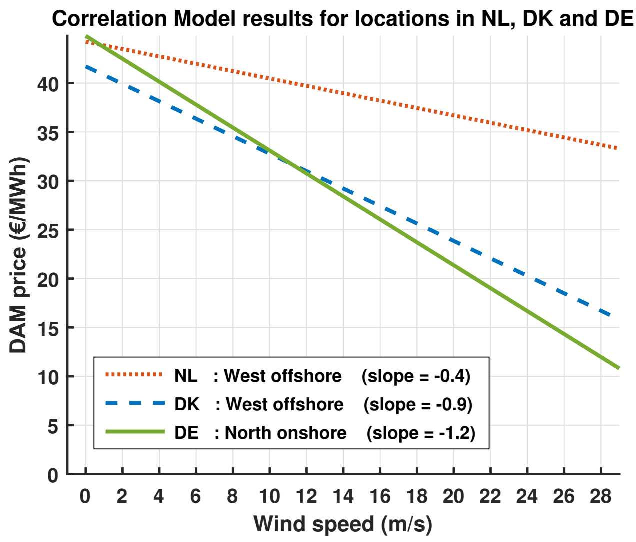


Figure 3.15: Correlation model results for locations in Netherlands, Denmark and Germany

The correlation model forms the first step of developing a decision support framework for the system design of utility scale AWE based on optimization of value. Following section explains the development of the value model and its integration with the correlation model.

3.3. VALUE MODEL

This section addresses the second, the third and the fourth step formulated in the approach to answer the research question. It explains the value model which is an integration of the correlation model, a revenue model and the existing cost model of the company. Figure 3.16 shows the framework of the value model. The model has been developed in MATLAB environment. The framework of the existing cost model of the company has already been explained in section 2.3.1.

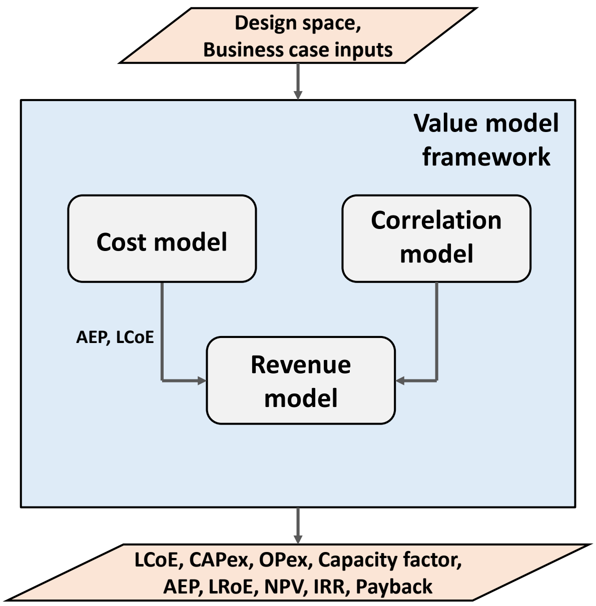


Figure 3.16: Value model framework

In addition to the business case inputs to the cost model, the value model requires assumptions for the energy price. The revenue generation can be based on a subsidy scheme or on the DAM. Correlation model results are used as the inputs for a DAM based revenue generation scenario. Following subsection explains the revenue modelling method based on the the assumptions of the revenue rate. The energy price can be assumed to be a feed-in-tariff (FIT), a feed-in-premium (FIP) or based on the DAM.

REVENUE MODELLING

We know that,

$$Revenue = Energy\ produced\ X\ Energy\ price \tag{3.7}$$

Here, the energy price is modelled as an input based on any one of the following three categories of revenue generation: DAM based, FIT based or FIP based.

In a FIT based revenue generation scenario, the revenue rate is fixed and is not dependent on the wind speeds. In a DAM and FIP based revenue generation scenario, the revenue rate is dynamic in nature and is dependent on the wind speeds. Figure 3.17 shows the revenue modelling method based on the three types of energy price scenarios.

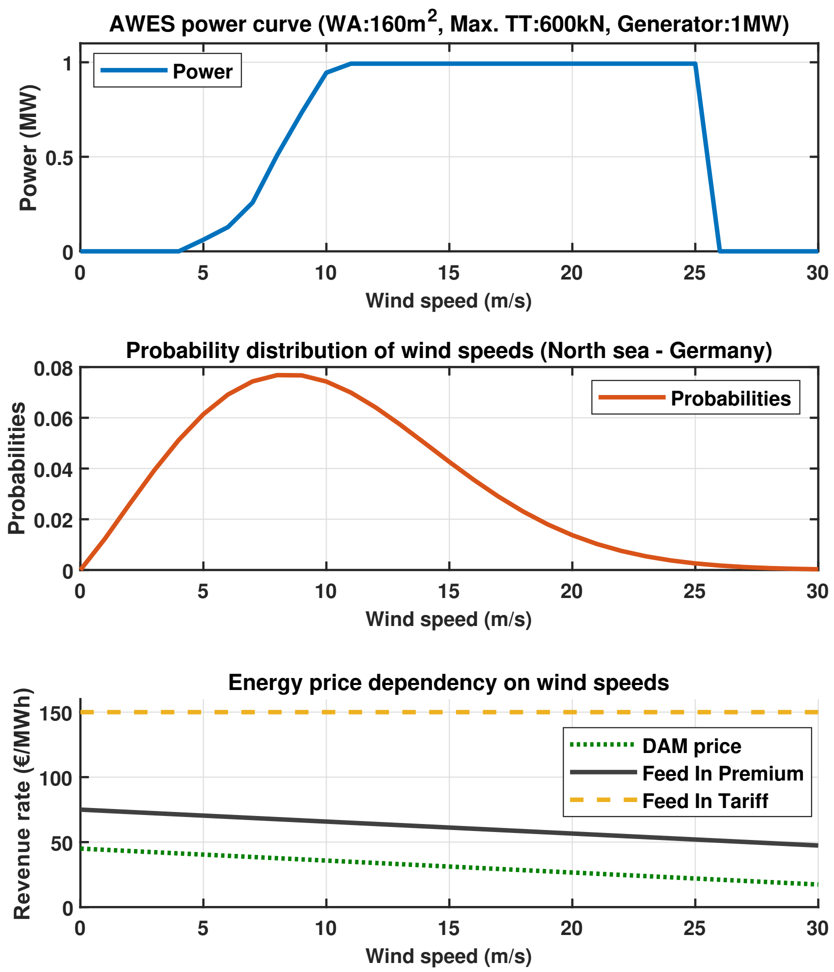


Figure 3.17: Revenue modelling based on energy price as a function of wind speeds

We know that,

$$Revenue\ in\ a\ year = Annual\ Energy\ Production\ X\ Energy\ price \tag{3.8}$$

here,

$$AEP = 8760 \int_{min\ u}^{max\ u} f(u)P(u)du \tag{3.9}$$

u	:	Wind speed
f	:	Probability of wind speed
P	:	Power generated by AWES

Since the revenue rate has been modelled as a function of wind speeds,

$$Revenue\ in\ a\ year = 8760 \int_{min\ u}^{max\ u} f(u)P(u)p(u)du \tag{3.10}$$

where,

p	:	Energy price

Further, it is a possibility that the revenue is not solely dependent on the subsidy scheme for its entire lifetime and is a combination of a subsidy based revenue generation and DAM based revenue generation. Therefore, to compare different systems based on their average revenue rates over their entire project lifetime, levelized revenue of energy (LRoE) is calculated as follows:

$$Levelized\ Revenue\ of\ Energy = \frac{Total\ lifetime\ revenue}{Total\ lifetime\ energy\ production} \tag{3.11}$$

$$LRoE = \frac{\sum_{t=1}^{T} \frac{(p_t + Subsidy_t)E_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \tag{3.12}$$

Where,

$LRoE$	:	Levelized Revenue of Energy
t	:	Time instant
T	:	Economic lifetime of the project
p	:	DAM price
$Subsidy$	:	Subsidy scheme awarded by the Government
E	:	Energy produced
r	:	Discount rate

Since the LCoE and the LRoE are both discounted for the time value of money,

$$Net\ Present\ Value = E(LRoE - LCoE) \tag{3.13}$$

where,

E	:	Energy generation discounted for entire economic lifetime
$LRoE$	:	Levelized Revenue of Energy
$LCoE$	:	Levelized Cost of Energy

LCoE is the cost based metric, LRoE is the revenue based metric and NPV is the value based metric. The user can choice a system based on any of the metrics depending on the business case and the market requirements.

The developed framework has been shaped into a decision support tool with specified inputs and outputs. Following section summarizes the scope, the inputs and the outputs of the tool.

3.4. USING THE TOOL: INPUTS-OUTPUTS

Section 3.1 explained the framework of the developed decision support tool, section 3.2 and section 3.3 explained the correlation model and the value model which are a part of the developed tool. This section explains the scope, the inputs and the outputs of the tool.

SCOPE

The developed tool can be used to understand the optimal system design of AWES for a particular type of market or a business case. Since the tool has been built on the existing cost model, the cost assumptions are based on the current knowledge of the company. The tool can be used for three types of business cases:

1. Offshore repowering
2. Offshore floating
3. Onshore

INPUTS

As explained in section 3.1, the tool requires two types of inputs:

1. Design space of AWES
2. Business case assumptions

The design space of AWES is generated using the analytical performance model of the company. The input is basically the combinations of the aircraft wing areas, maximum tether tensions, associated aircraft masses, generator sizes and the corresponding power curves.

The DAM price and the wind speed timeseries data form the major inputs when considering a DAM based revenue generation scenario. For a fixed revenue rate, the subsidy schemes can be directly assumed by bypassing the DAM price timeseries data.

Other business case inputs include, the number of AWES, lifespan of the project, discount rate, target IRR, wake loss assumption, AWES spacing, distance to port etc.

OUTPUTS

The tool outputs the LCoE, the LRoE and the NPV values for each AWES, in each type of business case. The tool plots the optimal tether tension configurations for each of the generator sizes, for every business case, based on the mentioned economic indicators.

Other outputs of the tool include the energy production of the wind farm, CAPex, OPex, capacity factor, total revenue, internal rate of return (IRR), payback period and a minimum FIP required over the DAM price to achieve the target IRR.

Based on different business case assumptions, the user can understand the optimal system design for AWE for that particular type of business case. Following chapter presents a case study and its results which help to understand the use cases of the tool and to answer the research question.

4

CASE STUDY

This chapter addresses the fifth step formulated in the approach to answer the research question of comparing 'cost driven system design' with 'value driven system design' based on the developed tool. Section 4.1 states the assumptions of the case study, section 4.2 discusses the results for a subsidy based revenue generation scenario, section 4.3 discusses the results for a DAM based revenue generation scenario and section 4.4 discusses the results from the case study.

4.1. ASSUMPTIONS AND INPUTS TO THE TOOL

As identified in chapter 2 and section 3.2, the merit order effect has been more pronounced in locations in Germany as compared to other European countries. Therefore, Germany has been chosen for this case study. Figure 4.1 shows the three business case locations for the case study.

▼ Offshore floating location (55˚N 6˚E)

▼ Offshore repowering location (54˚N 7˚E)

▼ Onshore location (53˚N 12˚E)

Figure 4.1: Case study location [11]

The repowering business case is based on the wind farm 'Nordsee one' owned by RWE Renewables and consists of 54 turbines. The floating business case is based on one of the development zones in the German exclusive economic zone [67]. The onshore location is based on using open farmlands in north eastern part of Germany near Plattenburg. The wind speed data for these locations has been obtained from ERA5 Reanalysis dataset [45]. Table 4.1 shows the case study assumptions and the inputs to the tool.

Table 4.1: Case study assumptions and inputs to the tool

Input	Repowering	Floating	Onshore	Units	Source
Location	54°N,7°E	55°N, 6°E	53°N, 12°E	-	Google maps
Number of AWES	30	30	30	-	Assumption
Lifespan	20	25	25	Years	Assumption
Distance to port	100	150	-	km	Google maps
Export cable length	-	160	-	km	Google maps
Wake loss	1%	1%	1%	-	Assumption
AWES spacing	400	400	400	m	Assumption
Discount rate	10%	10%	10%	-	Assumption
Avg. wind speed at 300m	10.2	10.7	8	m/s	ERA5

A suitable design space was generated using the analytical performance model of the company as explained in chapter 3. As advised by company experts, the analytical performance model was used for the wing area and tether tension range shown in Figure 4.2. The wing areas range from 70m^2 to 220m^2 with a resolution of 70m^2, the tethers range from 300kN to 900kN with a resolution of 100kN and the generators range from 1MW to 3MW with a resolution of 1MW. As a result of all the combinations in the the given range and resolution of wing areas, tethers and generators, the design space includes 126 configurations. These 126 configurations are given as the input to the tool.

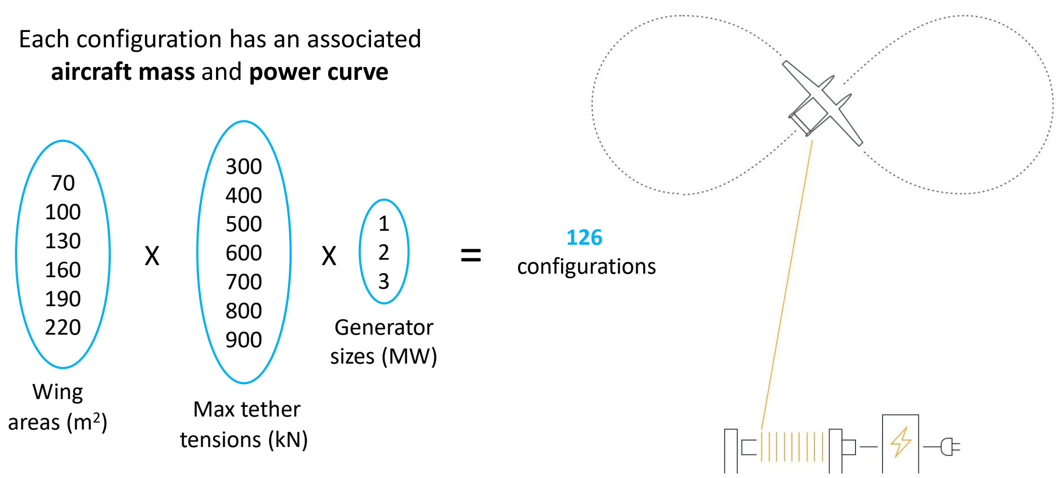


Figure 4.2: Design space input for case study

Two different revenue generation scenarios are compared to understand the influence of DAM on value driven system design:

- Scenario 1: Subsidy based revenue generation - Since the revenue rate for the energy produced at any time is constant, there would not be a difference in 'cost driven system design' and 'value driven system design'.
- Scenario 2: DAM based revenue generation - Since the revenue rate is dynamic and dependent on wind speeds, there could be a difference in 'cost driven system design' and 'value driven system design'.

DISCLAIMER FROM THE RESEARCH PARTNER

The cost model of Ampyx Power distinguishes between the first series production costs (limited-run manufacturing of around 50 systems) and recurring production costs (mass manufacturing of around 1000+ systems). It is also equipped to account for future improvement trends in materials, manufacturing techniques etc. LCoE also relies strongly on the park size. This thesis aims to investigate the dependencies, and not the future commercial potential. For this reason, the analysis is limited to the first series production cost assumptions for park size of 30 systems.

Ampyx Power currently foresees the following commercial scenarios [68]:

- Approximately 1 MW for onshore remote grid solutions (series of 1000 in first 5 years)
- Subsequently, approximately 3 MW for onshore and offshore repowering,
- About 5 MW and larger for floating offshore.

To keep a limit on the amount of extrapolation necessary, for comparison purposes, the three business cases onshore, offshore repowering and floating offshore are compared only at 1, 2 and 3 MW in this work.

4.2. SCENARIO 1: SUBSIDY BASED REVENUE GENERATION

Table 4.2 states the subsidy scheme assumptions for this scenario. FIT is a price-based policy instrument irrespective of the DAM price, whereby the eligible renewable energy generators are paid a fixed price at a guaranteed level for the electricity produced and fed into the grid [55].

Table 4.2: FIT assumptions for the subsidy based scenario

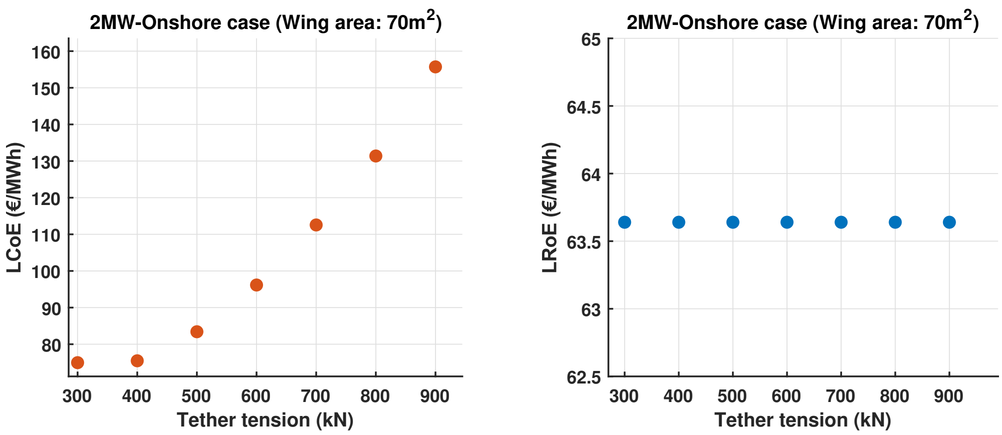
	Repowering case	Floating case	Onshore case	Unit
Feed In Tariff	120	200	70	€/MWh

4.2.1. CONCEPT OF AN OPTIMAL TETHER TENSION

The tool gives the LCoE, LRoE and NPV values for each of the 126 system configurations in the design space and for each of the three business cases. Consider the following system configuration out of the 126 configurations:

Aircraft wing area : 70m^2
Generator size : 2MW

There are 7 tethers which can be coupled to the above combination to give 7 different configurations. Figure 4.3 shows the LCoE and the LRoE values for the onshore business case with these 7 configurations. Each marker on the graph represents value of the economic indicator for a particular tether tension combination with the above configuration.



