Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

Eivind Jamessen

Economical Optimisation of Wind Powered Pump Hydro Storage Systems in Norway

Master's thesis in Environmental Engineering
Supervisor: Ümit Cali
Co-supervisor: Marthe Fogstad Dynge
June 2022

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Preface

This master thesis is written at Norwegian University of Science and Technology (NTNU), at the Department of Electrical Power Engineering, and is part of the MSc programme Energy and Environmental Engineering.

The thesis is a cooperation between NTNU, Statnett and Nordkraft to investigate solutions of distribution of transmission capacity in Sørfjord. Statnett has been a contributor to develop the necessary framework in the study. In addition, Nordkraft has provided wind and hydro system data, and has also given advice regarding techno-economic analysis. There are persons from all three institutions that deserves an acknowledgement for their contributions in this study.

I want to thank my internal supervisor at NTNU, associate professor Ümit Cali for academic advice and guidance through the project. Further, my co-supervisor Marthe Fogstad Dynge deserves my gratitude for her participation in academic discussions, proofreading, and bringing up suggestions to improve the framework from the beginning. Also I want to thank professor Magnus Korpås for great input in the modelling part, and proofreading. To my external collaborators, I want to express my appreciation to Knut Styve Hornnes and Matthew Homola. Knut provided not only helpful advice and crucial input in the start up phase of the framework, but he also gave informative explanations of optimisation theory. Finally, Matthew Homola, a representative of Nordkraft was more than accommodating by providing system data for the wind farm and hydro plant in Sørfjord. Further, he has also given useful advice for creating scenarios of system simulations.

Trondheim, 15.06.2022

Eivind Jamessen

Abstract

The increased global average temperature is causing an energy transition, and there are estimated that wind and solar power are gonna be the fastest growing renewable energy sources in Norway in the coming years. These types of energy sources are variable and uncertain because of the dependence on the weather. For that reason, innovative solutions for combining new variable energy sources with the existing hydro plants are necessary to obtain a reliable and sustainable renewable electricity generation in Norway.

In this thesis, it is investigated how the capacity at the Sørfjord wind farm can be increased although it will exceed the grid capacity. This is feasible because of the new *Regulation on grid regulation and the energy market* (NEM) rule that allows grid connection with terms of limitation of production. Two main approaches are tested at the Sørfjord wind farm: a standard model where the wind farm only uses the remaining capacity after the hydro production, and the other method is to adopt a multi-objective framework (MOF) as an optimisation tool that uses a pump of 20 MW to create a wind-pumped hydro storage (PHS) system. The latter aims to find a trade-off between the wind and hydro plant. Different trade-offs are created by assigning weight numbers to the objectives and expanding the wind farm by scales between 1 and 3. Both approaches are created in Python with the package *Pyomo* as the optimisation tool.

The obtained framework in this thesis treats wind and hydro production as two competitive objectives with the same target: to achieve the best possible income by energy export through a 140 MW line. Both weights and wind farm scales affect the way the MOF is considering the importance of each objective relative to each other. With the current size of the hydro and wind plant, an equal weight ratio leads to a power production dominated by hydropower as the decision maker in the MOF finds it more valuable. As the wind farm scale increases, the decision maker prioritises wind power export more.

The simulations of the ideal production pattern of both plants show that the major production occurs in the period December-March. Therefore, it is necessary to move hydropower outside this period when more wind power penetration is desired. With the spot price data from 2019, it turns out that about 8% of the annual wind power can be curtailed without causing any significant decrease in the wind farm income. Considering this, the wind farm can be expanded by a factor of 2 with the standard simulation approach. Further, setting 8% as a curtailment limit in the wind-PHS model, makes it possible to increase the wind farm capacity by a factor of 3.

Considering that a positive relative income for both producers is a fair trade-off, the simulations have shown that this requires a weight ratio more than 3/1 and a wind farm up-scale limited to 2.25. In addition to higher wind power penetration, adapting the wind-PHS is beneficial for grid utilisation and the system operator. It turns out that both a wind farm expansion and more transfer priority for the wind power producer increase the grid utilisation. A wind farm upscale of 3 will increase the grid utilisation from 25 % to more than 50 %.

Sammendrag

Den økte globale gjennomsnittstemperaturen har sørget for en energiomstilling hvor vind- og solkraft vil være de størst voksende energikildene i årene som kommer. Denne type energkilder er variable og usikre ettersom de er avhengig av været. Av den grunn vil innovative løsninger for å kombinere variable energikilder med eksisterende vannkraft, være nødvendig for å oppnå en fullstendig fornybar elekstrisitetsproduksjon i Norge.

I avhandlingen er det undersøkt hvordan Sørfjord vindkraftverk kan bli utvidet selv om det medfører overskridelse av nettkapasiteten. Dette kan muligjøres ved hjelp av en lov i *Forskrift om nettregulering og energimarked* (NEM), som nylig har åpnet for at produsenter kan kobles til nettet med vilkår om produksjonsbegrensning. To tilnærminger er undersøkt i Sørfjord hvor den første er en standard simuleringsmodell som kun lar vindkraftverket bruke resterende ledig nettkapasitet etter vannkraftproduksjonen. Den andre tilnærmingen er et multi-objektivt rammeverk (MOF), som bruker en pumpe på 20 MW for å simulere et vind-pumpekraftverk system. Hensikten med det kombinerte kraftverket er å finne et kompromiss mellom produsentene. Begge tilnærminger er modelert i Python med *Pyomo* som et optimeringsverktøy.

Optimeringsmodellen i avhandlingen behandler vind- og vannkraft som to motstridende objektivfunksjoner med samme formål: oppnå best mulig inntekt ved energieksport gjennom en 140 MW transmisjonslinje. Både vekttall og skaleringsfaktorer påvirker måten MOF betrakter viktigheten av hver objektivfunksjon i forhold til hverandre. Med nåværende størrelse av vind- og vannkraftverket vil et likt vektforhold føre til en samlet kraftproduksjon dominert av vannkraft siden ”beslutningsalgoritmen” anser vannkraft som mest verdifullt å transportere. Etter hvert som vindparken blir skalert opp, vil ”beslutningsalgoritmen” prioritere vindkrafteksport i større grad.

Simuleringene av optimal produksjon fra begge kraftverkene viser en høyest andel produksjon i perioden desember-mars for begge produsenter. På den måten er det nødvendig å regulere vannkraften vekk fra disse månedene jo mer vindkraftproduksjon som skal prioriteres. Med spot pris data fra 2019 kommer det frem at 8 % av den årlige vindkraften kan bli strupet uten å påvirke inntekten til vindprodusenten nevneverdig. Basert på dette viser simuleringene at vindparken kan utvides med en faktor på 2 ved bruk av en standard simulering tilnærming. Ved å også bruke 8 % som en strupegrense i MOF modellen er det mulig å øke vindparken med en faktor på 3.

Tatt i betrakning at en positiv relativ inntekt for begge produsenter vil være et rettferdig kompromiss, kreves et vektforhold på minst 3/1, og en vindskaleringsfaktor begrenset til 2.25. I tillegg til en høyere vindkrafteksport vil dette vind-pumpekraftverket systemet også øke nettutnyttelsen, noe som også gagner systemoperatøren. Det kommer frem at både økt vindkraftkapasitet og økt prioritet til vindkrafteksport øker nettutnyttelsen. En utvidelse av vindkraftverket med en faktor på 3 øker nettutnyttelsen fra 25 til over 50 %.

Contents

Preface i

Abstract ii

Sammendrag iii

List of Terms vi

List of Acronyms vii

List of figures viii

List of tables ix

1 Introduction 1
1.1 Background 1
1.2 Problem description 2

2 The Nordic Power Grid and Market 3
2.1 Norwegian power grid structure 3
2.2 Grid development in North Norway region 4
2.3 Regulation of grid operation 5
2.3.1 Connection process and regulation 5
2.3.2 NEM connection rules 6
2.4 Today's power market 7
2.4.1 Nord Pool and spot prices 7
2.4.2 Renewables and its impact on the power market 8
2.5 Market participation 9
2.5.1 Ancillary services and balancing market 10
2.5.2 Bilateral and PPA agreements 10

3 Wind and hydropower systems 12
3.1 Wind Energy 12
3.1.1 Technical review 12
3.1.2 Wind energy in Norway 13
3.1.3 Wind power economy 14
3.2 Hydropower and pump storage 15
3.2.1 Technical review 16
3.2.2 Hydropower in Norway 17
3.2.3 Pumped hydro storage 18
3.2.4 Cost review 20
3.2.5 Importance and challenges with regulated hydropower 21
3.2.6 Profitability and economic challenges 22
3.3 Wind and hydro as a complementary system 22
3.4 The need for coordination of wind-hydro systems 24

4 Optimisation and decision making 25
4.1 Linear programming 25

4.2 Multi-objective optimisation . . . 25
4.2.1 The weighting method . . . 26
4.2.2 Augmented epsilon-constraint algorithm . . . 26
4.3 Decision making . . . 28
4.4 Multi-objective optimisation in power systems . . . 30

5 Methodology **32**
5.1 Data collection . . . 32
5.2 Reference case . . . 33
5.2.1 System specifications . . . 33
5.3 Multi-objective linear programming . . . 36
5.3.1 General flowchart . . . 36
5.3.2 Procedure . . . 37
5.3.3 Configuration of the multi-objective linear problem . . . 39
5.4 Techno-economic analysis . . . 42
5.5 Configurations of bilateral agreement wind & PHS . . . 43

6 Results **44**
6.1 System simulations . . . 44
6.2 MOLP simulations . . . 47
6.2.1 Statistics for different weights . . . 47
6.2.2 Pareto front and fuzzy graphs . . . 48
6.3 Sensitivity . . . 50
6.3.1 Wind curtailment NEM reduction VS MOLP . . . 50
6.3.2 Wind curtailment for different pump sizes and wind scales . . . 51
6.3.3 Wind curtailment for different pump sizes and weights . . . 51
6.3.4 Relative revenue analysis . . . 51

7 Discussion **53**
7.1 Wind and hydropower production pattern . . . 53
7.2 Statistic analysis . . . 54
7.3 Sensitivity analysis . . . 55
7.3.1 Wind curtailment . . . 55
7.3.2 Revenue analysis . . . 55
7.4 The new NEM rule . . . 56
7.5 Wind-PHS in future energy market . . . 57
7.6 Trade-off and bilateral agreement - different points of view . . . 58
7.7 Shortcomings and areas of improvement . . . 59

Conclusion and further work **61**

References **64**

A Consumption pattern in NO4 **I**

B Pay-off tables - all simulations **II**

C Statistic simulations **III**

List of Terms

Term	**Definition**
Bottleneck	The phenomena when the amount of transferred energy is limited by maximum transmission line capacity.
Decision variable	Representing an activity in the optimisation model.
Effective solution	A solution where the objective can not be improve without degrade one of the others.
Multi-objective optimisation	Optimisation model where more than one objective shall be solved.
Off-taker	An energy actor that buys power via utility power purchase agreement for a defined time period for a fixed price.
Pareto front	A set of solutions where in each solution, one objective can not be improved without aggravate at least one other objective.
Pay-off table	Table showing the maximum and minimum values for the objectives in order to define the search area for the optimisation algorithm.
Price volatility	The degree of variation of the spot price
Reactance	Resistance for AC current by inductors and capacitors.
Utility number	Value describing significance of solution.
Value factor	Achieved average spot price for a power plant divided on the general average spot price.
Water value	The expected value of stored water for later use.
Weakly efficient solution	A solution where it exists alternative optima where a non-binding constraint can be improved.

List of Acronyms

Acronyms	**Explanation**
AUGMECON	Augmented epsilon-constraint
CAPEX	Capital expenditure
FDM	Fuzzy decision maker
HRES	Hybrid renewable energy system
LCOE	Levelized cost of energy
LP	Linear programming
MOF	Multi-objective framework (lexicographic programming, AUGMECON, FDM)
MOLP	Multi objective linear problem
MOO	Multiple objective optimisation
NEM	Regulation on grid regulation and the energy market
OED	Ministry of Petroleum and Energy
OPEX	Operational expenditure
PPA	Power purchase agreement
WPC	Wind power curtailment
RME	Regulation Authority
rpm	Rotations per minute
STHP	Short term high production
TLC	Transmission line capacity
TOPSIS	Technique for order preference by similiarity to ideal solution
UPPA	Utility power purchase agreement

List of Figures

2.1 Illustration of power steps from producer to end user [8]. 3
2.2 Map of 420, 300 and 132 kV transmission lines in north Norway [12]. 5
2.3 Nord Pool pricing map areas [18]. 8
2.4 Expected price variations on a seasonally and weekly basis [4]. 9
2.5 Three main business models of hydro storage [20]. 9
2.6 Figure of PPA between off-takers, intermittent renewable enegy source and consumers [23] 11
3.1 Illustration of a wind turbine connected to the grid [26]. 12
3.2 Operation areas for a wind turbine [28]. 13
3.3 Areas in Norway suited for wind power integration [25]. 14
3.4 Future wind production in Norway [31]. 14
3.5 The Francis turbine from above and horizontal point of view [38]. 17
3.6 The figure shows how the total inflow to Norwegian magazines can vary. Average/normal inflow is represented by the dotted graph, while green and blue graphs show maximum and minimum inflows respectively. Blue graph is the inflow pattern of 2020 [41]. 17
3.7 Illustration of ha pump hydro storage system [46]. 19
3.8 Most promising areas for PHS [47]. 20
3.9 Estimated cost of pumped hydro storage systems from diverse studies [48]. 21
3.10 Illustration of a complementary system of wind farm, hydro and pump turbine [54]. 23
4.1 Picture of all steps required to define the lexicographic ranges which shall be used in the AUGMECON algorithm [61]. 27
4.2 Different shapes of the membership function [64]. 29
5.1 Line diagram representing wind power plant, hydro plant, load and virtual dump load connected. 33
5.2 General flowchart of all contributions for the simulations. 36
5.3 Procedure of lexicographic calculation, AUGMECON and fuzzy decision maker. 37
6.1 Current wind farm capacity. 44
6.2 Wind farm scaled by factor of 1.5. 44
6.3 Desired hydropower production. 45
6.4 Desired wind power production. 45
6.5 Total grid system when the hydro plant can produce the desired production profile. 46
6.6 Annual reservoir levels for the desired hydropower production. 47
6.7 Obtained Pareto front for wind farm scale 1.5 49
6.8 Obtained Pareto front for wind farm scale 3. 49
6.9 Fuzzy utility values for wind farm scale 1.5 and all weights. 49
6.10 Fuzzy utility values for wind farm scale 3 and all weights. 49
6.11 Wind power curtailment for all wind farm scales and weights. 50
6.12 Wind curtailment sensitivity with different pump capacities and $w5$. 51
6.13 Conditional format table of relative hydro incomes. 52
6.14 Conditional format table of relative wind incomes. 52
A.1 Annual consumption pattern for NO4 in 2021. I

List of Tables

2.1 Overview of consideration and implementation time for transformer capacity upgrade, new substation and new power line operations. 6
5.1 Parameters for the reference case. 35
5.2 Pay-off tables for wind farm scale 1 and 3. 38
5.3 All weight ratios priorities between the wind farm and hydro plant. 39
5.4 Nomenclature explaining all variables and parameters in the MOLP. 40
6.1 Measured parameters from MOLP simulation with a wind farm scale of 1.5. . . . 48
6.2 Measured parameters from MOLP simulation with a wind farm scale of 3. 48
B.1 Pay-off table for both objectives in the reference case for wind farm scales. All values are measured in $M\ NOK$. II
C.1 Measured parameters from MOLP simulation with a wind farm scale of 1. III
C.2 Measured parameters from MOLP simulation with a wind farm scale of 1.25. . . III
C.3 Measured parameters from MOLP simulation with a wind farm scale of 1.5. . . . III
C.4 Measured parameters from MOLP simulation with a wind farm scale of 1.75. . . IV
C.5 Measured parameters from MOLP simulation with a wind farm scale of 2. IV
C.6 Measured parameters from MOLP simulation with a wind farm scale of 2.25. . . IV
C.7 Measured parameters from MOLP simulation with a wind farm scale of 2.5. . . . V
C.8 Measured parameters from MOLP simulation with a wind farm scale of 2.75. . . V
C.9 Measured parameters from MOLP simulation with a wind farm scale of 3. V

1 Introduction

1.1 Background

The world is moving towards a green energy transition as the negative trend of more CO2 emission and increased global average temperature must be reversed. Such a transition requires international agreements where the main industrial countries participate and development of alternative energy sources that can replace conventional polluting plants. The major climate agreement is the Paris agreement [1], which contains crucial targets to limit the global average temperature to 1.5 $°C$. In the climate report *Global Energy Review 2021* published by the International Energy Agency, there is emphasised that increasing CO2 emission and higher energy demand is still an obstacle to the renewable transition. This is highlighted through key findings that the CO2 emission in 2021 had the second-largest increase ever, the global coal demand in 2021 exceeded the 2019 level and the growth of the electricity demand is the fastest in 10 years. At the same time, renewables provided more than half of the global increase in electricity supply during 2021. [2]

Electricity production can be divided into three main types: conventional plants, dispatchable renewable energy plants, and variable renewable energy sources (VRES). Some major characteristics distinguish renewable energy sources (RES) from conventional plants. The most crucial difference is the dependence on weather conditions such as wind, rainfall, and solar radiation, and therefore it makes the generation forecast unpredictable. VRES as wind and solar power is dependent on the weather because it can not save potential energy for later use without an external storage unit. Compared to conventional plants which are often centralised, large-scale, and close to urban areas, RES occurs from very small to large-scaled and is distributed more across the grid. RES is beneficial for the environment, but it still needs to be matured in terms of being the main supplier of the energy demand. To make RES robust enough to generate a reliable energy supply, some main challenges must be solved. [3]

Boston Consulting Group (BCG) [3] categorizes the major challenges with VRES into four main areas: Resource adequacy, network adequacy, frequency stability, and voltage stability. The former addresses the issue of not having enough generation that matches the demand, while the network adequacy refers to sufficient grid capacity to transfer all electricity from the generating units to consumption centers. When the amount of generation and consumption is not in balance, the frequency starts varying and a problem with VRES may be that the frequency stability is not maintained within secure limits. Lastly, fluctuation of generation from VRES can cause varying voltage levels which can lead to damage to the grid and equipment. [3]

Many VRES are often located in district areas where the transmission capacity to urban areas is relatively poor. Distributed and weak grid connections can cause congestion issues, and especially the Northern part of Norway is an example of a location with good wind conditions, but poor transfer capacity. It has during recent years been decided to invest in several wind projects. According to NVE estimations, the wind power production will increase by 4 TWh towards 2040, but there is potential for even more wind projects [4, p. 34]. More wind power in North Norway causes lower spot prices, but also bottlenecks more frequently. Higher local demand will counteract these consequences and contribute to facilitating more wind power. To solve the problems, wind power can be combined with pumped hydro storage (PHS) and take advantage of new rules of grid connection.

New power plants have in principle the right to get sufficient grid capacity when the connection to the power grid is applied for. Usually, when the capacity is not sufficient, the grid company must invest in grid reinforcements and the power plant owner pays their part of the investment. Therefore, maximizing grid utilisation is important for both the grid company and plant owners in terms of avoiding/delaying grid investments. In addition to the economic perspective, grid reinforcements are an intervention of the landscape and nature. The Norwegian Ministry of Petroleum and Energy (OED) secures an effective energy market with a societal rational business of energy supply through The Regulation of grid regulation and the energy market (NEM). The laws determined in NEM cover fields such as production, transmission, energy distribution, and consumption. Recently, NEM has opened so that a new generation can connect to the grid, even though the grid capacity is not suited for it, in terms of reduction of production [5]. There can be different ways how this limitation of generation can be carried out to maximize the utilization of the grid capacity.

1.2 Problem description

The thesis aims to create a model that represents a transfer capacity problem in a reference area. As the wind farm capacity increases, the line will be congested, which is a problem as both the wind farm and a hydro plant use the same line to export energy from the location. The current agreement gives the wind farm transmission priority as long as it does not disrupt the planned hydro production. Since NEM has opened for new connections in terms of production limits, a wind farm can apply to increase the installed capacity even though the grid capacity is not sufficient. As long as the total output from the wind-PHS system is within the grid capacity, an optimal way to carry out this limitation and the trade-off between both producers can be proposed through a bilateral agreement.

In this study, some main contributions are included to investigate how the regulation of hydro plants can support the increase of wind farm capacity. A co-simulation framework is developed to optimise the wind-PHS integration. The overall framework consists of four main components: a standard simulation model, a multi-objective optimisation (MOO) model, a fuzzy decision-maker, and a techno-economic analysis. The standard simulation follows a NEM policy where the connection is done with terms of reduction. In the MOO, different trade-offs are proposed through the augmented epsilon-constraint (AUGMECON) algorithm. A fuzzy decision-maker (FDM) is used for a fair comparison of all proposed solutions, and a techno-economic analysis examines the impacts of different scenarios and provides recommendations for power production.

Following question will be answered through the thesis:

- How can multi-objective linear programming be used to schedule a wind-PHS system?
- How can wind farm projects be enabled in Norwegian locations with good wind conditions, but poor transfer capacity out of the area?
- Can wind-PHS systems be a solution to obtain grid investment deferral?
- How can different trade-offs between a hydro and wind power producer look like, and what factors must a bilateral agreement take into account?
- What is a reasonable expansion of the wind farm at the reference location?

2 The Nordic Power Grid and Market

The Nordic power grid area consists of Norway, Sweden, Finland, eastern Denmark (DK2), and the Baltic states that constitute one synchronous area. Through the western Denmark area (DK1), the Nordic power grid is connected to the continental Europe power grid through direct current (DC) transmission connectors. The Nordic area is an electricity market where the power flows between all price areas, and the transmission system operators (TSO) in each country follow some common operating principles through "The Nordic System Operation Agreement" described in [6].

2.1 Norwegian power grid structure

The Norwegian power grid is divided into three main sections that cover different parts of the grid from producer to consumer. The three main parts are called transmission, region, and distribution grid and cover certain voltage levels. The transmission part is the main grid and is used to transfer energy over long distances at high voltage levels between 132 and 420 kV to avoid energy loss. This part of the grid connects all major production and consumption areas in Norway together, as well as the European grid. The transmission grid is owned and ruled by the Norwegian TSO Statnett, which has a monopoly in terms of ownership and operating activities. Below the transmission level, there is region and distribution level. The region section covers voltage levels between 33 and 132 kV, while the distribution part is the section that connects the grid to the consumers at voltage levels between 0.2 and 22 kW. Figure 2.1 illustrates the mentioned power grid sections between producer and end-user. The operator of the region and distribution grid is called the distribution system operator (DSO). [7, p. 9]

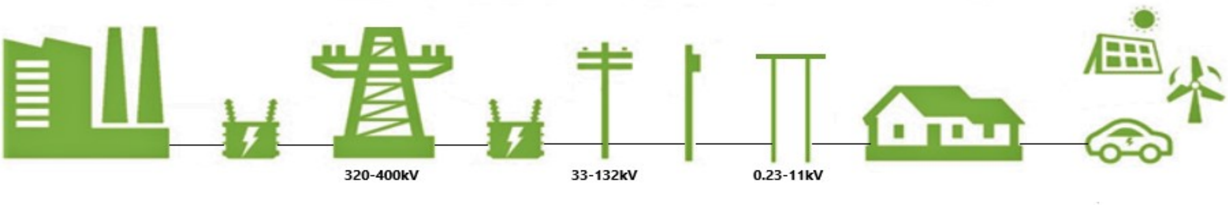

Figure 2.1: Illustration of power steps from producer to end user [8].

