Graduate thesis

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

Torbjørn Indrekvam Horstad

# Co-Simulation Model for Optimal Wind-Hydro Coordination Using Wind Farm Control Dynamics

## A Case Study of a Hybrid Wind and Hydro Plant System

Graduate thesis in Energy and Environmental Engineering
Supervisor: Ümit Cali
Co-supervisor: Marthe Fogstad Dynge, Magnus Korpås
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# Abstract


The growing share of Variable Renewable Energy Sources (VRES) in power systems presents challenges for regulators, grid operators and energy producers. The VRES' have limited flexibility in their operations, as they are highly dependent on ambient environments. Further, issues of technical reliability and power fluctuations should be considered. To address these challenges, decision-makers must consider multiple objectives. Among these are revenue, power system services and mechanical load on wind turbines. Coordinated operation of power plants and different wind farm control strategies are examples of measures that can benefit these objectives.

This study proposes a Multi-Objective Linear Programming (MOLP) model to simulate the optimum operation of wind and hydropower plants that share limited transmission capacity. Further, wind farm control dynamics are included to obtain realistic output power and accumulated damage. Resulting in a co-simulation model for optimal wind and hydropower coordination. From this, a case study based on a relevant location in Norway is presented to analyze the improved effect of wind-hydro coordination and wind farm control in achieving the objectives of accumulated wind turbine damage and total revenue of the hybrid power system. In addition, the study considers the potential advantages of adding a variable speed pump to the hydropower plant using a baseline approach of single-objective optimization.

The results demonstrate the potential improvements in the overall performance by using multiple conflicting objectives in the optimization rather than a single objective. By utilizing the flexibility of hydro storage and control options for the wind farm, the decision maker may adjust to obtain the most desired outcome. The objectives are conflicting, where the optimal solution for minimizing damage accumulation results in a reduction by 74.3 % for the total revenue, which is not an economically viable solution. However, a significant reduction in damage may be obtained from other candidates. For example, when considering coordinated operations and granting the revenue a higher priority in the optimization process, the results show that the accumulated damage can be reduced by 8.2 %, with a substantially less decline of 1.5 % in revenue.

Moreover, the added flexibility provided by utilizing a pump for hydro storage offers great benefits, including improvements as high as 5.6 % in the combined revenue of the power plants and a reduction in wind energy curtailments to approximately 36% compared to results obtained without Pumped Hydro Storage (PHS). However, the benefit is highly sensitive to the variations in the power prices, showcased by simulations using historical spot prices from 2019 and 2021. Furthermore, less impact is observed from using a variable speed pump compared to a fixed speed pump.

# Sammendrag

Den økende andelen variabel fornybar energi i kraftsystemene medfører utfordringer for reguleringsmyndigheter, nettoperatører og energiprodusenter. Variable energikilder har begrenset fleksibilitet i driften sin, da de er sterkt avhengige av omgivelsene. Videre må man ta hensyn til teknisk pålitelighet og kraftsvingninger. For å håndtere disse utfordringene må beslutningstakere vurdere flere målsetninger. Blant disse er inntekter, kraftsystemtjenester og mekanisk belastning på vindturbiner. Koordinert drift av flere kraftverk og ulike kontrollstrategier for vindparker er eksempler på tiltak som kan bidra til å oppnå disse målene.

Denne studien presenterer en modell for flerobjektiv lineær programmering for å simulere optimal drift av vind- og vannkraftverk som deler begrenset overføringskapasitet. Videre inkluderes kontrolldynamikker for windparken for å oppnå realistisk resultater for kraftproduksjon og akkumulert skade på vindturbinene. Dette resulterer i en samkjørende simuleringsmodell for optimal koordinering av vind- og vannkraft. Basert på dette presenteres en referansestudie basert på en relevant lokasjon i Norge for å analysere den forbedrede effekten av vind-vannkraft koordinering og vindparkkontroll, med tanke på objektivene for akkumulert skade på vindturbiner og total inntekt for det hybride kraftsystemet. Studien vurderer også de potensielle fordelene ved å legge til en pumpe med mulighet for varierende hastighet i vannkraftverket ved bruk av en forenklet tilnærming der kun inntekt som objektiv for optimeringsproblemet.

Resultatene viser potensielle forbedringer i den samlede ytelsen ved å bruke flere motstridende objektiver i optimaliseringen i stedet for kun et objektiv. Ved å utnytte fleksibiliteten fra lagring i vannmagasin og kontrollstrategier for vindparken, kan beslutningstakerene gjøre tilpassninger for å oppnå ønsket resultat. Målsetningene til de to objektivene er motstridende, der den optimale løsningen for å minimere skadeakkumulering resulterer i en reduksjon på 74.3 % i total inntekt, noe som ikke er økonomisk levedyktig for en kraftprodusent. Imidlertid kan betydelig reduksjon i skade oppnås fra andre kandidater. For eksempel viser resultatene at når man utnytter seg av koordinert produksjon og gir inntekten høyere prioritet i optimaliseringsprosessen, kan den akkumulerte skaden reduseres med 8.2 %, med en betydelig mindre nedgang på 5.84 % i inntekt.

Videre viser den økte fleksibiliteten ved å bruke en pumpe til å transportere vann til lagring i magasinet store forbedringer på opptil 5.6 % i samlet inntekt for kraftverkene og en reduksjon i ubenuttet vindpotensial til om lag 36 % sammenlignet med resultater oppnådd uten bruk a pumpe. Imidlertid er fordelen svært sensitiv for variasjoner i strømprisene, noe som er demonstrert ved simuleringer som bruker historiske spotpriser fra 2019 og 2021. Videre observeres det mindre påvirkning på resultatene ved bruk av en pumpe med mulighet for variabel hastighet sammenlignet med en pumpe med fast hastighet.

# Preface

This Master's thesis is written as part of the 5-year Master of Science programe Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU), for the Department of Electric Power Engineering. The work has been supported by NorthWind (2021-2029), a Centre for Environmental-friendly Energy Research co-financed by the Research Council of Norway (contract 321954). And is a collaboration between the university and SINTEF Energy Research.

In January 2023, a visit to the DeepWind conference in Trondheim was supported by the Department of Electric Power Engineering at NTNU. The project work and suggested outline of the master thesis were presented through a poster at the poster sessions, which provided a valuable opportunity for learning and engagement. Engaging in discussions at the poster sessions and attending interesting presentations during the conference was a valuable experience, that also contributed to broadening my perspective on different topics in my thesis.

Additionally, a visit to Idaho National Laboratory (INL) has been funded by the Department of Electric Power Engineering at NTNU and SINTEF Energy Research. The visit was done in connection with the work to enter a collaborative conference paper for the international conference on Smart Energy Systems and Technologies (SEST) regarding my master's thesis work. This visit also served to aid the collaboration between the U.S. Department of Energy and Norway's Royal Ministry of Petroleum and Energy on hydropower R&D activities. The DOE's EERE Water Power Technologies Office (WPTO) and the Norwegian Research Centre for Hydropower Technology (HydroCen) are brought together through an Annex to a 2004 memorandum of understanding (MOU) signed in 2020, to plan and coordinate hydropower R&D activities.

Throughout the work on my masters' thesis, there have been several people involved to contribute and support my work. First of all, I would like to express my sincerest gratitude to my supervisor, Ümit Cali, for his valuable supervision throughout my project and master's thesis and for his collaborative efforts to connect me with other knowledgeable researchers. He has done more than what is required of his role to aid me throughout the semester. I also wish to thank my co-supervisor Marthe Fogstad Dynge for her valuable aid in discussions, optimization modeling, and other technical issues. Further, professor Magnus Korpås deserves gratitude for his contributions with proofreading and arranging funding for my US visit.

I also want to thank Spyridon Chapaloglou, Michael Belsnes, Konstanze Kolle and Valentin Chabaud at SINTEF Energy for valuable discussions regarding the objectives and methodology for my thesis. Special gratitudes are extended to Spyridon Chapaloglou for sharing his wind farm control dynamics model. Furthermore, assisting in implementing applicable modifications for my study and engaging in insightful discussions to explain the model's processes.

Finally, I would also like to express my gratitude to the employees at INL in the Energy System Lab for a very welcoming visit to Idaho Falls and the lab. A special thanks to Juan F. Gallego-Calderon at INL for his efforts to make me feel welcome both in the lab and outside work, in addition to great inputs in proofreading, collaboration on modeling and wind farm control, and valuable discussion on relevant topics.

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# List of Acronyms

**ACO** Ant Colony Optimization. 29, 31, 36

**aFRR** automatic Frequency Restoration Reserve. 9

**AIC** Axial Induction Control. 15–17

**AUGMECON** Augmented Epsilon-Constraint. 3, 34, 35, 39, 45, 46

**AVR** Automatic Voltage Regulator. 23

**CEDREN** Centre for Environmental Design of Renewable Energy. 26

**DE** Differential Evolution. 29, 30

**DLC** Design Load Cases. 17

**DLR** Dynamic Line Rating. 39, 66

**DSO** Distribution System Operators. 5, 6

**EA** Evolutionary Algorithms. 29, 30

**ENTSO-E** European Network of Transmission System Operators for Electricity. 22

**FCR** Frequency Containment Reserves. 8

**FDM** Fuzzy Decision Maker. 36, 39

**FFR** Fast Frequency Reserves. 9

**GA** Genetic Algorithm. 29–33

**LCOE** Levelized Cost of Energy. 10

**LP** Linear Programming. 29

**mFRR** manual Frequency Restoration Reserve. 9

**MILP** Mixed Integer Linear Programming. 32, 62

**MOF** Multi-Objective Framework. 3, 39

**MOLP** Multi-Objective Linear Programming. iii, x, 3, 34, 35, 41, 46–48, 77

**MOO** Multiple Objective Optimization. 29, 32, 33, 62, 66

**NBM** Nordic Balancing Model. xiii, 9, 60

**NEM** Legislation on Grid Regulation and the Energy Market. 6, 39, 60

**NEWA** New European Wind Atlas. 40, 42

**NN** Neural Network. 32

**OED** Norwegian Ministry of Petroleum and Energy. 5–7, 17

**OPEX** Operational and Maintenance Expenditures. 17, 66

**PHS** Pumped Hydro Storage. iii, x, 2, 22, 24–27, 39–41, 49, 52–54, 59–61, 63, 65, 66

**PPA** Power Purchase Agreements. 10

**PSO** Particle Swarm Optimization. 29, 31–33, 36

**PSS** Power System Stabilizer. 23

**RES** Renewable Energy Systems. 1, 21, 63, 65

**RME** Regulation Authority for Energy. 5, 6

**RoR** Run-of-the-river. 22, 27

**SCADA** Supervisory Control and Data Acquisition. 14

**SDDP** Stochastic Dual Dynamic Programming. 31, 32, 62

**SEA** Strategic Environmental Assessment. 19

**SIA** Swarm Intelligence Algorithm. 29–31

**SRHM** Stochastic Rolling Horizon Model. 31, 32, 62

**TSO** Transmission System Operator. 5, 6, 8–10, 17

**UPPA** Utility Power Purchase Agreements. 10, 60

**VRES** Variable Renewable Energy Sources. iii, ix, 1, 2, 8–11, 21, 24, 25, 59, 60

**WOA** Whale Optimization Algorithm. 32

**WSC** Wake Steering Control. 15, 16

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# Chapter 1

# Introduction

## 1.1 Motivation and Background

The energy sector is facing a significant challenge in meeting the growing global energy demand while simultaneously mitigating the adverse effects of climate change. Recent data from the International Energy Agency (IEA) [1] reveals that the energy sector constitutes a significant contributor to greenhouse gas emissions. The energy combustion and industrial processes during 2021 contributed to $CO_2$ emissions of 36,1 gigatonnes. In order to reduce these emissions, there is an increasing global shift towards Renewable Energy Systems (RES) as an alternative to conventional energy sources. [2], [3]

The integration of RES is essential to obtain the agreements made in the Paris Agreement, reaching the goal of keeping the temperature increase below 2 $°C$ [4]. However, an increased share of RES causes new problems in the power grid and market. The integration of wind and solar power into the energy market can be challenging due to the inherent uncertainty in their production. This is due to their dependence on weather conditions, which can be difficult to predict accurately. As a result, market integration of these RES can be challenging. To address this issue, it may be necessary to implement measures such as improved forecasting techniques and increased flexibility in the power system. The VRES are also not able to provide inertia in the same way as conventional power plants, resulting in a high demand for reserves to balance the power system. [2], [3]

The modern energy sector is confronted with several future challenges. However, in recent times, it has witnessed significant technological advancements transforming how energy is generated, distributed, and consumed. Considerable research efforts have been dedicated to exploring various technical solutions aimed at addressing these challenges. Among these are numerous optimization techniques applied in different control systems, granting system operators and power producers a range of possibilities. Furthermore, emerging options for energy storage have strengthened flexible operations. The energy sector is expected to continue evolving as innovative technologies are further developed and adopted, leading to a more sustainable and efficient energy system. [2], [3]

In Norway, hydropower is the primary source of electricity, with a total installed capacity of 33.4 GW going into 2022 [5]. The IEA identifies hydropower as the currently best option to provide emission-free flexibility to the power system [6]. However, a significant portion of the newly installed power capacity in Norway comes from wind farms, reaching a capacity of 5 GW by August 2022 [7]. Moreover, the Norwegian Energy Agency (NVE) has recently launched a report identifying potential areas for 30 GW of offshore wind along the Norwegian coastline [8]. Wind farms are not able to provide the same flexible operation as hydropower. Thereby, the need for coordination between wind- and hydro plants is an emerging topic. Technical solutions for wind farm control and hydro reservoir systems with or without pumping capability may contribute to increased flexibility and optimal operation of the power plants in grid-constrained areas. [2]

Several research projects and organisations have presented possibilities to utilize Norwegian hydropower as a large-scale battery to provide more flexible operation to wind and solar-dominated continental Europe [9]. This battery may serve as a balancing power entity, with the market coordinating the balancing exchanges between different market areas. However, when there is congestion within a price area, options for optimal coordination become a relevant topic. In order to optimize such operations, IEA [10] identifies the importance of coordinated operation with variable renewable energy sources such as wind and solar power.