(a) LCoE (b) LRoE

Figure 4.3: LCoE and LRoE values for all tether tension combinations with a 70m^2 wing area and 2MW generator size for the onshore business case: FIT based revenue generation scenario

Figure 4.3a shows that the minimum LCoE is obtained for the combination with the tether tension of 300kN. LCoE for the combination with the tether tension of 400kN is almost the same. With further increase in tether tension the LCoE is increasing, indicating that cost is scaling faster than energy production. This shows that for a particular wing area, generator size and the type of business case, a particular tether tension leads to the minimum LCoE. This tether tension is referred to as the optimal tether tension for that configuration.

Figure 4.3b shows that the LRoE for all combinations is the same. This is the result of the fixed revenue rate (Feed in Tariff) of 70 €/MWh. Since the LRoE is discounted for the time value of money, the LRoE in this case comes out to be 63.6 €/MWh.

Figure 4.3 showed the LCoE and LRoE values for a configuration with a single wing area coupled with 7 tether tensions in a particular business case. Similarly, Figure 4.4 shows the LCoE, LRoE and NPV values for each of the 6 wing areas in combination with each of the 7 tether tensions coupled with a 2MW generator for the onshore business case.

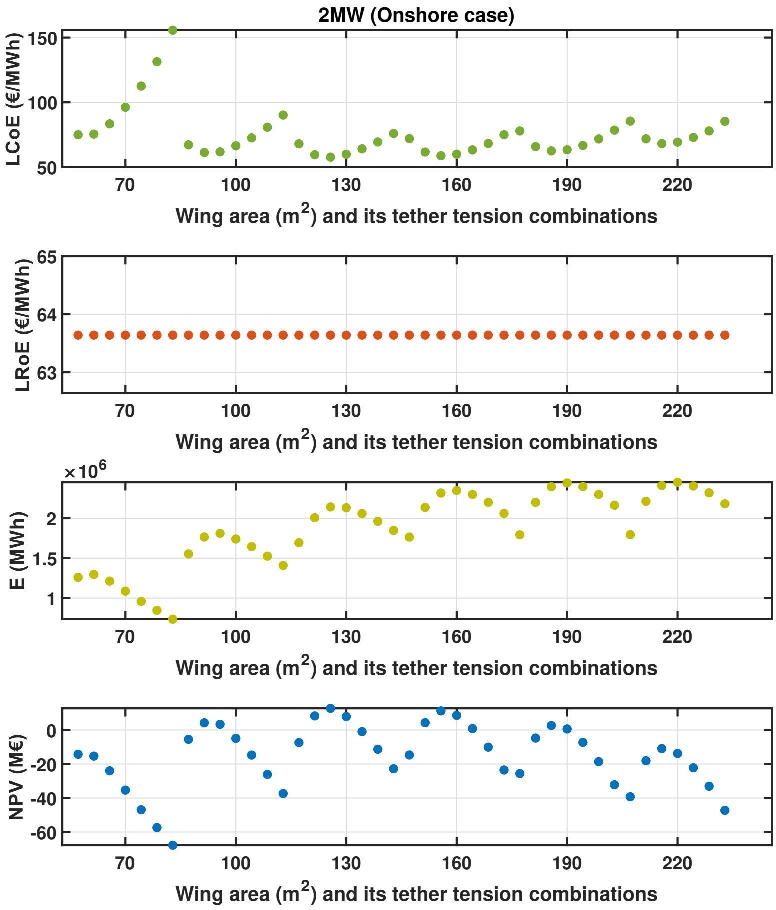


Figure 4.4: LCoE, LRoE and NPV of all tether tension combinations for each wing area in the design space coupled with a 2MW generator for the onshore business case: FIT based revenue generation scenario

It can be observed that for each wing area, there exists an optimal tether tension with respect to LCoE and NPV. Since this scenario is based on FIT subsidy scheme, all the tether tension combinations have the same LRoE. Tool outputs for all the three generator sizes and for all the three business cases are provided in appendix A.1.

It is known from section 2.3 that,

$$NPV = E(LRoE - LCoE) \tag{4.1}$$

Since the LRoE for all the combinations is the same, the optimal tether tension with respect to LCoE is same as that with respect to NPV. Therefore, in a FIT based subsidy scenario for a particular business case and for a particular generator size, there is no difference in cost driven system design and value driven system design.

Figure 4.4 is a representative tool output. It shows the values of the economic indicators for a particular generator size and a particular business case. Following subsection, discusses the tool outputs showing the optimal tether tension configurations for all the three generator sizes and all the three business cases.

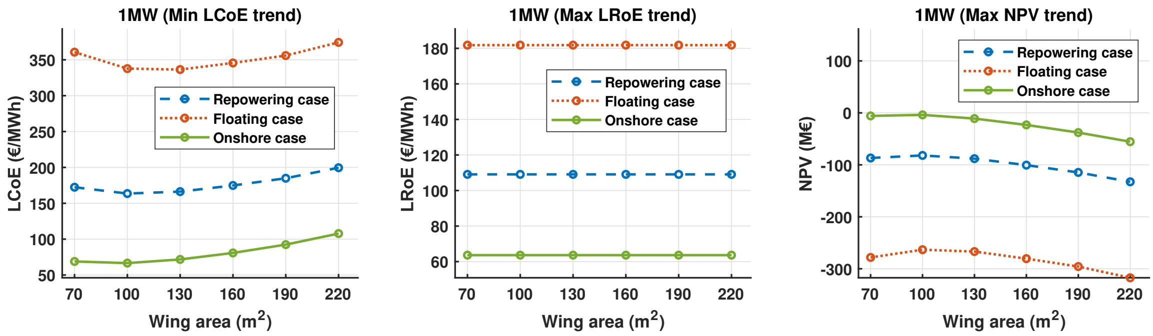
4.2.2. OPTIMAL SYSTEM CONFIGURATIONS

From subsection 4.2.1, it is known that for a given wing area and a given generator size, there exists an optimal tether tension with respect to any of the economic indicators. This is valid for any type of business case.

Any aircraft and a tether combination can be coupled to any of the generator size. Depending upon the aircraft wing area and the tether tension, a particular combination would be able to produce maximum possible power based on the generator size. It is known that energy production increases with increase in wing area and tether tension, but the cost also scales with wing area and tether tension. Therefore, there is an optimal system configuration for a given generator size after which the cost scales faster than the energy production.

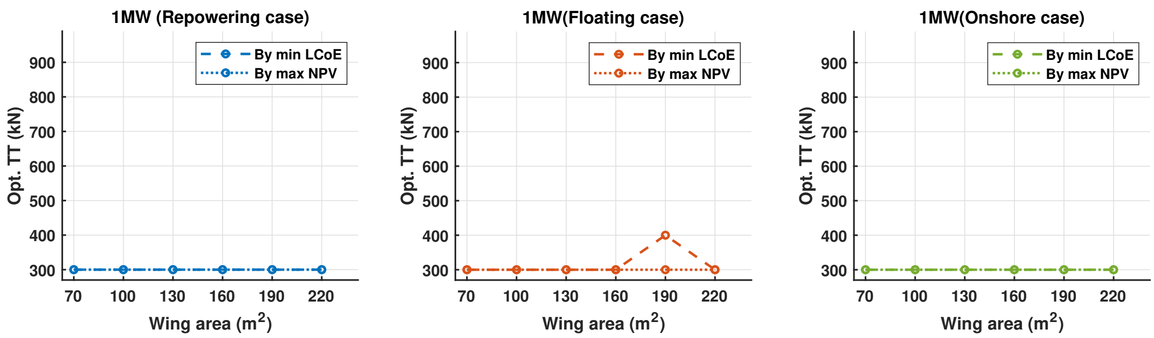
1MW GENERATOR

Figure 4.5 shows LCoE, LRoE, NPV trends with the optimal tether tension for each wing area and Figure 4.6 shows those optimal tether tensions in all the three types of business cases.



(a) LCoE (b) LRoE (c) NPV

Figure 4.5: LCoE, LRoE and NPV trends with the optimal tether tension for each wing area, for the generator size of 1MW: FIT based revenue generation scenario



(a) Repowering (b) Floating (c) Onshore

Figure 4.6: Optimal tether tensions for each wing area, for the generator size of 1MW: FIT based revenue generation scenario

As discussed in subsection 4.2.1, the LRoE values for all the configurations in a FIT based scenario are the same. Figure 4.5b also shows that in each of the three business cases LRoE of all the configurations is the same. Therefore, from equation 4.1, the optimal system configuration with respect to LCoE will be the same as that with respect to NPV.

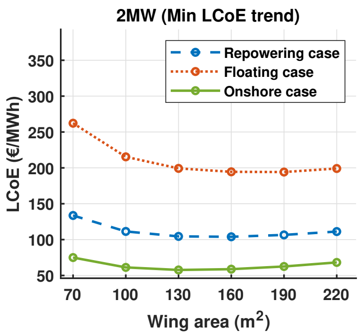
From Figure 4.5c, it can be observed that for all the three types of business cases, the point of inflection falls at the wing area of 100m^2 (max NPV). Therefore, the optimal wing area would be 100m^2. There is minimal additional benefit in NPV and LCoE of the 100m^2 wing area than the 70m^2 wing area. On the other hand, there could be an additional technical risk of scaling up the aircraft from 70m^2 to 100m^2. Therefore, there lies a trade-off between the 70m^2 and the 100m^2 based on the technical challenges in upscaling and the additional economic benefit. All inclusive, for a 1MW generator size, an aircraft of wing area of around 70m^2 to 100m^2 seems suitable.

From Figure 4.6, it can be observed that the optimal tether tension with respect to cost and with respect to value is the same with an exception for the wing area of 190m^2 in the offshore floating case. For that particular combination, the NPV and LCoE values at the tether tensions of 300kN and 400kN are almost equal. For a

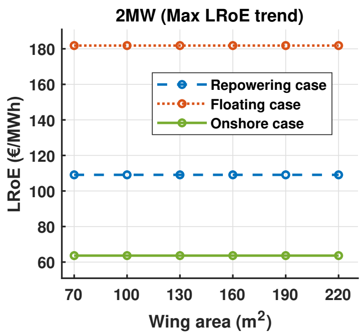
1MW generator size, lower tether tensions are optimal. The design space does not include a tether tension lower than 300kN, but if included, it is a possibility that tether tensions lower than 300kN might be optimal for a 1MW system.

2MW GENERATOR

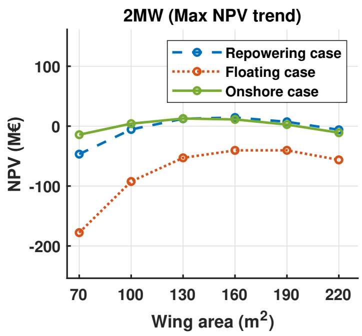
Figure 4.7 shows LCoE, LRoE, NPV trends with the optimal tether tension for each wing area and Figure 4.8 shows those optimal tether tensions in all the three types of business cases.



(a) LCoE

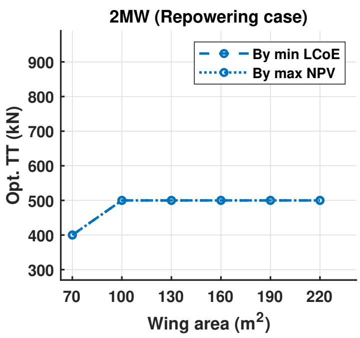


(b) LRoE

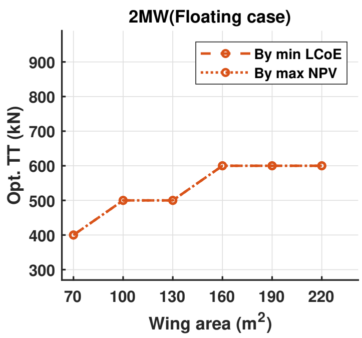


(c) NPV

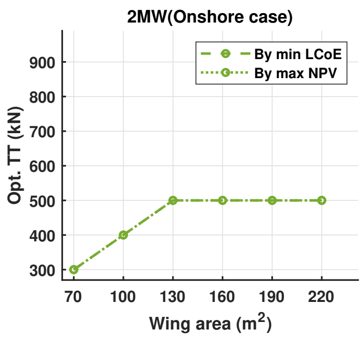
Figure 4.7: LCoE, LRoE and NPV trends with the optimal tether tension for each wing area, for the generator size of 2MW: FIT based revenue generation scenario



(a) Repowering



(b) Floating



(c) Onshore

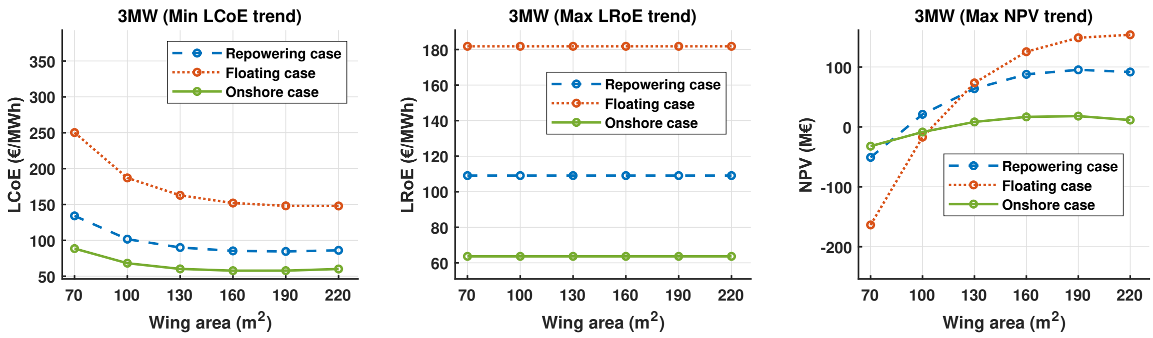
Figure 4.8: Optimal tether tensions for each wing area, for the generator size of 2MW: FIT based revenue generation scenario

Similar to 1MW, the optimal system configurations with respect to LCoE are same as that with respect to NPV. Figure 4.8 shows that, for the offshore floating case, the point of inflection lies between the wing areas of 160m^2 and 190m^2, for the repowering case, it lies between 130m^2 and 160m^2 and for the onshore case, it lies around 130m^2. For all the three types of business cases, the additional economic benefit decreases after around 130m^2. Considering the scaling risks, for a 2MW generator size, an aircraft of wing area of around 130m^2 seems suitable.

From Figure 4.8, it can be observed that the optimal tether tension with respect to LCoE and that with respect to NPV is the same. With increase in wing area, the optimal tether tension also increases and overall, the optimal tether tensions for a 2MW system are higher than as compared to 1MW systems.

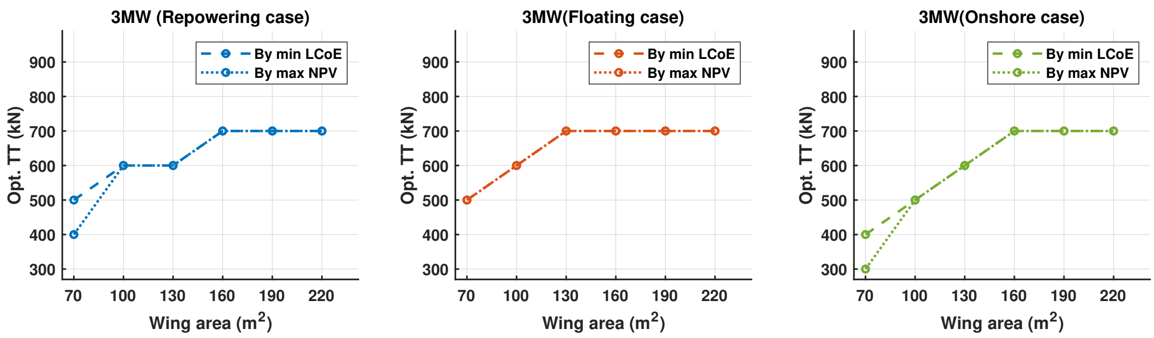
3MW GENERATOR

Figure 4.9 shows LCoE, LRoE, NPV trends with the optimal tether tension for each wing area and Figure 4.10 shows those optimal tether tensions in all the three types of business cases.



(a) LCoE (b) LRoE (c) NPV

Figure 4.9: LCoE, LRoE and NPV trends with the optimal tether tension for each wing area, for the generator size of 3MW: FIT based revenue generation scenario



(a) Repowering (b) Floating (c) Onshore

Figure 4.10: Optimal tether tensions for each wing area, for the generator size of 3MW: FIT based revenue generation scenario

Similar to 1MW and 2MW, the optimal system configurations with respect to LCoE are same as that with respect to NPV. For the floating case, the point of inflection is not clearly visible. The curve already flattens at around 220m^2. For the repowering and onshore case, the point of inflection lies at 190m^2. For all the three cases, the additional economic benefit decreases drastically after around 160m^2. Therefore for a 3MW generator size, an aircraft of wing area of around 160m^2 seems suitable.

From Figure 4.10, it can be observed that the optimal tether tension with respect to LCoE and with respect to NPV is the same with an exception for the wing area of 70m^2 in the repowering case and the onshore case. The LCoE and NPV values for the combination of the 70m^2 wing area with the tether tensions of 300kN and 400kN are almost the same. Optimal tether tensions are increasing with an increase in wing area and the tether tensions for a 3MW system are higher than the 2MW systems.

4.3. SCENARIO 2: DAM BASED REVENUE GENERATION

In this scenario, the revenue generation of AWES is based on the DAM. In such a scenario, output from the correlation model forms the basis for revenue calculations. Following subsection explains the effect of correlation between the DAM price and wind speeds on the revenue generation of AWES.