Statnett has a monopoly on the operation of the transmission grid in Norway and is a state-owned enterprise where OED is responsible for the state's ownership. Although Statnett is responsible for the operation of the transmission grid, they are not allowed to either directly or indirectly control any other companies that perform production or supply. This was highlighted in the release of the EU third energy market package. Statnett's main tasks in their turn are frequency regulation, balancing power production and consumption, streamlining the grid development and utilisation, facilitating international trading, handling congestion, and coordinating power supply from different producers. Statnett is responsible for facilitating connections of new producers by improving the capacity, or eventually designing agreements regarding grid connection with terms of production reduction which will be further explained in the section 2.3.2. [9]

Economy grid reinforcement

According to [10], Statnett's revenue is supposed to cover the development, maintenance, and re-investments of the grid. In addition, the revenue shall give a reasonable return on the invested capital. The maximum allowed income for Statnett is ruled by the government, and the preconditions are that the planning, the engineering, operation, and maintenance, are done cost-effectively. In [10, p. 22], Statnett shows a roughly cost overview of different parts of an investment project. 60-70 % of the costs come from the entrepreneur, 10% is maintenance, 5% by the system operator, 0-5% marked planning, 5-10% property operation, and 2-3 % is planning. [10]

The TSO is committed to making sure that all new connected producers have sufficient transfer capacity. Later in this section, it can be seen that exceptions for this commitment have been allowed in recent years. However, the TSO can require a connection facility fee when consumers or producers shall connect to the grid, increase the capacity or improve the supply quality. In some cases, the TSO may require the new producer to pay the whole facility fee. Such a scenario may occur if the increased transfer capacity will only be used by the new producer and no other will connect within ten years. In such scenarios, the TSO will find the investment unnecessary and impose all costs on the power plant owner. The re-investments and reinforcements are going to increase towards 2025, with new projects going on all over the country. Especially the north region needs upgrades to handle the new wind projects and expected increased consumption from industry and private households. [11]

2.2 Grid development in North Norway region

The north grid region seen in Figure 2.2, which is defined as the area from Trøndelag to Finmark, will experience high growth in power production and power-intensive industry in the coming years. Grid reinforcements in the north are therefore important for economic growth and the development of more RES projects. Through the grid development plan in Statnett [12], the vision is to improve the facilities for supply reliability, electrification, and green economic growth, and contribute to accelerating the green transition. An investment done by Statnett impacts the Norwegian society in different ways. Grid investments facilitate for development of new industry, and new power production and affect the energy prices in terms of transfer capacities, bottlenecks, and potential new grid tariffs. Because of the responsibility associated with the development of the grid, Statnett is committed to statutes and laws that emphasize the importance of societal rational grid development. In other words, the societal benefits of a grid investment must be greater than the societal costs if projects shall be executed. [10, 12]

The grid development is planned based on the future growth of production and consumption. In [12, p. 45] all requests regarding consumption and production licenses received by Statnett are shown on the map. It turns out that more industrial power production and aquaculture industry stood for most of the requests for new production and consumption capacity in the period 2018-2021. Both small and large scale industry establishments in Troms county are planned shortly, and that will require higher capacity in the county and more local production capacity as well.

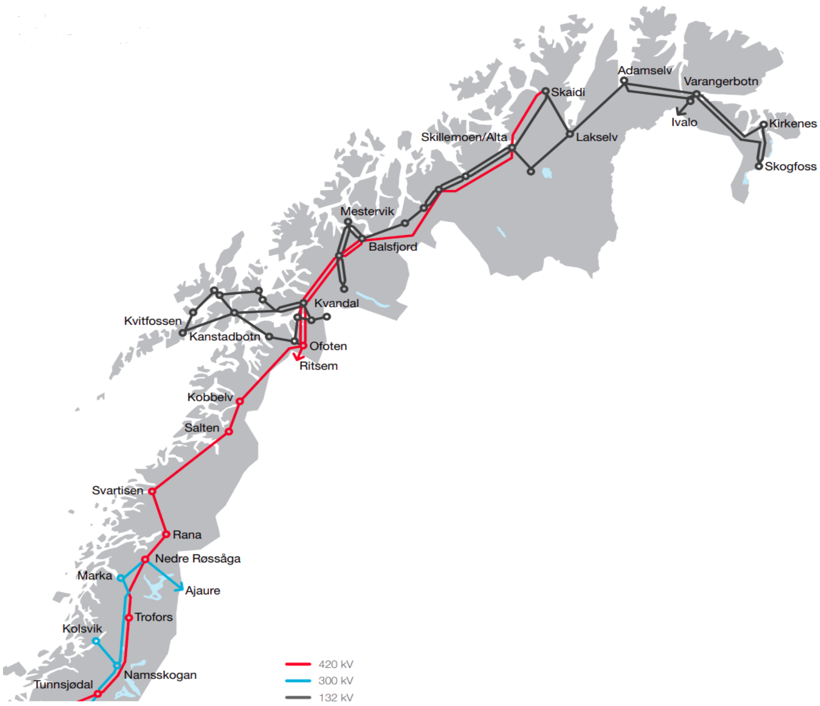

Figure 2.2: Map of 420, 300 and 132 kV transmission lines in north Norway [12].

The area north of Balsfjord has a surplus of power during the summer months but got a deficit of power in the colder periods during winter. For the area south of Ofoten, there is a surplus throughout the whole year. The natural flow of power is south from Ofoten through Norway and to Sweden. There are many hydro and wind plants located in Finmark, but the transmission capacity is poor with limited opportunities for new producers and consumers to connect to the grid. Statnett experiences a growing demand for new industry establishments in Northern Norway. There is estimated that future new industry consumption will take place in Finmark and Rana, and Statnett expects large grid upgrades in these areas, but an upgrade of the power transmission lines between Trøndelag and Nordland, which is one of the oldest transmission lines, will not be completed before 2040. [12]

Today, there is a deficit of power in Finmark and poor opportunities for new grid connections for consumers. Therefore, it is necessary to increase the capacity of the area to meet the growing demand. Statnett has also developed a staged rollout plan for the grid upgrade in Lofoten/Vesterålen area (close to Sørfjord). The plan includes a new line that will increase the capacity of the 132 kW line between Kvandal and Kvandstadboten (the black line that connects the locations can be seen in Figure 2.2). There is also possible that a capacity upgrade of the 420 kV line between Ofoten av Nedre Røøsåga must be done if all the planned increase in consumption gets realised. [12]

2.3 Regulation of grid operation

2.3.1 Connection process and regulation

The fundamental prerequisite for a power system is that grid companies shall allow connection to the grid for every actor. Alternatively, the grid companies can apply for an exception from the connection duty if they can justify that grid investment for more production are not socially beneficial. The grid companies is ruled by the government through *the regulation authority* (RME). In 2019, RME got the authority delegated by OED, to regulate the terms of connection and use of the grid. RME is an independent department in NVE and works according to the principles of the energy law § 2-3 and the natural gas law § 4. The main function of REM is to observe and control the grid companies, and secure an effective operation of the power grid with equal terms of competition for all actors. REM's responsibility is to make sure that power is supplied with sufficient supply quality for a reasonable price. Also, they prevent that grid companies benefits from their position as the monopoly of the grid area. It is the government that decides the NEM laws, but the decisions are strongly based on the proposal provided by RME. [13]

According to NVE, a new connection to the grid can only be conducted when it is within safety and quality limits. This means that the voltage has to remain within predetermined limits and connection is done without harming the delivery quality to other customers. The TSO can not require production limitations unless the consumer or producer wants to connect by the new NEM rule which will be explained in section 2.3.2. For new producers, another way to connect to the grid is to make an agreement with the existing producers with storage. In this way, the new producer can secure that the operation of the grid area is within safety limits until the grid investment is accomplished. The TSO is obliged to check if the agreement between the producers doesn't cause big changes in the grid operation before the agreement can be accepted. NVE has also added a condition regarding such agreements, which is that a concession for necessary grid investments must has been given for the area. Therefore, producers who want to connect to the grid area before the grid investment have to make an agreement with the grid company for permission for early connection with terms of production reduction or create an agreement with another producer with regulator facilities. [14]

The duration of the temporary alternative agreements depends on how long it takes before the necessary grid reinforcement is done such that the infrastructure is sufficient enough to handle the desired production or consumption. Table 2.1 is extracted from Statnett's home pages and shows an overview of approximated duration of concept consideration and implementation time for different types of grid upgrades. Considerations of different investments take between 1 and 12 months, and implementation time is 3-4 years for a transformer upgrade and 5-10 years for new substations and power lines. [15]

Table 2.1: Overview of consideration and implementation time for transformer capacity upgrade, new substation and new power line operations.

	Concept consideration	**Implementation time**
Increased transformer capacity	1-4 months	3-4 years
New substation	6-12 months	5-10 years
New power line	6-12 motnhs (+ 12-18 months external quality ensurance)	5-10 years

2.3.2 NEM connection rules

According to NEM law § 3-3: *The obligation to provide a connection for production of electrical energy.* The TSO is by law, committed to making sure that new connectors get sufficient grid capacity to secure a satisfactory connection. The grid company must in some cases analyse the need for reinforcements and the TSO and producer must then share the costs. As aforementioned, alternative agreements can be done as an alternative solution because of the lack of sufficient grid capacity. In 2019, REM launched a new NEM rule that opens for such solutions. As an option for reinforcements, the producer can connect to the grid with terms included in the contract, which require the power plant to reduce the generation in periods to keep power flows within the transmission capacity. The idea with the new NEM rules is better grid utilisation and faster and more effective solutions for grid connections. [5]

A grid company and a power plant can make an agreement regarding production limitations based on the aforementioned new NEM rules. However, such an agreement must be accepted by both the grid company and producer, and the connection must be secure in terms of operation and connection for all licensees. The criteria regarding when and how the production shall be downregulated or shut off must be specified in the agreement between the grid company and producer. The producer can not enter into agreements that deviate from the concession. Agreements with terms of reduction of production in either the regional or transmission grid must be considered by Statnett. Also, Statnett approves the connection and is responsible to make sure that the terms in the agreement are fulfilled. Any issues regarding terms of connection will be handled by RME. [16]

2.4 Today's power market

2.4.1 Nord Pool and spot prices

The Nordic power market is a liberalised market where all trade offers from both producers and consumers are sent to a common stock market. The power price is set based on the offers from the producers and the bids by the buyers. The stock is called Nord Pool and is the place where producers can submit how much they want to sell and to what price, and at the same time buyers will state how much they are willing to pay for power. The deadline for the submissions is 12:00 CET every day, and an algorithm calculates the market energy price, also known as the spot price. [17]

A spot price represents the cost of the last generator unit needed to match the load demand and will vary with different price zones and transmission capacities. Norway is divided into five price zones denoted as NO1-NO5. Between each price zone, there are transmission lines with a given capacity that connects all areas. A price area can either be in deficit, surplus, or balanced energy status. The power flows from areas with surplus to deficit areas, and price differences occur when the transmission lines are congested. A congested line will lead to an increased spot price in the deficit area. However, if the power flow is within the capacity, both areas will experience the same spot price. Each price area has a different bias between consumption and generation, and therefore areas with high generation and low consumption will experience lower spot prices than the opposite case. [17]

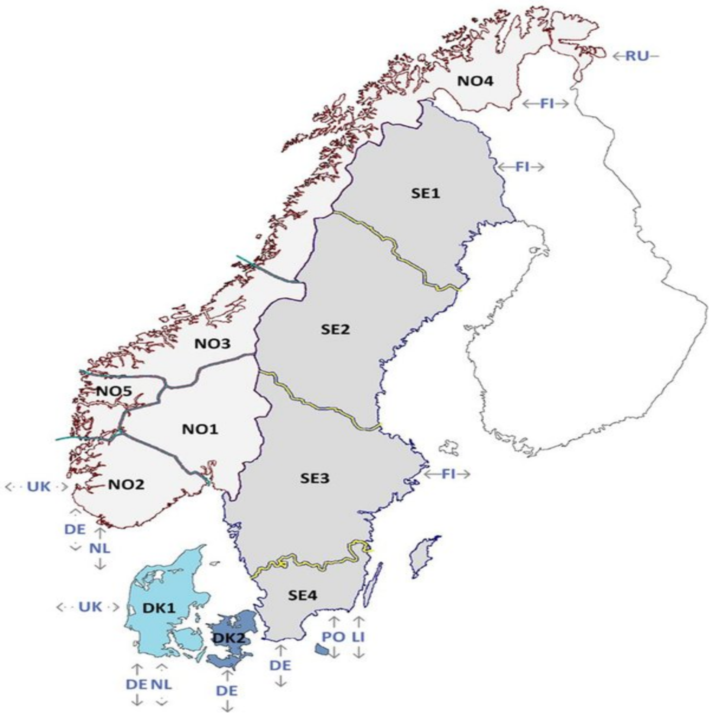

Figure 2.3: Nord Pool pricing map areas [18].

2.4.2 Renewables and its impact on the power market

A higher share of renewables is expected to dominate the future Nordic power system. The investment in RES has been high in the Nordic countries in recent years, and it will have an increasing impact on the spot price by 2030. The power price is affected by different factors such as costs related to power production in thermal, gas, and coal plants. Although Norway has almost 100 % renewable energy production, the spot price is affected by fossil plants because of the steady increase of the interconnection lines between the European and Nordic power markets. A power market analysis was done in 2021 by NVE as a result of a request from OED. The study aimed to create an overview and estimations of how the future power prices towards 2040 will look like. The spot price will increase towards 2030, mainly because of a more strict CO2 market and more interconnecting cables, but start to decrease towards 2040. In addition, the analysis estimates smaller price differences between north and south in 2040. [4]

Historically, the spot prices in Norway have varied a lot because of the amount of hydropower and its dependence on inflow to the reservoirs. NVE's analysis estimates that the spot price will vary even more in the future because of the expected amounts of new wind and solar projects, and higher CO2 and fuel prices. An increase in VRES production combined with improved transfer capacities will increase the short-term price volatility. The seasonal price differences is to be decreased towards 2025, but then increase after this point. For regulated energy sources such as hydro plants, higher price volatility is beneficial and will increase the income. At the same time, VRES will experience lower spot prices and a reduction of income. [4]. Figure 2.4 shows how the weekly price variation will behave in 2025 (black graph) and the green shaded area shows the possible weekly variation in 2040.

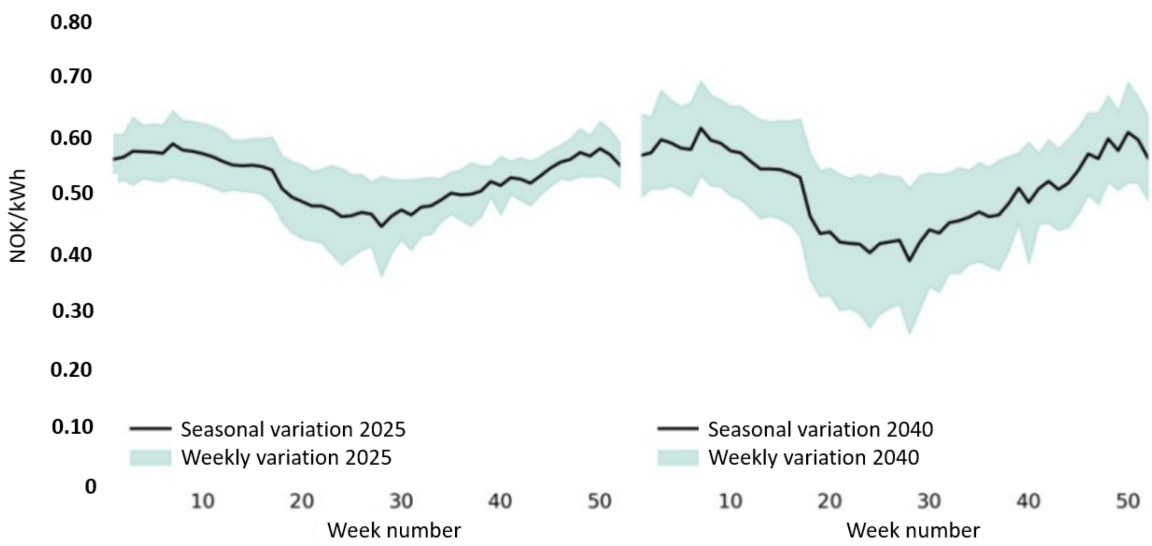

Figure 2.4: Expected price variations on a seasonally and weekly basis [4].

A spot price pattern with higher short-term volatility may cause regulated power plants to change the production profile, because of the opportunities for gained income by frequently short-term high production (STHP). More rapid variation force the plants to utilise favorable production prices more often to maximise their income. Therefore, the operational pattern of the hydro production can go from being day-ahead based, to being characterised by more intra-day tradings. [19]

2.5 Market participation

In addition to the spot energy market, energy can also be delivered through alternative markets for energy. Figure 2.5 shows three main business sections that power producers can participate in: Arbitrage (spot market), ancillary services, and the capacity market. Arbitrage is the concept of importing energy during cheap periods (if the plant has rechargeable storage) and storing it for later production when there are more favorable spot prices. The ancillary service market is a cooperation between producers and the TSO for stabilising and maintaining the reliability of the energy delivery in the power grid by keeping frequency and other grid constraints within secure limits. A capacity market involves the ability to put amounts of energy into the grid on short notice. Capacity providers are important for securing a balance between production and consumption. The advantage of being a capacity provider is that such deliveries of power are usually priced higher. These prices are determined through direct agreements between TSO and producers. [20]

Figure 2.5: Three main business models of hydro storage [20].

In the capacity market, there is a seller, buyer, and capacity price. The buyers are usually large energy users who want to hedge against high spot prices, while a capacity seller offers to provide energy because a guaranteed income is desired. The concept is that the buyer pays a fixed price per MWh to the seller. With more participants that distributes flexible capacity, new solutions must be adapted in the control of the power system. [20]

2.5.1 Ancillary services and balancing market

Primary (FCR), secondary (aFFR), and tertiary (mFFR) reserves are acquired through market solutions similar to the Nordpool spot market explained in section 2.4.1. The TSO needs reserve capacity in scenarios when unexpected actions happen where more or less power production or consumption is required to maintain a power balance in the grid. The producer's willingness to provide reserves for the TSO is dependent on the profitability compared to the spot market participation. Producers can, as in the spot market, submit bids for providing balance and ancillary services. If reserves are needed, the producers are paid by the TSO for activating the reserves. [21]

Statnett is about to develop a new coordinated cross-border spot and reserve power market called aFFR. The new aFFR concept is the reservation of cross-zonal capacity (CZC), and the main reason behind the new capacity market is because the Nordic market consists of many small bidding zones with unevenly distributed balancing resources. Therefore, more cross-border balance of power exchange is necessary to maintain operational security in all areas, because some areas have a deficit of power. Reserving more power for exchange in the CZC market means that less capacity is given in the day-ahead and intra-day market. The reservation of the capacity has to be reserved by forecasting of the day-ahead value of CZC, and the TSO will further submit a aFFR demand in MW each direction for each bidding zone. [22]

2.5.2 Bilateral and PPA agreements

Between 2013 and 2018, the power volume in power purchase agreements (PPA) increased from 127 MW to 2330 MW, and Norway and Sweden have during the last five years signed more than half of these agreements. Wind power composed 75% of signed PPAs between 2016 and 2020. The main drivers for the increased use of PPA are the acceleration of wind and solar projects and the increased amount of high-consuming data centers. In addition, the demand for documentation of green power consumption is growing among the power-intensive industries, hence the interest in PPA signings with RES plants has increased. [23, p. 8-9]. PPA works as a bilateral contract between a producer and a consumer. Compared to the most common power trading through the spot market, PPA's are a type of agreement that commits the parts to power trading for several years ahead. [23]

In recent years, the interest in using PPA in the power market has increased and different ways of configuring PPA's have occurred as the power market has become more complex with higher shares of VRES. RME has published an external report done by Copenhagen Economics [23], that splits PPA into two categories: New corporate PPA for large consumers that support the development of projects as new wind farms, traditional PPA between regulated power companies and consumers, and utility PPA (UPPA) that aims to sell power to energy companies that store the energy. The report defines a UPPA as: *" Utility PPAs which involve selling power to a utility* *or an energy company instead of directly to the consumer.".* Figure 2.6 shows different types of PPA between energy companies, VRES as a wind farm, and consumers. As seen in the Figure, a utility power purchase agreement (UPPA) can be created between an energy company and a wind farm. A UPPA is a type of agreement where power producers such as wind or solar farms sell power to an energy company with storage opportunities, and the energy company works as an off-taker for the new producer and supports the finance of the new VRES. [23]

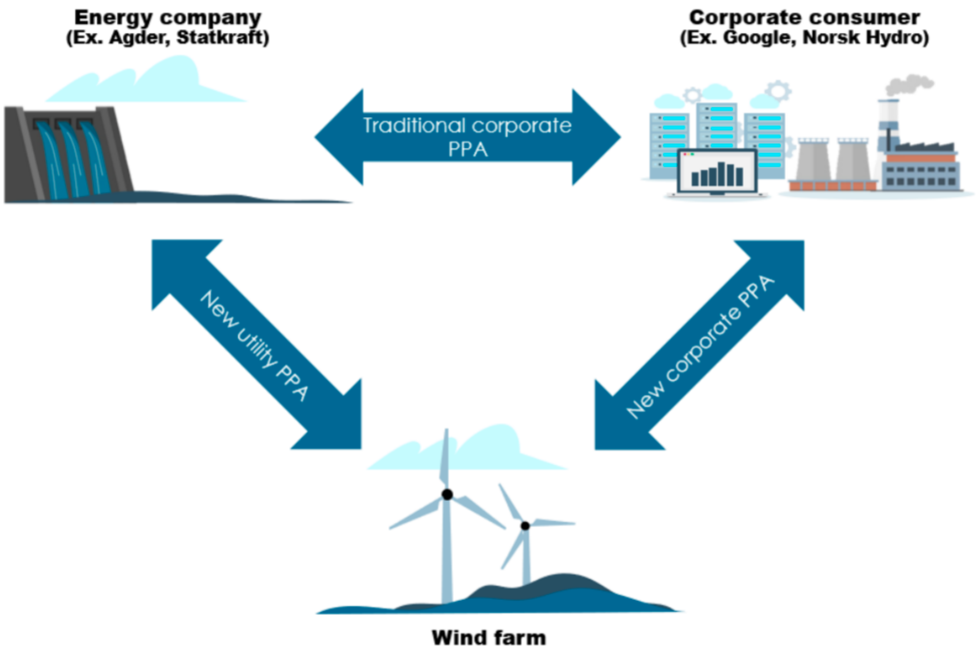

Figure 2.6: Figure of PPA between off-takers, intermittent renewable enegy source and consumers [23] .

Projects that involve solar or wind development are more likely to be interested in hedging the lifetime of the projects because of the uncertain and unreliable energy production. According to Copenhagen Economics [23], to be granted loan by banks, wind projects need to prove a certain revenue stream through a signed PPA. Each agreement will be different such that a PPA must be customised for all individual cases. From a Nordic practice's point of view, typically elements which are to be discussed in PPA's are physical or financial agreement, price, duration, volume, balance volume, and Energy Attribute Certificate (EAC). During negotiations regarding price in PPA's, the price for the contract duration has to be determined. Normally, an excess amount of producers offering PPA's contributes to pressing the prices down, leading to an agreed price below the expected spot price.

3 Wind and hydropower systems

The section contains an overview of the state of the art of hydro and wind power, where the power generation is explained and which components are included. Further, future and current hydro and wind power potential in Norway are highlighted and key values for economic parameters are given. The description of economic parameters and key values in Section 3.1.3 is extracted from the project preceding this thesis in Jamessen [24]. Finally, coordination of the energy sources is explained and the need for such systems is highlighted from different point of views.

3.1 Wind Energy

3.1.1 Technical review

A wind turbine produces power by converting the energy of the rotating turbine into electrical energy through a generator. The most conventional type of wind turbine is the horizontal axis wind turbine with three rotors. Besides the turbine, the wind power concept requires additional components to convert the mechanical energy to electricity. As Figure 3.1 shows, the wind turbine is connected to the grid through a gearbox, generator, transformer, and collector bus. The turbine makes the main shaft rotate and is coupled to the gearbox, which adjusts the rpm. Further, the next shaft after the gearbox rotates in the generator and induces a current. It is necessary to step up the current's voltage, to secure sufficient quality of the delivered power to the grid, through a transformer. The fed power also experiences some induction loss before it is transferred, represented by the reactance between the transformer and collector bus in Figure 3.1. [25, p. 13-14]

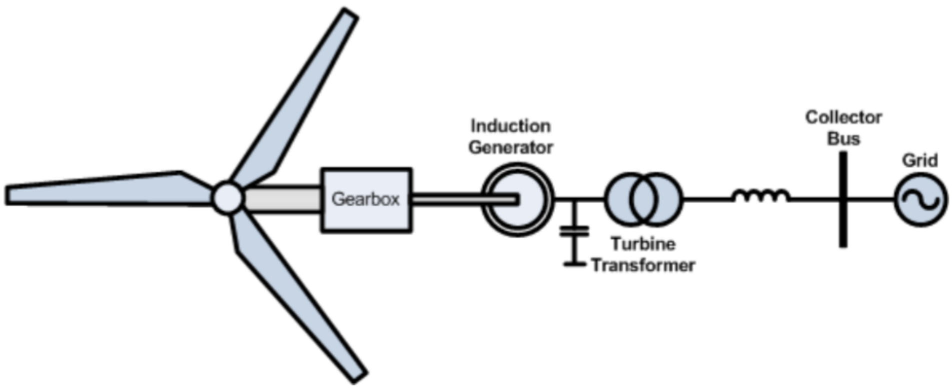

Figure 3.1: Illustration of a wind turbine connected to the grid [26].