Overall, utilizing hydropower coordination together with wind farm control may benefit various different aspects such as minimizing curtailments and flooding, grid utilization, power balancing, ancillary services and revenue for the power plants [2], [11] [12]. Another important aspect for the power producers is the damage accumulation to the wind turbines during operation, as this may lead to additional maintenance costs [13]. In order to increase the life span and reduce the maintenance costs on the turbine, control options to reduce the wear and tear on the turbines may be desired.

Previous studies investigating wind-hydro power coordination in congested areas [14], [15], [16], shows great benefits on grid utilization and wind energy curtailment from a coordinated effort utilizing the flexibility of the hydro reservoir.

## 1.2 Scope and Objectives

In this thesis, the aim is to investigate different actions to improve the operation of a congested hybrid system by implementing coordination and control of a wind farm and a hydropower plant using multi-objective optimization. To achieve this a co-simulation framework based on the work of Jamessen [17] and Stave [18] will be applied to a case study of a remote hydro plant and wind farm sharing a limited transmission capacity. The model investigates the different objectives of total revenue for the power plants and damage accumulation to the turbines of the wind farm. The second objective is analyzed by implementing wind farm control simulations using a damage-aware wind farm controller designed by Spyridon Chapaloglou.

Furthermore, this study examines the impact of enhancing system flexibility by implementing a PHS system in conjunction with an existing hydropower plant. Additionally, it seeks to investigate the effects of employing a variable speed pump on power plant operations and compare these effects with those resulting from using a fixed speed pump.

Overall, the study will review relevant topics regarding coordinated wind-hydro operations and explore measures to enhance the optimization of the model. This covers different technical solutions and the business aspects associated with hydropower plants and wind farms. By addressing these topics, the study aims to provide some answers to the following research questions throughout the study.

- What is the impact of VRES on the power grid operations and the power market?
- What are the different optimization techniques that can be applied to power system operation and coordination, and how can they be utilized in the context of multi-objective programming?
- How does a variable speed pump affect the operation and revenue of a hybrid wind farm and PHS system?
- How can wind farm control dynamics be integrated to achieve improvements for wind-hydro coordination?
- How can the objectives of wind farm control dynamics be identified and appropriately weighted in accordance with their relative significance to the decision makers?

### 1.2.1 New Contributions

The thesis builds on the work of Stave [18] and Jamessen [17]. This research has introduced several new contributions, with the primary contributions including:

- Literature survey conducted on emerging optimization techniques that may be applied to wind and hydro operation, in addition to multi-objective optimization in hybrid renewable energy systems.
- Further development of a co-simulation model for a hybrid wind-PHS system by considering multiple objectives of the total revenue and damage to the wind turbines.
- Comparative analysis of using a variable speed pump to the case of a fixed speed pump or no pump installed.
- Integration of wind farm control dynamics for improved wind-hydro coordination, using the accumulated turbine damage as an objective to control the power of the wind farm.

## 1.3 Thesis Overview

This section will serve to present the outline of the thesis, and provide elaboration and background for each chapter throughout the thesis. The master thesis builds on the project work [3]. If not explicitly identified in this section, the paragraphs taken from the project work are marked using this citation. It should be noted that there are generally made modifications of these part to fit the new scope of this thesis, including several expansions and revisions. Additionally, a submitted conference paper for SEST is attached to the thesis.

In this thesis, a literature survey on different relevant aspects is conducted. Thereby, some theory relevant for the problem description and case study are presented in the following chapters. The theory conducted in these chapter is overlapping the previous work performed in the project work [3]. However, some noteworthy additions are included in the master's thesis:

- Chapter 2 - Trends in the Norwegian Power Grid and Market

Section 2.4, is extended to include an analysis on the impact from hydro inflow variations on the power market.

- Chapter 3 - Wind Power

A new addition to this chapter is Section 3.3, which aims to describe relevant aspects regarding the dynamics of wind farm control and the accumulation of damage in wind turbines.

- Chapter 4 - Hydropower and Pump Storage

This chapter does not include any new additions, instead, it focuses on a thorough revision and update of the existing content.

- Chapter 5 - Materials on Optimization Techniques

Section 5.3.1 is included to properly introduce the theory of the Multi-Objective Framework (MOF). Furthermore, subsection 5.4.2 outlines the approach of fuzzy logic being incorporated into the applied framework for this study.

In chapter 2, an overview of the Norwegian power grid and market is presented, emphasizing the trends that may impact the environments of the operating power plants, including market mechanisms and the different regulations they are subject to. In chapter 3 and chapter 4, the technical and environmental aspects of respectively wind and hydropower operations are presented. Wind farm control dynamics are granted a significant part as it is included in the co-simulation framework. In addition, different flexibility options are explored for hydropower to enhance its flexible operation. Further, their application and potential use in Norway are presented to display the current and future situation in the power grid and market.

In order to obtain an appropriate model for the multi-objective problem some background on different optimization techniques and decision making is presented in chapter 5. This includes the methods of lexicographic optimization, Augmented Epsilon-Constraint (AUGMECON) and fuzzy logic, which is utilized in the MOLP. Further, a literature survey on different optimization techniques is performed in order to explore the different options to improve the model, especially considering efforts to reduce the computational efforts of simulations.

The description and presentation of the model and resulting simulations from the case study are presented in chapter 6 - chapter 9: Based on the background theory and materials on optimization techniques, the methodology of the co-simulation framework applied to the case study is presented in chapter 6. Providing an overview of the proposed methodology, as well as more detailed descriptions on the multi-objective optimization part and the wind farm control simulations. Additionally, the reference case applied to this study is presented. The results from the case study are displayed in chapter 7. This includes an analysis conducted from single-objective simulations utilizing a hydro pump. In addition to the multi-objective optimization case on operation and coordination of the wind farm and hydro plant. Chapter 8 discuss the relevant business aspects and modeling issues, as the results from the simulations are being analyzed. Finally, some concluding remarks and suggestions of further work that may extend the scope and improve the accuracy of the co-simulation framework and case study is put forward in chapter 9.

# Chapter 2

# Trends in the Norwegian Power Grid and Market

## 2.1 The Norwegian Power Grid

The Norwegian power grid is a state-controlled monopoly that is governed at three operational levels: the regional grid, the distribution grid, and the transmission grid. The system is regulated by the Norwegian Water Resources and Energy Directorate (NVE), which also grants licenses for the production and transmission of renewable energy. [19]

The transmission grid is operated by the Transmission System Operator (TSO) in Norway, "Statnett," whose task is to operate and maintain the transmission grid while also ensuring the balance between consumption and production in the power system. The transmission grid transfers power from where it is produced to areas where it is needed, connecting different parts of Norway and interconnecting to neighboring countries. To reduce transfer losses over large distances, the transmission grid mainly operates at voltages ranging from 300 to 420 kV. The network structure is meshed to ensure a reliable power supply even during faults and maintenance. Meanwhile, the regional and distribution grids, often just referred to as the distribution system, are operated by the Distribution System Operators (DSO)s. Areas of the distribution system are divided by several regional DSOs. The number of DSOs is decreasing as many are being merged in order to facilitate more efficient coordinated operations. The distribution grid supplies power to smaller end users, operating at voltages from 230V to 22 kV. While the regional grid operates within a voltage range of 33 to 132 kV, often serving as an intermediary between the transmission and distribution grids. In addition to maintaining its own connections for production and consumption. [20]

### 2.1.1 Evolution of the Infrastructure

Traditionally, the structure of the power grid has been mainly centralized and unidirectional, with large conventional power plants supplying areas of demand. This is demonstrated in the current distribution area (orange) shown in Figure 2.1. However, the distribution is becoming more decentralized, with smaller renewable energy sources contributing an increasing share of energy production and the implementation of the smart grid. Additionally, more prosumers are participating in the market, meaning that they may produce energy at one time and consume it at another, making the flow of power bipolar. This evolution is illustrated in the smart distribution section (green) in Figure 2.1.

## 2.2 Grid and Market Regulation

The Norwegian Ministry of Petroleum and Energy (OED) serves as the primary regulator to achieve coordinated and integrated energy policy [22]. In accordance with §2-3 of the Energy Act and §4 of the Natural Gas Act, OED authorized the Regulation Authority for Energy (RME) as a regulatory authority on November 1 of 2019 to carry out the functions as an independent regulatory authority [23]. The RME regulates the power grid companies, ensuring their compliance with rules that promote fair competition in the power

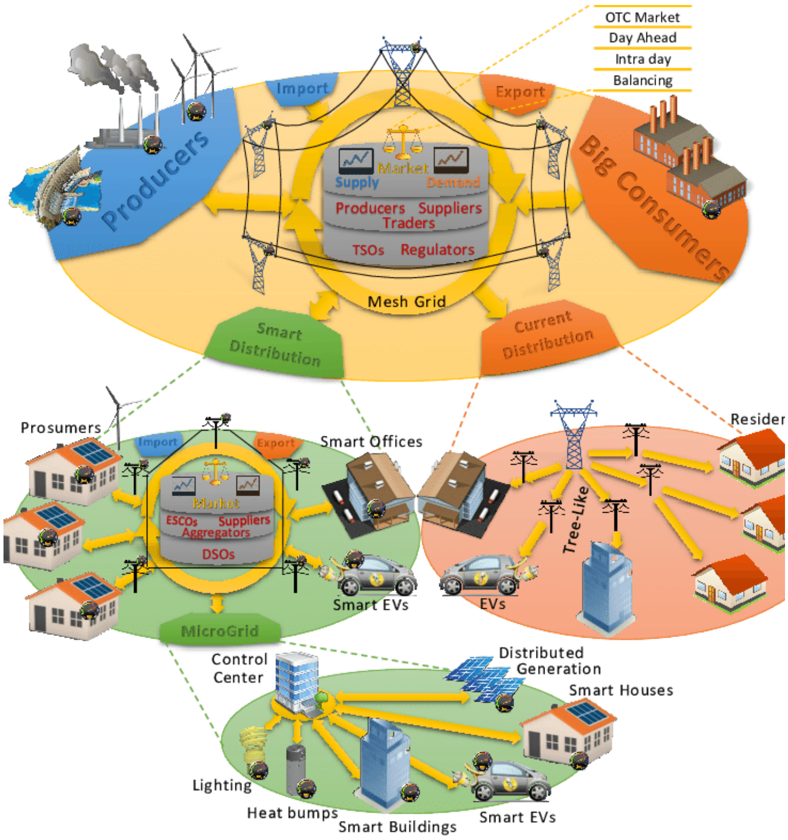



**Figure 2.1:** The current structure and the evolution of the power grid in a future scenario. [21]

market and the efficient operation of the power grid. One of RME's primary objectives is to ensure safe operations and maintain sufficient power quality. [23].