4.3.1. EFFECT OF THE DAM PRICE DEPENDENCY ON WIND SPEEDS

Figure 4.11 shows the output from the correlation model for this case study. All the three business case locations have a statistically significant negative correlation between the DAM price and wind speeds. The repowering location has a correlation of -0.33, the floating case location of -0.29 and the onshore location of -0.31. In this scenario, the value of energy generated at low wind speeds is higher than the value of energy generated at higher wind speeds. Figure 4.11 shows the model results for the locations. The onshore location has the highest drop in the DAM with increase in wind speeds followed by the repowering location and the floating location respectively. The average DAM price is 35.5€/MWh. This shows that, the revenue generated by AWES above the wind speeds of around 10m/s will be lesser than the average revenue generated by other power plants in the market.

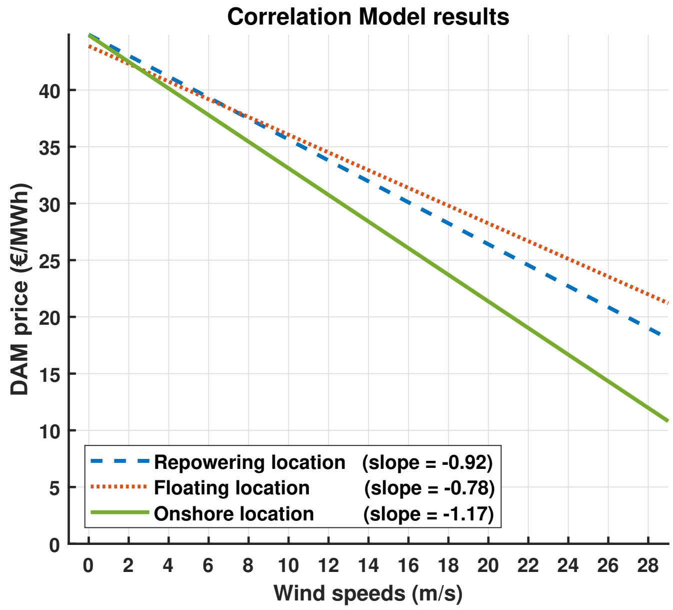
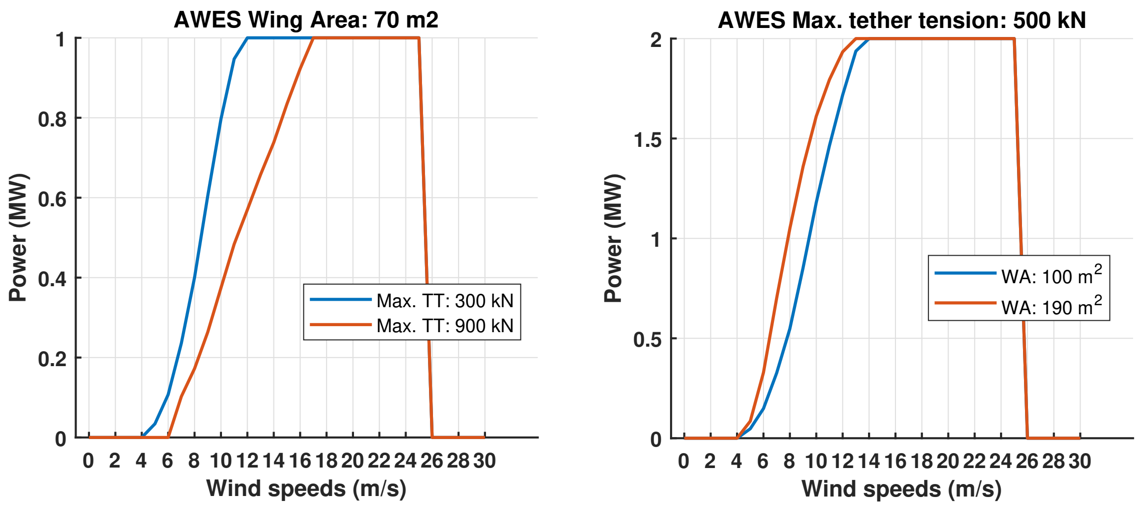


Figure 4.11: Correlation model results: Case study from Germany

Figure 4.12 shows sample power curves from the design space. Figure 4.12a shows the power curves of two configurations in which a wing area of 70m^2 coupled to tether tensions of 300kN and 900kN. The configuration with smaller tether tension produces more power at lower wind speeds than the configuration with higher tether tension. Figure 4.12b shows the power curves of two configurations in which a tether of tension 500kN is coupled to two different wing areas of 100m^2 and 190m^2. The configuration with higher wing area produces more power at lower wind speeds than the configuration with lower wing area.



(a) Wing area: 70m^2

(b) TT: 500kN

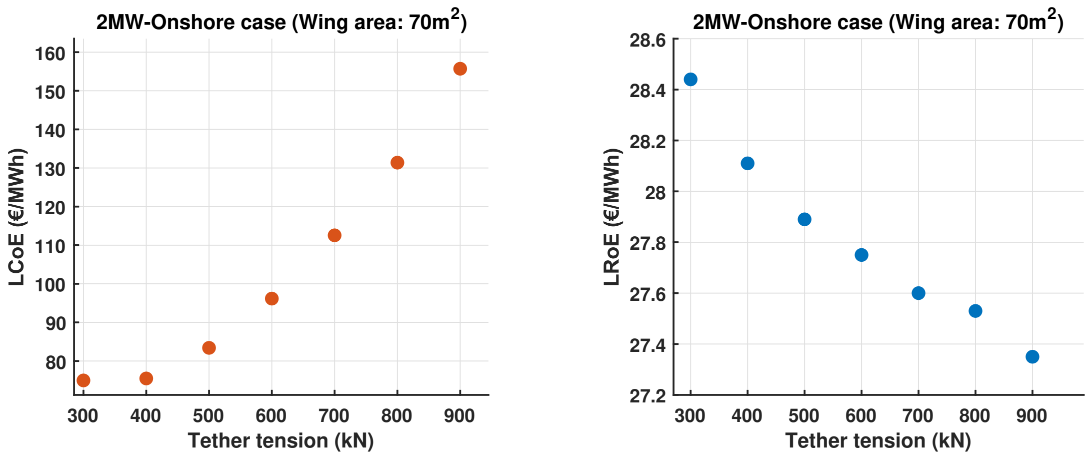
Figure 4.12: Sample power curves from design space showing different power production profiles at low wind speeds

From Figure 4.11, it is known that the value of power produced at lower wind speeds is higher than that produced at higher wind speeds. From Figure 4.12, it is known that different configurations of AWES produce different power at low wind speeds. Therefore it can be inferred that unlike the FIT scenario, the LRoE of each configuration will be different.

Figure 4.13 shows the LCoE and LRoE values for a configuration with a wing area of 70m^2 coupled with a 2MW generator in the onshore business case. Each marker on the graph represents value of the economic indicator for a particular tether tension combination.

From Figure 4.13a it is observed that the LCoE increases with an increase in tether tension and the minimum LCoE is at the tether tension of 300kN. Therefore, 300kN is an optimal tether tension for this case with respect to LCoE.

Figure 4.13b shows that LRoE drops with increase in tether tension, which is unlike the FIT scenario where the LRoE for each tether tension was the same. As evident from Figure 4.12a, for a configuration with a wing area of 70m^2 lower tether tensions produce more power at lower wind speeds than higher tether tensions and since in a DAM based scenario the value of power at lower wind speeds is higher, the LRoE drops with an increase in tether tension. Therefore, the optimal tether tension with respect to LRoE is 300kN. The average DAM price is 35.5€/MWh and the maximum LRoE is 28.5€/MWh, which is around 20% lesser than the average DAM price.



(a) LCoE (b) LRoE

Figure 4.13: LCoE and LRoE values for all tether tension combinations with a 70m^2 wing area and 1MW generator size for the onshore business case: DAM based revenue generation scenario

Though in this case it appears that the optimal tether tension with respect to LCoE is same as that with respect to LRoE, it might not necessarily be the case always. Figure 4.14 shows the LCoE, LRoE and NPV values for each of the 6 wing areas in combination with each of the 7 tether tensions.

Unlike Figure 4.4 in the FIT based scenario, the LRoE values for all the configurations are different. The optimal tether tension with respect to LCoE may not be equal to that with respect to LRoE. As in the case of wing area of 130m^2, the optimal tether tension with respect to LCoE is 500kN (the third marker) and the optimal tether tension with respect to LRoE is 300kN (the first marker). Therefore, from equation 4.1 we can infer that the optimal tether tension with respect to LCoE may not be equal to the optimal tether tension with respect to NPV.

Since LRoE values for all the configurations are lower than the LCoE values, the NPV values are negative. This indicates a loss making scenario. Therefore, the objective changes from profit maximization to loss minimization. The configuration which makes minimum loss is termed as the optimal system configuration based on value.

Figure 4.14 is a representative tool output. It shows the values of the economic indicators for a particular generator size and a particular business case. Following subsection, discusses the tool outputs showing the optimal tether tension configurations for all the three generator sizes and all the three business cases.

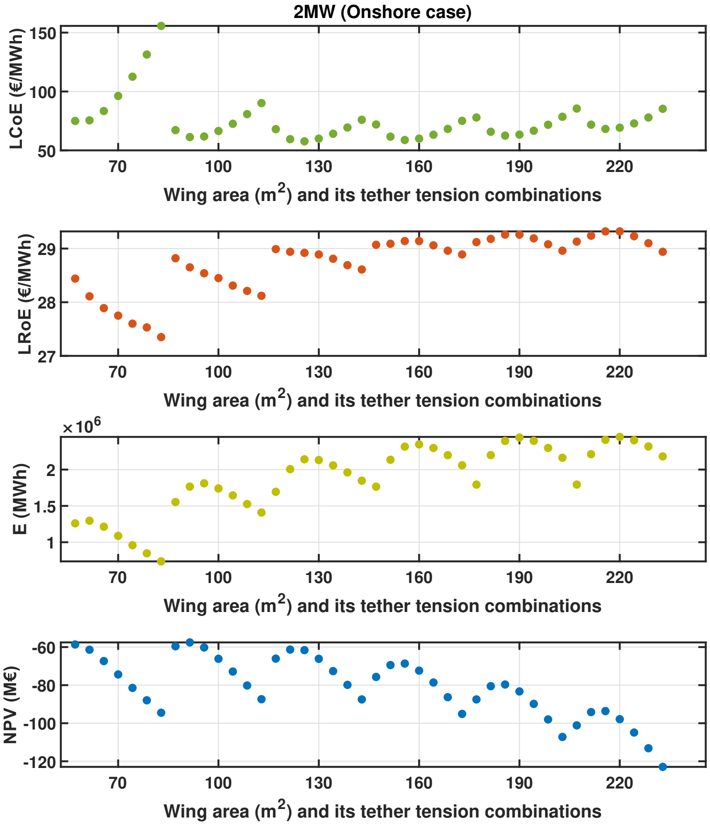


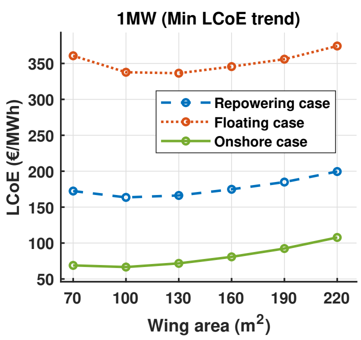
Figure 4.14: LCoE, LRoE and NPV of all tether tension combinations for each wing area in the design space coupled with a 2MW generator for the onshore business case: DAM based revenue generation scenario

Tool outputs for all the three generator sizes and for all the three business cases are provided in appendix A.2.

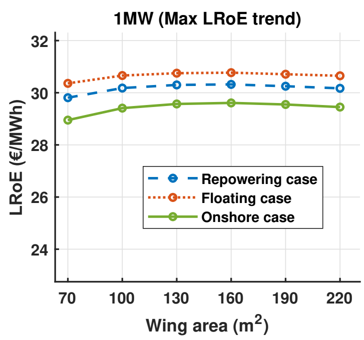
4.3.2. OPTIMAL SYSTEM CONFIGURATIONS

1MW GENERATOR

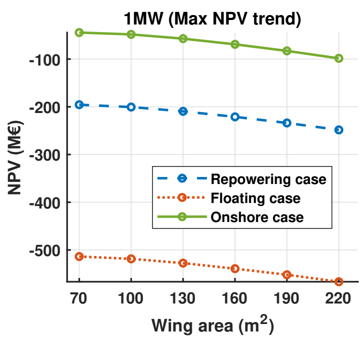
Figure 4.15 shows LCoE, LRoE, NPV trends with the optimal tether tension for each wing area and Figure 4.16 shows those optimal tether tensions in all the three types of business cases.



(a) LCoE

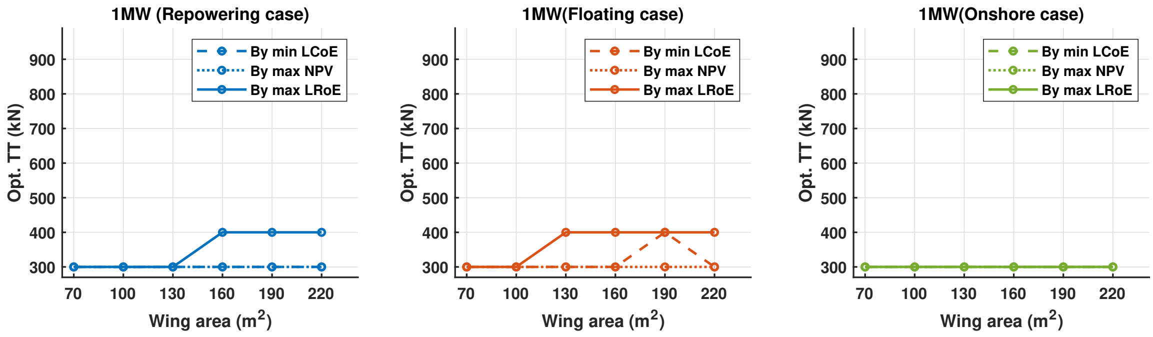


(b) LRoE



(c) NPV

Figure 4.15: LCoE, LRoE and NPV trends with the optimal tether tension for each wing area, for the generator size of 1MW: DAM based revenue generation scenario



(a) Repowering (b) Floating (c) Onshore

Figure 4.16: Optimal tether tensions for each wing area, for the generator size of 1MW: DAM based revenue generation scenario

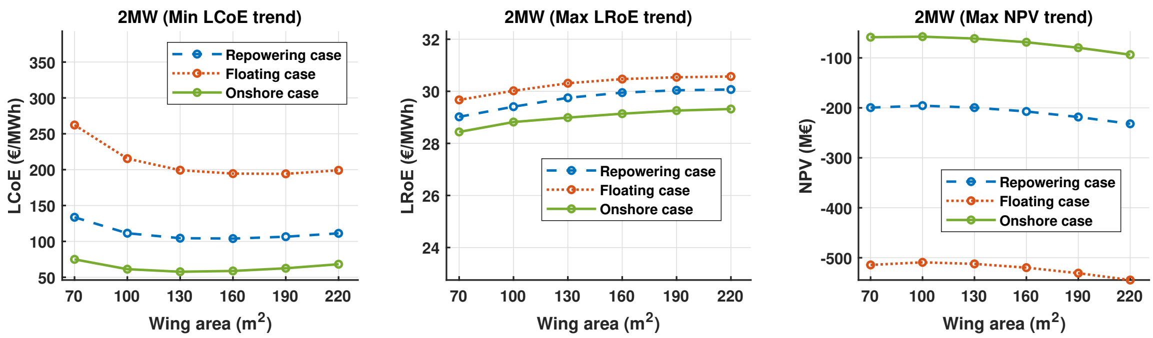
Figure 4.15a shows the LCoE curves which are same as that in the FIT based revenue generation scenario. But, unlike the FIT based scenario, the LRoE values are not the same for all configurations. According to the correlation model results, the onshore location has the maximum drop in the energy price followed by the repowering location and then the floating location. LRoE curves for all the three business cases have the inflection point at 160m^2. Since the LRoE values are smaller than LCoE values for each configuration, the NPVs are negative.

In all the cases, the configuration minimizing the loss is with the aircraft of 70m^2 of wing area. This is mainly due the fact that smaller configurations produce lesser energy as compared to configurations with larger aircrafts. This is evident from Figure 4.14. This indicates that when the LRoE values are smaller LCoE values, value driven optimization will always lead to smallest configurations to minimize the loss.

Figure 4.16 shows the optimal tether tensions for each wing area for all the three types of business cases. It is observed that for certain configurations, the optimal tether tension for wing areas with respect to different economic indicators is different. In the FIT based scenario, optimal tether tension with respect to LRoE did not exist. For higher wing areas, the optimal tether tension with respect to LRoE is higher than that with respect to LCoE and NPV.

2MW GENERATOR

Figure 4.17 shows LCoE, LRoE, NPV trends with the optimal tether tension for each wing area and Figure 4.18 shows those optimal tether tensions in all the three types of business cases.