The performance of a wind turbine is dependent on the wind conditions and control technology adapted to the turbine. In Figure 3.2, the four regions I-IV illustrates the operation modes for a wind turbine due to different wind speeds. Region I tells that a minimum wind speed, called cut-in speed, is required to start the power production. From the cut-in speed in region II, the power output increases proportionally to the wind speed until it reaches the rated speed for the current turbine. At the rated speed, the wind turbine operates at the nominal power which is the ideal operation mode. Nominal power is the capacity of the turbine and varies for different types of turbines. The wind turbine can operate at nominal power until the wind speed reaches the cut-out value. At this point, the wind turbine stops producing power to avoid failures and damage. [27]

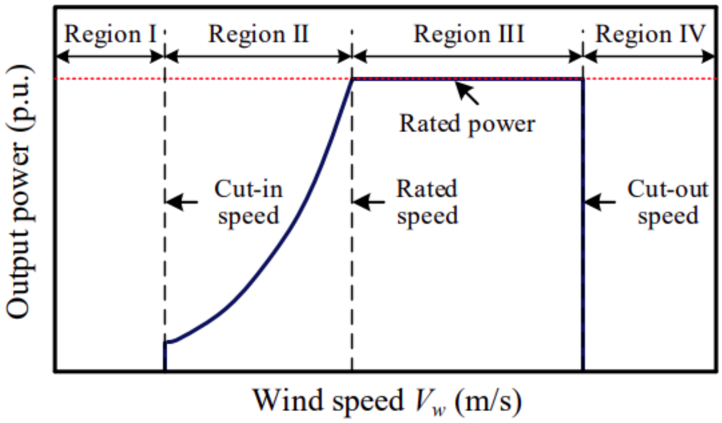

Figure 3.2: Operation areas for a wind turbine [28].

Some major parameters are commonly used to describe the technical performance of a wind turbine. A wind turbine's capacity is usually given with an installed power which is the maximum power output from the turbine, also known as the rated power from Figure 3.2. Due to varied wind conditions, the full-load hours from a wind turbine is a crucial parameter because it tells how man operating hours in a year at rated power that is required to obtain the estimated annual production. Other values describing the performance are the capacity factor and efficiency. The capacity factor is the annual average power output divided by the maximum power capability, while the efficiency is the power output divided by the potential power in the kinetic wind energy. Capacity factors between 0.26 and 0.52 are normal for onshore wind turbines, and a maximum efficiency value is 0.59, which is defined as the Betz limit. [29]

Wind power technology is developing and contributes to improving the power output and lowering costs. Especially, advanced control systems for wind turbines have been developed. Compared to older versions, modern turbines can maintain the operation even though wind speeds exceed 25 m/s, which is a typical cut-out speed for wind turbines [25, p. 14-15]. Under high wind speed conditions, the blades' angle can be adjusted to reduce the force working on the blades. Such control is called "pitch angle control" and aims to adjust the pitch angle β to maintain the output at rated power. β is increased during high wind speeds to lower the pressure on the surface, while it is increased at lower wind speeds to increase the pressure and torque to achieve max power output. By looking at the Figure, this means that in region II, the blades are tipped such that the blades accelerate and get closer to rated power, while in region III, the pitch angle is adjusted to maintain the production at rated power and limit the rotation speed as the wind speed increases. [27]

3.1.2 Wind energy in Norway

In the second quarter of 2022, there are 64 operating wind power plants in Norway where 1305 turbines correspond to a total installed capacity of 4655 MW. All turbines have in total a mid-production of 15455 GWh. The price areas NO1-NO4 stands for 786, 4868, 6999 and 2802 GWh respectively [30]. Among all countries in Europe, the Norwegian wind resources are one the most promising. The main reason for the good wind conditions is that the coastline is located in the area where cold air from the North hits warmer air coming from the south. This air interaction accelerates the wind speeds and the wind flows along the sea with no obstructions before it faces the Norwegian coastline. In addition to the promising wind conditions, the production cost of wind power in Norway has a positive trend and it turns out that the development of wind power technology contributes to an annual decrease in the LCOE. [25]

According to the research *Long term market analysis* [31], done by Statnett, the wind power will be dominant in the future Nordic power system. Towards 2040, the amount of wind power is estimated to increase from 3 TWh to 31 TWh, which is shown in Figure 3.4. This increase in wind power capacity is estimated to be integrated into the recommended areas shown in Figure 3.3. The wind map shows the most suited areas for wind farm expansion in Norway. The map consists of 13 areas, and the locations are based on wind potential, profitability opportunities, and contradictory interests in the desired wind farm site [25, p. 93].

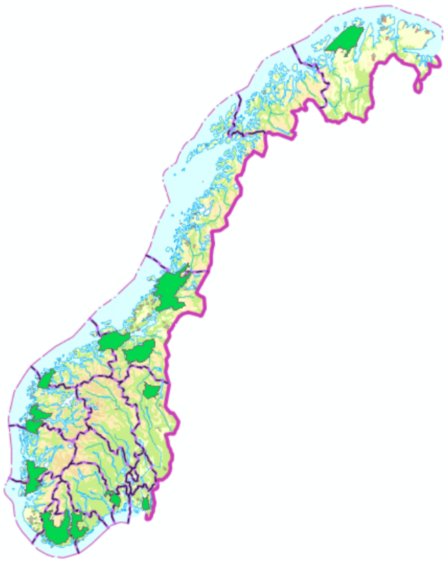

Figure 3.3: Areas in Norway suited for wind power integration [25].

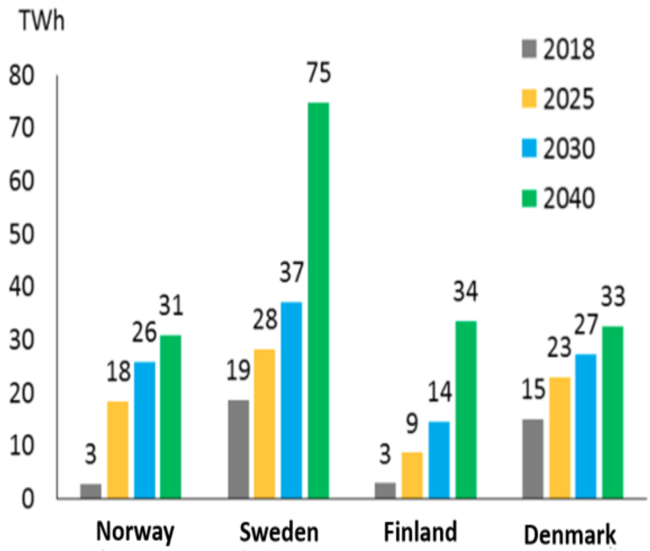

Figure 3.4: Future wind production in Norway [31].

Since the production and installation costs have decreased significantly in recent years, wind power is nowadays profitable without subsidies. The reason why wind power will remain profitable in the coming years is that even though the share of wind power increase in the North, the transmission capacity between the south and north will be unchanged in the near future, and therefore, especially price area NO1, NO2 and NO5 will still have high prices which will benefit the wind farms. On the other side, the profitability in Norway is more uncertain towards 2040 because of the achieved amount of installed wind power all over Europe. In addition, the uncertainty also relies on the development of the transmission capacity. A power market consisting of more intermittent power generation will require more power exchange and upgrade of transmission lines which will have an impact on the spot price as explained in section 2.4.1. [31]

3.1.3 Wind power economy

The economic aspect is an important factor when considering wind farm investments. An essential parameter from an economic point of view is the levelised cost of energy (LCOE), which describes the total costs of a wind farm and can be used as an investment indicator. LCOE is a cost per unit value and aims to help developers to make investment decisions. When considering an investment of a RES, an important pointer is the LCOE and grid parity. If the LCOE achieves grid parity, then the cost of generation is competitive against other generation technologies in the market, and the energy production will be profitable [32]. An LCOE is calculated by adding the CAPEX and OPEX divided by the total energy production from the plant during the lifetime [33].

CAPEX and OPEX stand for capital expenditures and operating expenses. CAPEX represents the capital input for the project and covers the expenditures during the life which can be divided into four categories: turbine cost, electrical system, support system, and project development and management. For the OPEX costs, the value is often determined as a percentage of the CAPEX and consists of main expenditure elements such as insurance, regular maintenance, repair, spare parts, and administration. For CAPEX, installation and transport costs are usually given as a percentage of the total turbine costs, while the support system often is a percentage of the manufacturing cost. The cost of the electrical system is more uncertain because several elements have an impact on the cost as installed capacity, distance from manufacturer to plant location, and what components are needed in the electrical system. Anyway, the electrical installation cost is often given as a percentage of the overall turbine cost. [34, p. 28-45]

A trend in the wind power industry is that the cost has decreased to a grid parity level in recent years. The main drivers for the positive economic trend are improved generation technologies and a longer lifetime of wind projects. According to Beiter et al. [35] the LCOE in 2050 will be between \$20 and \$30/MWh which corresponds to half of the LCOE value in 2021. The LCOE of onshore wind power decreased by 28-36 % between 2014 and 2019, while it decreased by 28-49 % for offshore wind. Beiter et al. [35] also investigated the cost trend in the period 2000-2020. The future trend of the LCOE is challenging to estimate, and there exist different assumptions about the reduction of LCOE. Beiter et al. [35] refer to several estimations where DNV GL assumes a reduction of 29-40% in 2035 while NREL provides a larger range of 15-49% reduction [35]. When it comes to the capital cost, Beiter et al. [35] measured that between 2015 and 2020, the global average CAPEX got reduced from 1250-1700 $\$/MWh$ in 2015, to 1050-1450 $\$/MWh$ in 2020. Stehly et al. [36] takes a 2.6 MW land-based wind turbine as reference and estimates a CAPEX of 25 $\$/MWh$ and a OPEX of 11.5 $\$/kW/yr$. For off-shore wind farms, the global average CAPEX is estimated to be 2600-3675 $\$/kW$ in 2020, and the LCOE for commercial scale-floating projects in 2019 was between 95 and 175 $\$/MWh$.

3.2 Hydropower and pump storage

Hydropower is one of the oldest technologies in the energy production field and is also the most conventional RES worldwide and the major energy source in Norway. Norway is well suited for hydropower because of the landscape dominated by mountains and an environment characterised by great rainfall conditions. The first hydro plant in Norway was released in 1890 and 95% of the Norwegian electricity consumption was covered by hydropower in 2014 [37]. This section gives an overview of how a hydro plant works, and how it can be complemented by a pump facility. Some main economic parameters are highlighted, and the hydro plant's ability to regulate power and future potential regarding this are highlighted. Further, challenges regarding the operation of hydro plants and participating in the power market are explained.

3.2.1 Technical review

The main parts required in a hydro plant are a water source, a waterway that leads the water mass to the generating unit, a power station with turbine and generator, a transformer, and a tail-race for the outlet of water. A hydro plant can either utilise the potential energy stored in a reservoir or the kinetic energy in a flowing river, and Kilintveit [37] divides hydropower plants into these two main concepts: a run-of-river and storage hydro. A run-of-river-based hydro plant extract water from a river flow and the production profile will therefore follow the pattern of the water flow in the river. For a hydro plant with reservoir storage, water can be saved for later use and got more opportunities to schedule the production as well as include pump-back-to-reservoir facilities.

Both types of hydro plants utilise the energy released by water moving from one height level to a lower through a water-way to the outlet. The waterway is usually a pipping line that connects the water source to the turbine chamber. Water stored at a height contains potential energy which can create mechanical energy when the water mass drops. The energy in the water mass can be extracted and converted to electricity by use of a turbine that receives the flowing water mass. The output power from a hydroelectric turbine can be described as in the equation 3.1:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta \tag{3.1}$$

where ρ is the density of water where a value of 1000 kg/m^3 is common used, g is the gravity ($9.81m/s^2$), Q is the volume stream in kg/s, H is the elevation drop and η is the turbine efficiency. The amount of energy produced by the hydro plant (E) is a product of the output power multiplied by the time the plant has been producing as equation 3.2 shows. [37]

$$E = P \cdot \Delta t \tag{3.2}$$

The mechanical energy is created when the flowing water hits the shovels attached to the turbine, such that the water mass pushes the turbine and causes a rotational motion. There exist different types of hydro turbines suited for different waterfall heights, locations, sizes, and water flows. Hydro turbines can be divided into two main types: impulse and reaction turbines. The principle of an impulse turbine is that a water stream hits every bucket and pushes the turbine in a rotation motion. One of the most used impulse turbines is the Pelton turbine where jets are used to lead the water to the buckets. This type of turbine is suited for high heads and lower water flows. Compared to the impulse turbines, a reaction turbine leads the water flow over the blades through a runner instead of letting the water hit every bucket. Such types of turbines are meant for lower waterfalls and higher flows. The two main types of reaction turbines are the Kaplan and Francis turbines. [38]

The Francis turbine is one of the world's most used turbine types due to its flexibility. The turbines are characterised by their flexible usage in terms of different head heights and flow rates. The Francis turbine has a radial flow axis where the water goes through a runner that curves along with the blades. The runner is a curved tube called "volute" with valves along the spiral where each valve point at a blade. The jets from each opening creates a rotational flow that induces a rotation of the turbine. Figure 3.5 shows the turbine from two angles: water enters the turbine through the tube in the left picture, and it is showed how the shovels are positioned relative to the water streams in the right picture. [38]

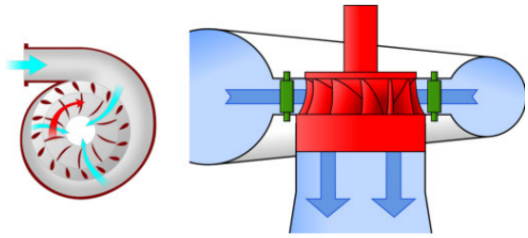

Figure 3.5: The Francis turbine from above and horizontal point of view [38].

Two fundamental parameters can describe the quality of the turbine and production: Efficiency and capacity factor. The efficiency is a measure of much energy the turbine can extract from the bypassing flowing water. A Francis turbine's efficiency is between 90 and 95% and provides the best performance where the head height's range is 100-300 m [38]. A capacity factor is the actual annual production divided by the theoretical potential if the turbine runs at full capacity throughout the whole year, both values measured in Wh. The value of a capacity factor for the Francis turbine is often between 0.4 and 0.6. [37]

3.2.2 Hydropower in Norway

Approximately 90% of the Norwegian hydro resources are owned by the state or county municipalities, which is a result of the licensing system implemented by the Norwegian parliament in 1909 that secured national authority over hydropower resources [39, p. 275]. About three-fourths of the hydro plants in Norway have reservoir storage. A typical pattern of Norwegian reservoirs is characterised by an emptying of the magazines during the first months of the year, because of the high electricity consumption during the winter. Then a filling period when the snow melts in the spring period occurs and the reservoir level increases. Historically, the inflow to the reservoirs is at the highest during May, June, and July. On average, the highest inflow is in June, and it decreases until the end of July/start of August when the reservoir levels peak before the producers start to increase the production in November/December. [40]

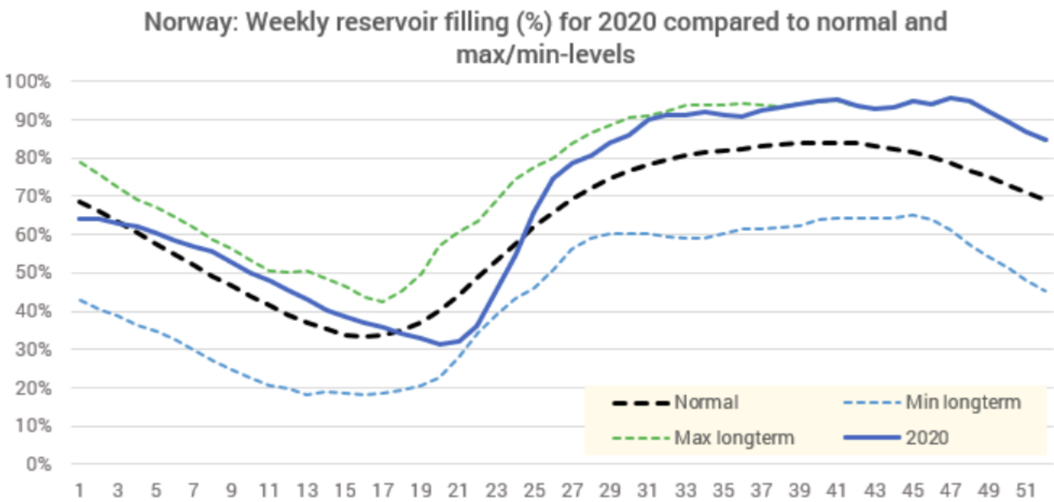

Figure 3.6: The figure shows how the total inflow to Norwegian magazines can vary. Average/normal inflow is represented by the dotted graph, while green and blue graphs show maximum and minimum inflows respectively. Blue graph is the inflow pattern of 2020 [41].

The Norwegian geography is well suited for hydropower as the country has high amounts of steep terrain, a significant amount of annual rainfall, many rivers that gather and create dams and lakes, and a major part (approximately 40%) of the land mass has a height of more than 600 m. Due to the landscape, about 80 % of the Norwegian hydropower system is high head plants that store water in high elevation levels. The hydropower system in Norway consists of more than 1000 reservoirs that cover a capacity of about 85 TWh. The Norwegian reservoir capacity represents 50% of the total hydro storage capacity in Europe, but the potential hydro storage capacity in Norway is estimated to be 212 TWh distributed on 132 new projects. The number of hydro plants was 1681 at the beginning of 2021, with a total capacity of 33 055 MW. Normally, annual production from the Norwegian hydropower system is 136.4 TWh. This corresponds to 90% of Norway's total power generation. At the beginning of 2021, an additional 2.3 TWh was under construction. In 2020, 1175 plants were in the range of $0 - 10\ MW$, 255 plants between 10 and 100 MW, and 80 power plants were larger than 100 MW. The 80 power plants were 80 % of the total contribution in terms of production. [39, 42]

Hydropower has played a crucial role in the development of Norwegian industry and economic growth and is also an important resource due to the storage of energy produced by VRES in central Europe. Using Norwegian hydro reservoirs as storage for European surplus production is a major tool to improve the green transition in Europe. In addition, Norwegian hydropower developers can benefit from offering storage to Europe and importing cheap power, which can improve the economic frames regarding hydropower projects. [39, 43]

3.2.3 Pumped hydro storage

The main idea of a pumped storage hydro plant is to fill the upper reservoir by pump water from a lower level water source. Storing more potential energy during low-demand periods improves the hydro plant's ability to produce energy in high-demand periods with a higher energy price. Therefore, a significant difference between the spot price in low and high-demand periods is necessary to achieve a profitable operation of the PHS. As seen in Figure 3.7, a reverse-turbine connects an upper and lower reservoir and can either operate in generating or pumping mode. The characteristic of a PHS makes the hydro plant able to offer the crucial type of services in terms of power system regulations and maintenance of power supply quality. [44]

Pumped storage is suited for markets where the difference between high and low-demand periods is significant. Based on the variation of the spot price, an operational pattern of the pump can be on a daily, weekly, or seasonally basis. Daily pump storage empties and fills the reservoir for 24 hours, a weekly pattern fills the reservoir moderately on weekdays and completes the filling during weekends. For a seasonal operation, a large annual variation of inflow makes it favorable to pump and produce during specific months of the year. [45]

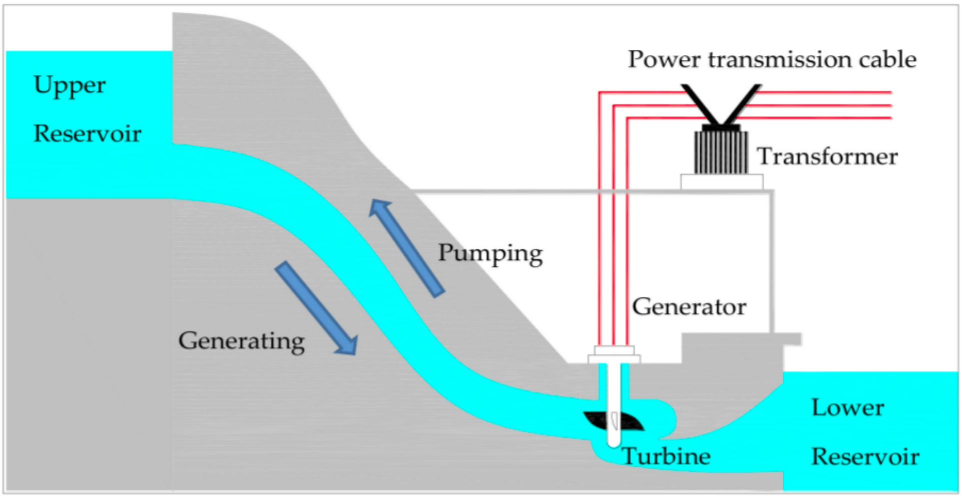

Figure 3.7: Illustration of ha pump hydro storage system [46].

PHS systems can be categorised based on the frequency of pump operations, capacities, and technical dimensions. The most common-known PHS arrangements are open-loop, closed-loop, and pump-back storage. An open-loop system means that there is a powerful natural stream of water to the upper reservoir or lower reservoir. Usually, naturally flowing water creates the lower reservoir, therefore the lower reservoir is a dam built in the flowing river and the water can be transferred between the upper reservoir, lower reservoir, and the downstream river. While the closed-loop interferes with natural water streams/dams, a closed-loop PHS is isolated from the natural water flows and instead, consists of artificial lakes/dams in both the upper and lower reservoir. A closed-loop system is usually suited for daily or weekly storage because of the poor water inflow conditions. The pump-back storage is a type of PHS system where a reverse hydro turbine is placed between a dam and another lower reservoir downstream. In this case, the water flows back and forward the two reservoirs according to the need for storage and production respectively. [45]

In 2022, there was 30 pumps in Norwway in Norway, with an annual energy production of $-0.2 TWh$. According to Cedren [48] , there is a pump power potenial of 20 GW in Norway, and many Norwegian reservoirs can be utilised even better with pump facilities. Significant amounts of available short term storage can be utilised without reducing the seasonal regulation with PHS, and hence increase the income. Further, NVE [47] emphasises that hydro plants with most promising PHS potential is where the plants already are located between two regulated reservoirs with a capacity more than 100 millionn m^3. In 2011, it was estimated that there are 20 plants that fulfill these criteria. Figure 3.8 shows 4 of the most promising areas for PHS operation.

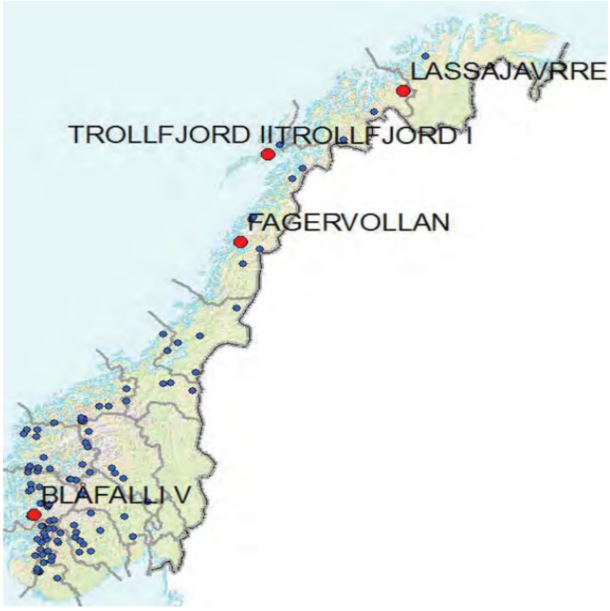

Figure 3.8: Most promising areas for PHS [47].