According to regulatory laws, all customers and producers must be provided with a grid connection by the TSO and/or the DSO of the concession area, provided that they pay a connection charge [19]. §3-4 of the energy act legislates this. However, exceptions may be granted by the OED if it is deemed not socially advisable to connect [24].

### 2.2.1 Legislation on Grid Regulation and the Energy Market

In Norway, regulations relating to the grid and the energy market have undergone changes in recent years to facilitate better utilization of the power grid. The establishment of Legislation on Grid Regulation and the Energy Market (NEM) in 2019 provided an alternative to the obligation of ensuring sufficient grid capacity to connect new power producers. This alternative allows for connection with terms that require the producer to reduce its power generation whenever transmission capacity is exceeded, resulting in an agreement between the producer and the grid company on terms for production limitation under §3-3. As a result, the TSO may require fewer grid investments, further leading to lower investment costs for the producer. [25]

In April 2021, the Ministry of Petroleum and Energy introduced some new regulations regarding the conditions for disconnection or reduction of consumption [26]. The changes made in §3-1 and §3-2 allow the TSO and DSO to make permanent agreements with the customer on connection to the power grid with terms of disconnection or reduction in the power supply. Previously, this type of arrangement was only permitted on a temporary basis. However, the TSO is still given the responsibility for approving the terms that are applied to ensure safe operation and efficient utilization of the power system [27].

## 2.3 The Norwegian power market

As previously mentioned, the transmission and distribution of power are monopolies and do not participate in the market. On the other hand, production and consumption are open to trading in the market. Norway is taking part in a common Nordic power market together with Sweden, Denmark, and Finland [28]. In addition to being integrated into the European market through interconnections to Great Britain, Germany, the Netherlands, the Baltic states, Poland and Russia [29]. In NVE's long-term analysis of the power market [30], the current exchange capacity out of the Nordics of 10 GW is expected to increase to around 14 GW by 2040. The current interconnection and the predicted interconnections to be installed by 2040 are presented in Figure 2.2.

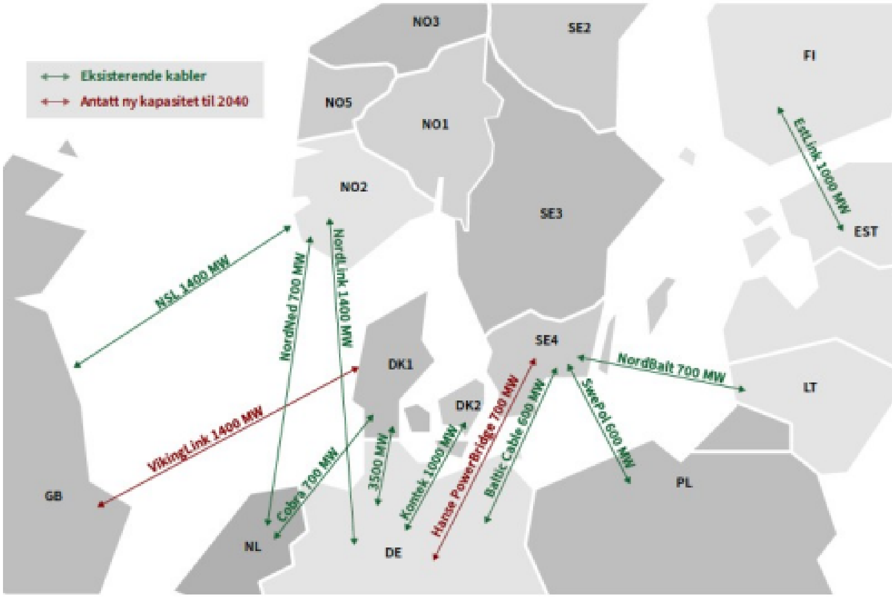



**Figure 2.2:** Existing interconnections out of the Nordics as of October 2021. The green arrows show the current interconnections, while the red arrows present the assumed new interconnections by 2040. [30]

### 2.3.1 Nordpool

In 1991 the Norwegian parliament decided to deregulate the electrical energy market, introducing marked-based power trading [31]. After being established in 1993, Nordpool became the first ever marketplace to cross national borders with the establishment of joint power exchanges between Norway and Sweden in 1996 [32]. Nordpool currently operates as the primary power trading platform in the Nordic region, with the additional capability of trading with a significant portion of Europe. The platform holds licenses from both NVE and OED [33].

The main objective of Nordpool as the market operator is to maintain an equilibrium between production and consumption at all times. In order to plan for a balanced schedule, a market clearing is carried out in the main market of Nordpool, the "day-ahead market", where bids and offers from all the participating consumers and producers are received. The market is cleared at 12 am the day ahead of the operation. At this time, a price is set for each hour throughout the day for each area. [34]

A theoretical system price is also presented in the day-ahead market, which calculates a price for the entire system, assuming there are no power flow limits between the areas. However, in practice, this may not be the case. When the transmission capacity between two areas becomes binding, this results in different prices for each area. The areas are cleared individually with the export/import set at maximum transmission capacity. In Figure 2.3, the five pricing areas of Norway are presented.

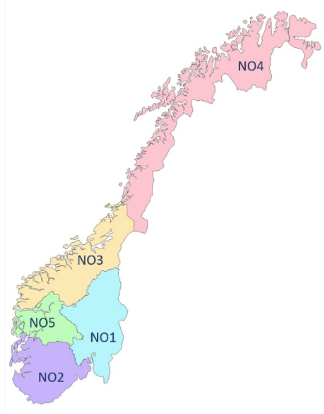



**Figure 2.3:** Division of price areas in Norway. [35]

When closing up to the scheduled time of operation, the situation of a producer or consumer may be changed, it may not be profitable for them to operate at this hour anymore or there may be an outage that makes them unable to fulfill their bid or offer. The intraday market then serves as a platform for them to trade closer to the time of physical delivery, which aids in ensuring the balance between supply and demand. Although this market currently is minor compared to the day-ahead market, its influence continues to grow as the share of VRES' in the market increases. [36]

### 2.3.2 Balancing Market and Ancillary Services

The intraday and day-head market contribute significantly to maintaining balanced operations. However, outages of transmission lines, power plants, and the unexpected demand of large consumers may cause an immediate imbalance in the system. The TSO is responsible for handling such events and restoring balance to the system.

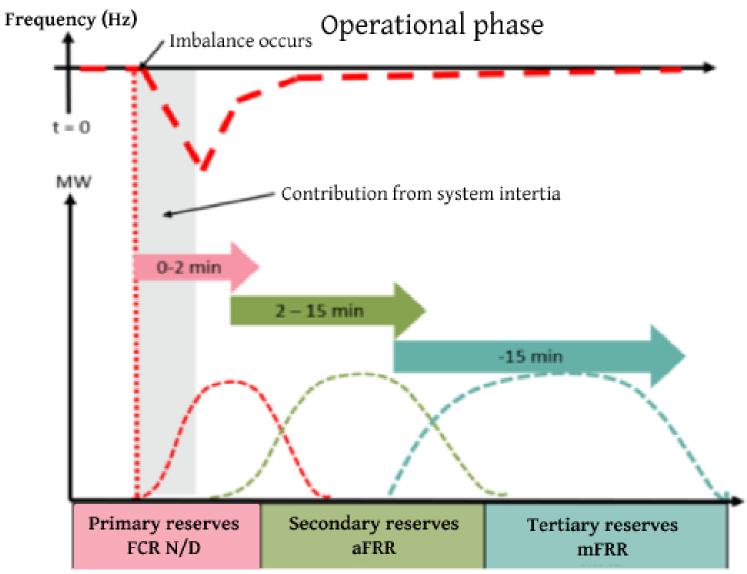



**Figure 2.4:** Step-by-step balancing response after an outage [37]. (Translated from Norwegian)

In Figure 2.4, the process of restoring balance to the system by the TSO, Statnett, is illustrated step by step. The inertia of the rotating mass in the system will initiate by converting kinetic energy to electrical energy. The physical response of the conventional generators is to increase the speed of the turbine and thereby the active power for a decrease in system frequency [38]. When the frequency changes, the primary reserves, the Frequency Containment Reserves (FCR), are automatically activated. These reserves are divided into two categories, reserves for off-nominal operation FCR-D and reserves for normal operation FCR-N, maintaining a stable frequency at each state [39].

In order to bring the system back into balance and release the primary reserve to be available for new faults that may occur. Secondary reserves, automatic Frequency Restoration Reserve (aFRR), are activated providing balancing power in the Nordic system. This is evenly distributed between the applicable producers. The control system is centrally controlled by the TSO [40]. In the event that an imbalance persists in the system, the tertiary reserves, known as manual Frequency Restoration Reserve (mFRR), are activated. This process is settled in the market, where the participating producers are proposing a price to change their production or consumption, and the cheapest bid is being prioritized given that there are no issues of congestion [41].

The green transition in the power market is resulting in increased integration of VRES' in the power system. However, VRESs like wind power are not able to provide inertia to the power system in the same way as synchronous machines, such as hydropower plants, do. Therefore, for areas with a large share of wind power and imported power, the grid frequency will drop fast in the cases of an outage, especially when the load and production level is low. Khodadi et al. [42] state that in a case of low inertia, the current reserve products available are not able to respond fast enough to avoid the frequency dropping below a critical operational level. To address this problem, the Nordic TSOs are establishing a market for providing Fast Frequency Reserves (FFR). The FFRs activate within a second when the frequency drops below a certain value in order to ensure a safe operation of the power system in cases of large outages. [43]

**Nordic Balancing Model**

The four TSOs of the Nordic countries are planning to automize the process of the balancing market with the introduction of a joint program, the NBM [44]. Automation of the mFRR is among the major targets of NBM introducing different automatized markets. The roadmap showcasing the schedule for the different targets is presented in Figure 2.5. The objective of the model is to prepare for the future challenges of the Nordic system from more exchange with continental Europe and a higher share of VRES by moving towards a more harmonized European electricity market [45].

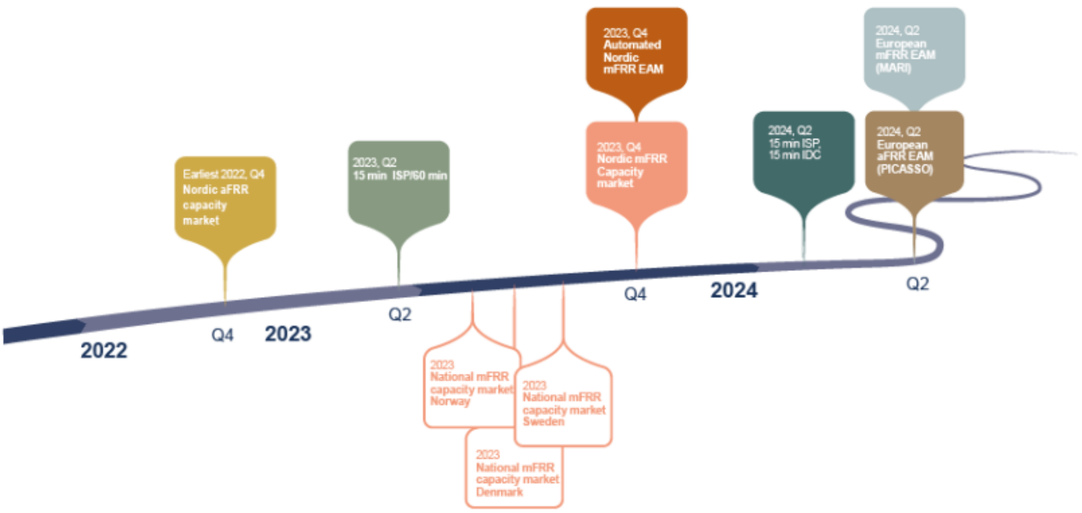



**Figure 2.5:** Roadmap of NBM. [46]

### 2.3.3 Power Purchase Agreements

The integration of VRES in the power system has led to a more unpredictable power market with varying power prices, which is expected to continue in the years to come [30]. Therefore, the prediction of power prices is a challenging task that involves a high level of uncertainty. Moreover, power producers face security demands regarding return on investment from investors and banks. As wind and solar power production experience a decrease in Levelized Cost of Energy (LCOE) and subsidies, ensuring a steady income for financial stability and liquidity becomes increasingly crucial for these producers. [47]