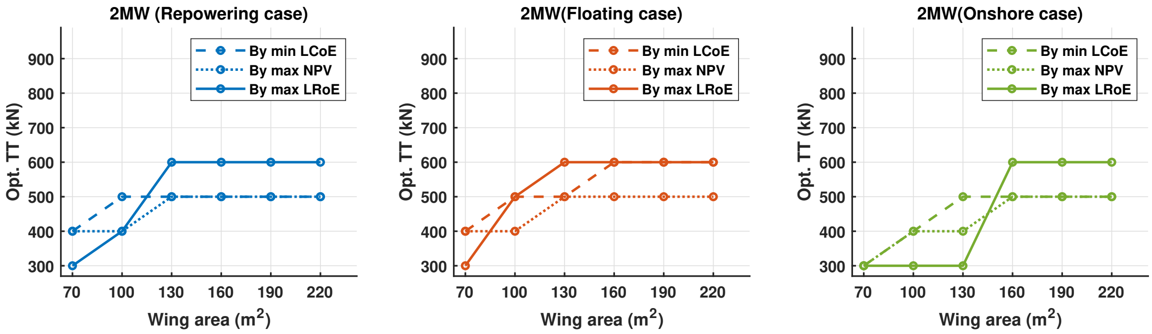


(a) LCoE (b) LRoE (c) NPV

Figure 4.17: LCoE, LRoE and NPV trends with the optimal tether tension for each wing area, for the generator size of 2MW: DAM based revenue generation scenario

Figure 4.17a shows the LCoE curves which are same as that in the FIT based revenue generation scenario. From Figure 4.17b, it can be seen that the LRoE curves do not have an inflection point but increase with wing area. In terms of NPV, the scenario is similar to the 1MW systems.

Figure 4.18 shows the optimal tether tensions for different wing areas with respect to different economic indicators are different. Overall, the optimal tether tension with respect to all the indicators increases with wing area and also are larger than the 1MW systems. The difference in optimal tether tensions with respect to LCoE and LRoE arises due to the difference in performance of different system configurations at lower wind speeds.

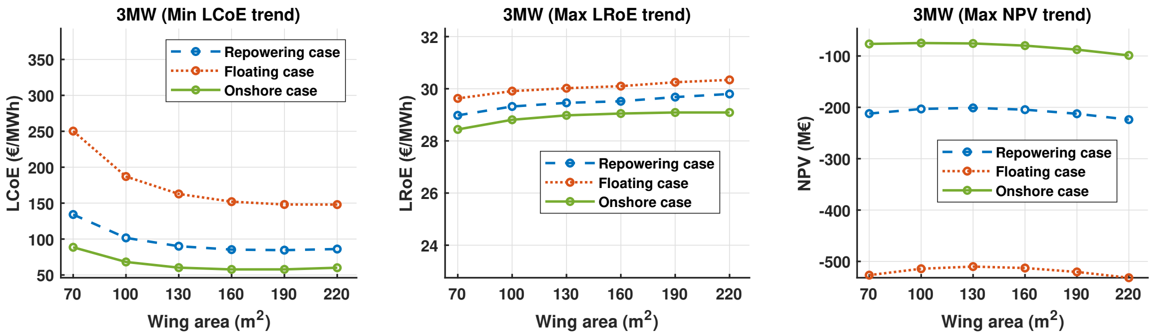


(a) Repowering (b) Floating (c) Onshore

Figure 4.18: Optimal tether tensions for each wing area, for the generator size of 2MW: DAM based revenue generation scenario

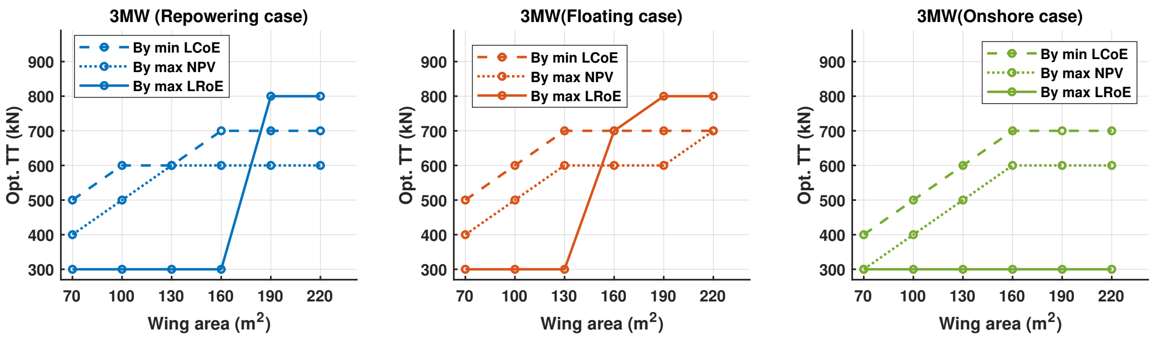
3MW

Figure 4.19 shows LCoE, LRoE, NPV trends with the optimal tether tension for each wing area and Figure 4.20 shows those optimal tether tensions in all the three types of business cases.



(a) LCoE (b) LRoE (c) NPV

Figure 4.19: LCoE, LRoE and NPV trends with the optimal tether tension for each wing area, for the generator size of 3MW: DAM based revenue generation scenario



(a) Repowering (b) Floating (c) Onshore

Figure 4.20: Optimal tether tensions for each wing area, for the generator size of 3MW: DAM based revenue generation scenario

Figure 4.19a shows the LCoE curves which are same as that in the FIT based revenue generation scenario. From Figure 4.19b, similar to 2MW systems, it can be seen that the LRoE curves do not have an inflection point but increase with wing area. In terms of NPV, the scenario is similar to the 1MW and 2MW systems.

Figure 4.20 shows the optimal tether tensions for each wing area with different economic indicators. It is observed that, for most of the wing areas, the optimal tether tension with respect to LCoE is higher than with respect to NPV. Overall, the optimal tether tension with each indicator increases with increase in wing area and are larger than as compared to 1MW and 2MW systems. Onshore location has comparatively stronger correlation of DAM prices and wind speeds, therefore configurations performing better at lower wind speeds i.e lower tether configurations are optimal.

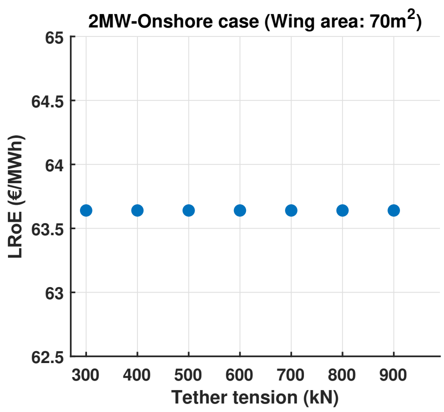
Discussion of results and comparison of the two scenarios of the case study is presented in the following section.

4.4. DISCUSSION OF RESULTS

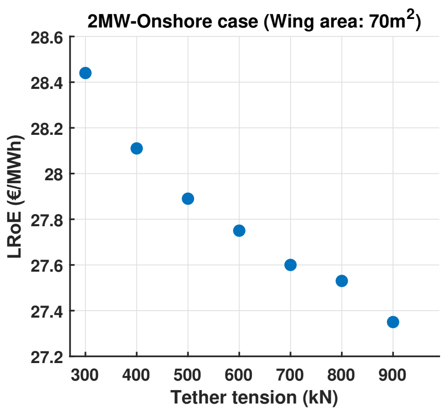
A case study of three different locations in Germany has been analyzed using the developed decision support tool. The case study involved three different types of business cases - Offshore repowering, offshore floating and onshore. The business cases have been analyzed for two different types of revenue generation scenarios - FIT based revenue generation and DAM based revenue generation. The main aim of this case study was to use the tool to understand the difference in the system design of AWES in both the scenarios.

The tool is used to compare AWES based on their LCoE, LRoE and NPV. Since the LCoE is independent of the revenue streams, the LCoE values of all configurations in both the scenarios are the same. In the FIT based revenue generation scenario, the energy price for all the systems is the same, and does not have a time component. In the DAM based revenue generation, the energy price is dynamic. Correlation model results confirmed the DAM price dependency on wind speeds. All the three locations from the case study have a negative correlation between the DAM price and wind speeds. This means that the power produced at lower wind speeds is more valuable than the power produced at higher wind speeds. Therefore, the energy price for all the systems is not same and has a time component.

Figure 4.21 compares the LRoE values for an aircraft of 70m^2 wing area coupled with the 2MW generator in the onshore business case. Each marker on the graph represents a specific tether tension combination for the above configuration. Figure 4.21a shows the LRoE values for the FIT based revenue generation scenario. Since the revenue rate in this scenario is same for all the configurations, the LRoE values for all the tether tension combinations is the same. Figure 4.21b shows the LRoE values for the DAM based revenue generation scenario. Since the revenue rate in this scenario is dynamic and is modelled as a function of wind speeds, the LRoE values for every tether tension combination are different.



(a) FIT based revenue generation



(b) DAM based revenue generation

Figure 4.21: Comparison of LRoE values in a FIT based revenue generation scenario and a DAM based revenue generation scenario

Generally, system design is based on optimization of LCoE. But, in a DAM based revenue generation scenario, different systems will generate different revenue. LRoE is a metric which can be used to compare systems based on their capability to generate revenue. NPV is a metric which captures both of these aspects, since:

$$NPV = E(LRoE - LCoE) \tag{4.2}$$

If LRoE values for all the system configurations are the same, the optimal system configuration with respect to LCoE is same as that with respect to NPV. Therefore, in the FIT scenario, there is no difference is cost driven system design and value driven system design.

In a DAM based revenue generation scenario, the LRoE of different systems is different. Therefore, the optimal system configuration with respect to LCoE may not be same as that with respect to NPV. This is confirmed in the results from the DAM scenario. Value driven system design leads to a system performing better at lower wind speeds. Since LRoE values are smaller than the LCoE values for all the configurations, the NPV values are negative. Therefore, optimizing for value in this case means minimizing the loss. Since smaller aircraft configurations produce smaller amount of energy as compared to larger aircrafts, value driven optimization leads to smaller aircrafts.

Figure 4.22 shows the tool outputs for the 3MW floating business case. It can be seen that the LCoE decreases, whereas, the LRoE and E increases with wing area. Since LRoE is smaller than LCoE and the energy production increases with wing area, the NPV decreases with wing area. Larger wing areas have similar LRoE over the entire tether tension range. Overall, the optimal tether tension increases with increasing wing area. Tool outputs for all the generator sizes and all the three types of business cases are provided in Appendix A.2

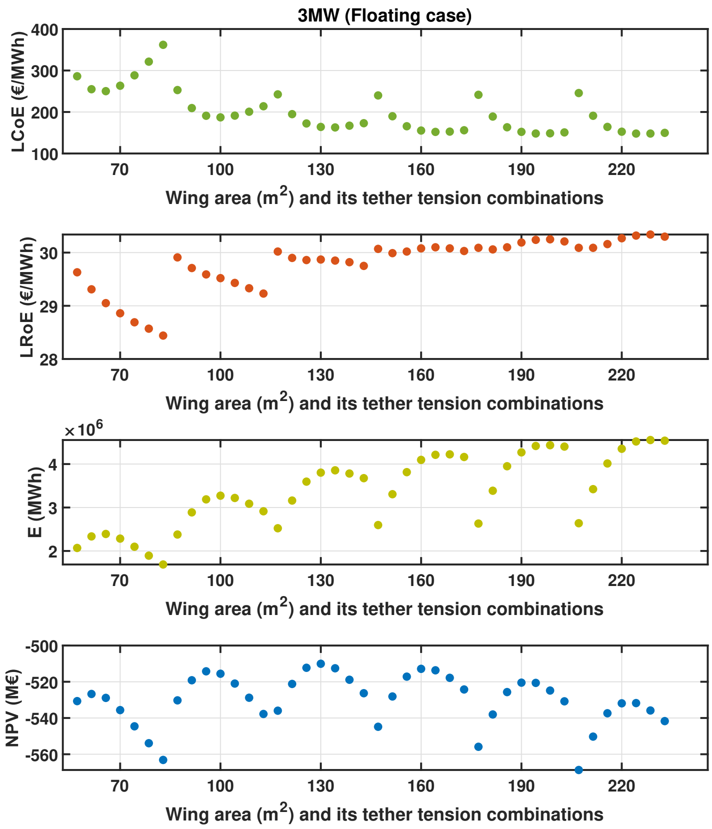


Figure 4.22: Tool outputs for the 3MW floating business case

The average DAM price is 35 €/MWh. Tool results show that maximum LRoE is around 30.5 €/MWh which is in the 1MW repowering and floating cases (refer Appendix A.2). This shows that the AWES are generating lesser revenue than the average revenue generated by other power plants in the market. This shows that there are uncertainties in revenue estimations in a DAM based revenue generation scenario. This tool can also be used in risk management by providing better understanding of the revenue streams.

The tool outputs are mainly influenced by the performance model used to generate the design space of AWES, the cost model assumptions, and the quality of DAM price and wind speed data for the chosen location. The range of the design space is limited by the performance model. The performance model used is not robust enough to accurately model the power curves and mass dependencies of the configurations but is more suitable for sensitivity studies and observing trends. Using a high fidelity performance model to generate the design space would make the tool outputs more reliable. Updating the cost model assumptions with recent knowledge might also lead to different results.

For the 3MW systems, the LCoE curves flatten out after around 190m^2 wing area. Normally, it would be expected that the LCoE curves have a clear inflection point. This could be explained in two ways - the design space is limited to wing area of 220m^2 and the inflection point might fall just beyond this range or, the current cost scaling functions might be optimistic and updating the cost functions might lead to an inflection point before 190m^2.

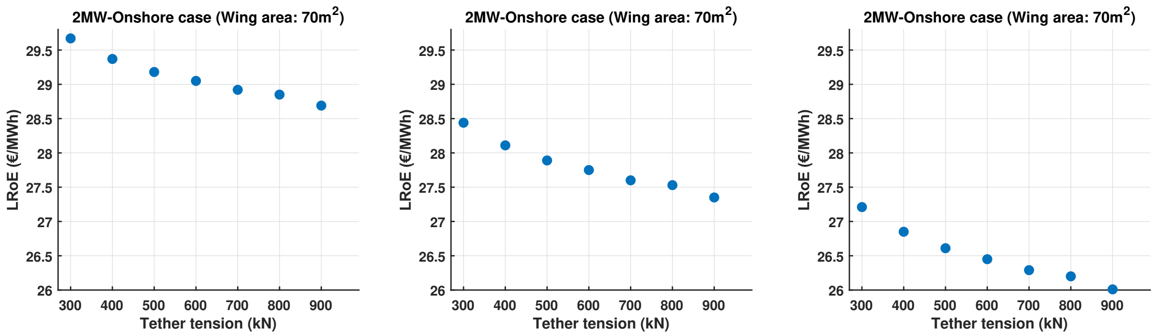
The cost assumptions are based on current knowledge of the company acquired through their experience and joint studies carried out with different institutions and companies involved in research and development of certain aspects of the technology. Innovation in materials and other long term gains will further reduce the cost of the technology which is not captured in these assumptions.

SENSITIVITY ANALYSIS OF DAM PRICE DEPENDENCY ON WIND SPEEDS

Continuous increment in the market share of wind power and other VRES is expected in the European countries. In a subsidy free future with the same market structure and policies, the effect of energy price dependency on wind speeds might increase due to the merit order effect. The current correlation of the DAM price and wind speeds could be valid for around one decade, but the assumptions and the input data needs to be updated in future. Change in policies or market design might lessen this dependency as well. Therefore, a sensitivity analysis for the dependency of DAM price and wind speeds is performed.

Figure 4.23 shows the sensitivity analysis of the LRoE for an aircraft of 70m^2 wing area coupled to a 2MW generator in the onshore business case. Figure 4.23b shows the base case values resulting from the correlation analysis. For the tether tensions from 300kN to 900kN, there is a drop of around 1 €/MWh and the maximum LRoE is 28.5 €/MWh. The average DAM price is 35.5 €/MWh.

Figure 4.23a shows the LRoE values for the reduced correlation strength scenario. 10% reduction in the strength (slope of the best fit-line) resulted in 4% increase in the maximum LRoE value than the base case. Figure 4.23c shows the LRoE values for the increased correlation strength scenario. 10% increase in the strength (slope of the best fit-line) resulted in 4% decrease in the maximum LRoE value than the base case.



(a) Low case: 10% reduction in the slope (b) Base case: original slope (c) High case: 10% increase in the slope

Figure 4.23: Sensitivity analysis: DAM price dependency of wind speeds

5

Conclusions and Recommendations

To recapitulate, the literature review led to the formulation of the following research question:

In a DAM based revenue generation scenario, is there a difference in the system design of utility scale AWE when 'optimizing for cost' vs 'optimizing for value'?

The short answer to the research question is 'Yes'. The long answer is as follows.

5.1. Key findings

Literature review provided the background knowledge required for this study. Current European electricity market framework and the economics of AWE was explored to identify the key market drivers for system design of utility scale systems. In a subsidy free scenario, the revenue generation of any variable renewable energy source (VRES) is dependent on the day-ahead market (DAM) and is dynamic in nature. It was identified that the merit order effect of VRES depresses the DAM price when there is high influx of renewable energy in the grid. Wind power has the highest share in the renewable energy mix of the European utility market and AWE is a direct competitor of wind turbines. Studying merit order effect of wind power indicated to quantify this effect and incorporate it in the system design of AWE. Currently, system design of AWE is entirely driven by cost, but, dynamic energy price scenario indicates to investigate if there is a need to shift from cost driven optimization to value driven optimization.

There exists a negative correlation between the DAM prices and wind speeds

A data driven statistical model was developed in MATLAB environment to identify and model the correlation between the DAM price and wind speeds. The model was tested for three different locations in Netherlands, Denmark and Germany. The results confirmed there exists a negative correlation between the DAM prices and the wind speeds for the tested locations in these countries. It was evident from the results that the electricity produced at lower wind speeds is more valuable than the electricity produced at higher wind speeds. Among the tested locations, the German DAM prices dropped by around 1.2 €/MWh, the Danish by around 0.9 €/MWh and the Dutch by around 0.6 €/MWh per 1m/s increase in wind speed. Different locations in different European markets have different strengths of the correlation depending on their wind climate and their energy mix.