3.2.4 Cost review

In 2011, Vattenfall Power Consultant (VPC) published a report, on behalf of NVE, that covered a study of the costs of PHS implementation at four major hydro plant locations in Norway. The requirements for the location of the study in Hamnaberg [47] were: opportunities for pump storage installation, a location with poor transfer capacity, and existing/future VRES plants in the area. This resulted in three locations in the north grid region NO4 and one in NO5. The study showed a clear relation between installed capacity and specific cost, and one of the major discovered trends was that a PHS with only a few cycles per year is much more expensive than PHS plants with many. However, large investments are required for the development of PHS and it turned out that the smallest projects had an investment cost of 300 million NOK, while larger projects with a pump of 1500 MW required an investment cost of almost 5 billion NOK. Small scale PHS projects had a specific cost between 15000 and 20000 NOK/kW, while the price can be pushed down below 5000 NOK/kW for pump capacities more than 500 MW. [47]

A study by CEDREN and NTNU in 2016 also investigated the cost of PHS projects and refers to approximately the same cost values as the aforementioned. Figure 3.9 shows that different studies have been conducted to determine the costs of the construction of PHS. In Killingtveit [48], there is shown that both NVE, CEDREN, and NTNU have done studies on the costs of pumped storage, and the resulting graph in Figure 3.9 shows the costs of small scale pumped storage is in the range 5000-20000 kr/kW and bigger plants over 1250 MW have a cost $<$ 5000 kr/kW. Hence, the cost per kW decrease drastically as the installed power gets bigger. Further, Killingtveit [48] states a rule of thumb is that costs for pump storage projects for capacities in the range $100 - 1500\,MW$ are $250 - 550$ €$/kW$. [48]

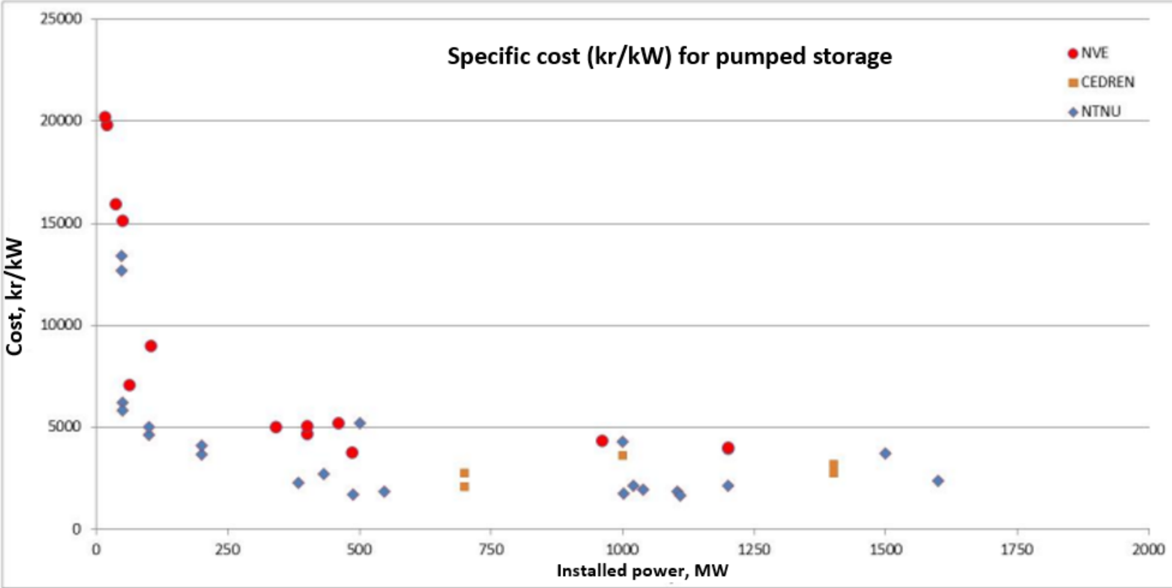

Figure 3.9: Estimated cost of pumped hydro storage systems from diverse studies [48].

3.2.5 Importance and challenges with regulated hydropower

A power system consisting of a higher share of VRES risks worse consequences during fault periods. Therefore, the flexibility is getting more important in order to handle types of grid challenges. In addition improved contingency plans during fault periods [49]. The increased capacity of interconnected cables mentioned in section 2.4.2, makes it more valuable to have the ability to regulate the power production. When VRES substitutes energy sources such as coal, gas, and nuclear plants, more fluctuations in the spot prices are to be expected. Both the weekly and seasonal. More periods with prices close to zero, but also more periods with high price peaks will be the characteristic of the future price profile. With such price characteristics, hydropower flexibility will be more valuable [4].

Although Norway has a significant total reservoir capacity, there exist obstacles that limit the use of reservoirs as reserves. Many reservoirs are connected to natural water streams that require a minimum of mass flow. This requirement forces the plant to bypass water and cause loss of potential energy. The consequences of this requirement depend on the amount of inflow compare to the minimum flow requirement, however it prevents flexibility to a certain extent. The frequency of regulating the reservoir level is also to be restricted because of animal life. As an example, too fast changes in the reservoir may cause fish to be stranded. Such restrictions also limit the plant to utilise short term price variations, and the ability to down-regulate production to provide Statnett balance service. Lastly, reservoir restriction is a type of constraint that set rules for when the plant can provide ancillary services. A reservoir restriction can either be an ”absolute” restriction, where the reservoir level is set in a given period. While a ”soft” restriction requires the plant to only operate in a filling mode in a given period. [50, p. 12-13]

From a societal point of view, restrictions that force the producers to move production from high price periods will change the trading pattern and generate a less socio-economic surplus. Changes in trading patterns may also reduce the producer’s ability to provide reserve and make the operation of the power system more expensive because of higher reserve prices. Lastly, since regulated hydropower is well used to solve challenges such as bottlenecks in poor capacity areas, reducing the regulating ability will lead to bigger system operation challenges. Hence, more grid reinforcements may be necessary which will cause more environmental damages and create issues regarding the principle of societal rational grid development stated in section 2.2. [49]

3.2.6 Profitability and economic challenges

Most of the Norwegian power is produced from hydro plants with large amounts of storage capacities. Such storage capacities make the plants able to choose when to produce and import power when needed. Having the opportunity to store energy is beneficial as a bidder in the power stock market, which is explained in section 2.4.1. The flexibility of the hydro production is mainly dependent on two factors; storage capacity and installed power. In addition, the annual inflow to the magazine is crucial for the hydro plant's operational strategy regarding participating in the energy market. [51]

The size of the storage capacity and the installed turbine power are crucial for the operational pattern of the production. In the NVE report Schemde [52], Thema consulting investigated how Norwegian hydro plants utilise the short term high production (STHP) potential. It turns out that many hydro plants and pump hydro storage can base the production on short-term high production (STHP) more than they do today if the load demand increases. A higher demand combined with bigger price volatility may affect the operational pattern and the income potential as well. Power plants with a significant usage time have limited opportunities to move the production without losing water. A paradox in the research is that it turns out that hydro plants with small reservoir capacities tend to operate with STHP more than plants with larger reservoirs that prioritise long-term disposition. The main reason behind this tendency is that plants with poor reservoir capacity can not store enough energy for seasonal operation. This means that small-scale plants only achieve a high value factor by STHP. Summed up, more installed power improves the ability of STHP, while better storage capacity increases the opportunities for long-term dispositions. [52]

Most of the interviews of producers in Schemde [52] were expecting that the short-term price volatility will increase in the coming years. The producers see this as an opportunity to increase their income by doing capacity upgrades. NVE estimates an increase in the weekly price volatility towards 2040, but even though all price areas are expected to get higher price volatility, the areas NO1 and NO2 are expected to experience the highest increase. For high price volatility, the operational pattern is mainly affected by installed power, but for lower price volatility, the profitability must be considered based on a balance between short and long-term production. However, according to Schemde [52], more comprehensive studies are required to find out the profitability of investment in upgrades of installed power and storage with future price structures.

3.3 Wind and hydro as a complementary system

The combination of the promising ability of regulated Norwegian and a higher share of VRES creates the basis for more research and solutions regarding cooperation and combination between different types of producers and scheduling of generator units from different plants [52]. A wind-hydro system is a combined renewable energy system that can avoid the problem of dependence on weather and climate. In addition to a more reliable power supply, integrating such wind-hydro systems can help countries to achieve ambitious goals regarding green energy integration. [53]. Figure 3.10 shows a system consisting of a hydro plant with two reservoirs, a hydro turbine and a pump that share the penstock, and a wind farm located at the same site. There are two arrows between the turbine pump and the external grid, indicating that power can both be exported and imported. The figure also illustrates that the wind turbines and the pump hydro storage use the same transmission line to the external grid [54].

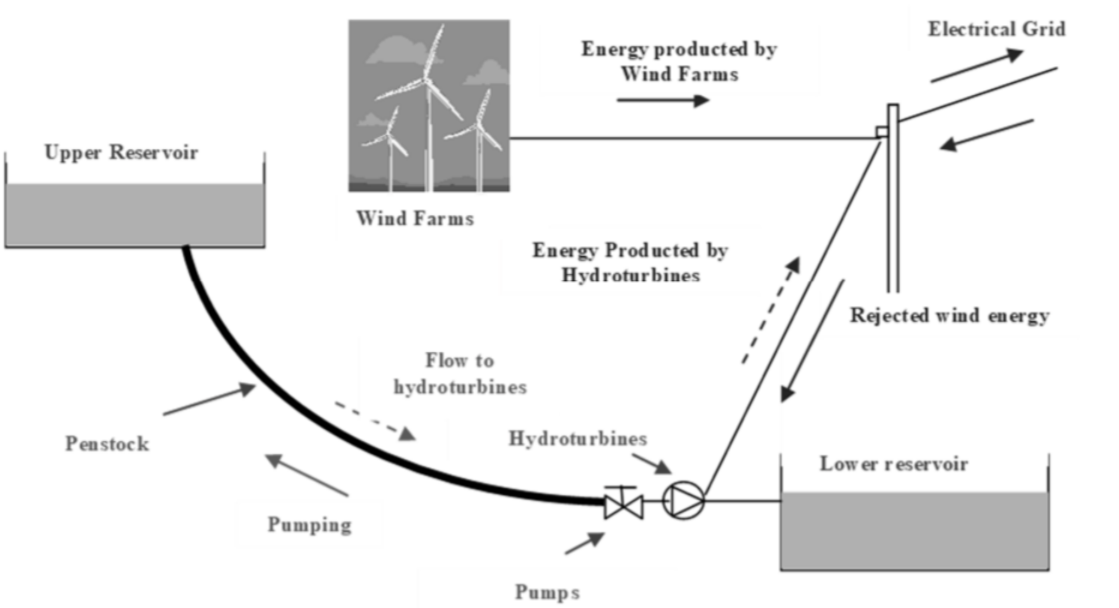

Figure 3.10: Illustration of a complementary system of wind farm, hydro and pump turbine [54].

Castronuovo and Lopes [55] give an introduction to how to set up an optimisation model for a wind-hydro system. In this case, both plants are treated as one system with only one power output from the combined wind-hydro model. The optimisation problem in Castronuovo and Lopes [55] consists of constraints that create the operational framework for the system. First, the total power in the system is the sum of wind and hydropower. A wind power balance is needed which says that available wind power can be distributed on the curtailed wind, wind power to the grid, and wind power sent to the pump. The reservoir balance defines all in and out values that affect the reservoir level, while the initial and final level of the reservoir has to be the same. The power output must be minimum of the demand to be supplied, but less than the transfer limit. The reservoir level must be kept within a minimum and maximum level and the pump power must operate within lower and upper limits. [55]

Another study of coordinated wind-hydro systems was done by Yi et al. [56], which is a research on optimal scheduling of coordinated wind-hydro power generation. The main objective of the optimisation model was to maximise the profit by participation in both the day-ahead and intraday market. An important result was that the wind power plant obtains a higher income when it operates with a reservoir as storage, compared to individually running. Further, the size of the wind farm and reservoir have a crucial impact on the performance of the coordinated system. Therefore, an important aim in the optimisation of such coordinated systems is to find the most proper size of these two units (installed wind power and storage size). Since the wind and hydro plant owners have different amounts of contributions, a method must be used to fairly distribute the increased income and costs associated with the execution of the coordinated scheduling. The ”Shaply value method” is used for this purpose in this case. [56]

3.4 The need for coordination of wind-hydro systems

The need for implementation of wind-hydro agreements can be considered based on factors such as climate ambitions, future energy market characteristics (spot prices and trading markets), pump storage potential, local infrastructure, and surrounding VRES. Especially local transmission capacity can be an obstacle to increasing the power production in certain areas. As seen from the power market theory, grid reinforcements are long-term projects and can require more time than wind farm investors are willing to wait. Some wind farms owner may be willing to expand the wind farms faster than the grid upgrades are done. Therefore, alternative operational ways of scheduling wind and hydro production may be needed as a temporary solution until the transfer capacity is sufficient enough to handle all desired production from all producers that share the line. Hence, a fair statement can be that these kind of optimisation tools that involves sharing grid capacity between different plants are necessary to speed up wind power integration.

Another reason to support coordinated wind-hydro systems is to make Norway’s share of energy sources more robust against weather variations and unfavourable spot prices. Since almost all Norwegian energy supply comes from hydropower, additional energy sources may increase the power supply reliability, but also improve the utilisation of all hydro reservoirs. The utilisation of reservoirs may be improved with wind-PHS systems because a pump will increase the inflow and increase the hydro plant’s ability to utilise STHP operation. Especially, if periods with poor inflow occurs, the wind and pump can contribute to compensate for the low water resources. Maximising the utilisation of energy storage is also beneficial for both the TSO and nature. The TSO can obtain grid investment deferral, and some unnecessary grid reinforcements can be avoided and therefore prevent encroachment of nature and landscape.

According to the literature review, using the wind-PHS system is possible based on Figure 3.8 and 3.3, where areas in Northern and South-West Norway are suited for both PHS and wind projects. As highlighted in section 2.4.1 about price areas, the south also experiences the highest spot prices because of the load demand compared to the transmission capacity into the area. A challenge with PHS profitability in north is the transmission capacity in the North-South direction. With limited transfer capacity, the PHS system will not be able to take advantage of the price volatility as in the south. A PHS system placed in the south will therefore generate more income and cover more of the expensive investments regarding PHS systems. On the other side, section 2.2 enlightened that the transfer capacity in the North-south direction will be upgraded and more industry consumption, which can strengthen the economic frame for more wind power projects in the north region.

4 Optimisation and decision making

The basis of the obtained optimisation framework in thesis is built on the principles from linear programming. This section gives an introduction of the fundamentals of linear programming, and explains how it can be developed to a multi-objective problem. The main tools lexicographic programming, AUGMECON and fuzzy decision maker are reviewed, and it is explained how these tools can be combined to solve optimisation problems. Some examples of previous usage of these optimisation approaches are referred at the end.

4.1 Linear programming

In scientific research and problem-solving, optimisation methods are useful tools to find an optimal solution. A case that is to be optimised can occur in different scales from smaller problems with just a few possible combinations of decision variables to bigger problems that require a high amount of simulations to test all combinations. Different programming methods, dependent on the type of optimisation problem, are used to find the optimum value of each decision variable. One of the simplest and most commonly used techniques in the optimisation field is linear programming (LP). The technique aims to allocate limited resources for competing activities in an optimal way. The term resource is what is needed to perform the desired activity, and contradictory activities that require the same resources are the reason why the LP method is adapted to the problem.

An LP model consists of an objective function with corresponding constraints, represented by mathematical functions. The target of the optimisation model is described through the objective function. Often used targets are minimise costs, maximise income or maximise production of a resource. The aim of the model is to search after the optimal combination of the decision variables that either maximise or minimise the objective function. By determining limitations through the constraints, the model has to find a solution that stays within the limits. Therefore, the constraints forms the feasible solution area. A constraint will always reduce the value of the objective function, and it often represents a limit for available resources or a required output of the decision variables. In LP solving, it is assumed that all mathematical functions in the model are linear. [57, p. 25-40]

4.2 Multi-objective optimisation

A more comprehensive LP model can contain more than one objective function that shall be optimised, and where each objective competes for scarce resources. MOO solving can be classified into the following three categories: priory, interactive and posterior methods. The three methods are categorised based on known information about the problem and knowledge about the importance of each objective. A priory method is used when the weight of the preferences of each objective is known and the weighting method can be adapted. In an interactive method, the procedure results in a solution based on cooperation between analysts and decision-makers where the target is to iterate towards an optimal solution. When there is not enough information to be sure how the objectives should be prioritised relatively, a posterior method is used, where a set of effective solutions are generated and given as a Pareto front. An approach to produce a set of solutions from a problem with contradictory objectives is the AUGMECON, which is described as one of the most commonly used improvements of the conventional epsilon-constraint method because of its ability to generate effective solutions. Such a set of solutions need a decision-maker to choose the most preferred and suggest a compromise between the objectives. [58]

4.2.1 The weighting method

A weighted sum method is a general approach for solving MOO, where the method involves putting all objectives into one objective function with corresponding weight numbers as equation 4.1 shows. The weights are values that reflect the importance of each objective. Setting the weights require great knowledge about the objective functions and their significance according to the aim of the optimisation. Hence, converting preferences into weights is the most challenging part of this method. [59, p. 201-206]

$$U = \sum_{i=1}^{k} w_i \cdot F_i(x) \tag{4.1}$$

As seen from the equation (4.1), all objectives are merged into one total objective multiplied by the corresponding weight. In addition to the fact that weights correspond to the importance of the objective, it must be assured that all objectives have the same magnitude of impact. Therefore, all objective functions must be scaled such that different units have the same magnitude on the total objective function. This is called the normalisation of the objectives. All obtained solutions with different weight compositions are part of the optimal Pareto front and it is up to the decision-maker to select the most preferred. [59, p. 201-206]

4.2.2 Augmented epsilon-constraint algorithm

The AUGMECON method is a well-established method used to handle multiple objective linear problems (MOLP) and is also used as a tool to solve diverse problems in the power system field. AUGMECON derives from the conventional epsilon-constraint method described in Mavrotas [60, p. 456-457]. There are several reasons why the AUGMECON may be preferred over the weighting method: The AUGMECON can determine the number of the generated efficient solutions based on the desired accuracy of the solution, avoid redundant runs of the model because different combinations that provide the same result is avoided, scaling all objectives to the same magnitude is not necessary and the ability to provide efficient solutions for integer problems. [60]

Before the AUGMECON algorithm can be executed, the ranges for each objective have to be set to define the search area the AUGMECON method shall iterate through. The collection of the ranges is called the *payoff table*. There are different ways to define the ranges, and Ryu [61] explains one of the approaches called lexicographic optimisation. This method aims to define a range that covers only efficient Pareto solutions. Figure 4.1, extracted from Ryu [61], shows the procedure for a two-objective linear problem where the ranges for a pay-off table are determined. [60]

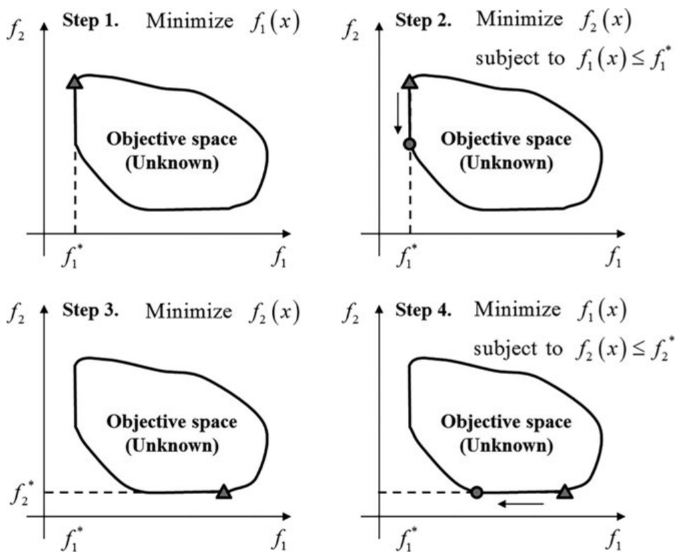

Figure 4.1: Picture of all steps required to define the lexicographic ranges which shall be used in the AUGMECON algorithm [61].

The lexicographic method illustrated in Figure 4.1 shows a minimisation problem, but the procedure is similar for a maximisation problem. In steps 1 and step 3, the objectives are optimised and the optimal solution to the objectives is set. These values are the best possible values for the objective functions. The purpose of step 2 and 4 is to find the worst possible optimal solutions, called nadir values, that ensures an efficient solution set. In these steps, each objective has to be optimised while not worsening the optimal value of the other objective. This can be seen in step 2 and 4 where the constraints $f_1(x) \leq f_1^*$ and $f_2(x) \leq f_2^*$ force the LP algorithm to hold an objective value better than or equal the optimal value. while the other is optimised. In this way, only efficient solution sets are produced because all solutions will be within the optimal and the nadir value. [60]

An optimisation problem solved with the AUGMECON method aims to optimise the first objective, while the other objectives are set to constraints. As Equations 4.2a-4.2d shows, for maximisation problems, the objectives which are set to constraints have to be equal to the variable ε, which is the RHS value of the constraints. This value is dynamic, and by adjusting the epsilon, possible solutions within the pay-off tables ranges are explored.

$$\max \quad (f_1(\mathbf{x}) + eps \cdot (s_2 + s_3 + ... + s_p)) \tag{4.2a}$$

$$\text{subject to} \quad f_2(\mathbf{x}) - s_2 = \epsilon_2 \tag{4.2b}$$

$$f_3(\mathbf{x}) - s_3 = \epsilon_3 \tag{4.2c}$$

$$f_p(\mathbf{x}) - s_p = \epsilon_p \tag{4.2d}$$

The optimisation problem consists of N objectives. All objective functions except the first prioritised one, are divided into n grid-points as intervals between the nadir and optimal value in the pay-off table. The epsilon value represents one grid-point value for each simulation, which can be seen in the constraints in Equations 4.2b-4.2d. Therefore, the obtained solution data is a Pareto front which shows all solution proposals within the ranges set by the pay-off table. To ensure that all Pareto solutions are efficient and not weak solutions, a slack variable s is included which makes the constraints to equalities. The purpose of including a slack variable is to search for alternative optima that improve the non-binding constraints until all constraints are binding.

When all constraints are binding, the solution of one objective can not be improved without worsening some other objective, and the effective solution is achieved. The slack variable's contribution is proved in [60, p. 460]. The output from the epsilon constraint method is, as mentioned, a Pareto front. A Pareto front solved with slack variables contains only efficient solutions. It should be mentioned that both adding objective functions and increasing the grid points extend the simulation time significantly. [60]

4.3 Decision making

As known, solutions provided by the AUGMECON are efficient and all solutions are seen as equally good from a neutral point of view, hence a decision-maker is therefore needed to handle all proposed solutions and determine the best one among the proposed. The chosen way to handle the proposed solutions depends on the preferences or desires assigned to the problem. For a problem with no preferences or desires, there is no need to do a decision making because all answers are seen as equally good. However, many problems have different parameters in a problem with varied importance based on different stakeholders. Therefore, different interests of stakeholders lead to the need for a decision-maker to choose the most promising solution from the Pareto front. Adapting a fuzzy decision maker (FDM) opens for different weight settings such that scenarios where the objectives have different importance relative to each other can be tested.

A commonly used decision-maker is the FDM. This is a well-established concept founded back in the 1960s. In [62], the term fuzzy logic is described as a natural phenomenon that is hard to describe precisely because it can occur in different shapes or versions. A fuzzy concept is therefore an object that is vague and not clear, and fuzzy logic is a way to describe the fuzziness. The fuzzy concept can be defined through "fuzzy sets", which is a class of objects with no explicit boundary of whether objects belong to the class or not. A fuzzy set contains a collection of objects with a corresponding value that describes to what extent the object belongs to the class, called "grade of membership", often denoted as μ. A fuzzy set can therefore be distinguished from classical sets by the fact that elements may have partial membership in a fuzzy set, but for a classic set, all elements are categorised as a full member of the class or not. [62, 63]

Usually, the lowest and highest grade of membership is 0 and 1 respectively. A value of 0 represents a solution equal or worse the nadir value, hence not a member of the fuzzy set. A value of 1 means a full member of the fuzzy set, and a value between 0 and 1 means that the value is a partial member of the fuzzy set. The μ needs to be estimated by a method that calculates a value between 0 and 1. Such methods base the calculation on experience rather than knowledge. The fuzzy method uses different formulas for calculating the membership value, but a commonly used method is the linear membership function. [62, 63]

Among different shapes of fuzzy membership functions, three forms are well used: linear, parabolic, and reversed parabolic. In Figure 4.2, a, b, and c show parabolic, linear, and reverse parabolic membership function shapes respectively. A linear membership function can be denoted as the moderate decision-maker. The y-axis goes from 0 to 1, which describes the membership value. In this case, f_l^0 and f_l^1 are the worst and best values, which is why the values correspond to 0 and 1. [64]

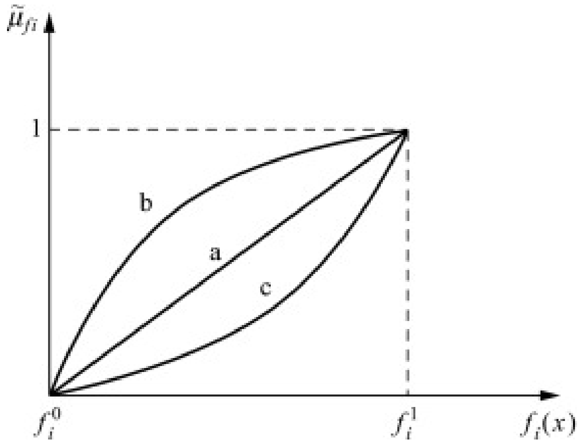

Figure 4.2: Different shapes of the membership function [64].