In light of this, Power Purchase Agreements (PPA) serve as an attractive option for handling the long-term risks of both producers and consumers. A PPA is a direct bilateral contract between a producer and consumer, where specifications typically are settled in terms of price, duration, energy attribute certificate ownership, and balancing responsibility towards the TSO. The agreement may be either physical, where the parties are directly connected or the volume is covered through the power grid, or strictly financial, where the parties buy and sell power on the market and settle the difference between the agreed-upon price and market price. [47]

Additionally, agreements must be made on the profile of volume delivered. Wind and solar plants may choose to deliver power "as produced" to reduce the risk of curtailment. Another option is to deliver a baseload. To align actual production and consumption, some options for flexibility becomes necessary. One option is to resolve the deviation through market settlement, where the use of an Utility Power Purchase Agreements (UPPA) may be involved. A UPPA with flexible generation and storage capability, for example, a hydropower plant, may function as a third party for VRESs such as wind power plants. By including the UPPA, the production is shaped into base loads, as often desired by the consumer. Large consumers often require a reliable and predictable power supply for their operations, which cannot be ensured by VRES alone. However, by integrating an UPPA a more stable and predictable power supply may be achieved. [47]

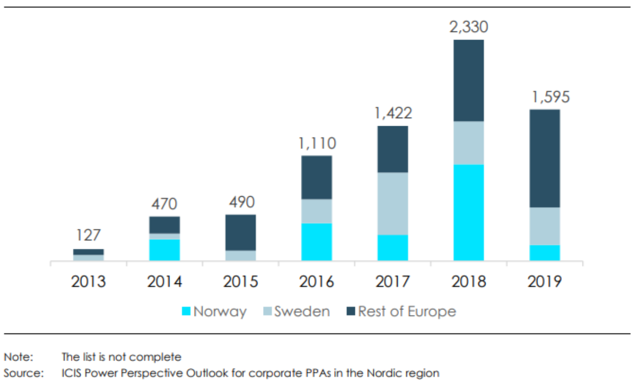



**Figure 2.6:** Signed PPAs in the Nordics and Europe. Presenting the total capacity in MW of the PPAs signed. [47]

In recent years, there has been a notable increase in the number of new PPA. As depicted in Figure 2.6, Europe experienced substantial capacity growth associated with PPAs in the period from 2013 to 2019. According to Statkraft [48], this number is expected to increase in the future. On the producer side, wind farms, solar and small hydro plants are the dominant providers of PPAs due to their weather-dependent nature, resulting in uncertain production volumes and selling prices. While on the consumer side power heavy industries dominate, with data centers becoming a new major participant in recent years. The power consumption cost constitutes a significant part of their operational cost, making the power price essential for their profitability. In conclusion, it is clear that there are economic incentives for both producers and consumers to make a bilateral agreement to help establish a more predictable future situation.[47]

## 2.4 Impact of VRES on the Power Market

As previously mentioned, the integration of VRES into the power system poses challenges regarding grid stability, and also increases uncertainties regarding power prices and available power in the power market. As a result, an increasing significance of balancing and intra-day markets is expected in the future.

The stochastic nature of VRES, such as hydro inflow and ambient wind conditions, leads to variations in the amount of power that the power producers are able to supply [30]. Large offshore wind farms, which are becoming increasingly prevalent, can experience significant variations in their production, as demonstrated in simulations from SINTEF [49] in Figure 2.7, where the mean value and deviation of the wind farms capacity factor throughout the year is presented.

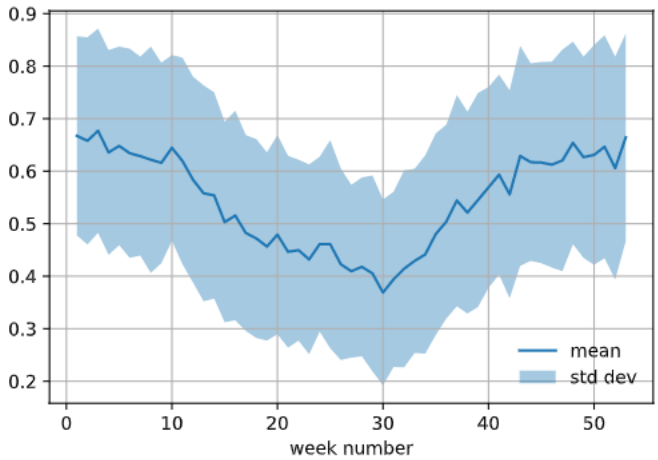



**Figure 2.7:** Simulation from SINTEF on power production from 15 potential offshore wind farms in Norway throughout the year [49]. The locations of the offshore wind farms can be found in Figure 3.6

Additionally, substantial variations in the yearly hydro inflow to hydro reservoirs may occur. Data from NVE [50] shows this, with historical variations up to approximately 50 TWh presented in Figure 2.8. Furthermore, the inflow varies throughout the year, as presented in Figure 2.9. Most of the inflow is observed to occur during the spring and summer as snow melts, whereas power production reaches its peak during the high-demand winter months. This highlights the importance of large-scale storage options.

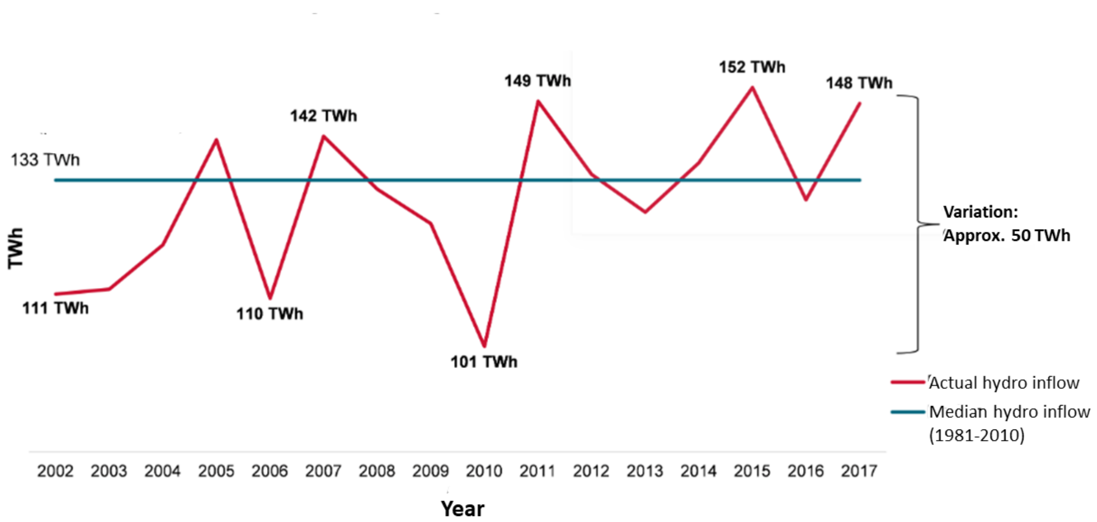



**Figure 2.8:** Hydro inflow variations in the Norwegian hydropower system. [50] (Translated from Norwegian)

These uncertainties have contributed to the significant fluctuations in power prices in recent years. According to NVE [30], these fluctuations are expected to continue in future scenarios, as shown in Figure 2.10. The prognosis for 2040 shows that the price differences will vary more both on a short-time basis and a seasonal basis. [30]

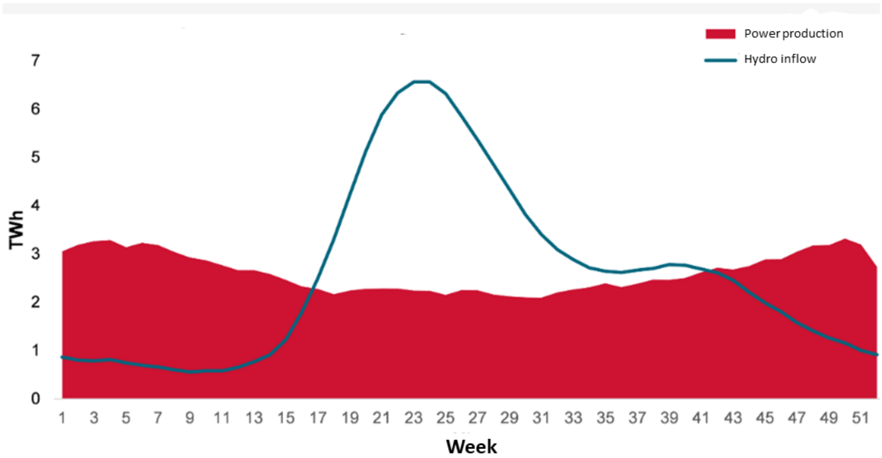



**Figure 2.9:** Power production and hydro inflow per week in Norway. [50] (translated from Norwegian)

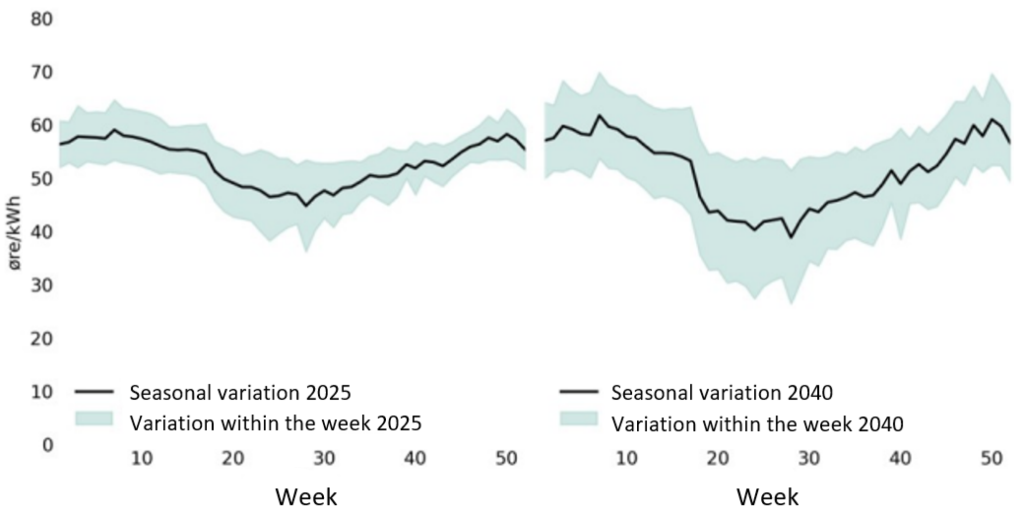



**Figure 2.10:** Price variations throughout the year. Comparing the power price prognosis for 2025 with 2040. [30] (translated from Norwegian)

# Chapter 3

# Wind Power

According to the IEA, wind power was the fastest growing energy source in 2021, with an increase in capacity of 17 % and a total generation of 1870 TWh, solidifying its position as the second largest renewable energy source behind hydropower. The increase in installed wind capacity is still dominated by plants located onshore, with 93 % coming from onshore wind farms. However, it is anticipated that the proportion of offshore wind energy will rise due to the ongoing establishment of numerous substantial offshore installations. Particularly given the technological advancements being made in floating wind solutions. [51]

## 3.1 State of the Art Wind Power Generation

Wind turbines generate power by extracting kinetic power from the wind passing through its rotor blades, converting it into electrical energy. The power extracted by the turbine is given by

$$P_{turbine} = \frac{1}{2}\rho A v^3 c_p \tag{3.1}$$

where $\rho$ is the air density, $A$ the cross area of the rotating rotor blades, $v$ the wind velocity and $c_p$ the power coefficient of the turbine. [**p.284**, 52]

The power coefficient has a theoretical limit of 59,3% due to geometry limits. This is known as the Betz limit, declaring the maximum kinetic energy possible to extract from the passing wind. In practice, the power coefficient of a commercial wind turbine is lower, as the rotor's aerodynamic performance will not be optimal and is dependent on attributes such as tip speed ratio and turbulence in the wind. Furthermore, energy losses will occur in the gearbox and other components. [**p.284**, 52]

## 3.2 Design of Wind Turbines

A typical simplified vertical wind turbine design configuration is presented in Figure 3.1. As the wind flows through the rotor, the aerodynamics of the rotor blades provide a lift that makes the rotor blades rotate, generating a torque on the turbine shaft. The power from the turbine is delivered at low speed and high torque due to the large dimensions of the rotor. As the generator ideally operates at high speed and low torque, the speed needs to be stepped up. This is the objective of the gearbox, stepping up the speed from the turbine shaft to the generator shaft. [**p.283**, 52]