Optimizing for value leads to a system performing better at lower wind speeds

A decision support tool for the system design of AWE was developed in MATLAB environment by integrating the correlation model with a revenue model and the existing cost model of Ampyx Power. The tool requires the design space of AWES and the business case assumptions as inputs. The tool is parametric for three types of business cases - offshore repowering, offshore floating and onshore. This tool can be used to understand the system deign of AWE based on three different metrics - LCoE, LRoE and NPV. LCoE is a cost based metric, LRoE is a revenue based metric and NPV captures both of these aspects

A case study of three different locations from Germany was analyzed using the developed tool to answer the research question. In the FIT based revenue generation scenario, the LRoE of all the systems is the same and hence there is no difference in cost driven system design and value driven system design. On the other hand, in a dynamic energy price scenario (i.e. DAM based revenue generation), value driven system leads to a different system than cost driven system design. The optimal system configuration shifts to the systems which can produce more power at lower wind speeds. In the locations with stronger correlation and bigger generator sizes, the optimal tether tension is lower when optimizing for value than when optimizing for cost. Overall, with increase in the generator size, the optimal system configurations tends towards bigger aircrafts with higher tether tensions. Smaller aircraft combinations are more sensitive to the DAM price dependency on wind speeds than larger aircraft configurations since the larger aircrafts produce more power at lower wind speeds than the smaller aircraft configurations.

5.2. REFLECTIONS AND FUTURE WORK

The research was intended to provide valuable insights on the influence of the European electricity market on the system design of AWES. It shows that in future, the certainty of revenue estimations might decrease, and hence a framework which captures the cost as well as the revenue aspect would help in reducing the commercial risks. This research provides the foundation for such a framework. Further, the current performance model and the cost model of the company are a work in progress. They are based on number of assumptions and hence have their own limitations. Using the tool with updated performance and cost models might lead to different and interesting results.

Instead of OLS, more sophisticated data analysis methods like the quantile regression could be used to better model the DAM price dependency on wind speeds. DAM clearing is a complex procedure involving the demand and the supply from all the types of power plants. Historic data can only be used to observe how the market behaved in the past, or how will it behave in the near future. Usually, five years is enough time for the market to change its nature. Policies, regulations and even the market design can change in around ten years. This model does not consider the interaction between different market actors. Many new power plants might be commissioned in the next five years. This will most likely change the market dynamics. This method is suitable for short-term analysis upto five years. The data and the assumptions in the model must be updated in the next five years before using the model. Instead of integrating a data driven correlation model with the revenue model, a comprehensive market model could be integrated to the revenue model. Number of open source market models developed by university research groups are available. Hans-Kristian Ringkjøb et al. [69] in 2018 published a review of modelling tools for energy and electricity markets. Few of the promising tools are BALMOREL [70], EMMA [41], COMPETES [71, 72] etc.

The research identifies that the value of energy sold at lower wind speeds is higher than that sold at higher wind speeds. Therefore, integrating a storage module in the framework would be interesting. There could be a tradeoff between selling the energy at high wind speeds vs storing the energy produced at high wind speeds and selling it at low wind speeds.

The framework could also be extended to integrate solar PV installations. The main drawback of integrating solar with conventional wind turbines is the tower shadow of wind turbines on the solar panels. Wind turbine towers block the incident irradiation on the PV panels which decreases their output. This phenomenon is irrelevant in terms of AWES since there are no towers to cast a shadow. This indicates that a hybrid park of solar with AWES maybe more suitable than with conventional wind turbines. This could in-turn increase the value of AWE.