A fuzzy decision method has been used in different approaches for optimisation problems where a solution among all Pareto efficient solutions is needed. Aghaei [65] use FDM where an electricity market clearing is optimised, while Du et al. [66] adapts FDM for a MOO where seawater desalination is the aim. The algorithm defines a linear membership function for each objective in the optimisation problem. Equation 4.3 shows how a linear membership function for a maximisation problem is defined for an objective that is to be maximised. The index r stands for one Pareto solution from the Pareto set, while i represents the objective function. Hence, a membership function value is calculated for each Pareto solution and each objective.

$$\mu_i^r = \begin{cases} 0, & f_i^r < f_i^{min} \\ \frac{f_i^r - f_i^{min}}{f_i^{max} - f_i^{mi}}, & f_i^{min} \leq f_i^r \leq f_i^{max} \\ 1, & f_i^r \geq f_i^{max} \end{cases} \tag{4.3}$$

In the membership equation, $f_{i,max}$ and $f_{i,min}$ are the range values from the calculated pay-off table while f_i^r is the tested value from the Pareto front. As mentioned, the grade of membership is often given as a μ, and therefore the definition of the grade of membership can be interpreted as an indication of how strong the Pareto solution is, as a result of how close the solution is to the optimal value. In addition to the membership value of the Pareto solution, the weighting number must also be taken into consideration when the best solution shall be determined. The weighting values can be adjusted according to the significance of each objective and chosen priorities with the optimisation model. Based on the value of the membership function combined with the weighting value that represents the importance of each objective, equation 4.4 is used to give each Pareto solution the membership value between zero and one. As seen, μ is only indexed with r, because the aim is to find a utility number μ_r for the Pareto solution. Equation 4.4 aggregates all membership function values times the objective's weight for all objectives. The Pareto solution with the highest μ_r, is the proposed optimal solution. [65]

$$\mu^r = \frac{\sum_{i=1}^{p} w_i \cdot \mu_i^r}{\sum_{i=1}^{p} w_i} \tag{4.4}$$

4.4 Multi-objective optimisation in power systems

Different optimization approaches are widely used in power systems. Some examples of applications of MOO in power systems are scheduling production from generating units, minimising energy costs, and the environmental-economic approach minimising emissions. Other approaches such as fluctuations or voltage stability optimisation are also typical examples when an optimisation method is needed. This section denotes lexicographic programming, AUGMECON, and FDM in the given order as the "multi-objective framework" (MOF), and gives some examples of previous use of these contributions, or parts of it, in both power system calculation, but also to other purposes.

Some examples of the use of the MOF can be reviewed to give an overview of the flexible usage of the MOF methods and to show why the MOF in the mentioned order is useful in the power systems, as well in other fields. First, Rezvani et al. [67] has adapted the MOF for environmental-economic scheduling of a micro-grid with several renewable sources combined with a battery. The multi-objective problem consisted of two conflicting objectives: one objective is generation costs and one representing emissions. The micro-grid contained a PV, fuel cells, battery, wind turbine, and micro turbine which was to be scheduled for 24 hours. In this case, lexicographic programming combined with a hybrid augmented-weighted epsilon constraint method was adapted to solve the multi-objective optimisation problem and produce the Pareto front. A fuzzy technique was used to pick the most preferred Pareto solution, where the weighting rations 1/1 and 1/2 were tested as importance for cost and emission. These two ratios can be seen as equal importance through 1/1, and for 1/2, reducing emission is higher prioritised than minimising costs. Two cases were used to test the efficiency of the multi-objective framework.

Another example of usage of the MOF is the environmental-economic combined heat and power scheduling in Ahmadi et al. [68]. Like the previous example, the two conflicting objectives are minimisation of energy production costs and pollutant emissions. In this case, the weight ratios 1/1 and 1/2 are tested, and the chosen number of grid points in the Pareto front is 20. Ahmadi et al. [68] also compare the AUGMECON with FDM against conventional methods such as NSGA-II, SPEA, and MLCA. It was concluded that the proposed method in the research provides positive solution quality and execution time compared to the other methods. Moreover, the research also emphasises that the procedure of adding more objectives is straight forward, which makes the method flexible and a good option to simulate more advanced systems.

The MOF is also used for a schedule of power production from combined energy source systems. Aghaei et al. [69] show how a combined hydro-thermal power system uses lexicographic programming, AUGMECON, and FDM to schedule a short term day-ahead schedule of production. The research uses a profit equation as the first and prioritised objective and expected emission from the thermal plants as the second objective. The article also highlights the advantage of changing the weighting factors in the FDM, based on the stakeholder's preferences. One example of different interests highlighted is that a generation company desires optimal profit, and has fewer concerns about emissions than politicians or conservation associations. The Pareto front obtained in the research is tested with weighting factors of 1/1 and 1/3 in the FDM.

In the wind power field, there also exist multi-objective optimisation approaches for different purposes. Like the combined hydro-thermal system, the multi-objective framework has also been used in studies for wind-thermal systems. Falsafi [70] conducted a multi-objective optimisation for scheduling energy and reserves provided by the wind and thermal generating units. The aim was to cover uncertainties of wind production by use of demand response in an efficient way. The objective was functioned for minimising energy costs and emission of air pollutants. For this study, the best solution from the Pareto front was determined by the use of the technique for order preference by similarity to the ideal solution (TOPSIS), which is a decision-maker introduced in [71]. Further, Sharifi [72] use AUGMECON to optimise the scheduling of maintenance of wind turbines and the MOF has also been adapted to other kinds of wind optimisation problems. Stoilova [73] tests the epsilon constraint method with an FDM as tools to solve an optimisation problem for transport planning with various criteria.

5 Methodology

The method section contains an explanation of how the required data and information are collected, the reference case and corresponding values, a step-wise description of all steps in the optimisation model, and an explanation of how parameters and values are adjusted in order to conduct techno-economic analysis. There is chosen to treat the reference case as a MOLP. The main objective is to optimise the wind power export, but a second objective that demands the hydro producer to maximise its profit is added because it would have been the common approach from a business perspective. Hence, the model aims to maximise the amount of exported wind energy, but at the same time, take the hydro plant's desired business strategy into account.

5.1 Data collection

Input parameters and power plant location are needed to create a reference case. The input data are provided by Nordkraft and NordPool, and some values are set arbitrarily. The Nordkraft group is an actor in different fields such as power production, energy operation, and consulting. The power production segment of the Nordkraft group operates a total installed capacity of 672 MW with an annual production of 2.09 TWh distributed on hydro plants and wind farms [74]. The data given by Nordkraft are wind power potential on the location, inflow time series to the reservoir, turbine capacity, reservoir capacity, and maximum bypass of water.

The inflow data is an average time series based on previous measurements between 2011 and 2015. Unlike the inflow, wind power production is not a measurement, but an estimation of potential wind power done by Nordkraft. The method used to estimate wind power potential throughout the year is a combination of weather data and the use of a standard power curve of the wind turbine. With estimated wind speeds from the weather data, the power curve similar to Figure 3.2 can be used to determine the output power. Previous use of this wind power estimation approach can be found in Korpås [75], where the aim was to investigate the opportunities of wind farm expansion by down-regulation of hydro production. A wind farm usually consists of many wind turbines, but to simplify, the model can treat the wind farm production as one total installed capacity parameter which means that the nominal power of each turbine is summed up. In addition, the same wind speed over the whole area is assumed. A similar approach to wind farm simplification is done in [76].

The capacity of the transmission line is also needed to set a limit for the export out from the area. A capacity of a transmission line is sensitive information and can not be shared by Statnett. Therefore, an arbitrary value of the transfer capacity is used in this thesis. An arbitrary value is also chosen for the pump capacity because there exists no pump at the hydro plant at the moment, but the thesis aims to investigate how the conditions for expanding the wind farm can be improved by including a pump. The spot price time series is extracted from NordPool's databases [17] and used for calculating the income and costs for both power plants. To use representative spot prices, the chosen values are extracted from historical data from 2019 in Tromsø which is a city close to the reference location area. The model will benefit from the fact that fixed time series of parameters reduce the search area for the optimal solution and is effective for the run time of the model. The data described in this section contributes to forming the reference case used to test the two main approaches.

5.2 Reference case

Figure 5.1 illustrates how the whole system is connected and in which directions the power can be transferred. The reference case is built on previous work by Stave [30] to test the functionality of the proposed MOF. The case is based on a real power plant located in northern Norway in Sørfjord municipality. There exist two active power plants in the area, which are the hydro plant Søfjord II and the Sørfjord wind farm. Both plants use the same transmission line which is seen in Figure 5.1. P_p and P_s are pump and turbine power, while P_w is the wind power. The power from the wind farm and the hydro plant is a total exported power represented by P_e. In addition, the figure includes P_l and P_d which stand for local load and dumped power. A local load is included if there is any local load demand that must be covered, and the dumped power is curtailed power if not all potential wind power can be used.

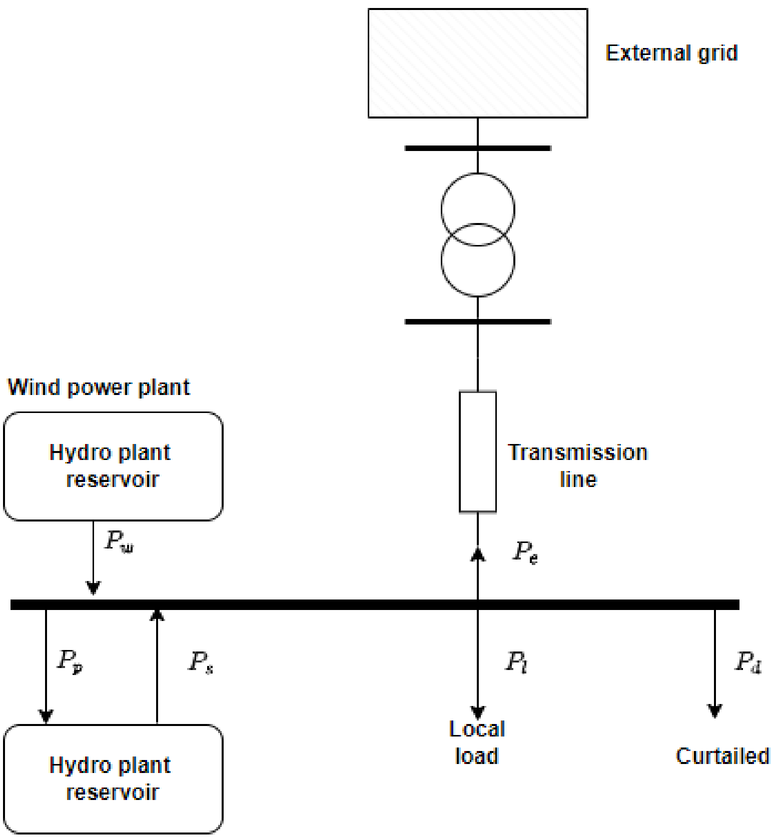

Figure 5.1: Line diagram representing wind power plant, hydro plant, load and virtual dump load connected.

5.2.1 System specifications

As known, the main parts in the reference case are the hydro plant, wind farm, and transmission line. All these elements have technical specifications and simplifications to suit the contribution to the optimisation model. The wind farm, hydro plant, and transmission line are presented in respective order, where all crucial values and calculation methods are given.

Wind farm

The wind farm consists of 23 Siemens Gamesa 4.2 DD 130 turbines with an installed power of 4.2 MW each. Nordkraft has provided a wind time series of the annual estimated hourly wind power potential which is as mentioned, based on weather data and power curve data. Nordkraft estimates that the potential increase of the wind farm capacity is +25 % by adding more wind turbines between the existing ones. If there is a desire to increase the capacity, even more, the wind farm area has to be extended. The possible extension of the wind farm area is uncertain because of the potential encroachment of nature and landscape. A license application has to consider the potential risks of damages to nature against the rewards of more power production. However, for the sake of simulation, Nordkraft suggests a wind farm capacity increase of +150 %, which corresponds to an upscale of the wind farm by a factor of 2.5.

Hydro plant

To simplify the hydro generating unit, Stave [30] shows modifications and simplifications to aggregate the cascaded hydropower system to a single hydropower plant and reservoir. The hydro plant Sørfjord II consists of two generators where the major unit has a rating of 67 MW and the other is a small-scale generator with an installed capacity of 5 MW. The small-scale generator utilises the waterfall from a small additional reservoir down to the main reservoir. The start-up time for the generators is 5-6 minutes from stop to full operation and the turbine type is Francis (elaborated in chapter 3.2.1). The generators are combined into one single generating unit at the location of the largest reservoir. To combine the two reservoirs, the minor reservoir that belongs to the 5 MW plant must be scaled and added to the main reservoir. Stave [30] assumes that the only difference between the minor and main reservoir is the net head, based on the fact that the net head is proportional to the power potential as equation 3.1 indicates. Equation 5.1 is reused from Stave [30], and shows the scale of the minor reservoir contributions ($E_{minor,reservoir}$) to the aggregated reservoir. This leads to a total turbine rating of 72 MW and a reservoir capacity of 97020 MWh.

$$E_{minor,reservoir} = E_{major,reservoir} \cdot (\frac{h_{minor,reservoir}}{h_{main,reservoir}}) \cdot (\frac{V_{minor,reservoir}}{V_{main,reservoir}}) \tag{5.1}$$

Further, the efficiencies for the hydro turbine and pump are determined based on the theory from chapter 3.2.1. Although the turbine has different efficiencies dependent on the power output, the best theoretical value is adapted in the simulations for the sake of simplicity. Anyway, the preferred operation area is $40-69\,MW$, which is also the range that achieves the best efficiency. The provided data regarding inflow is a weekly-based time series, which means that an inflow number for each week is given. To make the time series for the inflow fit into the simulation model, a resolution of hour data is needed. Therefore, it is assumed that the inflow is the same for all hours during one week. The hydro plant also has the opportunity to let water bypass the turbine to avoid flooding. For the cascaded hydro plant in Sørfjord, the maximum release of water is 67.74 MW per hour.

Transmission line

The transmission line is 19 km long and is a three-phase overhead line with a voltage of 132 kV. Because of sensitive information, a general value of 140 MW was chosen in order to continue the study from Stave [30]. This value is close to the maximum total combined output from the wind farm and hydro plant, and congestion will therefore occur with additional expansion of the installed wind power.

Table 5.1 shows an overview of the required values for the grid, hydro plant, and wind farm to run the model. These values in addition to the mentioned time series for the reservoir, wind farm, and spot price create the basis for the simulation.

Table 5.1: Parameters for the reference case.

Parameter	Rating	Unit
Grid		
Transfer limit	140	MW
Hydro		
Turbine capacity	72	MW
Turbine efficiency	0.95	
Pump rating	20	MW
Pump efficiency	0.85	
Max reservoir level	97020	MWh
Min reservoir level	0	
Bypass of water	67.74	MW
Wind		
Installed wind capacity	96.6	MW

5.3 Multi-objective linear programming

5.3.1 General flowchart

As explained in section 4.2, the main purpose of a multi-objective method is to find a trade-off between two or more contradictory objectives. Using MOLP as an approach to find a compromise in the reference case is appropriate because the two producers have an ideal production pattern that may overlap. Since there are not given any indicators of which producer should be prioritised, it is chosen to study the system for different desires of prioritisation, which is described more in detail in section 5.5. With limited knowledge and indicators, the AUGMECON method is chosen to conduct the optimisation and find different suggestions for trade-offs. Conducting the MOLP may lead to a set of different optimal solutions, which is to be analysed and discussed. Figure 5.2 shows a flowchart of the procedure from input parameters to the final trade-off proposal.

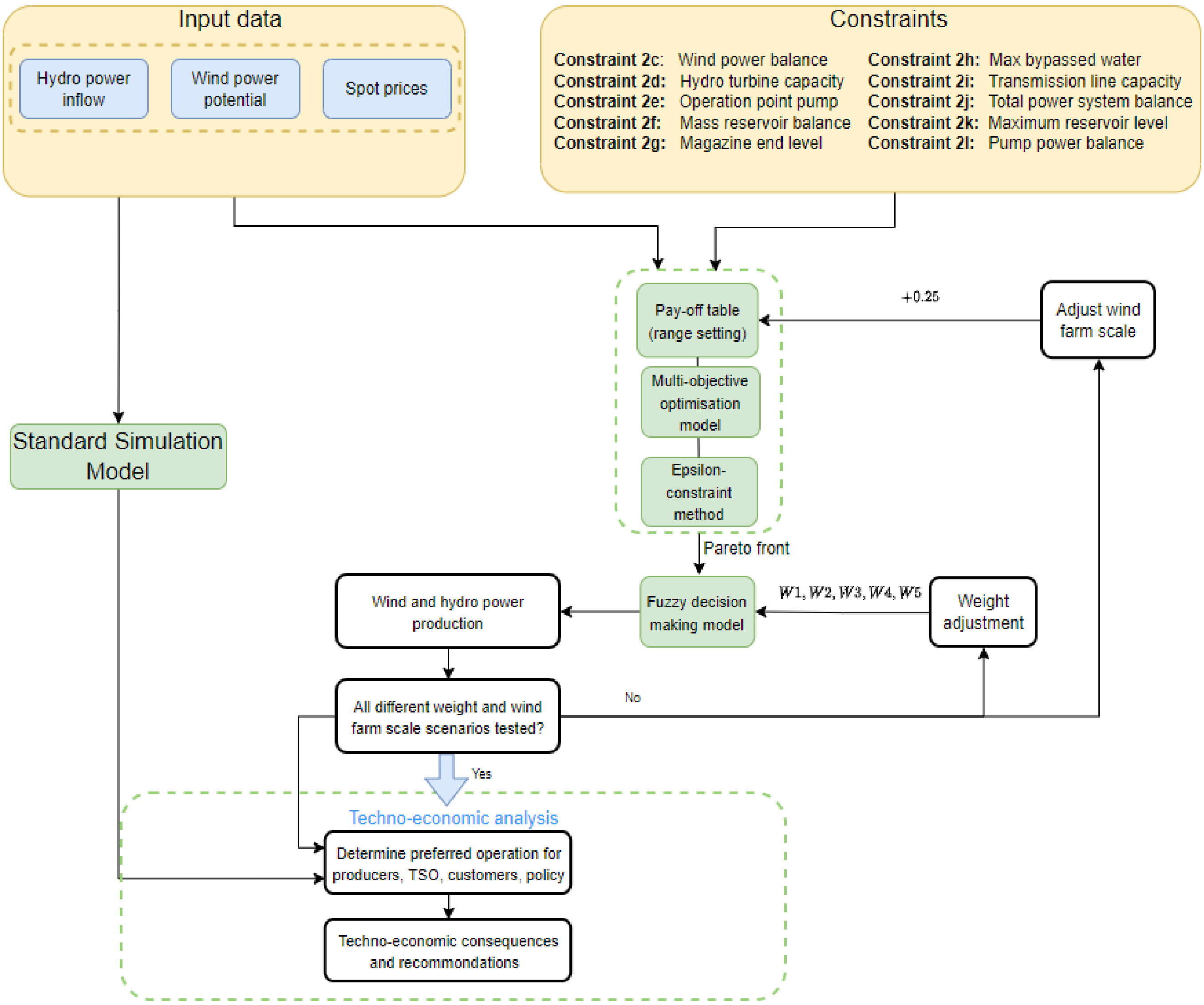

Figure 5.2: General flowchart of all contributions for the simulations.

The general flowchart contains two main simulations: The standard simulation model and the MOF. Yellow boxes are denoted as input boxes, and green boxes symbolise simulations. While the standard simulation model only needs the given time series in the left input box plus the transfer limit, the optimisation model needs the constraint inputs in addition to the input data to conduct all simulations. The flowchart shows parallel simulation models where the standard simulation model only let the wind farm use rest-capacity after the desired hydro production, while the optimisation model uses the MOF as a tool to find trade-offs. The output data from the MOF is the power production from the wind-hydro system. The output data given by both the standard simulation and the FDM provides a basis for an analysis that considers how different trade-offs can be configured through a bilateral agreement between the producers.

5.3.2 Procedure

The MOF procedure is done several times with different weights and wind farm scales as seen in the flowchart in Figure 5.2. The order of the steps in the procedure can be seen in figure 5.3. The rest of this section provides a more detailed explanation of the implementation of all three contributions for the reference case.

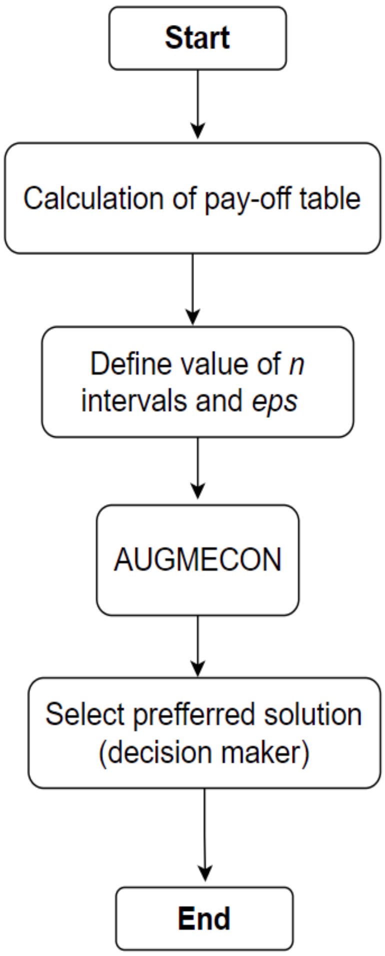

Figure 5.3: Procedure of lexicographic calculation, AUGMECON and fuzzy decision maker.

Pay-off table

The AUGMECON algorithm starts with the lexicographic method, which aims to set max and min values for both objectives in the problem through the pay-off table. The procedure is shown in chapter 4.2.2 through Figure 4.1. In this case, the objectives are demanded to be maximised, but the same procedure as the mentioned figure is followed. Each objective is optimised separately and works as a standard LP optimiser because there is only one objective. The values for objective 1 in the pay-off table will vary as the wind farm scale affects the wind export income. However, an example of how the pay-off table values are given in Table 5.2, where the wind farm scale 1 and 3 is used to illustrate how the pay-off ranges increase when the wind farm capacity is up-scaled. Appendix B contains all pay-off ranges for each wind farm scale.

Table 5.2: Pay-off tables for wind farm scale 1 and 3.

	Scale 1		Scale 3	
	f1	f2	f1	f2
max f1	77.8 M NOK	55.6 M NOK	195 M NOK	50.7 M NOK
max f2	76.6 M NOK	55.7 M NOK	138 M NOK	55.7 M NOK

A lexicographic-calculated pay-off table makes sure that the ranges for the objectives only contain Pareto optimal solutions. The max values for f1 and f2 are maximisation of each objective separately when the other is deactivated, and it is, therefore, the maximum possible income. For the min values for f1 and f2, each objective is maximised while the other is kept at its optimised value.

AUGMECON

When the ranges for the objective 5.4a and 5.4b are clarified, the AUGMECON algorithm can be executed. According to the algorithm's procedure in Mavrotas [60], the objective 5.4a is set to be maximised, by adding a slack variable times the parameter *eps*. To avoid weakly efficient solutions, objective 5.4b shall be subtracted with a slack variable and set equal to epsilon in constraint 5.3. By including the same slack variable in the objective function (5.2), the algorithm is forced to produce only efficient solutions.

$$Max\ f_1 + eps \cdot s_2 \tag{5.2}$$

$$f_2 - s_2 = \varepsilon_2 \tag{5.3}$$

There is chosen to divide the range between min and max value of objective 5.4b in the pay-off table, into 50 grid points. Each grid point value is represented by the epsilon ε_2 in constraint 5.3. The chosen number of intervals is a consideration between simulation time and the accuracy of the optimal solution. For each value out of the 50 in the range, the AUGMECON is simulated and an efficient solution is added to the Paret set. The AUGMECON algorithm is finished when all grid point values for ε_2 are tested, and the produced solution set is all points along with a Pareto graph.

The model tests the lowest value for f2 first, and then step-wise increases the value by iterating through all grid point values between min and max. For every time the value for ε_2 increases, the objective 5.4a is maximised simultaneously. The consequence will be that a higher value for ε forces f_1 to be decreased. The constant *eps* is a small number usually set between 10^{-3} and 10^{-6} [60, p. 460].

Fuzzy decision maker

A set of weight combinations is created to examine different approaches to wind prioritisation. The ratio between the weight numbers for objective 5.4a and 5.4b describes the relative importance for each objective. A ratio of 1/1 means that the decision-maker interprets the importance of wind and hydro production as equal, while the importance of wind penetration increases with a higher value in the nominator in the weight ratio in Table 5.3. The range for the weights in the table goes from hydro favorable (1/10) to a wind favourable weight ratio of 15/1. The weight set is determined by pushing the model to fully prioritise wind export and fully prioritise hydro export. The purpose of this was to find limits of the weight ratio to avoid redundant simulations where the solution converges. The ratio 15/1 makes approximately the wind farm the prior user of the transmission line. Therefore, a *high weight ratio* means a wind favourable weight, while a *low weight ratio* sees hydropower as more important. It also turns out that an equal weight distribution tends to approximately make the hydro plant the prior user of the grid, but to be sure, a ratio of 1/10 is used to fully prioritise hydropower export. Hence, the range of the weight ratios is as shown in Table 5.3.