The mechanical energy is converted into electrical energy using a generator. The generator may either be synchronous or asynchronous. A synchronous generator is directly coupled with the stiff grid, causing it to run at a constant speed. Thereby, turbulence coming from the varying wind on the turbine side is causing major mechanical stress on the gearbox, affecting the reliability of the turbine. On the other hand, an asynchronous generator operates with a slip, resulting in a difference between the synchronous speed and the rotor speed. If the torque applied by the turbine is abruptly changed, this will cause the speed of the generator also to change. This makes the mechanical stress on the gearbox less than for the synchronous generator, often making an asynchronous generator the most attractive option. The power generated is then finally stepped up by the transformer to a high voltage and thereby a low current in order to reduce transmission losses. [**p.287-291**, 52]

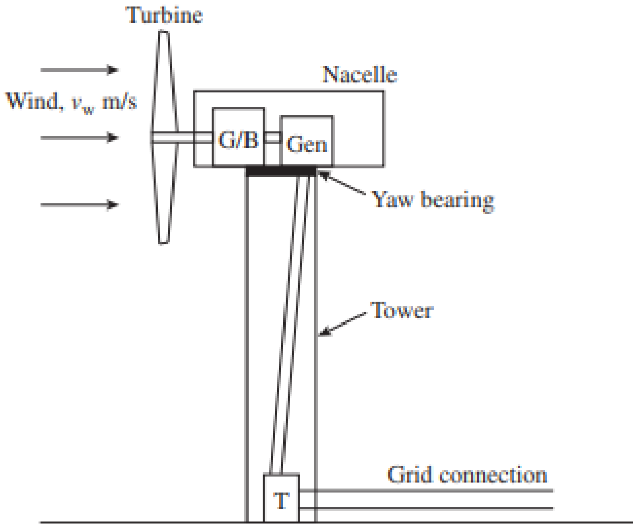



**Figure 3.1:** Typical wind turbine design. G/B is the abbreviation of the gearbox, Gen is short for generator and T represents the transformer connecting the grid. [**p.284**, 52]

## 3.3 Wind Farm Control

In order to maximize captured energy and ensure safe operation of the wind turbine, a control strategy is required. The various and unpredictable nature of wind power causes challenges regarding the planning and operation of the power system. There are various strategies for controlling wind turbines, each having its individual advantages and drawbacks.

Typical attributes that may be controlled in the turbine are the pitch angle of the blade, the yaw angle aligning the rotor with the wind, and the tip-speed ratio influencing the generator torque [53]. Reliable input data from sensors is essential to obtain optimal and stable control functions. Supervisory Control and Data Acquisition (SCADA) systems are developed for this purpose. The SCADA system measures electrical attributes such as voltages and frequency. The control attributes mentioned are also monitored by the SCADA system, in addition to external meteorological measurements of the wind, temperature, etc. [53], [**p.709**, 52]

There are different approaches to control the wind farm depending on the objectives, control structure, and adaptation of control concepts of the control system. The objectives considered by the wind farm controller may be maximizing the power production, safe operation considering mechanical loads and fatigue, and the ability to endure faults locally or externally in the power grid. In addition to requirements of upholding grid codes and providing ancillary services. The structure of the control system is highly complicated. Different concepts are developed depending on the main objective of interest. They are typically classified into categories of optimization-based, model-free, conventional feedback control, and model-based which may be either open-loop or closed-loop. In Figure 3.2, Andersson et al. [53] present an illustration of the structure of a closed-loop model-based wind farm controller. [53]

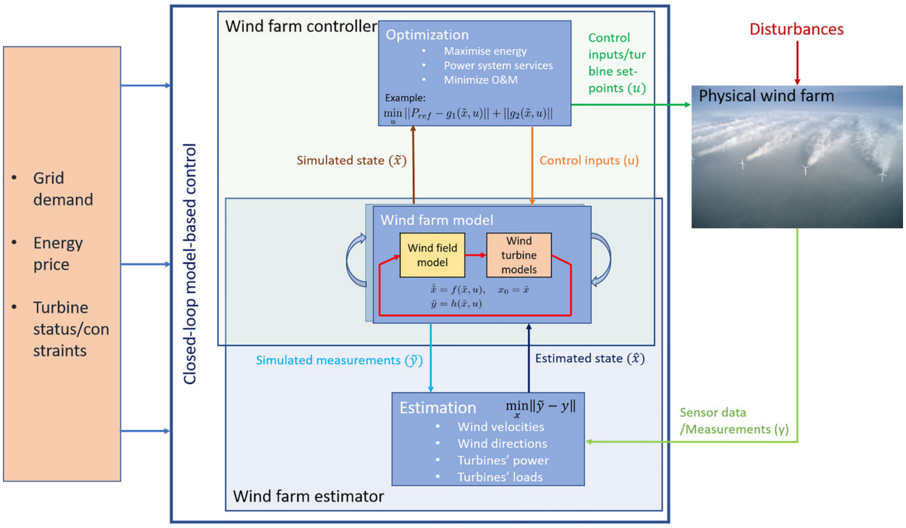



**Figure 3.2:** Structure of model-based closed-loop wind farm controller. [53]

### 3.3.1 Wind Turbine Wake Effects

The common practice in the industry has been to optimize each turbine individually, ignoring the interaction between the turbines. Within wind farms, upstream turbines extract energy from the wind, subsequently leading to a decrease in wind velocity and an increase in turbulence for the downstream turbines. As a consequence, the downstream turbines experience a reduction in their wind power production. This phenomenon is commonly referred to as wake losses. In recent research, wake losses are being considered in new control systems that aim to boost the wind farm's overall energy output and/or lessen the fatigue strain on individual turbines. [54]. Two common approaches in the literature are Axial Induction Control (AIC) and Wake Steering Control (WSC) (also referred to as Wake Redirection Control). [53]

AIC is an approach that adjusts the rotor's rotational speed in wind turbines to optimize its performance. It involves modulating the axial induction factor, which represents the ratio of effective wind speed to actual wind speed seen by the rotor. By increasing the axial induction factor, more energy can be extracted from the wind, but this also leads to increased aerodynamic loads, turbine fatigue and wake losses. The control is directly related to the power setpoint, which is the desired power output of the wind farm. The control system continuously monitors the turbine's actual power output and adjusts the axial induction factor to match the setpoint. This modulation of axial induction allows for a balance between energy capture and turbine load, ensuring efficient operation while meeting power output requirements. [53], [55]

The AIC strategy is designed to minimize wake losses by allowing de-rating of the upstream turbines, meaning that they may deviate from the individual optimal point of axial induction through adjustments in blade pitch angle and generator torque. Consequently, the power output of upstream turbines is decreased, leading to a reduction in wake losses. However, this reduction in wake losses has the potential to enhance the power production of downstream turbines. An illustration of this effect is presented in Figure 3.3, where the de-rating cause a lower wind speed profile for the downstream turbines. Furthermore, this approach may also reduce the overall mechanical stress on the turbines, thereby improving their long-term durability and performance. [56], [57]

The investigation of the AIC technique performed by Boersma et al. [54] and Andersson et al. [58] questions its impact on the total power output. These studies highlight various factors that contribute to uncertainties in assessing the efficiency of applying AIC, such as wind direction variability and the accuracy of aerodynamic models. The potential reduction in mechanical loads is also recognized as a significant area of interest. Boersma et al. [54] suggest that modifications to the structural design of the turbine could serve as a potential solution.

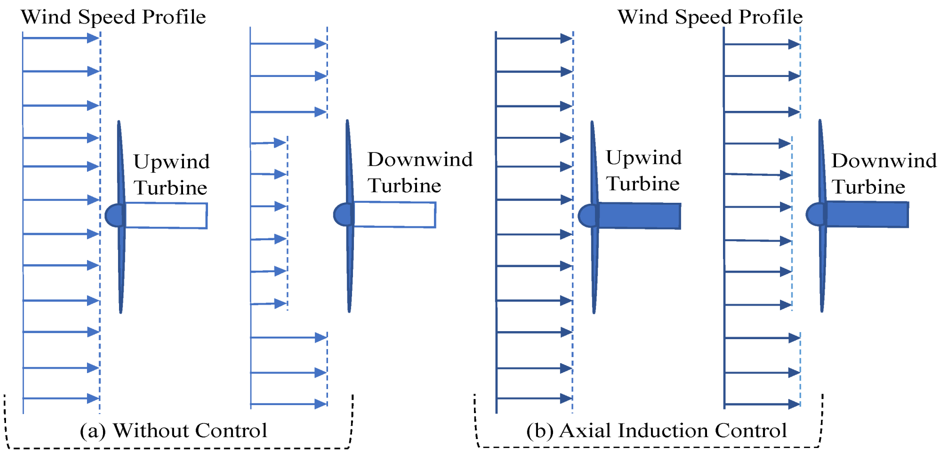



**Figure 3.3:** Schematic representation of AIC strategy. [57]

Alternatively, the WSC approach aims to steer the wake away from the downstream turbines. Boersma et al. [54] and Hoek et al. [56] discuss several methods to achieve this objective. Yaw misalignment, involving the horizontal rotation of the turbine to redirect the trailing wake, is identified as one technique [59]. An illustration of this strategy is given in Figure 3.4, where the yaw offset causes redirection of the wake, further resulting in a higher wind speed for a portion of the downstream turbine [57]. Other methods suggested for wake redirection include rotor tilting, individual pitch control, and repositioning of wind turbines. However, a notable concern associated with this approach is the potential increase in dynamic loads experienced by specific turbine components. Such increased loads may consequently reduce the lifespan of the wind turbines [58].

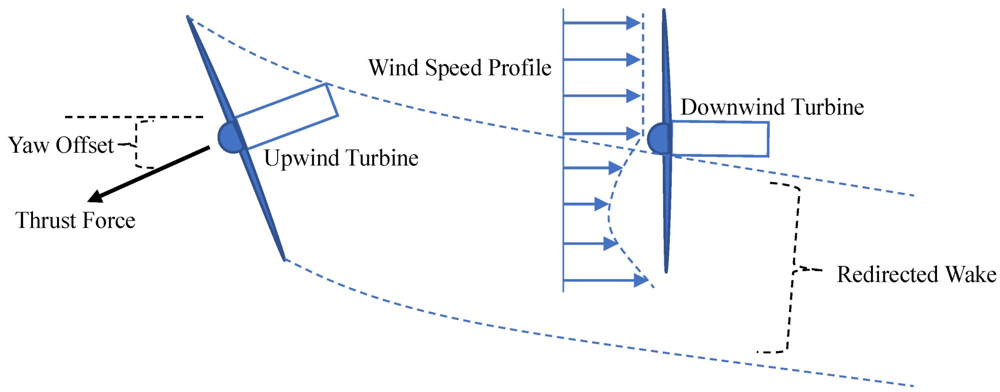



**Figure 3.4:** Schematic representation of a typical WSC strategy, using yaw misalignment. [57]

Several studies report some promising results from their investigation on WSC [60], [58], [54]. However, as with the AIC, the feasibility of the method is being questioned. Andersson et al. [58] underlines the need for longtime studies to investigate the consequences of fatigue on the turbine. Additionally, Boersma et al. [54] state the need for more testing of the method in the field. One approach mentioned by Boersma et al. [54] that may have great potential is to combine the two methods of AIC and WSC. However, there hasn't been much in-depth practical research on the topic.