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A

AGGREGATE GRAPHS: CASE STUDY RESULTS

A.1. FIT BASED REVENUE GENERATION SCENARIO

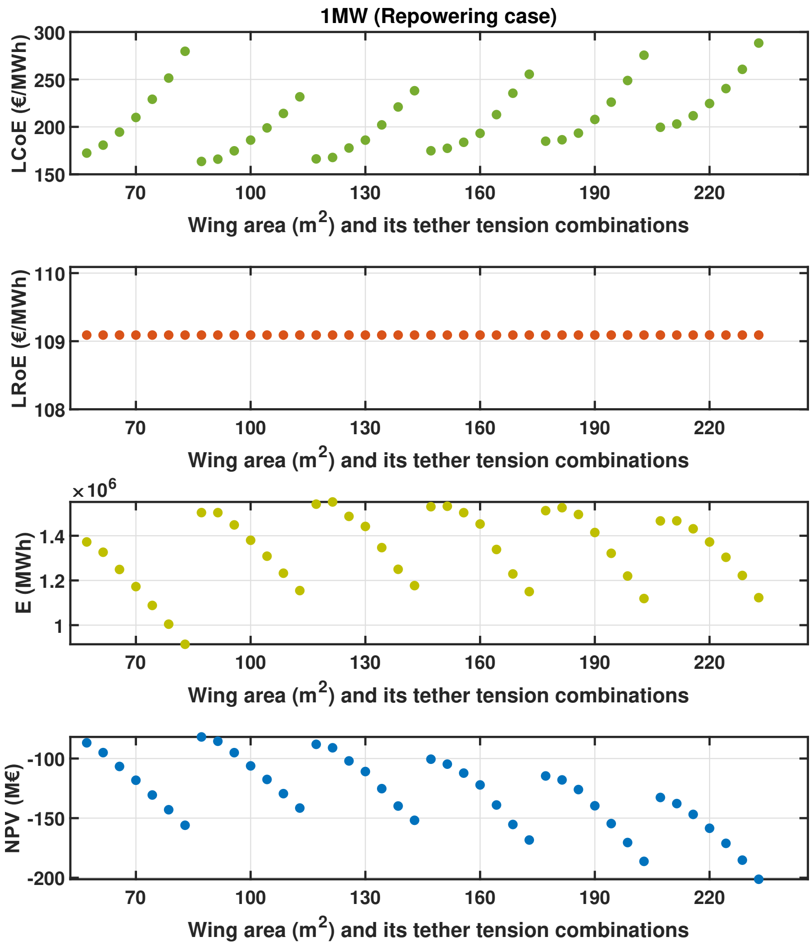

Figure A.1: 1MW (Repowering case): FIT based revenue generation

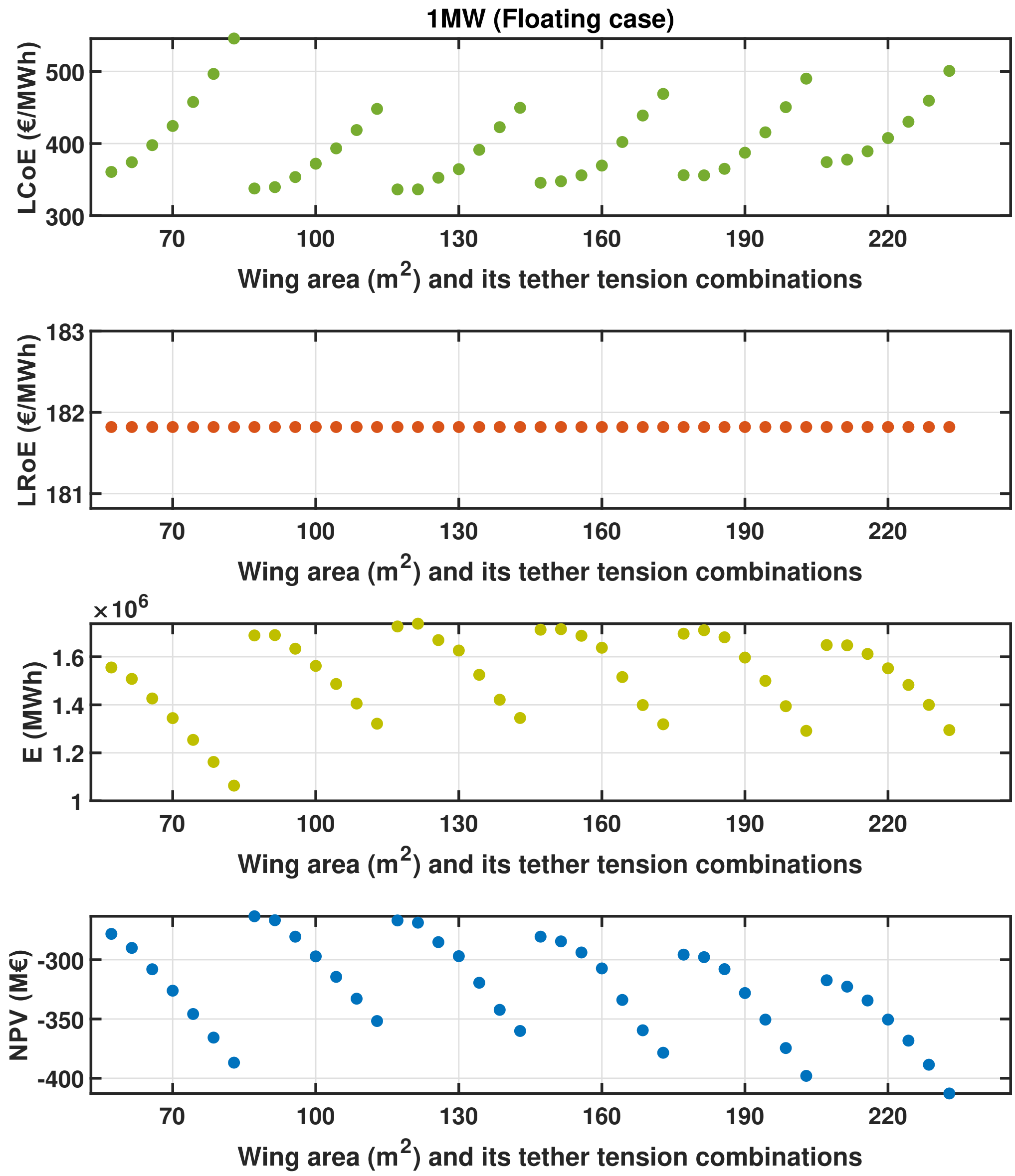

Figure A.2: 1MW (Floating case): FIT based revenue generation

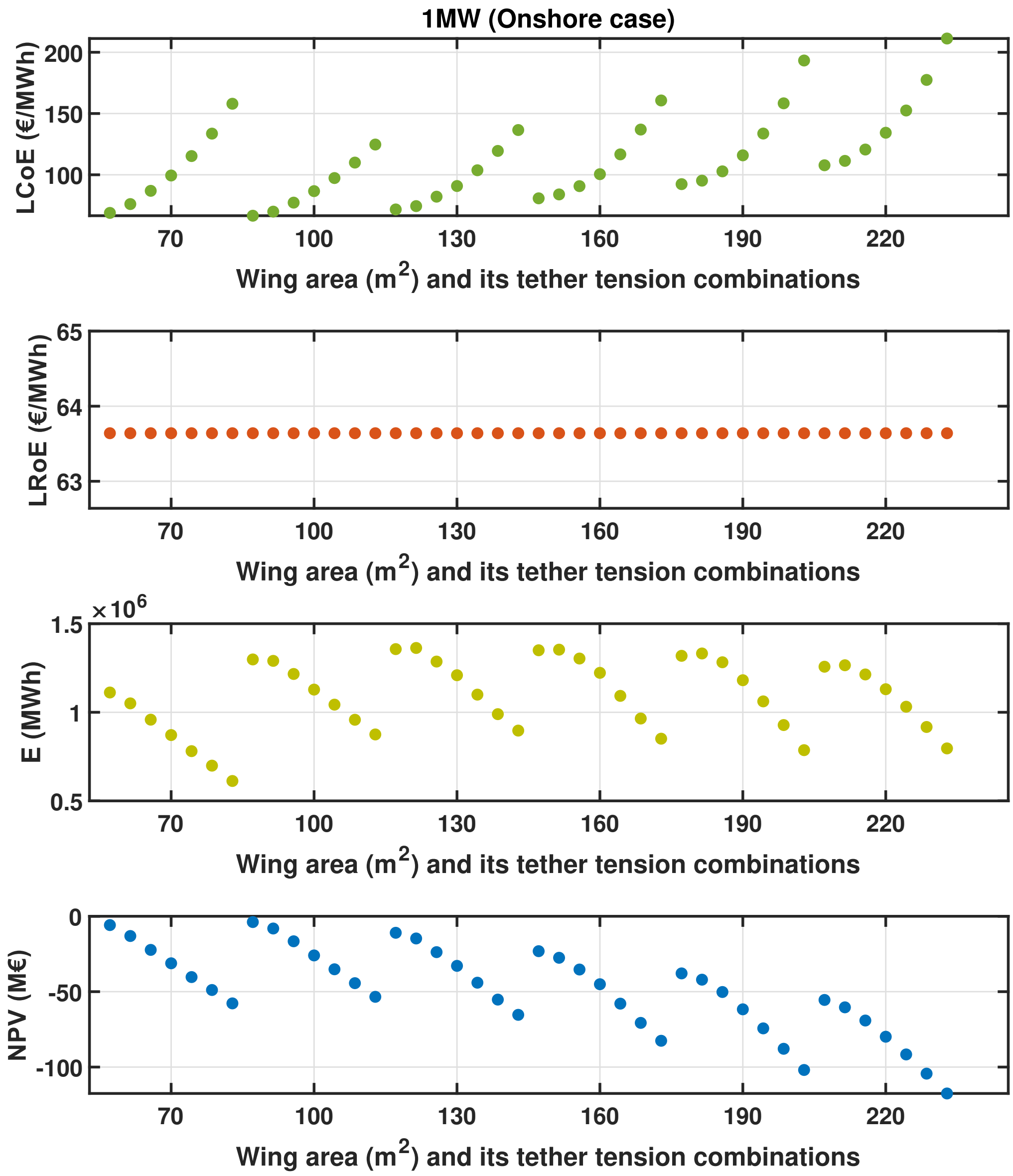

Figure A.3: 1MW (Onshore case): FIT based revenue generation

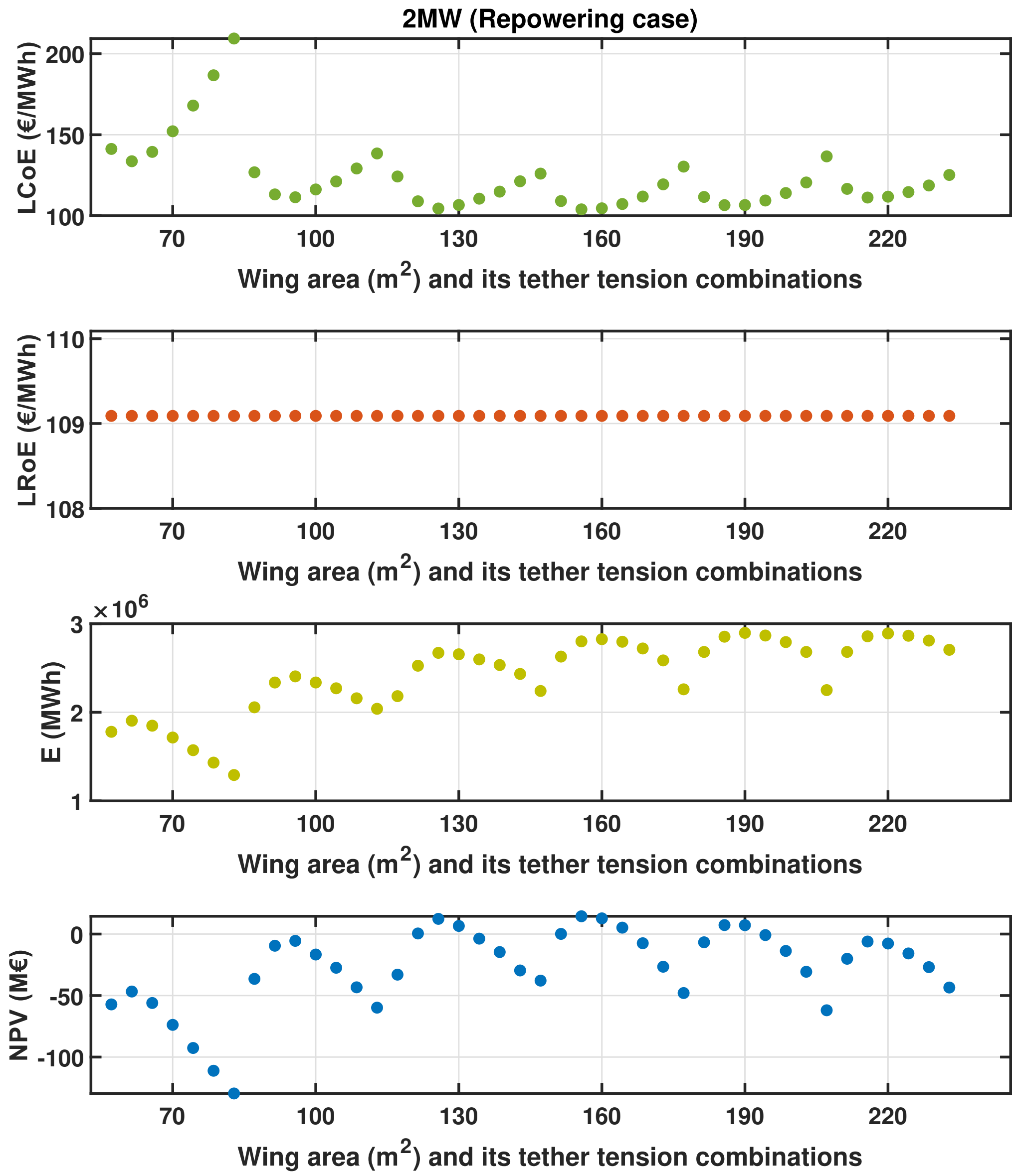

Figure A.4: 2MW (Repowering case): FIT based revenue generation

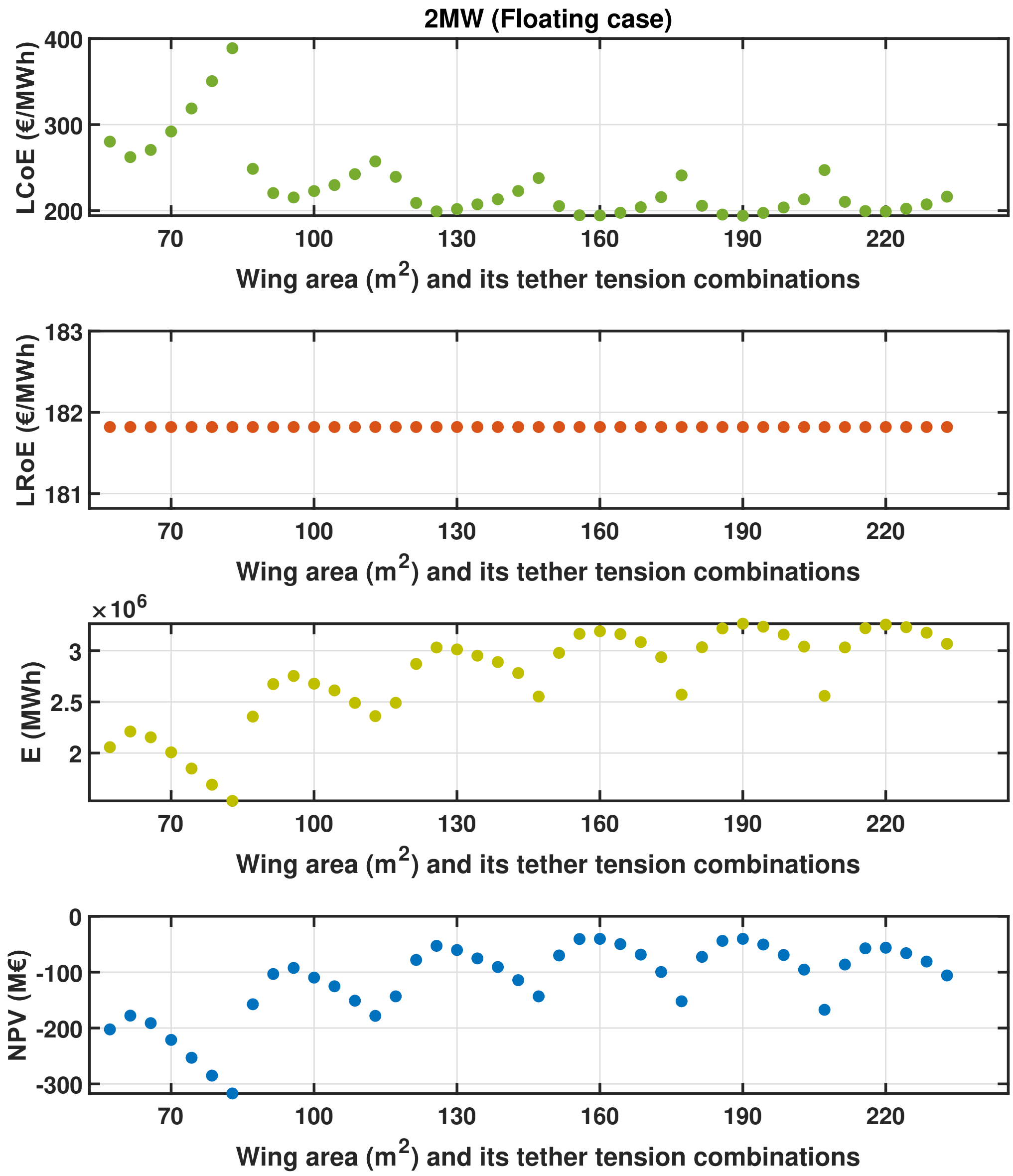

Figure A.5: 2MW (Floating case): FIT based revenue generation

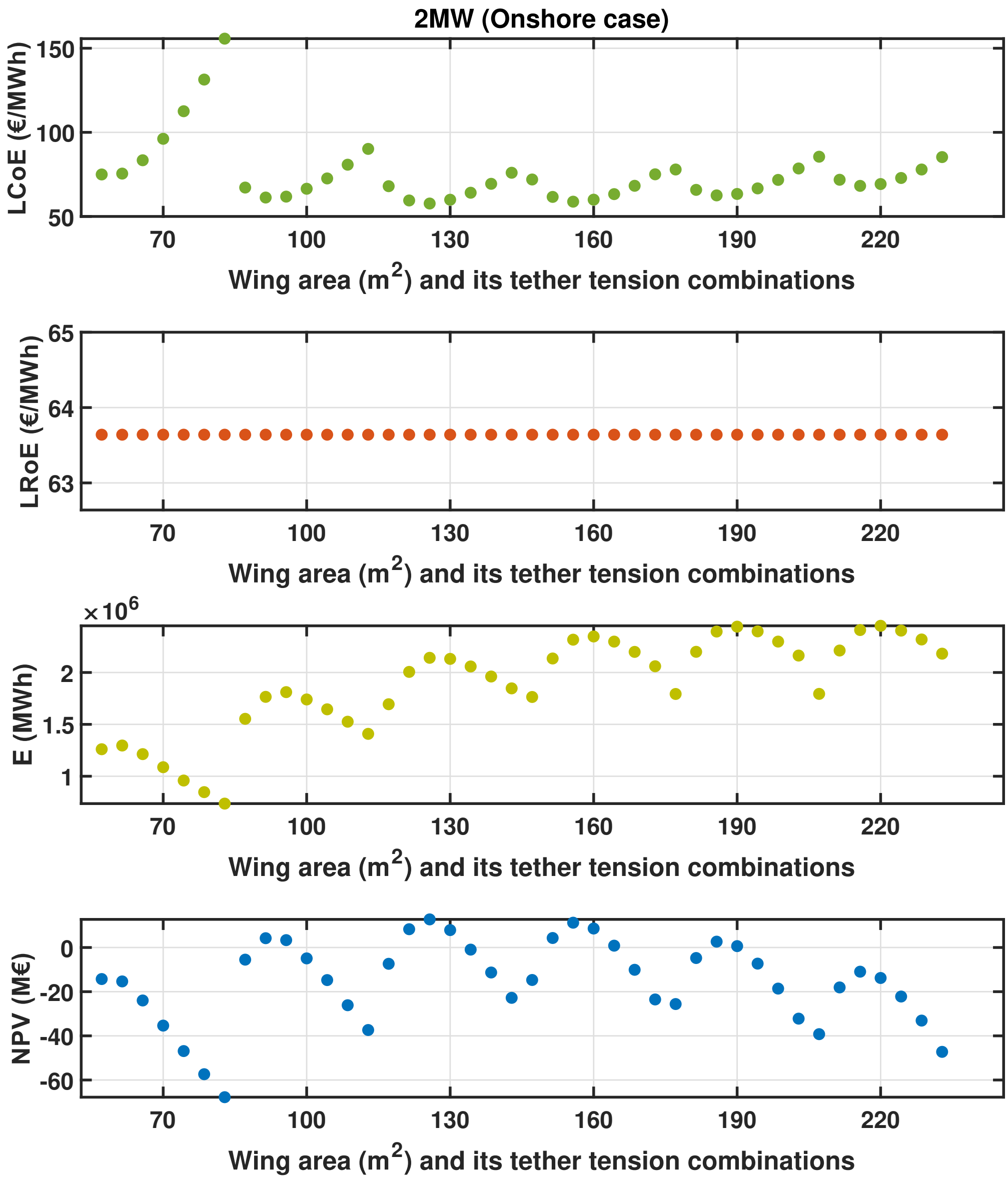