Table 5.3: All weight ratios priorities between the wind farm and hydro plant.

Weight type	**w1**	**w2**	**w3**	**w4**	**w5**
w_h/w_w	1/10	1/1	3/1	8/1	15/1

All weights from Table 5.3 are inserted into equation 4.4 and affect the value of the linear membership function μ_i^r which was defined in the previous stage in Figure 4.3. Hence, a higher weight ratio will cause a utility factor value that has a higher value for f_1 and therefore more wind power export. A lower weight ratio improves the utility factor for f_2, and decrease it for f_1.

5.3.3 Configuration of the multi-objective linear problem

The model is created in the open-source programming language Python and the tool Pyomo as an additional package. Pyomo is a Python-based software package that supports a selection of optimisation applications. Pyomo modeling objects are built with an embedded high-level programming language and provide a great amount of belonging libraries which makes the program more flexible than other conventional modeling languages [77]. The Pyomo model is simulated with solver Gurobi, which is a powerful mathematical programming solver. Gurobi supports different kinds of optimisation problems such as LP, mixed-integer linear programming (MILP) and quadratic programming (QP), and others. Gurobi is suited for python programming as it includes high-level modeling which makes it easy to build optimisation systems [78].

The MOLP of the optimisation model is an expansion from the LP model in the project Jamessen [24] preceding this thesis, where also descriptions of the constraints are reused. The MOLP consists of two objectives and corresponding constraints. Table 5.4 shows an explanation of all variables and parameters in the setup of the MOLP. Further, it can be seen how all variables and parameters are used through equations 5.4a-5.4m.

Table 5.4: Nomenclature explaining all variables and parameters in the MOLP.

Variables	
$P_{w,exp,t}$	Exported wind power in time step t [MW].
$P_{w,toPump,t}$	Wind power consumed by the pump in time step t [MW].
$P_{w,curt,t}$	Curtailed wind power in time step t [MW]
$P_{h,t}$	Exported hydropower in time step t [MW].
$P_{pump,t}$	Pump power in time step t [MW]
$E_{rest,t}$	Reservoir level in time step t [MWh].
$E_{res,t-1}$	Reservoir level in previous time step t [MWh].
$P_{h,loss,t}$	Lost hydropower in time step t [MW].
$P_{tot,exp,t}$	Total exported power from system in time step t [MW].
$P_{import,t}$	Imported pump power in time step t [MW].
Parameters	
$\Phi_{spot,t}$	Spot price at time step t [].
Cap_{res}	Reservoir capacity [MWh].
$E_{inflow,t}$	Inflow in time step t [MW].
$E_{res,end}$	Reservoir level in the last time step [MWh].
$E_{res,0}$	Reservoir level in the first time step [MWh].
$P_{ht,cap}$	Hydro turbine capacity [MW].
$P_{p,cap}$	Pump operation point [MW].
$P_{h,loss,cap}$	Maximum bypassed water [MW].
$P_{P_{line,cao}}$	Transfer line capacity [MW].
$P_{w,pot,t}$	Potential wind power in time step t [MW].

Out of the two objectives, the first objective 5.4a is the prioritised one. As explained in section 3.2.6, a hydro plant will maximize its income by exporting and importing power by considering the spot price variations for the long and short term. Hence, the objective for the hydro plant is exported production minus imported pump consumption. The objective for wind optimisation can be defined in several ways, and each way will have a unique impact on the model. As the objective is formulated in 5.4a, the model optimises wind production as exporting wind power to the grid and/or pump, with curtailment as a variable that reduces the objective. In this way, since all parameters are multiplied by the spot price, the $P_{w,curt}$ variable works and acts as a penalty for the objective function and the LP algorithm aims for less curtailment and more wind exported to the grid or pumps through the variables $P_{w,toPump}$ and $P_{w,curt}$.

$$\max \quad \sum_i \left(P_{w,exp,t} + P_{w,toPump,t} - P_{w,curt,t}\right) \cdot \Phi_{spot,t} \tag{5.4a}$$

$$\max \quad \sum_i \left(P_{ht,t} \cdot \Phi_{spot,t}\right) - \left(P_{pump,t} \cdot \Phi_{spot,t} \cdot 1.05\right) \tag{5.4b}$$

subject to

$$P_{w,exp,t} + P_{w,toPump,t} + P_{w,curt,t} = P_{w,pot,t} \tag{5.4c}$$

$$P_{ht,t} <= P_{ht,cap} \tag{5.4d}$$

$$P_{pump,t} = P_{p,cap} \cdot y_{p,t} \tag{5.4e}$$

$$\begin{aligned} E_{res,t} &= E_{res,t-1} + E_{inflow,t} \\ &+ P_{p,t} \cdot \mu_p \cdot \Delta t - P_{ht,t} \cdot \Delta t - Ph_{loss,t} \cdot \Delta t \end{aligned} \tag{5.4f}$$

$$E_{res,end} >= E_{res,0} \tag{5.4g}$$

$$P_{h,loss,t} =< P_{h,loss,cap} \tag{5.4h}$$

$$P_{tot,exp,t} <= P_{line,cap} \tag{5.4i}$$

$$\begin{aligned} &P_{ht,t} - P_{pump,t} + (P_{w,exp,t} + P_{w,toPump,t}) \\ &- P_{tot,exp,t} \cdot y_{1,t} + P_{import,t} = 0 \end{aligned} \tag{5.4j}$$

$$E_{res,t} < \mathrm{Cap}_{res} \tag{5.4k}$$

$$P_{pump,t} = P_{import,t} \cdot y_2 + P_{w,toPump,t} \tag{5.4l}$$

$$y_{1,t} + y_{2,t} <= 1 \tag{5.4m}$$

Constraint 5.4c creates the wind power balance, where the potential wind power can either be exported, pumped, or curtailed wind power. The nominal hydro turbine power is determined in constraint 5.4d, and 5.4e is the operational point of the pump. It is assumed that the pump has only one operating since such a large machine will have a synchronous motor with a fixed rpm. Therefore, the pump capacity is multiplied with a binary variable $y_{p,t}$ which decides whether the pump is on or off. The reservoir mass balance is represented in 5.4f and covers all in and out-contributes for the reservoir. Inflow and pump activity increase the reservoir level, while production and bypass of water decrease the level. In the reservoir mass balance, pump, hydro, and bypass power are converted to energy by multiplying with time as in equation 3.2. Constraint 5.4g makes sure that the end level of the reservoir level is equal to the initial level, to not affect the next year's simulation. By limiting water bypass, 5.4h prevents damage to nature and landscape.

The transmission line capacity is defined in 5.4i, and limits the total exported power within the line capacity. Total export $P_{tot,ecp,t}$ is also included in the total power system balance in constraint 5.4j. This constraint collects all power parameters into one equation: $P_{tot,exp,t}$ is equal $P_{ht,t} + P_{w,exp,t}$, and $P_{pump,t}$ consist of $P_{import,t}$ and/or $P_{w,toPump,t}$. To avoid overflow, constraint 5.4k holds the reservoir level below maximum level. The last power balance is the pump power balance in 5.4l, and states that the pump power consist of imported power from both the grid and the wind farm. Lastly, the binary constraint in 5.4m makes sure that exporting power and import can not appear simultaneously. This is also the reason why $P_{tot,expt}$, and $P_{import,t}$ are multiplied with $y_{1,t}$ and $y_{2,t}$ respectively.

5.4 Techno-economic analysis

To analyse the cash flow for the wind-PHS system, some equations must be used to calculate incomes, energy loss, and grid utilisation. As known, the wind farm gains the income by exporting the wind power to the grid or hydro pump. This results in equation 5.5 where the total exported wind power is multiplied by the corresponding spot price. It is assumed that the sale price of wind power to the pump is the same as the spot price.

$$I_w = \sum_{t=1}^{T_{max}} (P_{w,exp,t} + P_{w,toPump,t}) \cdot \Phi_{spot,t} \tag{5.5}$$

The hydro plant buys power from the spot market as a customer when importing pump power is preferred, and sells power to the spot market at more favorable prices. Hence, the hydro generating unit's income is determined by turbine production minus pump power times the spot price.

$$I_h = \sum_{t=1}^{T_{max}} (P_{h,t} - P_{pump,t}) \cdot \Phi_{spot,t} \tag{5.6}$$

Grid utilisation is determined by taking the annual power exported from the system, divided by the grid capacity which is the transmission line limit of 140 MW times the number of hours in a year. The utilisation value is denoted as $\mu_{utilisation}$ and the formula is given in the equation 5.7.

$$\mu_{utilisation} = \frac{P_{tot,exp,t}}{140MW \cdot 8760h} \cdot 100\% \tag{5.7}$$

5.5 Configurations of bilateral agreement wind & PHS

Adapting a trade-off suggestion from the MOLP model requires a bilateral agreement between the two producers. From the definition of types of bilateral agreements in chapter 2.5.2, the type of an agreement between the reference wind farm and the hydro plant can be called a UPPA because it is between a VRES producer and an energy company that may act as an off-taker for the output from the wind farm.

An important approach when the optimisation shall be conducted is to determine from what perspective the objective is meant. There are different stakeholders when it comes to energy sources and production. Politicians, the TSO, consumers, and the producers may have different interests regarding how the production planning is to be scheduled. From a green political standpoint, there is conceivable to assume that a higher share of wind energy is desired to improve the green transition. Moreover, a TSO might be more interested in minimising the overall energy loss to achieve better grid utilisation and decrease or delay the need for grid reinforcements. Since the TSO is responsible for the grid stability, a fluctuated production from the reference producers makes it more complicated for the TSO to maintain the stability. Therefore, steady production is likely to be desired from the TSO's point of view.

Since the study will consider different scenarios of trade-offs, the suggested trade-offs by the MOLP model will be examined in terms of economic and operational consequences for both the hydro plant and the wind farm. The performance of each producer must be seen relatively to an ideal scenario and used as a reference to decide whether the producer will benefit or not from the combined wind-PHS system instead of separate production. This will contribute to considering what is a fair trade-off in the bilateral agreement. Therefore, elements included in the process of configuring a reasonable bilateral UPPA are benefits for the TSO, drawbacks, and gains for the producers, socio-economic rewards, and relative performances.

6 Results

This section is divided into three main sections; pre-eliminary results, MOLP simulations, and sensitivity analysis. The system simulation results are meant to show what the power system in Sørfjordlooksk is like as an initial case. This part shows how the system behaves in standard simulation model operation (explained in 5.3.1). In addition, the system simulation results also show the optimisation of each objective separately, which can be seen as the desired production. This creates the basis for the reference performances. The purpose of the MOLP simulations is to analyse how the system in Sørfjord looks like when different weight ratios from the weight set in Table 5.3 are used in the FDM. The results of different weights can be considered as production patterns from the different stakeholders and interests that were mentioned in 5.5. Lastly, the sensitivity investigates the impact of different pump sizes, weights, and relative performance.

6.1 System simulations

Standard simulations

To highlight how the system looks like for a standard simulation approach, Figure 6.1 and 6.2 illustrate the behaviour of the reference system. Figure 6.1 is the current wind farm capacity added on the optimal hydro production (both optimal hydro and wind production can be found in Figure 6.3 and 6.4).

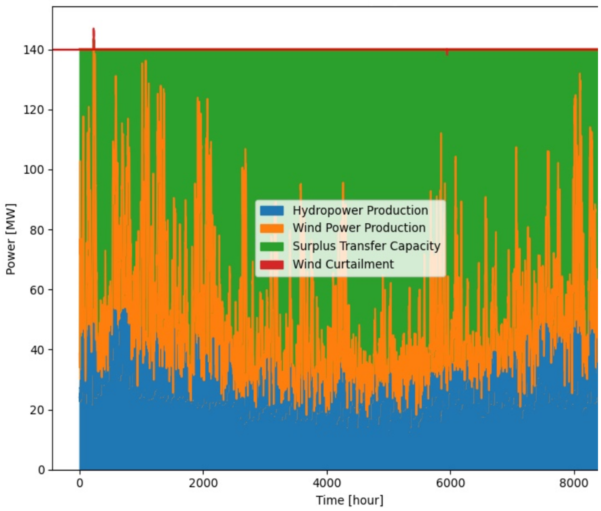

Figure 6.1: Current wind farm capacity.

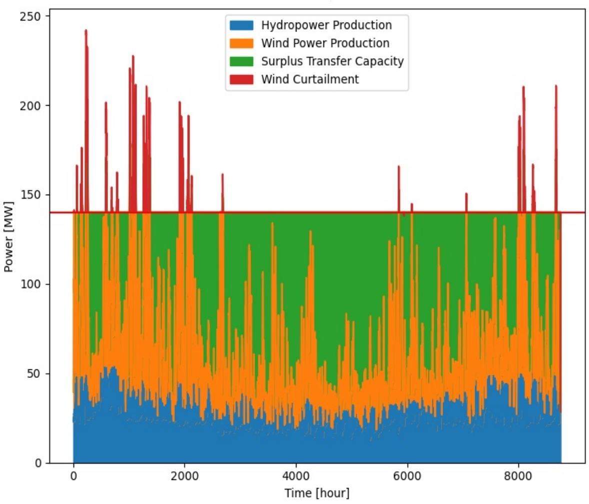

Figure 6.2: Wind farm scaled by factor of 1.5.

For the current wind scale 1, as seen from the figure, it is approximately no hour with a rate of production that exceeds the line capacity. In Figure 6.2, the transfer limit is congested, which means that significant amounts of wind power have to be curtailed since no alternative option as PHS is available. In such a case, the need for options regarding handling the overflow of wind power is clear. It should be mentioned that wind production exceeds the transfer limit at a factor of 1.5 (initial capacity is 96 MW). Another observation from the figures is that even though the line is heavily congested in some periods, there are high amounts of unused capacity during the summer months.

Desired production patterns

To give an overview of what the preferred production patterns from both producers look like, the two objectives from the MOLP 5.4a and 5.4b are optimised separately and the output production graphs from both objectives can be seen in Figure 6.3 and 6.4. The hydro objective is simulated with full availability to the transmission line and no pump included, and the result can be seen in Figure 6.3. For the desired wind production, Figure 6.4 shows the annual wind power production. Since the wind farm does not have a storage unit, the desired product is the same as the estimated annual wind power potential from Nordkraft's analysis (section 5.1).

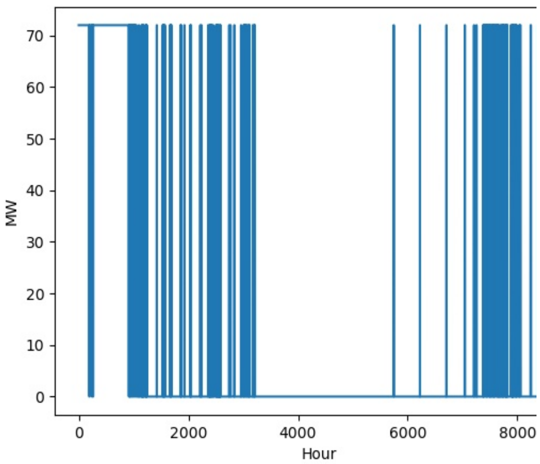

Figure 6.3: Desired hydropower production.

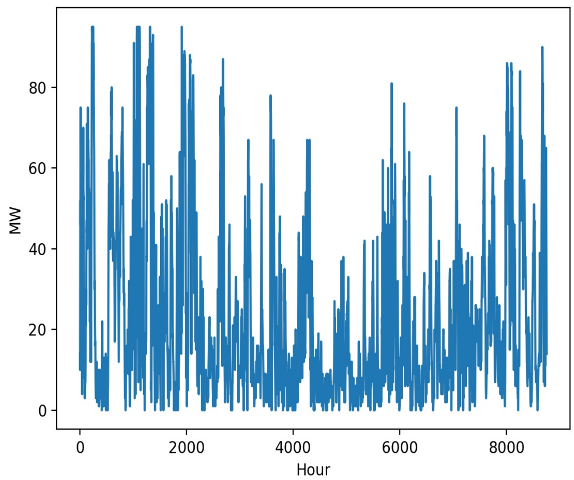

Figure 6.4: Desired wind power production.

The patterns in Figure 6.3 and 6.4 show that the major part of the production volume occurs during December-March. This high-production period corresponds to the load demand in NO4 in appendix A, where the same period has the highest consumption. It turns out that the optimisation algorithm tends to schedule all hydro production in the mentioned months and act in totally off-mode during the summer months. The summer period with no production will then be used for filling the reservoir. For a where both plants export their desired product, the system will look as illustrated in Figure 6.5. As observed, the hydro production profile from Figure 6.3 is set as the primary user of the grid, and then the wind power production is added to the hydro production profile. Then it can be seen how much wind power must be curtailed.

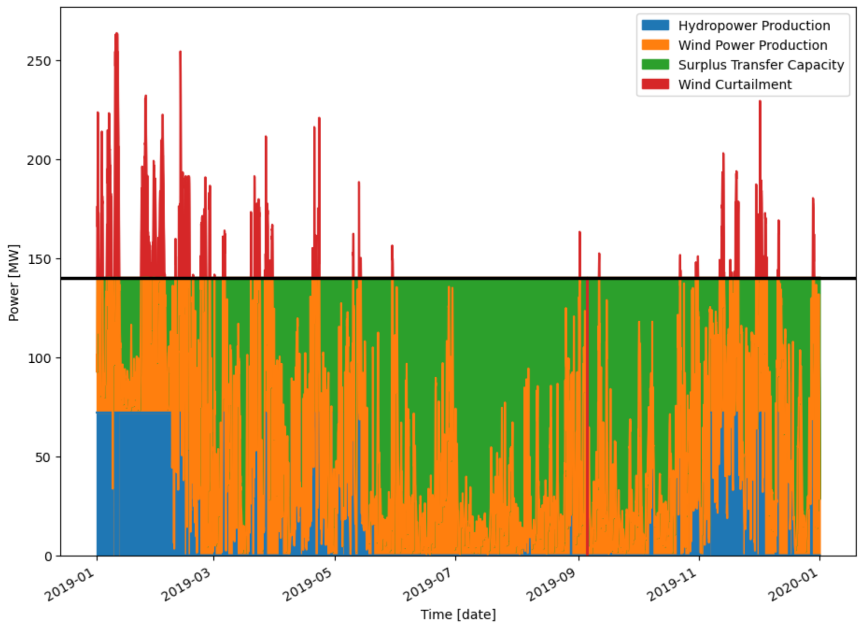

Figure 6.5: Total grid system when the hydro plant can produce the desired production profile.

The figure highlights two main problems: a major part of the wind power must be curtailed to keep the total load within the transfer capacity, and although the transmission capacity is congested, it still exists significant amounts of unused grid capacity (green area in Figure 6.5). Therefore, curtailed wind power and unused grid capacity highlight the need for a pump to avoid curtailment of wind power, which also strengthened the hydro plant's ability to fill the reservoir and hence use the grid more often so the grid utilisation is improved.

Annual reservoir level - desired hydro production

For the desired hydro production, Figure 6.6 shows what the annual reservoir levels will look like. The reservoir is emptied quickly during the first months of the year, and the level is held low until the spot prices decrease and inflow from the surroundings increases. As seen, the level increases fast during spring and summer, before the high scale production starts in the late autumn and December.

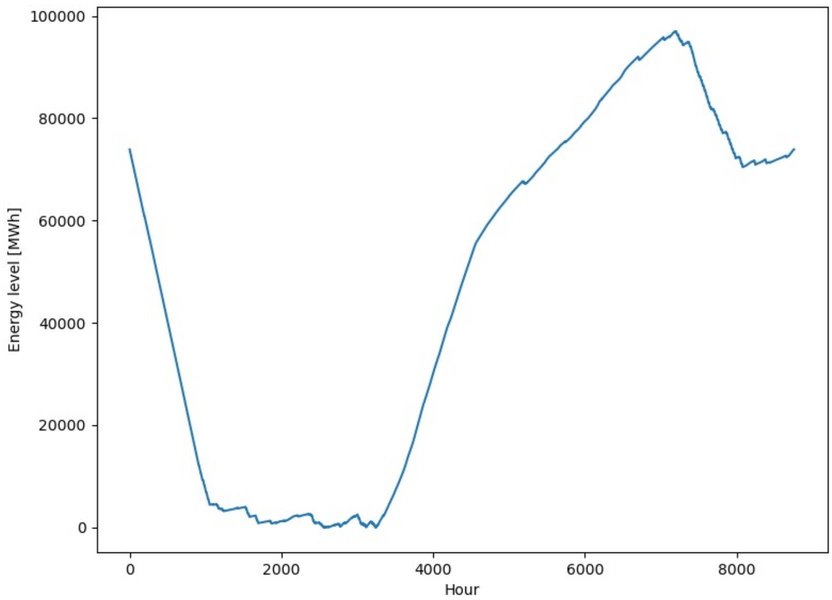

Figure 6.6: Annual reservoir levels for the desired hydropower production.

6.2 MOLP simulations

6.2.1 Statistics for different weights

Based on the capacity issues in the system simulations, an optimisation algorithm is conducted to investigate different ways of how the wind farm and hydro plant can share the transmission line better while not contesting the transfer limit. The sharing requires a compromise where the MOLP suggests different trade-offs through the MOF. Both plants desire to maximise their income, and each trade-off will cause consequences for one or both producers in terms of energy loss, change of production schedule, and income, dependent on the weight ratio.

Simulations for all wind farm scales can be found in appendix C. The scales for the wind farm are chosen based on the estimations from Nordkraft regarding possible wind farm expansion in section 5.2.1. The increase of the wind farm size by a factor of 0.25 can be seen in the general flowchart in Figure 5.2. In Table 6.1 and 6.2: wind curtailment is the ratio between the amount of total curtailed wind power and total potential power, reduced hydro and wind objective is how much the suggested trade-off deviates from the optimal value in the pay-off table. Lastly, wind curtail frequency is the number of times the wind curtailment variable is higher than zero, and grid utilisation is found by Equation 5.7.

Two wind farm scales are treated as the ”realistic” up the scale and the ”ambitious” upscale. Statistics for wind farm scales 1.5 and 3 are shown below with comments about trends and patterns. The wind farm scale of 1.5 is treated as a realistic expansion by increasing the number of turbines between the existing ones, and in addition, expanding the area to a certain rate. Wind farm scale 3 is a bit above the suggested upscale of 2.5 from Nordkraft in section 5.2.1, and is therefore treated as the ambitious upscale, where a significant extension of the wind farm area is required.

Table 6.1: Measured parameters from MOLP simulation with a wind farm scale of 1.5.

	Wind farm scale 1.5				
Parameter	**w1**	**w2**	**w3**	**w4**	**w5**
Wind curtailment	3.17%	3.17%	2.58%	0.62%	0.05%
Reduced hydro objective	0%	0.04%	0.58%	0.83%	0.87%
Reduced wind objective	8.0%	7.97%	6.63%	1.68%	0.14%
Wind curtailment frequency	390	390	313	122	52
Grid utilisation	32.81%	32.81%	32.95%	33.42%	33.56 %

Table 6.2: Measured parameters from MOLP simulation with a wind farm scale of 3.

	Wind farm scale 3				
Parameter	**w1**	**w2**	**w3**	**w4**	**w5**
Wind curtailment	18.26 %	16.10 %	10.64 %	8.08 %	8.03%
Reduced hydro objective	0%	0.36%	4.45%	8.55 %	8.73%
Reduced wind objective	29%	25.5%	7.61%	0.17 %	0.04%
Wind curtailment frequency	1688	1515	1221	1026	975
Grid utilisation	48.96%	50%	52.6%	53.69%	53.7%

It can be seen that treating the producers equally leads to almost a full prioritisation of hydro production. Anyway, a weight of 15/1 for a wind scale of 1.5, push the reduced objective to almost zero for both objectives. This indicates that a 1.5 upscale of the wind farm is reasonable to conduct by adapting wind-PHS coordination. However, the grid utilisation is still poor with this wind farm expansion.

In Table 6.2, the grid utilisation is increased to more than 50 %, but the income loss is also higher for one or both producers. It can be seen that the wind objective is changing faster than the hydro income when the weight is adjusted. The wind objective in Figure 6.2 deviates 29 % from the optimal value, in an hydro priority scenario, to almost zero in a case where the model is pushed hard to prioritise wind integration. At the same time, the reduced hydro objective is only right under 9 %. Hence, compared to Figure 6.1, weight $w5$ shows that a full prioritisation of wind export force the model to reduce the hydro objective. Another interesting observation at weight $w5$ is that even though the model prioritises wind export hard, it seems like the model converges against a point of the wind curtailment. There is approximately no reduction of the wind objective, but still 8 % wind curtailment. A reason may be related to low spot prices.