### 3.3.2 Wind Turbine Damage and Control

Wind turbines are exposed to harsh environmental conditions and a wide range of wind conditions. During the wind turbine certification stage, the manufacturer is required to prove their design is capable to sustain these conditions for the wind turbine's 20-year life expectancy. The IEC 61400 standard [61] specifies the essential design requirements to ensure the structural integrity of wind turbines, including all the subsystems such as control and protection functions, internal electrical systems, mechanical systems and support structures. The Design Load Cases (DLC) can be used to assess the response of the turbine to fatigue and extreme load cases. Even though there has been a thorough review of the turbine's performance, it is not always the case that the asset won't suffer any damage. The combination of harsh conditions, and highly dynamic loading, has a negative effect on the turbine and damage-induced failure is an option that operators consider under their operations and maintenance (O&M) strategy. [62]

Wind turbine damage comes in many forms. Some components are more prone to failure, e.g. power converters, but they are relatively simple to replace. In contrast, more complex sub-systems and components fail less often but are more complicated to replace, which leads to downtime and ultimately incurs higher replacement costs overall. The main bearing, gearbox and pitch bearing systems are prime examples of this. The reliability of these components can be driven either by fatigue [13] (mostly due to turbulence and the varying operation) or extreme loads [63] (sporadic events such as emergency brakes and low-voltage ride-through). [62]

Mehlan et al. [64] identify the geared drive-train of the wind turbine as a major contributor to Operational and Maintenance Expenditures (OPEX), as its victim of frequent failures and long downtimes. The drive-train is composed of the gearbox and the generator, which converts the torque of the blades into electrical power. The AIC approach can benefit the drive-train damage accumulated in each turbine. When a single turbine is de-rated, this means that the wind speed deficit behind the turbine will change, such flow coupling will affect the drive-train damage accumulated in each turbine due to different thrust levels, meaning that some turbines may be damaged at higher rates than others, leading to uneven degradation. Overall, several parts and components can be affected, with drive-train components being some of the most important. [65], [62]

The accumulation of damage primarily escalates with rising wind speed and heightened turbulence caused by fluctuations. The wake generated by upstream turbines contributes to reduced wind velocity and a higher turbulence intensity experienced by the downstream turbines. As a consequence, the accumulation of damage can significantly vary from one turbine to another, depending on its location. In situations where active power control is absent, the wake-induced turbulence is often dominated by the deficit in wake velocity, resulting in higher damage for upstream turbines compared to downstream turbines. [55]

## 3.4 Offshore Wind Power

Wind conditions offshore have the benefit of low turbulence due to relatively low surface roughness and vertical temperature gradients from the sun heating the surface. In addition, this causes minimal wind shear, meaning less rapid changes in wind velocity and direction. [**p.405**, 66]

The design of the wind turbines has some additional concerns regarding availability during the need for maintenance, repair, and construction of foundation and cable connections. Thereby low requirements of maintenance and reliability of the turbine are essential. However, certain concerns highlighted in section 3.6 concerning environmental factors like noise, visual impact, and area consumption are less critical for offshore wind farms. [**p.406**, 66]

From the TSOs perspective, the operational reliability of the power system is crucial when connecting new offshore power plants. In this process, it is necessary to consider the correlation between the onshore and offshore grids while analyzing the market and grid capacities. The OED has indicated that Statnett will assume a formalized role as a system manager at sea to efficiently ensure operational safety in the overall power system. [67]

In a public hearing to the OED, Statnett emphasizes the significance of coherence between the onshore and offshore grid[68]. Statnett highlights the need for capacity upgrades in certain areas of the onshore grid to accommodate the substantial supply from offshore plants. Moreover, they argue that employing a hybrid interconnecting link to connect the offshore wind farms with other countries would yield greater socio-economic benefits, as the wind farm able to take part in different markets. Additionally, the surplus capacity of the inter-connector may be used for the exchange of power, during periods of low wind farm production. [68]

However, the government have expressed concerns about the recent impact that inter-connections have made on the power prices in Norway. In a statement by the government regarding offshore wind in February 2022 [69], they express that they do not want to facilitate any more hybrid interconnections. By increasing the export capacity, Norway would become more reliant on the situation in continental Europe. This dependence has the potential to keep power prices high for consumers and even lead to further increases. [69]

## 3.5 Wind Power in Norway

According to NVE [7], by August 2022, Norway's total installed capacity of wind power stands at 5069 MW. This power is generated by 64 different power plants, comprising a total of 1386 turbines.

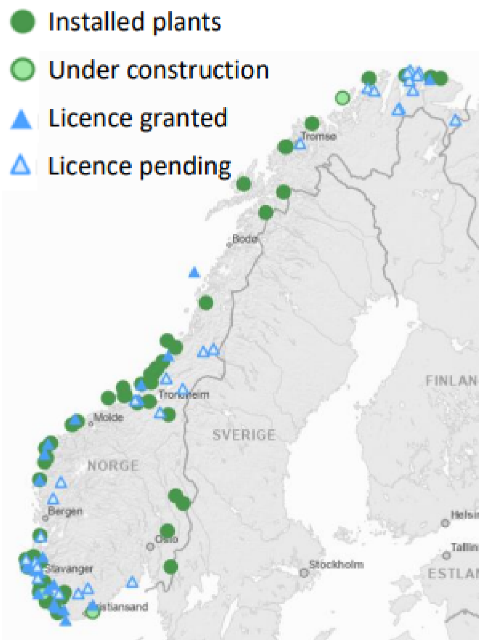



**Figure 3.5:** Map of wind power plants in Norway from NVE. [70]

The location of the power plants is presented in Figure 3.5. Showing the location of the current wind power plants installed, under construction, given concession, and pending a license. As observed from the map, many of the power plants are located in southwestern parts of Norway and mid-Norway. It can also be noted that there are many projects currently applying for a license in the northern part of Norway.

Statnett states that there is more room for developing new wind farms in Southern Norway compared to mid- and Northern Norway [71]. When considering the current state of power prices and grid capacity, southern Norway appears to be the most economically beneficial location. As stated by NVE [72], offshore wind conditions in Norway are highly favorable. However, the deep sea depth along the Norwegian coast presents a challenge for the installation of standing wind turbines, leading to increased construction expenses.

In order to construct any renewable production facilities at sea, such as offshore wind power, the Offshore Energy Act states that the OED has to open the geographical area for license application before construction. In 2013 NVE presented a Strategic Environmental Assessment (SEA), forming a basis for the decision of areas to open for license application. In the assessment, 15 different locations are considered, with different sizes and capacities depending on their conditions. The suggested areas are presented in Figure 3.6. The assessment considers environmental impacts, as well as their influence on business and public interests. [8]


**Figure 3.6:** Suitable locations identified by NVE for offshore wind in Norway. Note! Numbers 15, 16 and 17 belong to respectively Great Britain, Denmark, and Germany. [49]

According to the SEA, the locations: "Utsira Nord", "Sørlige Nordjø I ", "Sørlige Nordsjø II" and "Sandskallen - Sørøya Nord" make up the most promising cases. Stating: "*Wind power development within the zone is technically and economically feasible and will have relatively few negative impacts. Grid connection is possible before 2025*"[**p.8**, 8]. In June 2020, the areas "Sørlige nordjø II and "Utsira nordsjø" were opened for license application by the government, with the first phase scheduled to be open for bids in the first quarter of 2023 [73].

## 3.6 Environmental Impact of Wind Power

According to Manwell et al. [66], there are several environmental impacts to consider when planning a wind farm. These impacts include the potential for birds to collide with or be electrocuted by wind turbines, as well as the potential disruption of bird habitats. In order to minimize these impacts, various mitigation measures can be taken, such as avoiding habitats and fly zones that are highly populated by birds, increasing the size of turbines to reduce their number, and modifying tower design. However, it is important to note that these measures can cause implications for the power efficiency and cost of the wind farm. As the wind turbines are placed in well-exposed locations to obtain high production, the visual impact is naturally high. Other considerations, such as noise, electromagnetic interference, and land consumption, may also need to be taken into account when planning a wind farm. [**p.467-509**, 66]

# Chapter 4

# Hydropower and Pump Storage

By 2021, hydropower will continue to be the largest RES, producing more than all other RES put together. This is despite the fact that 2021 saw a minor decline in production as a result of the several draughts that hit nations with high-capacity hydropower around the world. IEA identifies hydropower plants as the most suited renewable energy source to provide the power system with much needed emissions-free flexibility. Hydropower stands out in the transition towards more RES due to its flexible operation utilizing its reservoir and providing inertia to the power system. However, the VRES' wind and solar power have received the majority of attention in recent renewable energy policies. According to the IEA, governments should evaluate the economic benefits of hydropower in order to attain better financial incentives for investments in new hydropower plants. Additionally, it will increase the appeal of investments in turbines, generators, digitalization, operational patterns, and modernization of existing plants. This may improve the plant's performance and flexibility, as well as provide social benefits like drought management and flood control. [6]

## 4.1 State of the Art Hydropower Design

Hydropower plants utilize the potential and kinetic energy of water flowing in rivers. The potential energy of the water is given by

$$E_{pot} = mgh \tag{4.1}$$

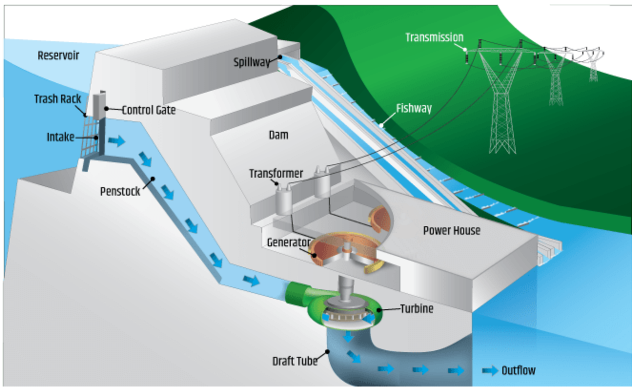
where $m$ is the mass of the water, $g$ the gravitational acceleration and $h$ the head of the penstock. [74]

As water flows downstream, the potential energy is converted into kinetic energy. The hydropower plant utilizes a rotating turbine being run by the downstream water. The turbine's mechanical energy is then converted into electrical energy using a generator. The power generated by the plant is then given by

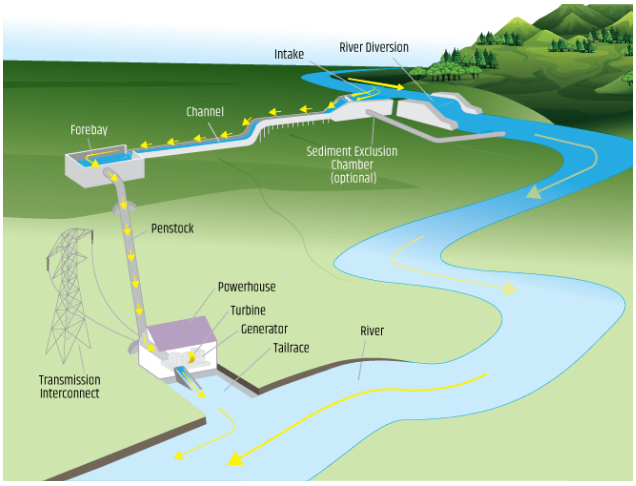
$$P_{gen} = \rho \cdot Q \cdot g \cdot h \cdot \eta \tag{4.2}$$

where $\rho$ is the density of water, $Q$ is the volume flow rate of water, and $\eta$ represents the efficiency of the power plant considering friction and turbulence losses in the pipe and turbine, as well as generator losses. [74]

According to Breeze et al.[75], the most common turbine types in modern hydropower plants are Francis turbines, Pelton turbines, propeller turbines, Kaplan turbines, and Deriaz turbines. The turbines may be differentiated based on the direction of the water flow. Where propeller and Kaplan turbines are axial flow turbines, having water flowing parallel to the rotor blades' axis. As opposed to radial flow turbines such as Pelton turbines with water flowing perpendicularly. Francis turbine is a mixed flow turbine, where the water leaving the turbine has a different direction from its entrance. The final type is named crossflow turbine, as the water flows across or diagonally to the rotor blades, whereas the Deriaz turbine was the first of its kind. The hydraulic turbines are also differentiated based on their impact on water pressure: Reaction turbines convert water pressure into mechanical energy, while impulse turbines utilize the high velocity of the water, where the pressure remains the same. Impulse turbines are most suitable for high-head locations with a low flow rate [76]. Francis turbine combines both impulse and reaction actions, making it often the preferred turbine as it is able to operate well at a wide range of head and mass flow rates. [77]




**(a)** Impoundment facility using a reservoir to store and control the river water. [78]




**(b)** A run-of-river facility. [78]

**Figure 4.1:** Typical design of hydropower plants

Hydro plants are differentiated between two main types of hydropower facilities. The typical design of these is presented in Figure 4.1. Run-of-the-river (RoR) facilities use the riverbed's naturally declining elevation to generate energy. A portion of the water flowing is directed into the penstock using physical barriers. The penstock channels the water to the turbine, where valves and gates regulate the water flow. The turbine utilizes the water flow to generate a torque before releasing it into the river. RoRs are often smaller hydro plants with a "low-head" of the penstock. Thereby, they mainly utilize a reaction turbine. According to Venus et al. [79], approximately 15 % of the hydropower capacity in Europe comes from RoR. As the majority of possible locations of large-scale hydro plants are already utilized, RoRs may take an even greater part in the future. Additionally, these smaller plants are subject to more relaxed environmental requirements, further being more likely to benefit from subsidies. [79]

As with wind and solar energy, RoR plants rely on weather conditions for production. The river's flow rate varies and may be unpredictable throughout the year, causing uncertainties in its operation. Furthermore, causing problems for the system operator regarding the provision of stability. Hydro storage systems have a significant advantage in this regard as they are able to use dams to store water from streams and rivers in storage reservoirs, which they may discharge whenever power is needed at the desired rate. It gives the flexibility to optimize their production regarding the plant's income and the provision of stability services to the power grid.