Figure A.6: 2MW (Onshore case): FIT based revenue generation

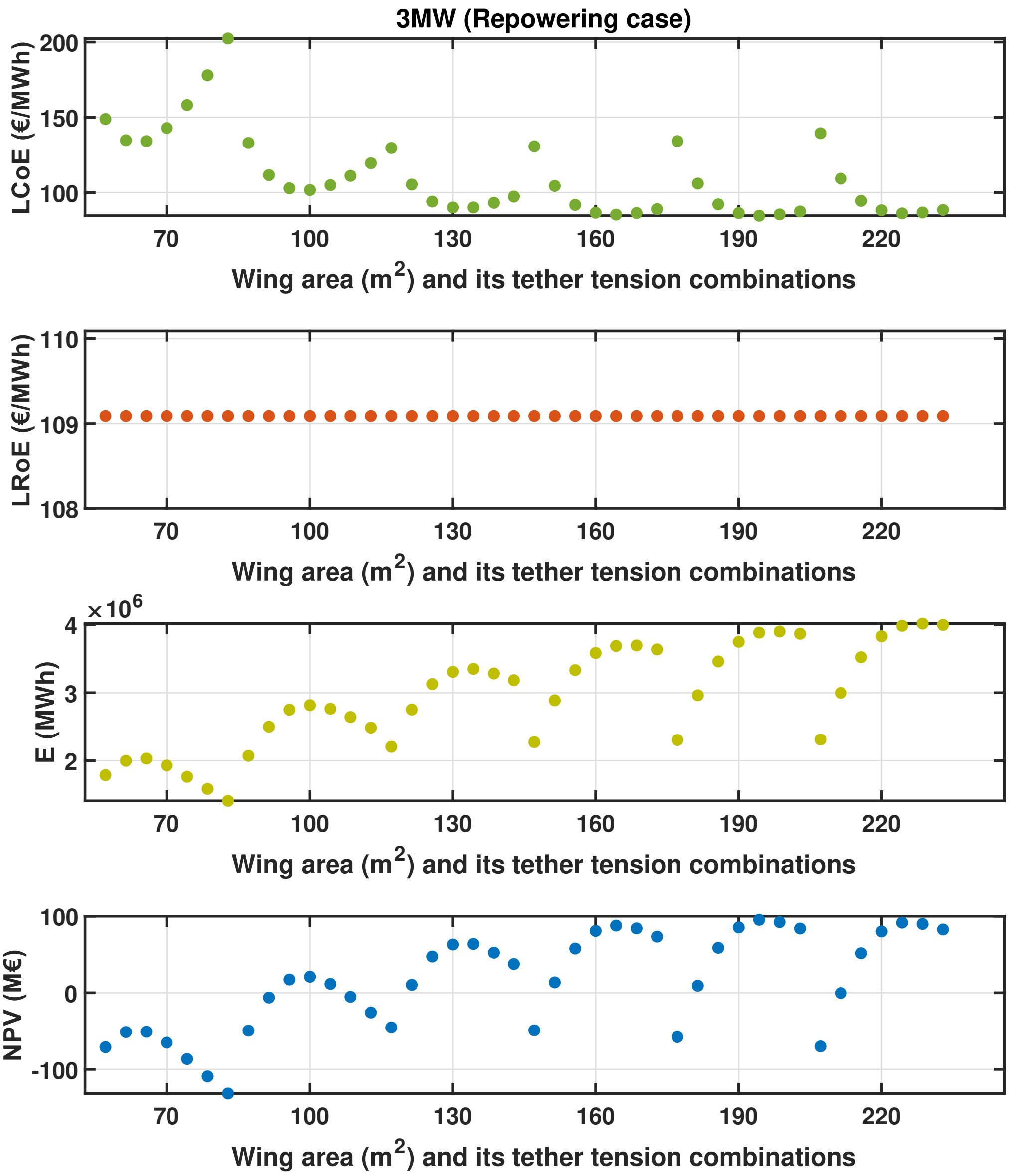

Figure A.7: 3MW (Repowering case): FIT based revenue generation

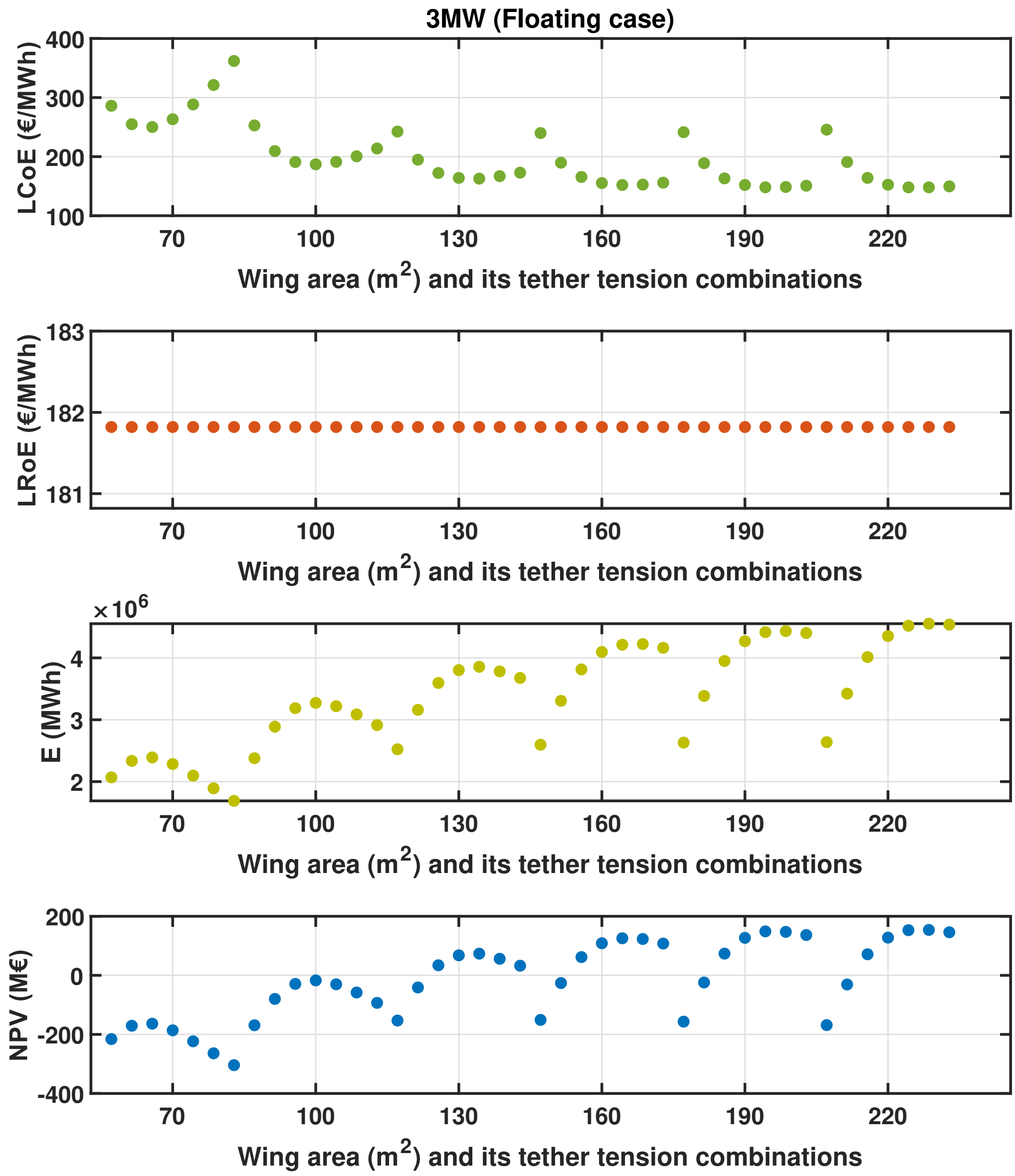

Figure A.8: 3MW (Floating case): FIT based revenue generation

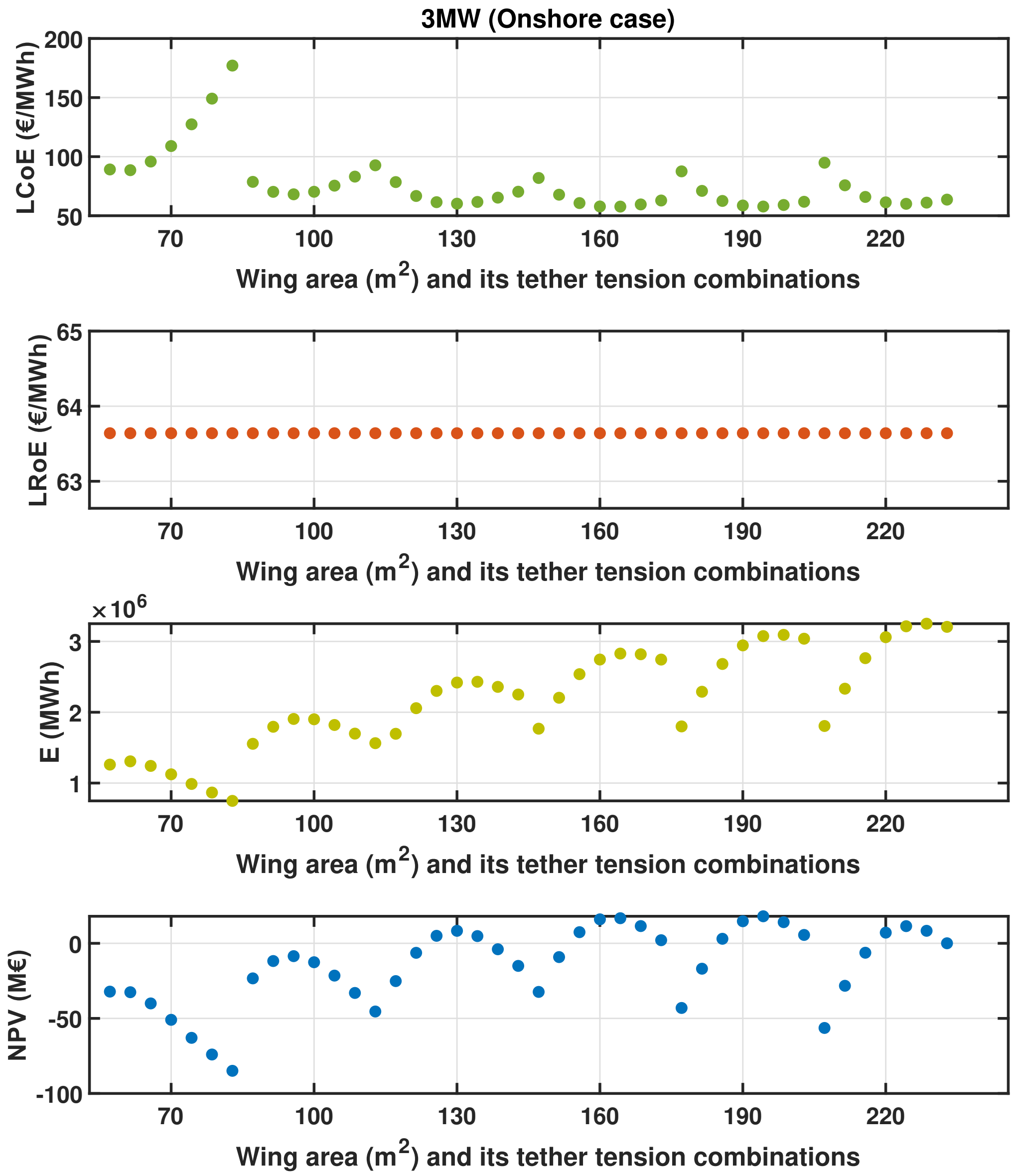

Figure A.9: 3MW (Onshore case): FIT based revenue generation

A.2. DAM BASED REVENUE GENERATION SCENARIO

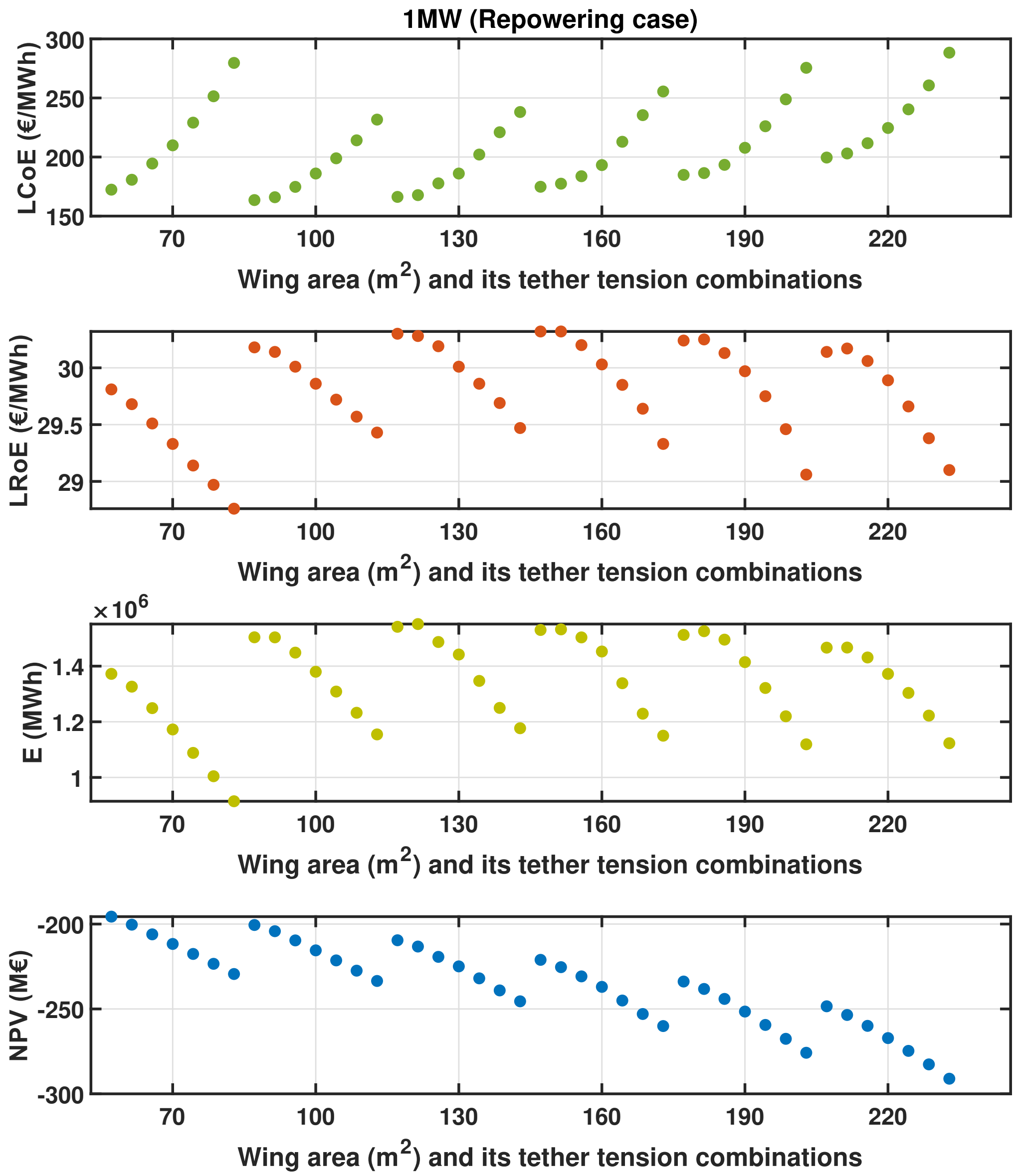

Figure A.10: 1MW (Repowering case): DAM based revenue generation

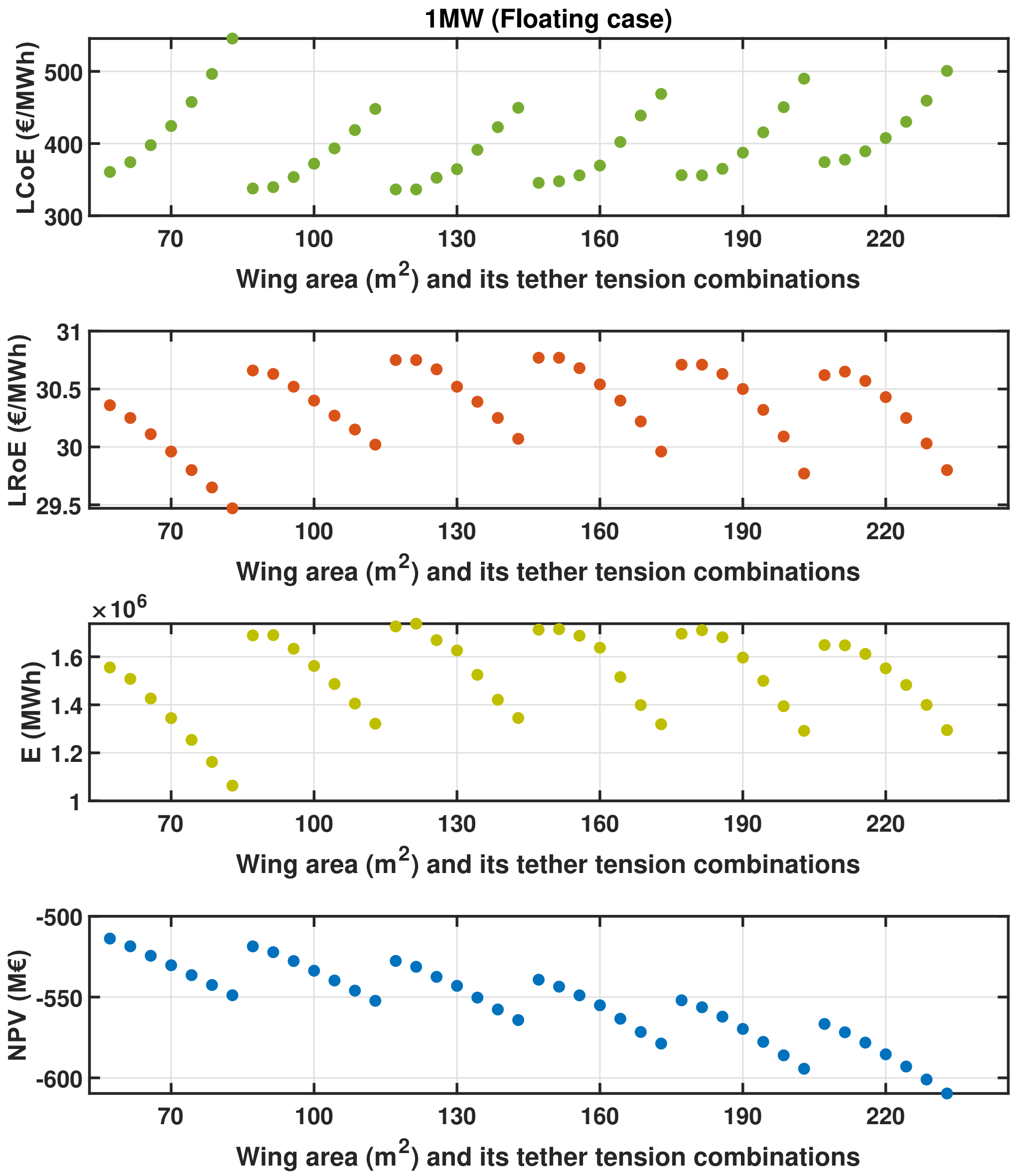

Figure A.11: 1MW (Floating case): DAM based revenue generation

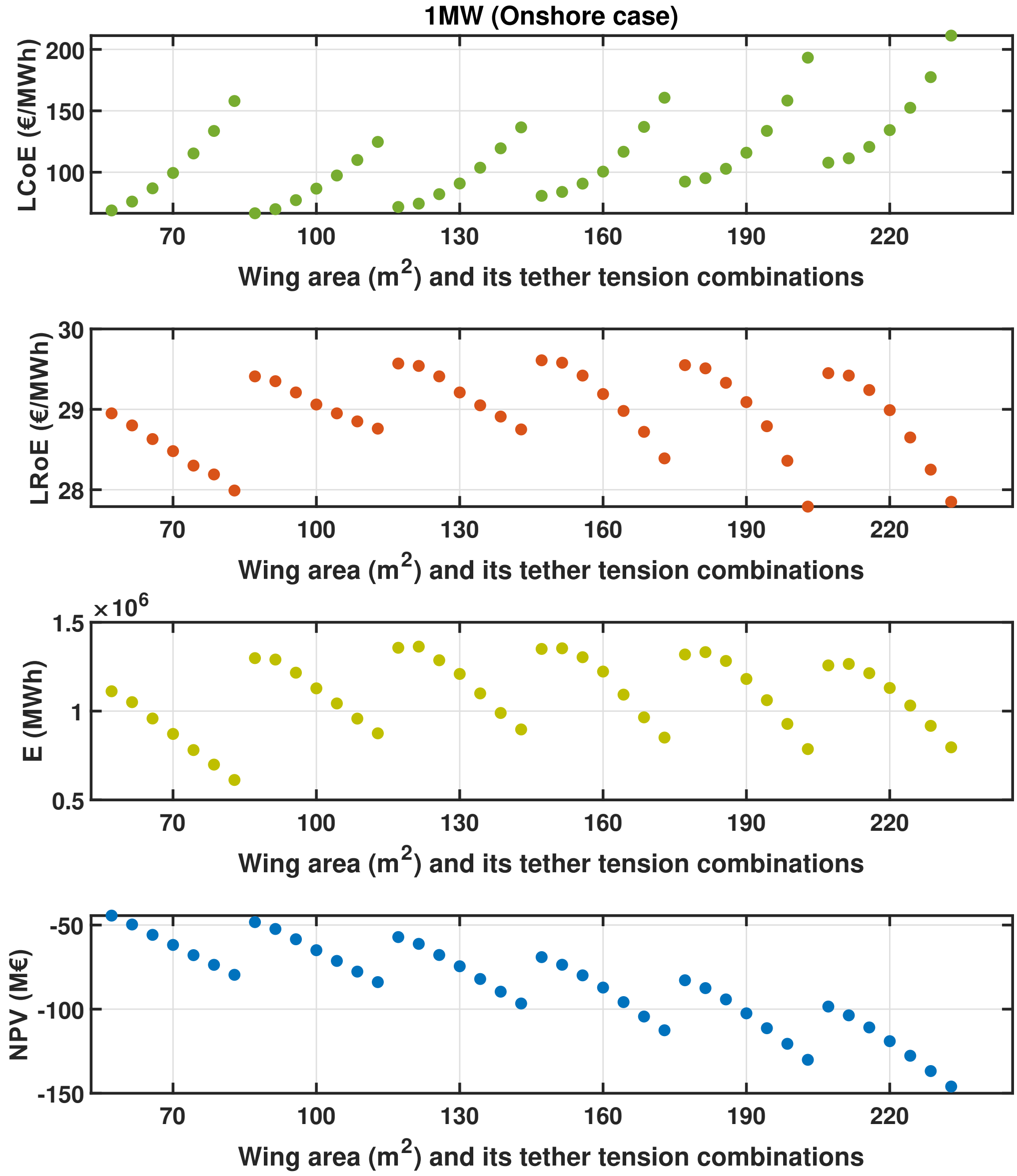