6.2.2 Pareto front and fuzzy graphs

In Figure 6.7 and 6.8, the Pareto front with all efficient solutions for a realistic and ambitious wind farm scale of 1.5 and 3 are shown. The number of points is 50 intervals and represents each a trade-off solution for the grid point values explained in 5.3.1. This solutions are all used to calculate a utility number to decide the most promising solution.

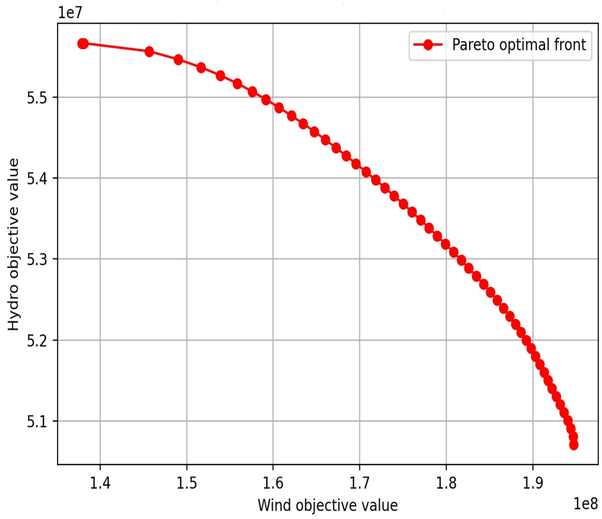

Figure 6.7: Obtained Pareto front for wind farm scale 1.5 .

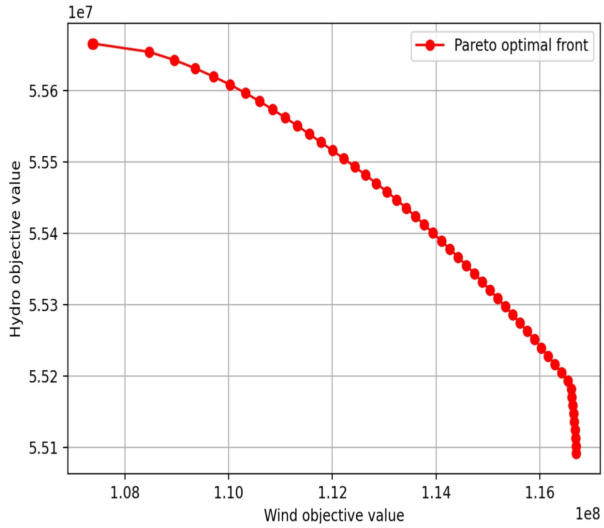

Figure 6.8: Obtained Pareto front for wind farm scale 3.

The Pareto front is characterised by a concave-shaped form, which means that the feasible area is a maximisation problem. It can be seen in the Pareto figures that the first point is minimum hydro value and maximum wind value, and the last point (in the upper left corner) is min wind value and max hydro value. The hydro plant size is constant, but the wind farm size can be adjusted. The x-axis in figure 6.8 has higher income values than the x-axis in figure 6.7, because larger wind farm capacity gains more income.

Fuzzy utility graph

The calculated utility number for each Pareto solution can be shown graphically. Figure 6.9 and 6.10 shows the utility numbers for each Pareto solution for all weight ratios. The fuzzy decision-maker interprets a higher utility number as a better solution. A value of 1 would be that both objectives are at the optimal value. The figures show two different shapes of the utility value characteristic for the aforementioned Pareto solutions in Figure 6.7 and 6.8.

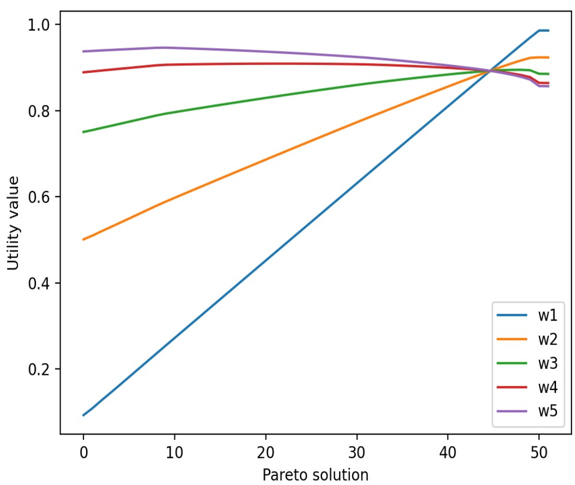

Figure 6.9: Fuzzy utility values for wind farm scale 1.5 and all weights.

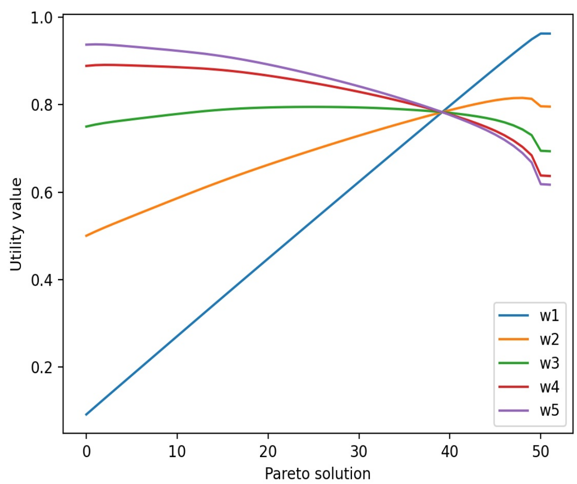

Figure 6.10: Fuzzy utility values for wind farm scale 3 and all weights.

As seen from the figures, the shape of the utility value graphs are different when the wind farm scale i adjusted. It is also interesting to see where the peak values occur in the figures. The peak values for scale 1.5 is located more to the right in figure, which means that hydropower is more prioritised than wind. Moreover, for a wind farm scale at 3, the peak values occur more to the left as the significance of the wind power is higher according to a larger wind farm. As an example, for $w3$, the peak value is close to the 50th solution in Figure 6.9, while the peak is about the 24th in Figure 6.10.

6.3 Sensitivity

The sensitivity section contains two wind curtailment analyses where ranges of wind farm scales and nominal pump powers are tested. In addition, a sensitivity analysis of relative income performance is presented through a conditional formatting table. The wind curtailment analysis shows how curtailment is affected by the size of the wind farm and pump and can be used as a tool to decide possible wind farm expansions. In addition, the formatting tables provide an indicator of the relative performance of a wind-PHS system compared to individual operations.

6.3.1 Wind curtailment NEM reduction VS MOLP

The graph in Figure 6.11 shows what the relationship between the size of the wind farm and the amount of curtailment looks like for different weight scenarios. As seen, the green graph shows how much of the wind power is going to be curtailed when the standard simulation NEM rule is used.

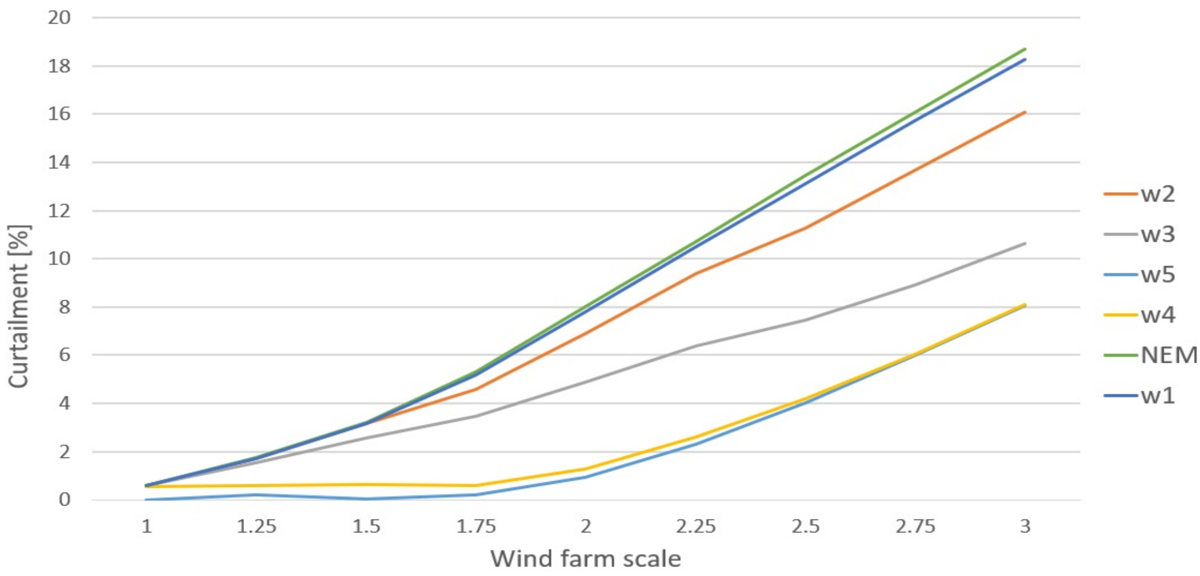

Figure 6.11: Wind power curtailment for all wind farm scales and weights.

The trend observed in graph 6.11 is that adjustment of the weights makes the model prioritise the export of more wind instead of curtailing it. A larger weight ratio pushes the graphs lower as the wind curtailment decreases. A full prioritisation of wind power export holds the wind curtailment close to zero until a wind farm scale of 2. By looking at the NEM graph, it is clear that a wind farm scale between 1.25 and 1.5 is a turning point where the transmission capacity is exceeded as the curtailment increase faster after this point.

6.3.2 Wind curtailment for different pump sizes and wind scales

To investigate the impact of the pump size, a sensitivity analysis can be done where the relation between wind curtailment and pump size is studied for different wind farm scales. Figure 6.12 shows a case for weight $w5$ where the wind power is curtailed for different pump sizes between 0 and 20 MW, where each graph represents a wind farm scale.

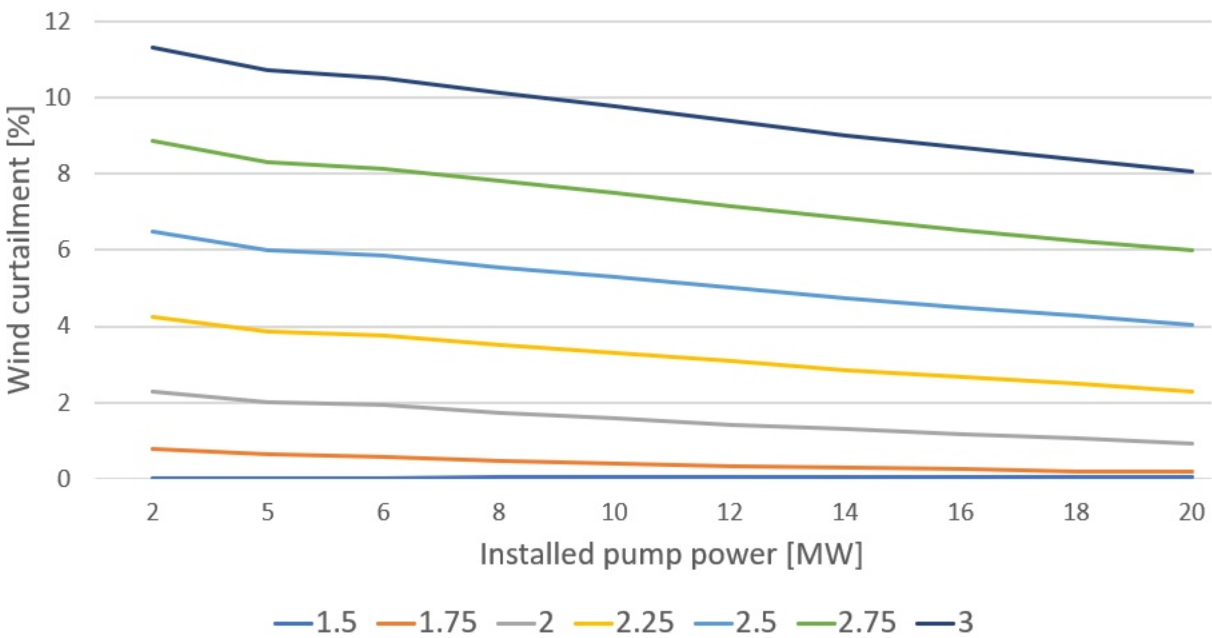

Figure 6.12: Wind curtailment sensitivity with different pump capacities and $w5$.

The trend for the wind curtailment graphs is that for small wind farm scales, the improvement of wind curtailment is approximately negligible. It can be said that for wind farm scales to 1.75, the impact of pump contribution is limited. However, the impact of the pump power is increasing when the wind farm scale is higher, which can be seen from the steepness of the graphs.

6.3.3 Wind curtailment for different pump sizes and weights

6.3.4 Relative revenue analysis

To interpret the quality of the obtained MOLP hydro and wind revenue, there is chosen to compare the incomes with the mentioned reference scenarios introduced in Figure 6.3 and 6.4. Measuring the MOLP revenues with the reference incomes gives an indicator of the effectiveness of the MOLP simulation with the MOF contributions. Table 6.13 and 6.14 shows the deviation between the MOLP trade-off incomes and the reference revenues. The reference incomes are incomes obtained from desired hydro production and wind power with full transfer priority with no pump. Then it can be seen how the income is either improved or worsened by adaption of the wind-PHS system with different weight ratios.

	w1	w2	w3	w4	w5
1.25	3.27%	3.27%	3.26%	3.22%	2.96%
1.5	3.27%	3.27%	3.23%	2.67%	2.39%
1.75	3.27%	3.22%	3%	1.64%	1.29%
2	3.27%	3.20%	2.65%	0.43%	0%
2.25	3.27%	3.17%	2.09%	-0.85%	-1.44%
2.5	3.27%	3%	0.95%	-2.50%	-2.90%
2.75	3.27%	2.95%	-0.19%	-4.12%	-3.71%
3	3.27%	2.91%	-1.33%	-5.56%	-5.74%

Figure 6.13: Conditional format table of relative hydro incomes.

	w1	w2	w3	w4	w5
1.25	-2.20%	-2.20%	-1.98%	-1.55%	-0.28%
1.5	-3.94%	-3.94%	-3.26%	-0.80%	0.00%
1.75	-5.49%	-4.76%	-3.46%	0.31%	0.73%
2	-6.89%	-5.87%	-3.40%	1.23%	1.62%
2.25	-7.92%	-6.66%	-2.93%	1.96%	2.38%
2.5	-8.63%	-6.46%	-1.46%	2.85%	3.06%
2.75	-9.10%	-6.68%	-0.26%	3.64%	3.71%
3	-9.47%	-6.82%	0.70%	4.08%	4.30%

Figure 6.14: Conditional format table of relative wind incomes.

The maximum improvement of the hydro income is 3.27 % compared to the reference hydro income. It can also be seen that the wind-PHS coordination in the best case improves the wind income by 4.3 % compared to the reference wind revenue. In Table 6.13, For higher weight ratios and larger wind farm scales, the hydro revenue decreases and all trends are equal in the horizontal and vertical direction, but for Table 6.14, some special trends are observed. The wind income gets better for higher weight ratios in the horizontal direction, but an interesting observation is a relation between wind farm scale and relative income in the vertical direction. For low weight ratios, the relative performance is worsening for larger wind farms. On the side, for higher weight ratios, the relative performance gets better when wind farm increases. Hence, the model behaves differently for low and high weight ratios when it comes to relative wind performance.

7 Discussion

The discussion part aims to discuss the performance of the AUGMECON based MOLP regarding scheduled power production from the reference area. Literature reviews and results have shown that coordinated wind-hydro systems can be configured in different ways and each solution has advantages and disadvantages for the wind farm and hydro plant. Based on the power market, wind, hydro, and optimisation literature review, the results will be used to answer the question in the problem description section 1.2.

7.1 Wind and hydropower production pattern

The annual reservoir level pattern in the AUGMECON simulation and the theoretical pattern from the literature in section 3.2.5 show distinctive similarities. As seen from Figure 6.6, the reservoir is emptied drastically during the first months of the year. The fact that the optimisation model tends to gain the major profit during the highest spot price is reasonable. By looking at the typical Norwegian reservoir patterns in Figure 3.6 , the variations are more even compared to the graph in Figure 6.6 where the change of the level is more rapidly. This behavior may be explained by the fact that the MOLP model in this thesis only focuses on optimising the participation in the spot market, without taking other factors such as minimum load cover, environmental consequences, or reserve requirement into account. There is therefore conceivable to believe that the optimised reservoir pattern fluctuates more rapidly than it would have been for a real operation.

For the wind farm, an ideal production pattern would have been the production profile in Figure 6.4 with no curtailment, but because of the transfer limit, the wind power must be occasionally curtailed. The core of the problem in the area is that the wind power potential is highest during December-March, which is also the preferred period to empty the water reservoir due to favourable spot prices. Therefore, if wind export shall be strongly prioritised, amounts of hydropower production must be moved to periods outside the mentioned months. Limiting production in this period will lead to an income reduction which may be difficult to cover in other months because of lower spot prices. Anyway, assuming that future estimations regarding less seasonally price variations and more frequent price variations are correct, then there will be more opportunities to distribute the hydropower production throughout the year, which makes it easier for the hydro owner to let wind power be prioritised during the winter months.

Possible future changes in the reservoir pattern are depended on the future price characteristic and the regulation of the energy market. A more intra-day affected production pattern and an increase of utilisation of short-term price variation may cause that hydro actor to invest in larger turbine and pump capacities to gain more income on shorter terms. For the reservoir level pattern, the seasonal trends of the emptying during winter and filling in the summer will then remain, but the levels will fluctuate more and not be as straight as Figure 6.6 shows because of more STHP operations.

More STHP operations can be beneficial for the wind farm because higher turbine and pump capacities lead to faster emptying of the reservoir and require better access to cheap pump power, where the wind farm can be a contributor by entering into UPPA's with the hydro producer. On the other side, as long as there is poor transfer capacity in a north-south direction, it was mentioned in 2.4.2 that the increased price volatility will be higher in the south than in the north price regions. A poor increase in the short-term price volatility may cause a hydro plant in NO4 continues with a production pattern characterised by seasonal production instead and less use of STHP.

7.2 Statistic analysis

According to the statistic tables, the elasticity of hydro objective and wind objective reduction is different. It turns out that the rate of reduced wind objective changes faster than for hydro objective. It can be seen that in all tables in appendix C, the reduced wind objective changes more than the reduced hydro objective for different weights. A reason for this may be that the hydro plant has more opportunities to schedule the hydro production to other time slots than the wind farm. Power from a wind farm has to be transferred immediately and the consequences of limited transfer opportunities are therefore worse than for the hydro plant. Hence, a key takeaway is that regulated energy sources with storage are more robust against poor transfer conditions than VRES as wind power.

Based on all simulations statistics from appendix C, wind farms scale up to approximately 1.5/1.75 finding a trade-off where the solutions are less than 1% from the optimal value, which means that both plants achieve almost the best possible production. A wind farm scale of more than 1.5/2 force the system to find a compromise solution which will result in a reduced objective value compared to the optimal values.

In the results, it was mentioned that in Table 6.2 (for an ambitious wind farm scale), the wind curtailment converges towards 8% even though the weight is increased significantly in favor of wind export. At the same time, the reduced income is almost zero (0.04%), which means that approximately no income compared to optimal value is lost. A possible reason for this result may be that the model finds a way to curtail the amount of wind power through periods with low spot prices such that the income loss is negligible. However, spot prices are dynamic with many influencing factors, so the price pattern may change in the future. Hence, a system that minimises the wind curtailment should be preferred anyway to be sure that the optimisation solution will avoid significant income losses for different spot price characteristics.

An overall trend for the grid utilisation can be seen by studying all tables in appendix C. The MOLP optimisation for the current wind farm scale is only able to utilise 25 % of the available annual capacity. The conceivable reason for that is that the hydro plant only produces power during favourable spot price periods and holds back the energy otherwise. With more wind power export from the wind-PHS system and the fact that wind power must be exported immediately, the grid utilisation was expected to increase. The reason is that there is room for more penetration of energy outside the hydro production hours, and these slots can be filled by intermittent wind power production. It can be seen that a higher weight ratio and larger wind farms increase the grid utilisation in appendix C. For larger wind farm scales, the grid utilisation is increased to more than 50% at a wind farm scale of 3, but the hydro plant must then accept an objective reduction of almost 9% in scenarios where wind power export is strongly prioritised.

In general, more wind power penetration increases the grid utilisation, but the hydro plant must re-schedule the production and accept income losses. A better grid utilisation means more penetrated energy and that will benefit the TSO because they will achieve more transferred energy in the North-South direction and supply more energy such that grid investment deferral is obtained. In addition, more energy penetration will contribute to lowering the price differences between the north and south. Therefore, expanding the wind farm in terms of more energy supply should be an argument for increasing the wind farm size from the TSO's point of view. More wind power penetration will also help Norway to reach the desired goals for electrification and decarbonisation. Hence, the consequences of better grid utilisation are elements that provide socio-economic benefits which is beneficial for the TSO's commitment regarding societal rational grid development as mentioned in section 2.2.

7.3 Sensitivity analysis

7.3.1 Wind curtailment

The wind curtailment sensitivity in Figure 6.11, may be a tool to determine a reasonable wind farm expansion. If zero wind power curtailment is the target, a reasonable wind farm expansion would be a scale of 1.75 by looking at the green graph for $w5$. The statistic in the Table C.4 shows that the hydro objective will then experience a 1.66% decrease, which may be acceptable. However, it was mentioned earlier in section 7.2 that even when 8 % of the wind power is curtailed, the income loss is negligible. Therefore, by looking at Figure 6.11, with full prioritisation of wind export ($w5$), the wind curtailment graph does not cross 8% before the wind farm scale is 3, and then the standard NEM graph (yellow), exceeds 8 % at the wind farm scale of 2. Therefore, it might be that with an approximately similar pattern of inflow, wind velocity, and spot prices, the system can handle a wind farm size of significant size if the hydro plant is willing to accept income losses.

Figure 6.12 can be a tool to see the impact of the pump for different weights and wind farm scales. An expected trend is that the curtailment decreases with a higher installed pump capacity because a larger pump can consume more wind power which would have been curtailed otherwise. As mentioned, it doesn't play any role if the pump imports power from the grid or wind farm from a hydro producer's point of view. Therefore, the pump's impact on reduced wind curtailment will be stronger as the weight ratio increases, because then the model understands that wind-to-pump operation improves the equation of objective 5.4a by reducing the value of wind curtailment with more pump activity. The pump's impact is also bigger for higher wind farm scales because there is more wind power the pump can consume and hence prevent curtailment. For that reason, since the pump has a limited impact on small wind farm scales, it might not be necessary for a pump installation for small wind farm scales. Such a sensitivity analysis can be a tool to consider the benefits of a pump versus the investment costs.

7.3.2 Revenue analysis

The relative income tables in Table 6.13 and 6.14 can be used to give some indicators of the relative performance of the MOF. It can provide a better basis to propose a reasonable wind farm expansion and a better overview of the benefits and drawbacks for both producers in each simulation scenario. The tables can also be a tool to understand how the AUGMECON and fuzzy algorithms work, as the trends in the tables might be distinctive.

As the relative hydro revenue is positive for low weight ratios is expected because it utilises the pump to gain the hydro plant's revenue. The relative hydro income is better for small wind farm scales and smaller weight ratios. The reason why the relative income stagnates at 3.27% even though the pump improves the inflow to the reservoir might be because the existing inflow conditions and storage capacity are sufficient. Hence, it is conceivable that the pump would have been more efficient at a location with worse inflow conditions. It can be seen that the hydro plant has a negative relative income under the following criteria: wind farm scale more than 2.25 and weight ratio higher than 3/1. Hence, if the hydro plant does not accept any worse income than the reference income, the whole wind-PHS system can not be operating within the latter criteria.

For the relative wind revenue in Table 6.14, the wind income is as expected relatively poor when the model prefers to prioritise as much hydro production as possible. For a wind farm scale of 1.5, the revenue remains the same as the reference value for $w5$ because the value is 0 % deviation. The reason behind this is because an upscale of 1.5 and a $w5$ weight can transfer all the wind power through the transmission line. Therefore, no wind power is lost, and the performance of the wind income is the same as the reference income. As known, the line starts to be congested for higher scales than 1.5, and the pump will have a stronger impact. The pump improves the wind revenue as long as the weight ratio is at least $w3$. For weights below $w3$, it is clear that the model aims to prioritise hydro so much that the wind-PHS wind revenue income is negative compared to the revenue potential (reference revenue).

As mentioned in the intro of this section, some trends can be quite explaining of how the AUGMECON works. The reason why the relative wind revenue improves for larger scales may be that larger wind farms mean more potential loss of wind power. For a larger wind farm, the MOLP sees that there is more power loss by not prioritising the wind farm and the FDM provides better utility values for wind export. Giving the best possible value for objective 5.4b is therefore, more important when the wind farm scale is large, and the relative revenue will also then be improved as well.