### 4.1.1 Hydro Power Control

As opposed to wind farms, hydro plants mainly utilize a synchronous generator and are directly connected to the grid [**p. 16**, 52]. Making the interaction between the plant and the grid significant. Thereby, the rotating masses of the synchronous generator provide inertia to the power system, which delays the immediate frequency change as a disturbance occurs and reduces the magnitude of the oscillations. The European Network of Transmission System Operators for Electricity (ENTSO-E) has conducted tests in the Continental European Synchronous Area (CESA) to determine exemplary inertia parameters for different energy production technologies [**p.746**, 52]. In this study, the inertia constant of PHS is second only to nuclear power, which states the relation of kinetic energy stored to the generator's rating. RoR and hydropower storage facilities also contribute with significant inertia, while wind farms onshore and offshore do not contribute as they are decoupled with the grid. [**p.742-746**, 52]

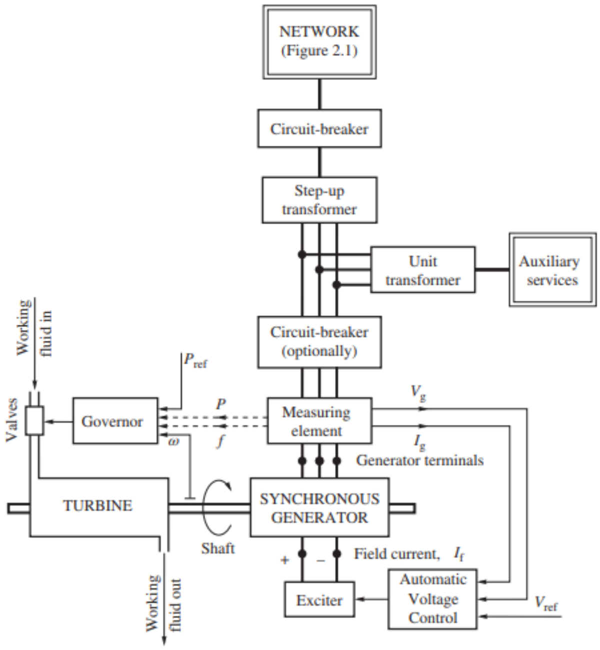



**Figure 4.2:** Block diagram representation of the control of a power generation unit, such as hydropower. [**p.18**, 52]

The hydro plant is supported by several controllers and supporting mechanisms providing voltage and frequency support, as well as ensuring safe operation and providing protection during faults. The main action of frequency support comes from the turbine governor. This, in line with a preset power-frequency characteristic, regulates either the turbine's speed or output power [**p.17**, 52]. There are several overall control functions required of a practical turbine governor. Machowski et al. divide these into *run-up control*, *load/frequency control*, *overspeed control*, and *emergency overspeed trip* [**p.33**, 52].

The generator's excitation is controlled by an Automatic Voltage Regulator (AVR). By controlling the field current, the generator terminal voltage is kept constant at the desired rating by the AVR as the electrical load seen by the generator changes. [**p.22**, 52]

A supplementary control loop referred to as a Power System Stabilizer (PSS) may be utilized to improve the power system's dynamic performance. A design of a PSS controller may be applied to both the generator AVR and the turbine governor. Including an AVR without supplementary control loops can reduce the damping provided by the damper and field windings in the generator [**p.410**, 52]. By including a PSS that provides an additional voltage signal to the excitation system during transient states, positive damping is provided to the generator. This damping component is in phase with the rotor speed deviation and compensates for the voltage oscillations. However, this does not necessarily improve the damping of the interacting generators in the system. Thereby, coordination between the generators is required to obtain an optimal global solution for the system operator. This is less of an issue for a PSS signal in the turbine governing system since the turbine governor dynamics are weakly coupled with the dynamics of the rest of the system. When applying PSS to the turbine governor, a positive damping is provided by applying changes of mechanical power in phase with the rotor speed deviation. [**p.410-416**, 52]

The use of an open loop fast control of the main or/and interception of the valves often referred to as fast valving, is another method of controlling the turbine. During a large disturbance, the fast valving method limits the accelerating torque of the generator rotor that occurs due to the sudden drop in the electrical power output. This is done by intercepting the valve, thereby rapidly reducing the mechanical input power. As large disturbances cause a sudden drop in the electrical power output of the generator, further causing the rotor to accelerate, the fast valving rapidly reduces the mechanical input power, thereby also limiting the acceleration torque. However, fast valving is not a feasible approach for hydro turbines as it requires changes within tenths of seconds in order to maintain synchronism with the power grid. In terms of mechanics, hydro plant control gates require a substantial torque and pressure change to move. [**p.415-417**, 52]

In light of this, other technologies to prevent loss of synchronism are utilized in hydro plants. Machowski et al. identifies breaking resistors and generator tripping, among others, as technologies often applied in hydropower plants. Breaking resistors may be connected at the terminals of the generator or substation, providing electrical breaking to reduce the acceleration of the rotor. In the case of several generators being connected to a common busbar, generator tripping of one or more of the generators serves as an option to maintain the stability of the other generators connected to the same busbar. [**p.419-423**, 52]

## 4.2 Emerging Technologies

Kougias et al.[80] mention several emerging technologies in the hydropower sector that aims to increase the efficiency and flexibility of the hydro plant, as well as reduce mechanical stress and environmental impact. Among these are technologies to mitigate flow instabilities. The implementation of VRESs necessitates flexible and wide-range operation of hydraulic turbines, which may result in operation outside their optimal efficiency point, leading to a loss of potential energy. Furthermore, this may cause pressure fluctuations that apply severe stress to mechanical components. Different control techniques may be applied in order to support flexible operation. Kougias et al. identify several passive and active control approaches, as well as the emerging Mangeto-rheological control method. [80]

Digitalization can provide better response time and enhance operational flexibility, ensuring stable and reliable operation in the power grid. Moreover, digitalization can aid in increasing the lifetime and efficiency of the plant. This may also be improved by utilizing variable-speed hydropower generation that is able to vary the rotational speed of the turbine. The main technologies being applied to enable variable speed operation are a converter-fed synchronous machine and a doubly-fed induction machine using power electronic converters. The variable speed operation results in better active and reactive power control, as well as greater fast frequency response by a larger spinning reserve capacity. [80]

The review of research and development in the field of hydropower technology performed by Kougias et al.[80] also presents some novel concepts of hydropower storage. As hydropower is slow to control its power input/output, integrating inverter-coupled energy storage technologies such as flywheels or supercapacitors into a hybrid system can be a good option. They are fast responding but have a small energy storage capacity, making them highly compatible with hydropower storage. A more commonly applied technology in the industry is pumped hydro storage. [80]

## 4.3 Pump Hydro Storage

In order to further utilize the reservoir of the hydro storage plant, a PHS facility may be applied. PHS is the major energy storage source globally, accounting for 95% of the power capacity and more than 99% of the energy capacity [81]. PHS may be characterized as either open-loop or closed-loop, differentiating between the type of location of the lower reservoir. An open-loop PHS is connected to a naturally flowing water source, while a closed-loop PHS is not continuously connected as the lower reservoir is located off-stream. A closed-loop PHS typically has a lower energy storage capacity. A typical configuration of a PHS facility is presented in Figure 4.3, illustrating how the turbine and generator are reversible, being able to change its operation between pumping water and generating power [82]. Another option is to utilize two separate penstocks, where one is used for pumping water to the upper reservoir and the other is used for generating electricity, allowing for charging and discharging to occur simultaneously. [83]

The main benefit of PHS, comparing it with other options for energy storage, is the possibility to store large amounts of energy efficiently. The hydro pumps utilized are typically able to operate at an efficiency of

75-85 % when accounting for friction losses and losses from elevating the water as the pressure decreases with height [84].

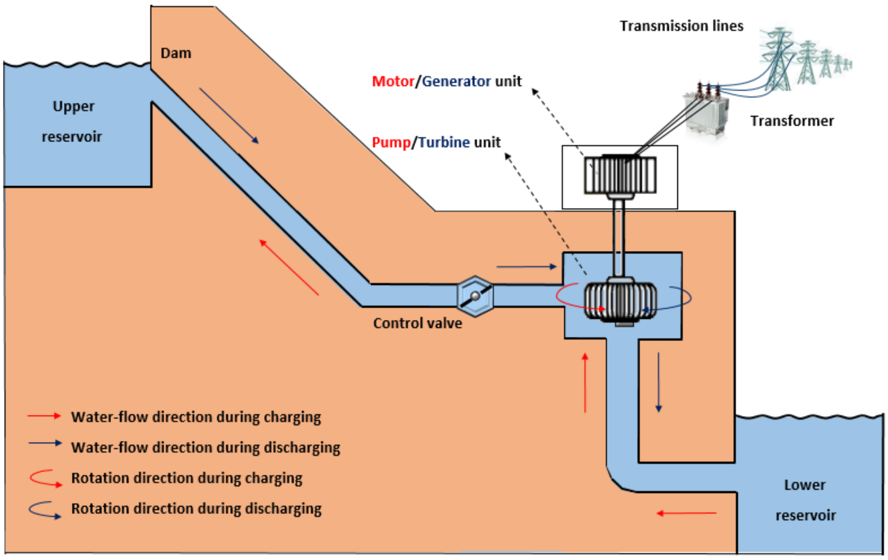



**Figure 4.3:** Schematic diagram of a PHS facility. [82]

Javed et al. mentions some key benefits of implementing PHS in hydropower plants. Among these are abilities of stability enchantments through voltage and frequency regulation, as they are able to quickly adapt and respond to sudden load events. This overall results in a better premise to implement VRESs in the power grid. [84]

The PHS may be categorized based on the size of the reservoir and how frequently it changes between pumping and generation. PHS with a large reservoir may be more seasonal based, pumping power when the conditions for wind and solar power are good and generating when the demand is high compared to the supply. Smaller reservoirs may be utilized more on a daily basis, typically pumping at night when the power demand is low and generating during the day when the demand is high. However, when considering solar generation, the opposite may occur, generating at night when there is no solar production and pumping during the day when the solar production is high. Moreover, it can be used to provide ancillary services like frequency balancing, removing harmonics in the grid, and backup power in case of supply disruptions. [83]

### 4.3.1 Variable Speed Hydro Pumps

The flexibility of the PHS is highly dependent on the choice of the turbine, operating with either a fixed speed turbine that is only able to operate at a fixed speed or a variable speed turbine that can operate at a range of different speeds. A variable speed pump can better provide fast frequency support to complement the VRESs, as the variable speed pump may vary the power output of pumping and generation. A study by Nobile et al. [85] testing the primary frequency control capability of a variable speed PHS in Linthal showed positive results for both pump and generation modes. The flexibility provided by PHS can assist in reducing the curtailment of surplus power from VRES in the network. [83]

Furthermore, this provides more flexibility to optimize the hydropower generation to achieve a greater income from the power plant by taking advantage of the varying power prices. Another benefit of the variable speed turbine is the ability to operate efficiently at a varying pumping head. As the reservoir level changes, the head, meaning the vertical distance between the water level and the turbine, will also vary. Consequently, the turbine can adjust its power output to achieve the optimal efficiency based on the current head conditions. However, as variable-speed pumps are more expensive than fixed-speed turbines, approximately 30 % more according to Hunt et al. [83], they are not as commonly applied in the industry as of today. [83]

## 4.4 Hydro power in Norway

According to numbers from NVE, there is a total of 1739 operational hydropower plants in Norway going into 2022. With a total installed capacity of 33.4 GW, it is the main provider of electrical energy in Norway. The average annual production stands at 137.9 TWh. The theoretical hydropower potential in Norway, if all existing waterfalls were utilized, exceeds 600 TWh. However, considering techno-economic and environmental restrictions, it is estimated that approximately 216 TWh of this potential can be realistically achieved. Furthermore, through reinvestments to upgrade the existing hydropower plants, 6-8 additional TWh may be possible to extract. [5]


**Figure 4.4:** Current PHS facilities in Norway by December 2022. Using the theme map of NVE [86].

Among the many hydropower plants in Norway, only nine have an installed PHS facility. The location of the current PHS systems can be seen in Figure 4.4. There are also constructed 30 separate pumping stations at different facilities around Norway in order to transport water from nearby dams to the reservoir being utilized by a nearby hydro plant [5]. Currently, both the PHS and pumping stations are mainly located in western- and southern Norway [86].