Figure A.12: 1MW (Onshore case): DAM based revenue generation

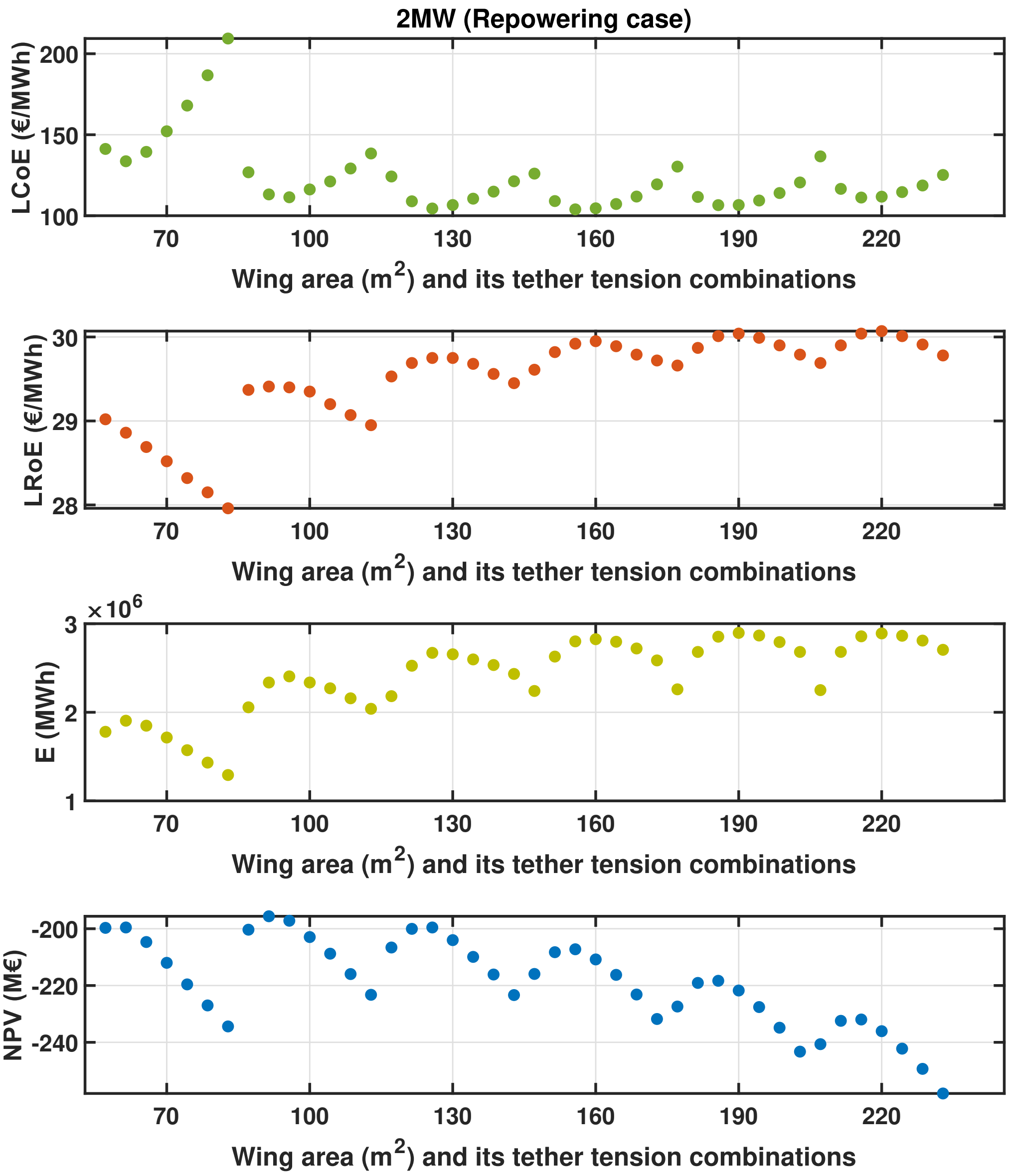

Figure A.13: 2MW (Repowering case): DAM based revenue generation

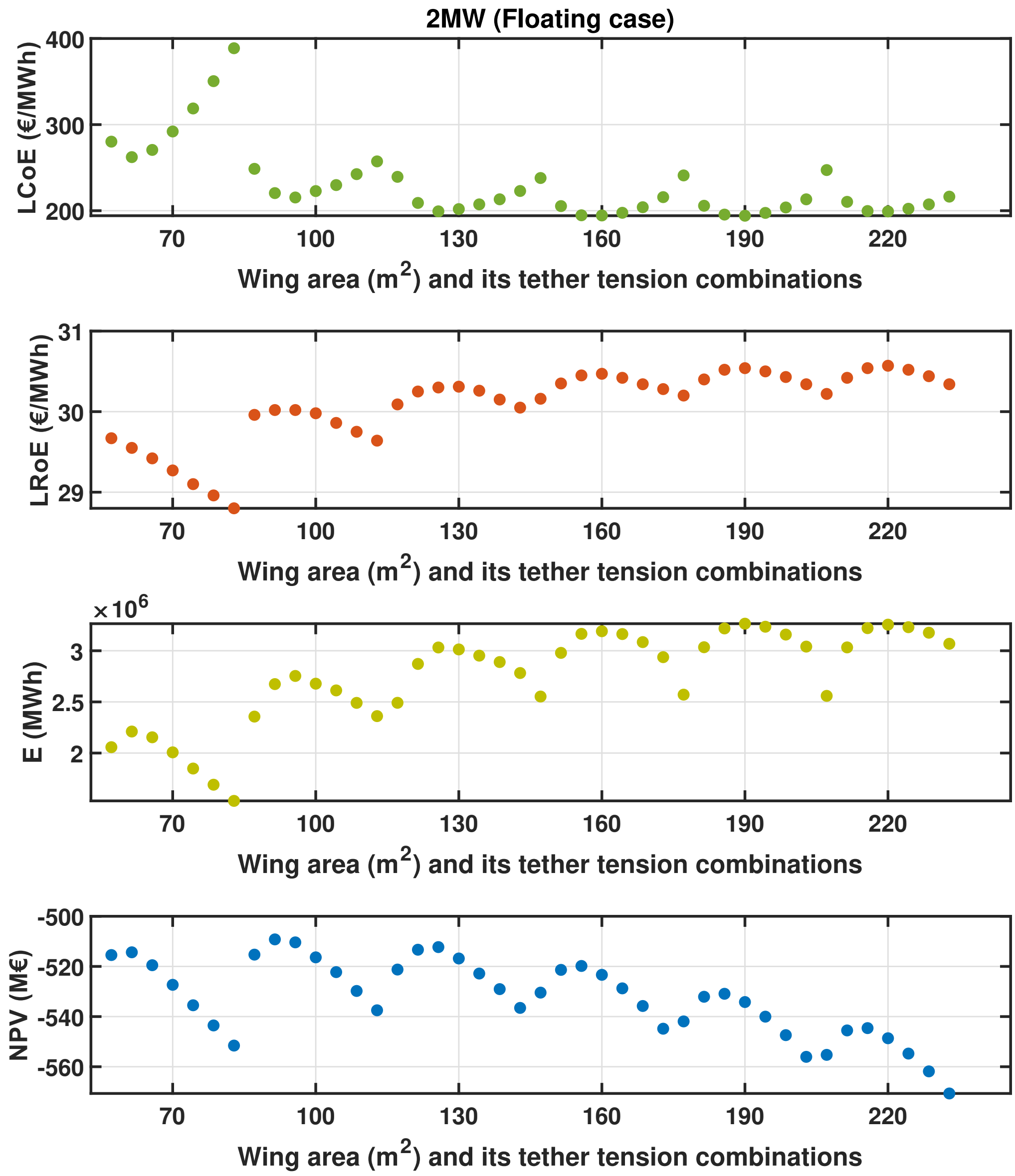

Figure A.14: 2MW (Floating case): DAM based revenue generation

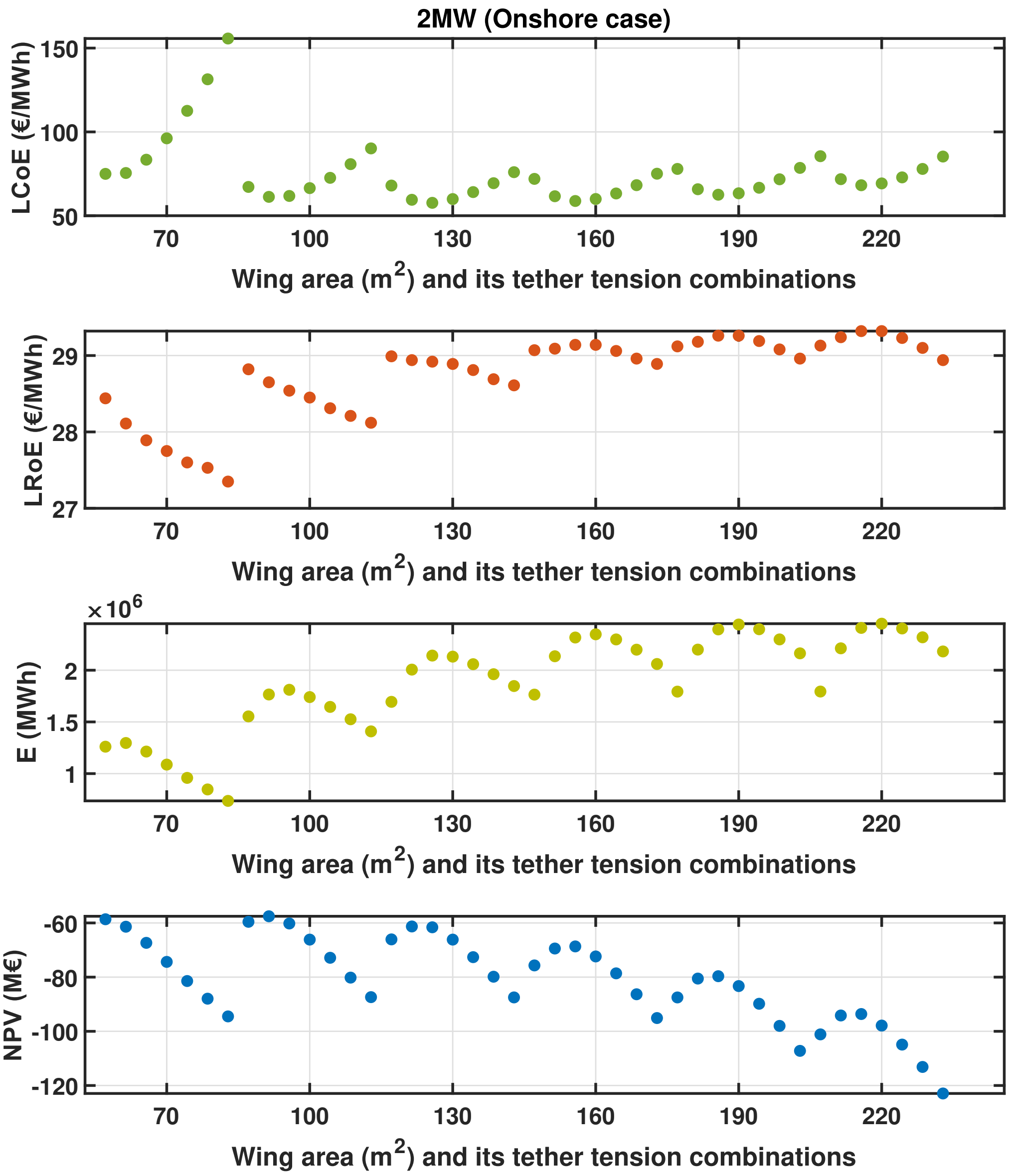

Figure A.15: 2MW (Onshore case): DAM based revenue generation

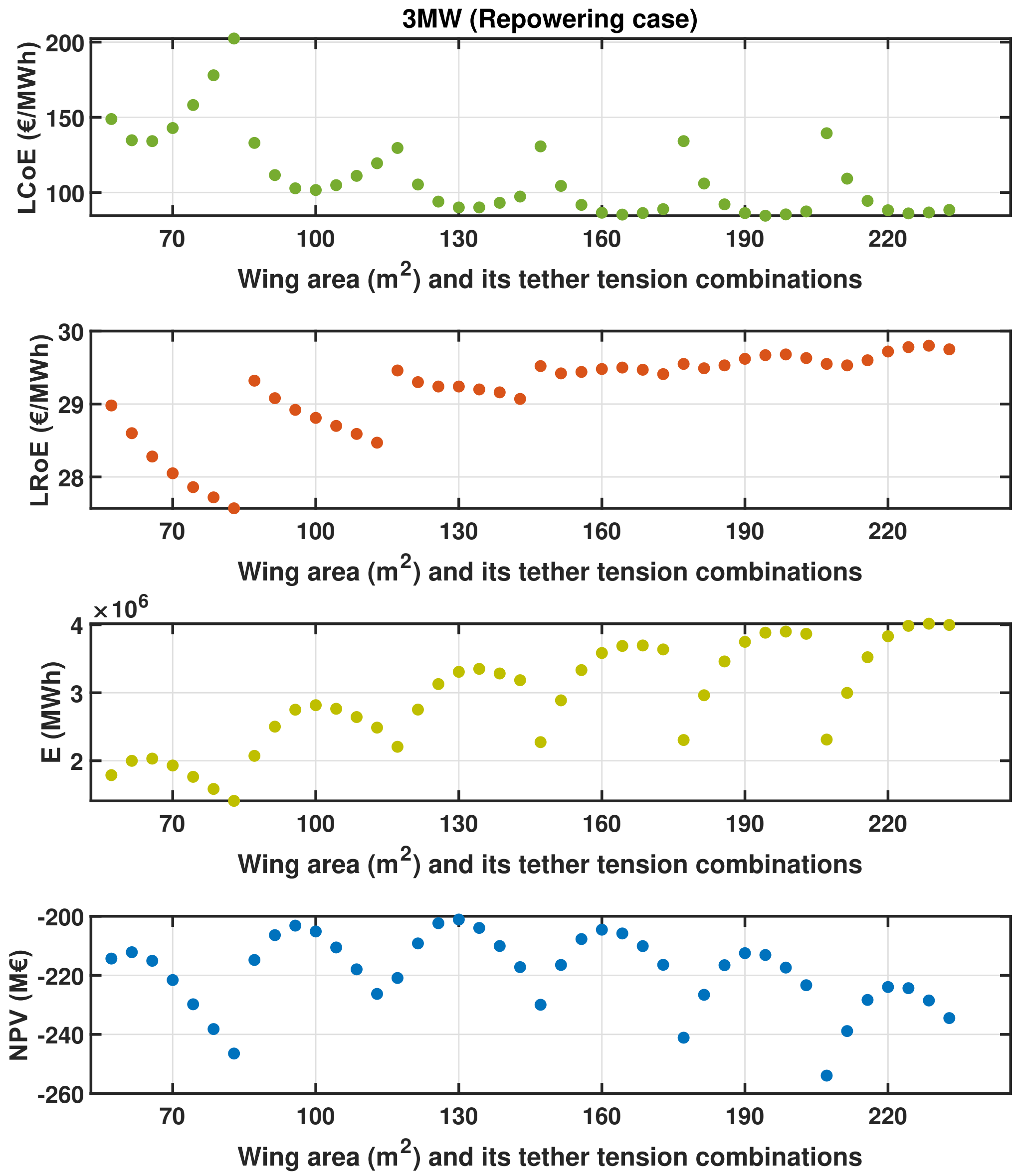

Figure A.16: 3MW (Repowering case): DAM based revenue generation

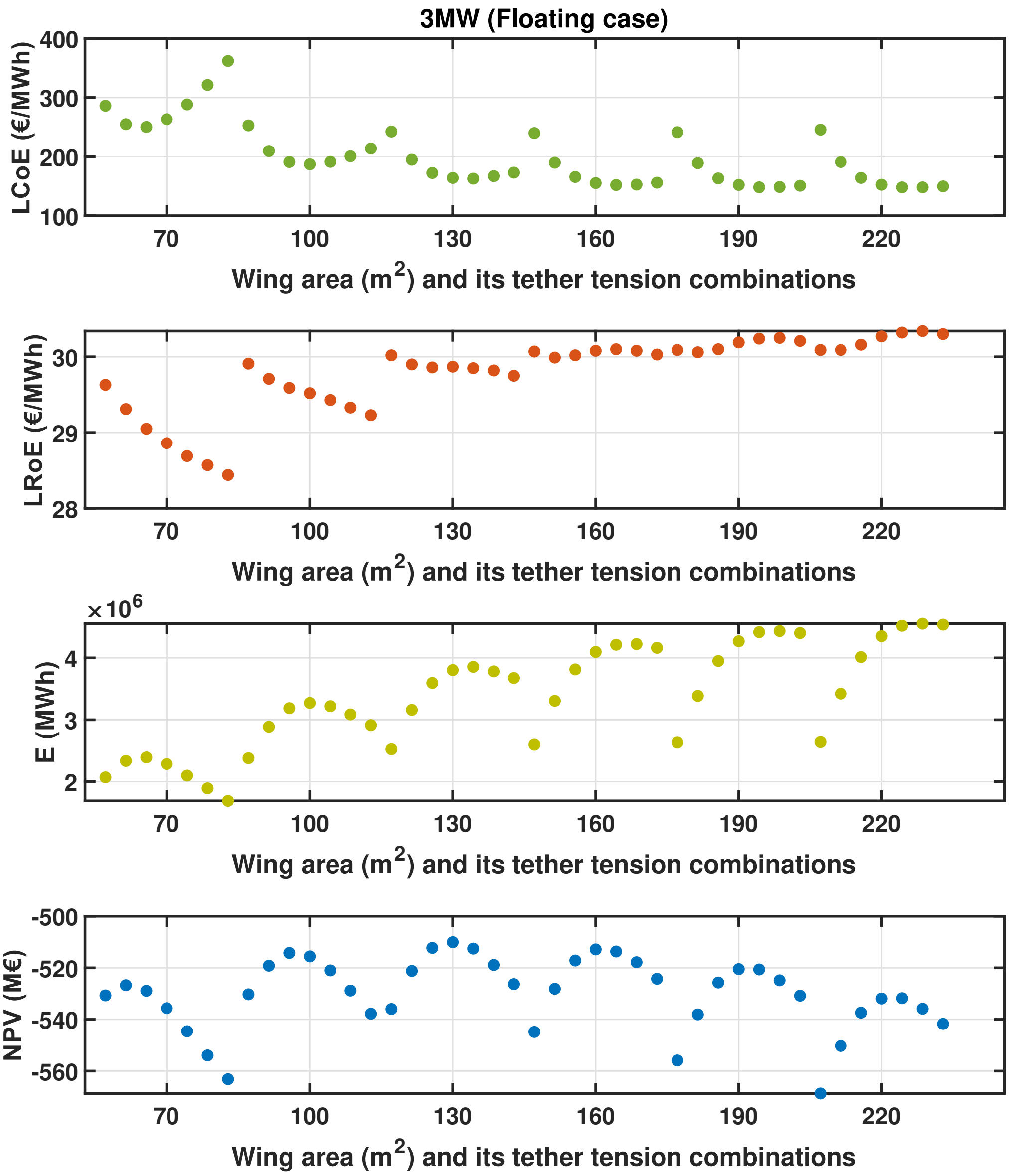

Figure A.17: 3MW (Floating case): DAM based revenue generation

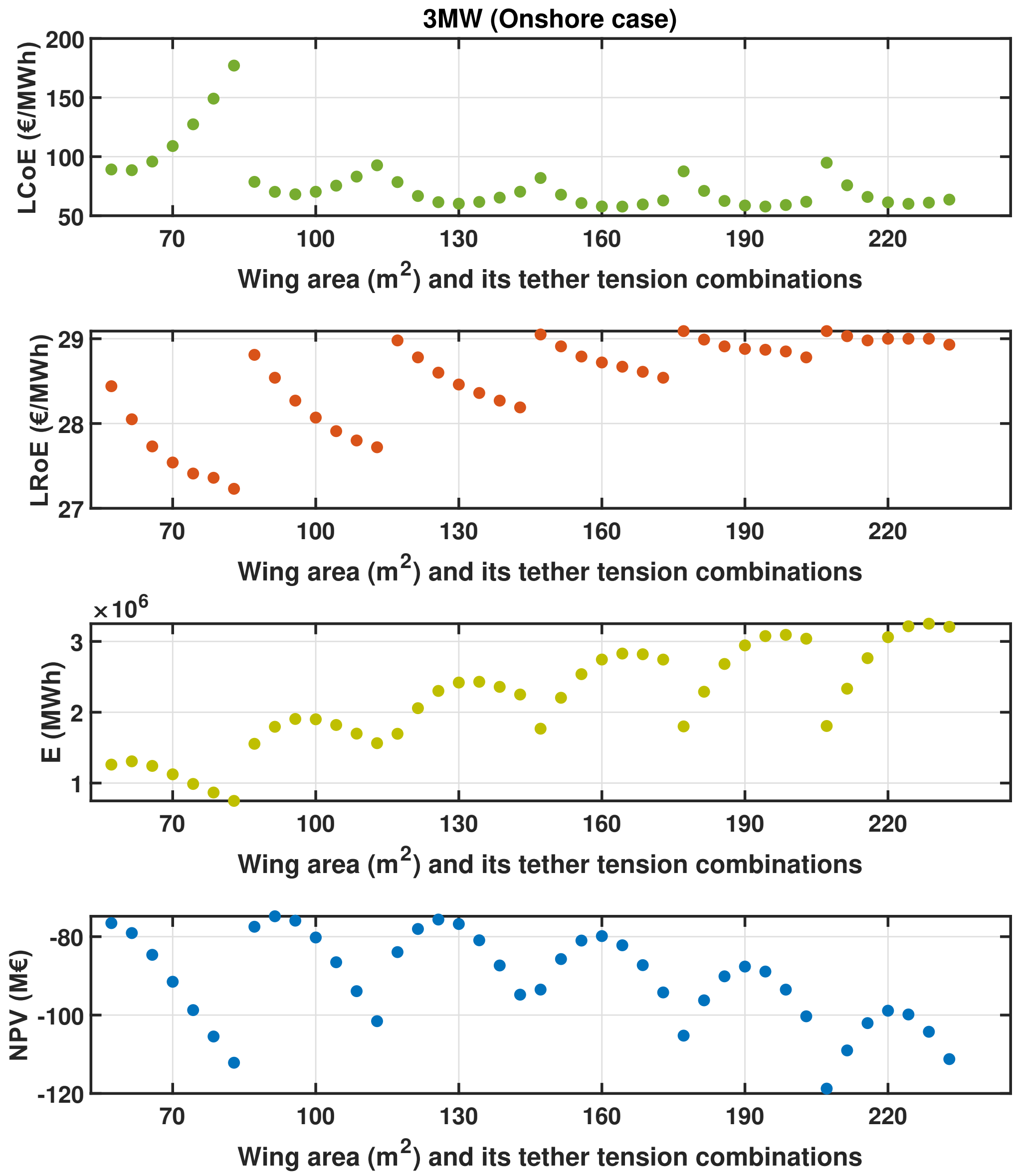

Figure A.18: 3MW (Onshore case): DAM based revenue generation