Summarised, a larger wind farm scale can be beneficial for the relative wind revenue with AUGMECON and fuzzy algorithm as simulation tools. For high weight ratios, a larger wind farm performs a better relative wind revenue than smaller wind farms. On the other side, the wind income loss is higher for lower weight ratios. In general, the weight ratio needs to be at least 3/1 to avoid a less wind income than the reference income. As a recommendation based on the tables, there are only four scenarios that lead to a positive relative income for both plants: wind farm scale 1.75 for $w3$ and $w5$, and wind farm scale 2 for w3 and w5. This can be seen in Table 6.13 and 6.14 as all values in both tables are positive. An operation like this would be beneficial for both plants.

7.4 The new NEM rule

The new NEM rule that allows connection with terms of reduction gives wind producers more freedom in how to conduct an expansion or installation of wind farms. There is conceivable that allowing producers to connect with such terms can contribute to accelerating the roll-out of wind power. As an argument, the MOLP simulations showed that significant amounts of wind power can be curtailed during low spot prices such that the income loss I negligible. Therefore, by moving the curtailment to the right periods, operation with the new NEM rule can be conducted, which is beneficial for the acceleration of wind power integration. An advantage of early connection through the NEM rule is that more wind power concessions can be used faster, and it also lets the producers test the system earlier while the grid reinforcement is ongoing. More tests can contribute to maturing the wind-PHS coordination and improve the optimisation strategies, and it will also give wind and hydro producers as well as the TSO more experience with such kinds of systems. This provides a better basis for adapting these strategies and coordination plans at other locations with the same transmission issue and hence, a need for temporary solutions before the reinforcements are done.

7.5 Wind-PHS in future energy market

It is worth discussing the opportunities for a wind-PHS system in the future energy market. A change in price volatility will strongly affect the way a PHS is operating in the future. As mentioned in the market review in section 3.2.6, higher demand and more short term price variations will make it beneficial to have more pump operations on shorter terms, because the gap between low and high prices makes it worth varying between importing and exporting more often. If more STHP operation is desired, there is conceivable that an upgrade of the turbine capacity is reasonable because it gains the income by improving the utilisation of short-term favourable spot prices. Higher utilisation of short-term prices and avail pump power from the wind farm may be good as it will benefit both energy sources because a higher pump activity will require more wind-to-pump energy, and improve the frames for achieving a profitable wind farm expansion. Also, the wind-PHS system will benefit the hydro plant even more if the wind-to-pump price is cheaper than the spot price because it will strengthen the hydro plant's competitiveness by a sufficient availability of cheap import power. However, a cheaper wind-to-pump price will reduce the wind income compared to the spot market, but it is still a better option than curtailment.

If the future spot price pattern is characterised by a flatter seasonally price variation, there is conceivable that the MOLP model sees more opportunities to move hydro production to other periods throughout the year. Moving amounts of hydro production from the most intense production periods will open for significant amounts of wind energy to be penetrated. Hence, the process of sharing the transmission line would be simpler as the hydro plant can re-schedule production easier. However, future price characteristic is an uncertain estimation because of the power market's complexity. If the seasonal price difference grows instead, the load on the transmission line will be even higher during the winter months. This will worsen the export capacity for wind power throughout the winter half-year, but it may also lead to a larger need for pump power in the summer and autumn due to filling the reservoir before the winter.

According to wind-PHS systems in the north grid region, even though the capacity in the north-south direction will be upgraded, new industry projects with large consumption can be an additional tool to improve the business frames from a producer's point of view. If the future transmission capacity is not sufficient to handle all the production from the area, then making PPA's with consumers would secure revenue for the wind-PHS system. It was mentioned in the power market section 2 that large-scale industry consumers shall be built in the north region, which may be potential PPA buyers. More opportunities for fixed delivery agreements may lead to more of the scheduled hydropower production being removed from the spot market, and through fixed deliveries. Less hydropower in the spot market may open for more wind power export through the spot market in a north-south direction because the available transfer capacity is higher.

In addition to future PPA's, both the hydro plant and wind farm can offer reserves in the mentioned cross-border reserve market aFFR in section 2.5.1. Bidding in such a power market is also an opportunity to secure predictable income and distribute the energy supply outside the intense high price periods in the spot market. Lastly, more industries that need energy supply will increase the overall demand, and contribute to increasing the spot prices in area NO4. Higher spot prices in NO4 will benefit the power producers in terms of better frames of investment and profitability.

7.6 Trade-off and bilateral agreement - different points of view

The need for a trade-off through a bilateral agreement is highlighted in Figure 6.5 where the transmission line is congested when both plants follow their optimal production patterns. A wind farm is allowed to enter into an agreement where the connection is done with terms of limitation of production. However, different configurations of the distribution of the transfer capacity should be investigated as long as the total production from the wind-PHS system is within the transfer limit. The terms of reduction can apply to both the wind farm and hydro plant, such that grid connection or increase of capacity can be done if it can be proved that other sources will reduce the production for the benefit of the wind farm.

Determine a concrete trade-off is challenging with the MOLP model created in this thesis because the simulation is based on data that will vary from year to year and because it is harder to predict future data on a long-term basis. Since the obtained production pattern only is an estimation of the coming year, the bilateral agreement can not specify the exact terms of the production schedule because of uncertainties regarding wind, load demand, and inflow conditions, which are historical data. Therefore, a possible issue with such a contract is that it can not be specified how much and to what time the wind energy and hydro energy shall be exported. Anyway, both the statistic and relative revenue tables can be used to see the number of losses for both plants for each trade-off suggestion.

Another way to conduct the simulation could be to do short-term simulations instead of annual based, with a weight that is pre-determined by all stakeholders. By doing simulations at a day-ahead term, the spot prices would be known, and inflow and wind conditions would be more certain. On the other side, optimisation daily will not consider saving water for later use, and the annual profit would then not be optimal. Probably, to be able to use this model as a tool to schedule the annual production distribution between both producers, simulations for different scenarios of spot prices, inflow, and wind potential must be done. With different simulations for diverse scenarios of the uncertain data, the model can be used to draw a rough overview of how the transfer capacity is distributed between the two producers throughout the year. The optimisation model will then be an indicator of different consequences for both plants for different prioritisation scenarios. Being aware of how the loss of income and curtailment pattern may look like can help the wind farm actors to plan the projects and do necessary hedging actions to avoid the potential economic deficit.

Other details in the bilateral agreement that is likely to be considered, is how the hydro plant is compensated for letting the expanded wind farm be the prior user of the transfer lines if a production pattern similar to scenarios with high weight ratios is chosen. Since the hydro plant is the initial user of the transmission line, it might be that the hydro plant requires to be compensated for not being able to fully utilise the income potential. To meet this requirement, a trade-off where both producers can be satisfied is if the wind farm uses the increased relative income, seen in Table 6.14, to pay the hydro plant as compensation for the loss of potential hydro income. In other words, the amount of wind income that exceeds the reference income goes to the hydro plant. A deeper look at Table 6.13 and 6.14 shows that the improved wind income can cover large amounts of the lost hydro income. Hence, there is likely to believe that allowing an upscaled wind farm access to the transmission line without worsening the hydro plant's income is possible by the use of a pump.

7.7 Shortcomings and areas of improvement

Since the model doesn't include any minimum load to cover, the regulated hydro plant tends to switch between off- and on-mode very often because it is not committed to covering a continuous load demand. The problem with this is that the frequent switch-on and off pattern may not be realistic because of start-up costs and tears on the machine. A constraint that says the production must be a minimum load profile and constraints regarding switching on and off mode could have been added. In addition, such frequent mode switching can cause unnecessary fluctuations of the grid voltage and challenge the operation of the grid. A constraint giving a maximum rate of output change could also have been included.

As mentioned earlier, the objectives can be configured in several ways as it exists different equations that describe the performance of a power producer. One issue with the hydro objective 5.4b is that the pump power must be multiplied by 1.05 to avoid production and pump operation at the same time. The pump power is not more expensive than the spot price, so the hydro objective will not represent the accurate real income. For objective 5.4a, the model aims to let the variables for wind export and wind-to-pump be as high as possible and do the opposite with the curtailment. The wind objective can not be said to be the real income because the curtailment is not a cost, just a penalty value in the mathematical expression. It might be that $P_{w,curt}$ is redundant as it is already included in the wind power balance.

The reason why the results are presented as percentage and relative values is that the concrete numbers of the income are based on participation in a spot market that consumes all the desired production. In other words, there is no load included at the consumer end of the grid. Including a load demand would have required a constraint telling that the total production can not be greater than the demand. For that reason, it is likely to believe that the real income would have been lower compared to the obtained revenues in this model.

Some simplifications are done due to the operation of the water flow between the lower and upper reservoir. The lower reservoirs contain unlimited amounts of water in this model. There are no restrictions for the lower reservoir which allows the model to pump water whenever it wants and as much as it wants. For a realistic scenario, there is conceivable that a lower reservoir has a limited amount of water, and it might be restrictions regarding how much water can be extracted from an environmental standpoint. A lower reservoir may be in some cases a river with a required flow level. Since the current hydro plant is not operating with pumping from lower reservoirs, no associated data is available for the lower reservoir which makes it hard to estimate the available amount of water the pump can extract. The pump activity pattern would therefore be different with a mass balance for the lower reservoir included unless the lower reservoir is such a size that the pump can operate as it wants. For the upper reservoir, it turns out from the results that the whole reservoir is emptied and then filled up again throughout the year. Using the whole range of the reservoir levels may not be a feasible way to simulate a hydro plant because a minimum water level would have been common to avoid encroachment on animal life, landscape, and nature.

Conclusion and further work

Conclusion

The results show that the pump contributes to better wind export conditions and improving the hydro income as it increases the hydro plant's stored energy in high price periods. The maximum improvement of the relative hydro income with a 20 MW pump is 3.27 %, and 4.3% for the wind farm. It can therefore be proved that both producer's income can improve with a pump facility. Moreover the results also indicate that the pump's impact on wind curtailment is more significant as the wind farm scale increases, which means that the nominal wind power should be larger than the exceeding scale limit (1.5) before a pump is necessary.

From a future power market perspective, the production pattern of the wind-PHS system can be characterised by more short term high production (STHP) operation. Such operation can be beneficial for the wind farm because STHP operation may require higher turbine and pump capacity, which leads to a faster emptying of the reservoir and higher demand for cheap import pump power. A wind farm supplying power to a pump can contribute to making more hydro STHP operations feasible. Especially if the wind-to-pump price is lower than the spot price, the hydro plant can take advantage of the cheap pump price at the same time as the wind farm avoids energy loss.

The new *Regulation on grid regulation and the energy market* (NEM) connection law can also improve the grid utilisation, and the simulations show that two key actions will improve the grid utilisation: a higher weight ratio and a larger wind farm scale. For the current wind farm size, the transmission line capacity is poorly utilised, and there are significant amounts of unused grid capacity, especially in the summers. The grid utilisation improves from 25 % to more than 50% if the wind farm is scaled with a factor of 3. The introduction of the pump is also beneficial for grid utilisation because the grid-to-pump flow utilises the grid capacity instead of letting it be unused during low spot prices. Achieving more penetrated wind energy without a negative impact on hydro production can trigger grid investment deferral.

A reasonable wind farm expansion in the reference case depends on the consequences the stakeholders are willing to accept. If the approach is to fully avoid wind power curtailment, the maximum wind farm expansion would be 1.75. Anyway, it turned out that about 8 % of the wind power can be curtailed with approximately no income loss. By using 8 % as a limit, the wind farm can be expanded to a factor of 2 with standard NEM simulation, and even 3 for optimisation with a wind export favourable weight ratio ($w5$).

By taking the hydro income into account, a logical approach would be to avoid a lower hydro income than the reference revenue. The wind-PHS system obtains a positive relative wind income if the weight ratio is 3/1 or more. Further, the consequences of providing the wind farm with such conditions would be that expanding the wind farm with more than a factor of 2.25 will reduce the hydro income relative to the ideal. This means that for the MOLP simulation of the reference case, a wind-PHS system with a pump of 20 MW improves both producer's relative income with a weight ratio higher than 3/1 and a wind farm scale below 2.25.

Further work

The created model in this thesis is designed to add more objectives, which can be additional energy sources such as solar, bio, or geothermal plants. Section 2 emphasises several times that besides wind power, the number of solar power projects will increase in the coming years. Therefore, it is conceivable that adding a solar power function as a third objective in the MOLP is a logical next step. With three objectives or more, the procedure of the optimisation setup would be the same by following the steps of the MOF in 5.3.2. In such a case, an additional objective describing the business equation for the new energy source would be needed, with corresponding constraints describing the technical frames. This would increase the pay-off table from 2x2 to a 3x3 matrix, and a similar constraint as 5.3 for objective 3 has to be created. The FDM will then include the new objective in the LMF calculation and utility number. A weight set that gives the added objectives weight values is also then needed for the utility number calculation.

For further development of the MOLP model, it should be possible to set a wind-to-pump price as an input parameter. This price can be determined in different ways, and the price can also be part of the configuration of the UPPA. The current price is the same as the spot price, which means that it doesn't play any role for the hydropower producer if the pump power is imported from the grid or the wind farm. By adjusting different wind-to-pump prices, the performance of both plants can be studied in terms of income.

At the moment, there is uncertainty about the wind and hydro income compared to the CAPEX and OPEX costs. A more comprehensive economic analysis should be conducted to investigate the profitability of wind and PHS coordination. It was mentioned that the grid parity of the LCOE is a well-used parameter to consider RES investments. An LCOE calculation of a wind-PHS system can therefore be a useful study because it may provide a better understanding of the business opportunities from the producer's perspective. It can also be discussed how the costs of the pump should be distributed between the wind and hydro plant based on to what extent the two producers benefit from the usage of the pump.

The model should be tested with a pump that supports operation at different speeds. The development of technology in recent years has enabled variable speed pumps, which makes the pump more flexible and able to consume smaller amounts of energy. With a variable speed pump, the wind farm can export different amounts of energy and the wind farm will then be able to avoid large and small scale curtailments, compared to the current pump which only consumes 20 MW or nothing. This may also be beneficial for the hydro plant because it opens for more detailed optimisation because of the opportunities to pump small and large amounts of energy.

Besides the day-ahead spot market, there exist additional ways of participating in the energy market that may be worth exploring to investigate if they can improve the integration of wind-PHS systems. Delivering energy through agreements with fixed volume and prices through PPA's and UPPA's are alternative options for selling energy. Such agreements create better predictability of future income, even though the producer risks missing possible high trading revenues during high spot prices. Other possible energy trading channels are ancillary and balancing services, and the capacity market. Adding these alternative revenue streams in.

addition to the day-ahead spot market in the MOLP problem is an interesting approach.

The hydropower and reservoir level pattern are altered as the pump will have an impact on the scheduling of production. This may cause environmental consequences for the surrounding landscape, local ecosystem, and water quality. Further studies should then investigate the impact on the mentioned elements and consider if the bilateral operation of the wind-PHS system is environmentally sustainable.

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A Consumption pattern in NO4

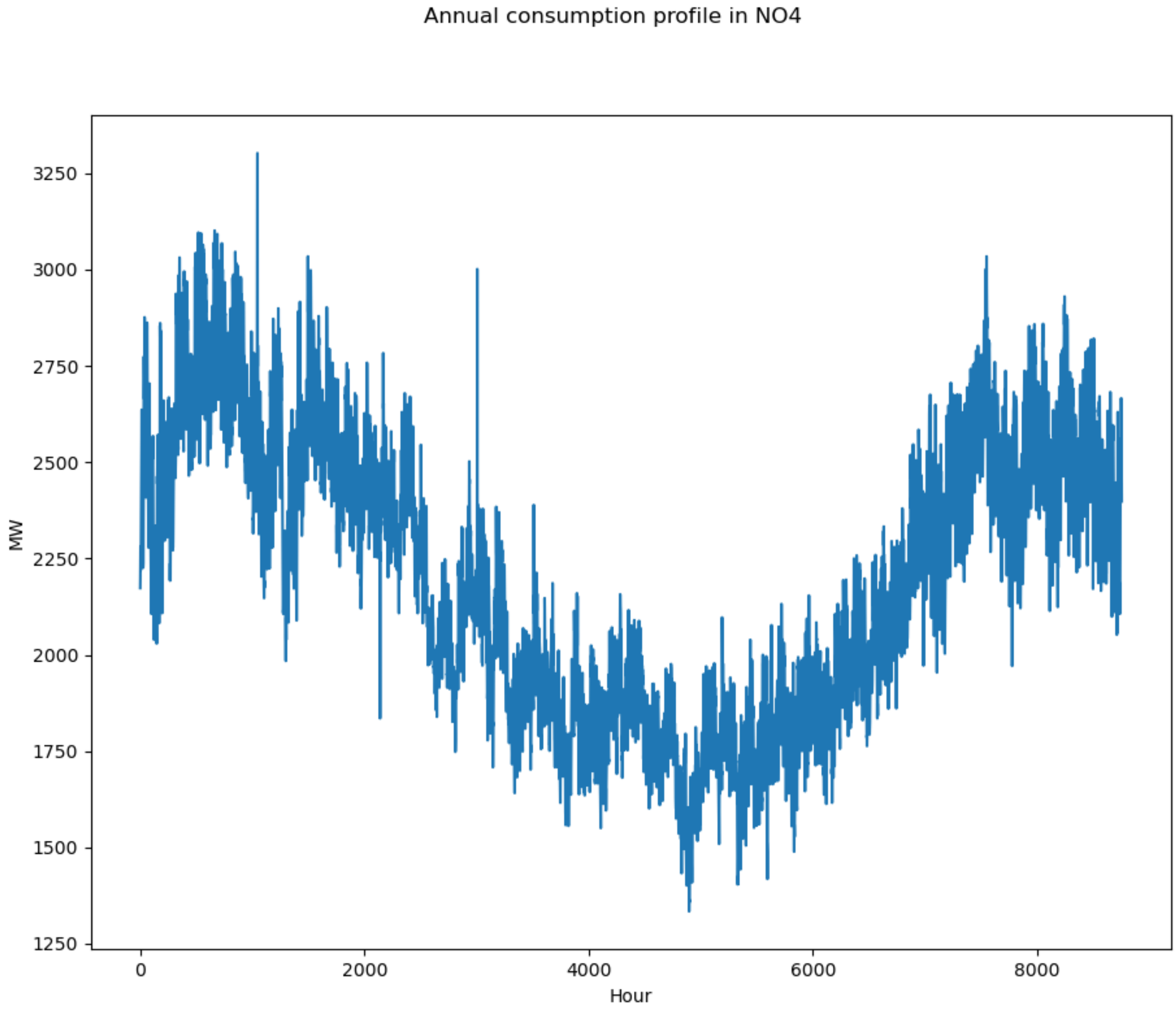

Figure A.1: Annual consumption pattern for NO4 in 2021.

B Pay-off tables - all simulations

Table B.1 shows the pay-off range for each wind farm scale between 1 and 3. Both objective's range increases as the wind farm is up-scaled.

Table B.1: Pay-off table for both objectives in the reference case for wind farm scales. All values are measured in *M NOK*.

	1		**1.25**		**1.5**		**1.75**		**2**	
	f1	f2	f1	f2	f1	f2	f1	f2	f1	f2
max f1	77.8	55.6	97.2	54.6	117	55.1	136	54.5	153	53.8
max f2	76.6	55.7	89.0	55.7	107	55.7	119	55.7	127	55.7

	2.25		**2.5**		**2.75**		**3**	
	f1	f2	f1	f2	f1	f2	f1	f2
max f1	167	53.0	178	52.2	188	51.3	195	50.7
max f2	132	55.7	136	55.7	138	55.7	138	55.7

C Statistic simulations

The table shows the stats for all wind farm scales and all weights. Reduced hydro and wind income is the proposed objective values divided on the optimal values from the pay-off table. Grid frequency is how often wind curtailment occurs, and grid utilisation is how much of total transfer capacity is utilised.

Wind farm scale 1

Table C.1: Measured parameters from MOLP simulation with a wind farm scale of 1.

Parameter	w1	w2	w3	w4	w5
Wind curtailment	0.58%	0.58%	0.58%	0.54%	0.44%
Reduced hydro objective	0%	0%	0%	0%	0.01%
Reduced wind objective	1.47%	1.47%	1.47%	1.36%	1.12%
Wind curtailment frequency	87	87	87	80	62
Grid utilisation	25.53%	25.53%	25.53%	25.54%	25.56%

Wind farm scale 1.25

Table C.2: Measured parameters from MOLP simulation with a wind farm scale of 1.25.

Parameter	w1	w2	w3	w4	w5
Wind curtailment	1.70%	1.70 %	1.52 %	1.17%	0.21%
Reduced hydro objective	0%	0%	0.01%	0.05%	0.29%
Reduced wind objective	4.30%	4.30%	3.89%	3.04%	0.58%
Wind curtailment frequency	247	247	220	162	45
Grid utilisation	29.24%	29.24%	29.27%	29.34%	29.53%

Wind farm scale 1.5

Table C.3: Measured parameters from MOLP simulation with a wind farm scale of 1.5.

Parameter	w1	w2	w3	w4	w5
Wind curtailment	3.17%	3.17%	2.58%	0.62%	0.05%
Reduced hydro objective	0%	0.04%	0.58%	0.83%	
Reduced wind objective	8.0%	7.97%	6.63%	1.68%	0.14%
Wind curtailment frequency	390	390	313	122	52
Grid utilisation	32.81%	32.81%	32.95%	33.42%	33.56 %

Wind farm scale 1.75

Table C.4: Measured parameters from MOLP simulation with a wind farm scale of 1.75.

Parameter	**w1**	**w2**	**w3**	**w4**	**w5**
Wind curtailment	5.21%	4.57%	3.48%	0.57%	0.19%
Reduced hydro objective	0%	0.04%	0.26%	1.58%	1.92%
Reduced wind objective	12.60%	11.16%	8.57%	1.09%	0.22%
Wind curtailment frequency	682	604	479	178	124
Grid utilisation	36.12%	36.30%	36.60%	37.41%	37.49%

Wind farm scale 2

Table C.5: Measured parameters from MOLP simulation with a wind farm scale of 2.

Parameter	**w1**	**w2**	**w3**	**w4**	**w5**
Wind curtailment	7.82%	6.92%	4.87%	1.26%	0.93%
Reduced hydro objective	0%	0.07%	0.6%	2.75%	3.15%
Reduced wind objective	17.04%	15.05%	10.13%	0.91%	0.14 %
Wind curtailment frequency	907	817	645	321	275
Grid utilisation	39.1%	39.38%	40%	41.20%	41.23%

Wind farm scale 2.25

Table C.6: Measured parameters from MOLP simulation with a wind farm scale of 2.25.

Parameter	**w1**	**w2**	**w3**	**w4**	**w5**
Wind curtailment	10.51%	9.4%	6.38%	2.62%	2.30%
Reduced hydro objective	0%	0.10%	1.14%	3.99%	4.56%
Reduced wind objective	20.7%	18.21%	10.73%	0.93%	0.08%
Wind curtailment frequency	1084	984	779	503	431
Grid utilisation	41.85%	42.24%	43.32%	44.61%	44.70%

Wind farm scale 2.5

Table C.7: Measured parameters from MOLP simulation with a wind farm scale of 2.5.

Parameter	**w1**	**w2**	**w3**	**w4**	**w5**
Wind curtailment	13.14%	11.29%	7.44%	4.19%	4.03%
Reduced hydro objective	0%	0.25%	2.24%	5.60%	5.97%
Reduced wind objective	23.81%	19.41%	9.28%	0.53%	0.10%
Wind curtailment frequency	1273	1128	899	711	630
Grid utilisation	44.42%	45.15%	46.67%	47.89%	47.93%

Wind farm scale 2.75

Table C.8: Measured parameters from MOLP simulation with a wind farm scale of 2.75.

Parameter	**w1**	**w2**	**w3**	**w4**	**w5**
Wind curtailment	15.72%	13.70%	8.92%	6.03%	5.98%
Reduced hydro objective	0%	0.30%	3.35%	7.16%	7.31%
Reduced wind objective	26.55%	21.54%	8.33%	0.27%	0.13%
Wind curtailment frequency	1478	1324	1053	875	842
Grid utilisation	46.8%	47.68%	49.76%	50.92%	50.93%

Wind farm scale 3

Table C.9: Measured parameters from MOLP simulation with a wind farm scale of 3.

Parameter	**w1**	**w2**	**w3**	**w4**	**w5**
Wind curtailment	18.26 %	16.1 %	10.64 %	8.08 %	8.03%
Reduced hydro objective	0%	0.36%	4.45%	8.55 %	8.73%
Reduced wind objective	29%	25.5%	7.61%	0.17 %	0.04%
Wind curtailment frequency	1688	1515	1221	1026	975
Grid utilisation	48.96%	50%	52.6%	53.69%	53.7%

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