In 2016 a collaborative study named HydroBalance was published by the Centre for Environmental Design of Renewable Energy (CEDREN), investigating the storage potential and utilization of Norwegian hydropower [87]. In the study, it was stated that installing at least 20 GW of additional pumping power is technically feasible. The current facilities do not utilize the price differences on a daily and hourly basis. As the design of the current PHS facilities in Norway is currently aimed at seasonal water disposal throughout the year, storing water from floods as snow and ice melt during the spring and for usage in the high-demand season during the autumn and winter. [**p.32**, 88]

## 4.5 Environmental impacts of hydropower

The construction and operation of a hydropower plant can significantly impact the surrounding environment. They are affecting the ecosystem of the reservoirs and the downstream rivers, as the operating hydropower influences the characteristics of the water flow and the natural temperature of the river. Furthermore, it can impact the surrounding ecosystems, impacting the forest, wildlife habitat, and agricultural land. RoR hydro plants generally have less impact on the surrounding environment compared to hydro storage plants [83]. This is because RoR hydro plants do not require the construction of dams for water storage, and therefore do not significantly alter the river flow. In contrast, hydro storage plants rely on dams to store water, which can have a significant impact on the surrounding environment. [89]

The hydro turbine may posses a danger to the fish in the river passing through the river. Fish passages are commonly used to direct the fish away from the turbine. However, according to recent analyses, they are not eco-efficient. The fish passages can be better adapted for fish behavior and fish reaction. Additionally, the design of the turbine can be designed to be safer for passing fish. The Alden turbine and the Minimum Gap Runner turbine are mentioned by Kougias et al. [80] as newly developed turbines aiming to be safer for passing fish. Tests conducted on both turbines have demonstrated promising survival rates for fish. [80]

According to Schaffer et al. [12], the operation of hydropower plants should consider environmental constraints, such as maximum and minimum discharge limits, in order to ensure the sustainability of the ecosystem and protect the ecological habitat of passing fish. Additionally, the operation of reservoirs below a certain low filling degree should be avoided in order to minimize environmental impacts. Although, power producers may already desire to have a minimum level in the reservoirs for risk management and to ensure the availability of balancing power, considering the uncertain hydro inflow.

The surrounding masses of the reservoir are another factor that should be considered. The ramp-up rate, which represents a rapid large change in power, is taken into account when managing grid code requirements as these ramping events can potentially introduce stability issues for the system operator. However, the ramp-up rate is also important for environmental considerations, as a quick reduction in reservoir level can affect the local geology, causing landslides and erosion. Additionally, rapid water level variations in the reservoir may also be undesirable for ecological reasons. [90]

Implementing a PHS can reduce the environmental impacts of the hydro plant by reducing the need for large capacity storage reservoirs and providing more flexible operation to prevent flooding and droughts. The open-loop PHS plants generally have a greater impact on the surrounding environment compared to closed-loop PHS, as storing water in large reservoirs within the main river can affect a larger population of wildlife and the surrounding ecosystem. [83]

# Chapter 5

# Material on Optimization Techniques

## 5.1 Linear Programming

Optimization models are frequently used for the planning of numerous activities to obtain an appropriate solution to large and complex mathematical problems. Depending on the structure of the problem and its complexity, a suitable approach is applied. The simplest and most common technique is Linear Programming (LP). It is necessary to make linear assumptions when creating an LP model. Adjustments must be made to create a linear objective function that is subject to linear constraints if it is not already linear. As a result, it is expected that the objective function and the constraints present are proportional. Further, by restricting the feasible solutions to those within the feasible region defined by the linear constraints, the process of finding the optimal solution in LP models becomes simplified. [**p.25-38**, 91]

## 5.2 Emerging Optimization Techniques

When a problem's complexity and size increase, LP models might not be adequate for identifying an appropriate solution. Obtaining reasonable assumptions for linearization can be challenging, and as the size of the problem increases, the program may take a long time to generate the set of possible solutions. To address the complexity, models may require techniques such as integer programming and non-linearity. Moreover, in computationally heavy problems, various machine learning-based algorithms can serve to identify appropriate solutions quickly. [92]

There are many emerging optimization algorithms developed for solving various complex optimization problems, many of which are applicable to problems regarding electric power system operation and power production [92]. In Table 5.1 examples of the application of some common algorithms used in power production and for Multiple Objective Optimization (MOO) are presented, as well as remarks on some of the advantages and drawbacks of the methods. This is based on an author-made literature survey on optimization algorithms typically used in electric power production and systems.

Heuristic techniques are becoming a more common approach to solving issues in the power system, where some of the most recognized algorithms are Evolutionary Algorithms (EA)s such as Genetic Algorithm (GA) and Differential Evolution (DE). In addition to Swarm Intelligence Algorithm (SIA)s such as Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO). The heuristic methods apply practical methods that speed up the process of finding an appropriate solution. A heuristic approach for optimization should get close to the global optimal solution, as opposed to a classical method, which in many cases yields a local rather than a globally optimum solution. [118]

**Table 5.1:** Optimization algorithms

| Modelling method | Wind operation application | Hydro operation application | Hybrid systems/ Multi-Objective Optimization) | Remarks |
|---|---|---|---|---|
| EAs | Optimal pitch angle [93], optimal design of wind turbine blades [94]<br>Micro-siting of wind turbines using GA [95]<br>Selection of wind turbine for any site-specific wind conditions [96]. | Common in short-term hydro scheduling [97]<br>Evolutionary Algorithm for Optimizing Hydropower Generation Considering Multireservoir Systems [98]. | Common in MOO [99], [100]<br>Off-grid Renewable Hybrid Energy System [101].<br>MOO for operation and maintenance assets of an offshore wind farm using genetic algorithms [99] | Well suited for discontinuous, non-differentiable, stochastic, or highly nonlinear problems. [102]<br>High probability of finding a solution close to the global optimum. [102]<br>Typically takes many function evaluations to converge. [102] |
| SIAs | Optimal pitch angle<br>Provision of grid services: Voltage and reactive power control [103].<br>Allocation problem in distribution systems with wind turbine generators [103].<br>Generator expansion problem [104]. | Common in short-term hydro scheduling [105]<br>Generator expansion problem [104]. | MOPSO models developed in order to obtain Pareto front of multiple objective optimization [106], [100].<br>Reactive power planning problem considering multiple objectives [107].<br>Off-grid Renewable Hybrid Energy System [101]. | Advantages of simplicity, flexibility, ergodicity, and efficient memory capability [106]<br>Well suited to solve non-linear, non-convex, continuous, discrete, integer variable type problems [106].<br>Weak theoretical foundation [106]. |
| SDDP & SRHM | Strategic generation investment [108]<br>Capacity Expansion Planning [109] | Very common approach in short-, medium- and long-term hydro scheduling. [110], [111] | - | Accounting for uncertainties in the input parameters [111] |
| MILP | Optimize the cable connections of offshore wind farm [112] | Short- and long-term hydro scheduling [113], [114] | MOO power generation expansion planning [115]<br>MOO power generation expansion planning [116] | Computional heavy for large systems [117]. |

### 5.2.1 Evolutionary Algorithms

The mentioned EAs and SIAs are all inspired by physical or chemical processes that act independently of the situation. This is the most common type of heuristic optimization, named meta-heuristic optimization [119]. The EAs consider evolutionary-inspired processes, whereas Darwin's theory of species evolution is especially considered in GAs. In this approach, a population of individual solutions is given a value based on the objective function, where the best candidates are selected as parents. The next generation of individuals is produced based on the "attributes" of the crossover of parents, where the attributes are given randomly based on the concept of mutation. Over successive generations, the population is moving toward an optimal solution. [102], [120]

Another emerging type from the EAs is DEs. By implementing the parent crossover after the mutation phase, DE algorithms differentiate themselves from GAs. Additionally, the mutation process is dependent on distance and directional information via unit vectors for reproduction rather than being randomly distributed. Slowik et al. [120] identify the main advantages of DE over GA as simple usage, fast convergence, efficient memory utilization, and computational scaling as the size of the problem increases. [121]

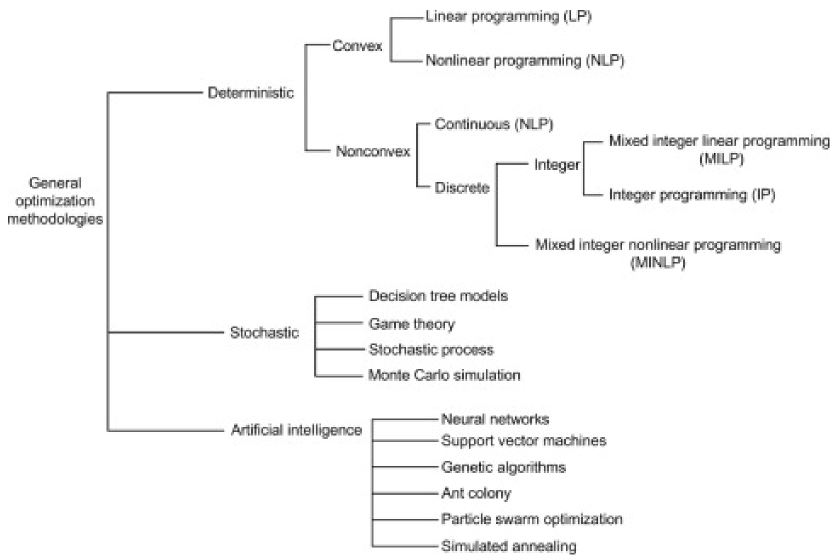



**Figure 5.1:** Overview of general optimization methodologies, with examples of common approaches within each category. [92]

### 5.2.2 Swarm Intelligence Algorithms

SIAs draw their inspiration from the collective behavior of the objects in a biological system. The group of objects, referred to as the swarm, together find an optimal solution using the knowledge of all the objects while also satisfying the needs of each individual object. SIAs are often employed when the size of the problem and the resulting number of possible solutions make the solving time too extensive. Furthermore, SIA methods are also effective in handling non-linear problems. [122]

The most common method of these is the PSO. The behavior of bird flocks and schooling fish inspires the PSO. A swarm of particles moves around in a search space, looking for the best solution to the problem. Each particle is defined by a position and velocity, interacting with each other and the environment. The position and speed are updated based on their experience until the best solution is obtained. [103]

PSO is often compared to GA, as their approach has many similarities. The difference is that PSO relies on the interaction between the individuals and the environment instead of crossover and mutation in order to update the attributes. PSO is generally faster and more efficient than GA, as it does not necessarily require a function to measure the performance of the problem. However, PSO has a significant limitation concerning its weak theoretical background and sensitivity to initial conditions, which makes assessing its stability challenging. Furthermore, since PSO incorporates stochastic elements, its effectiveness in finding an optimal solution may vary depending on the specific case. [103], [106], [101]

Another popular SIA is the ACO, which is inspired by the swarm intelligence of ant colonies working together. As with the PSO, they utilize an interacting swarm. However, where PSO uses a velocity term to control particle movement, ACO uses a probabilistic approach to explore the options of motion for the ants, where the path that has been successful in the past is given a higher probability. One of the key advantages of ACO is its suitability for dynamic problem applications. [106]

### 5.2.3 Stochastic Models

The previously described algorithms are all naturally stochastic [118]. Stochastic models, which account for uncertainties in parameters affecting a system, are commonly used in energy production scheduling due to the inherent uncertainties in inflow for hydro plants and ambient wind conditions for wind farms [111]. Two such models are Stochastic Dual Dynamic Programming (SDDP) and Stochastic Rolling Horizon Model (SRHM).

SDDP is an approximate cutting plane method that iteratively includes constraints to reduce the feasible solution space and converge towards an optimal solution. It is used to solve stochastic dynamic programming problems by solving a series of subproblems and iteratively repeating the process to improve the accuracy of the approximation. [123]

SRHM is an extension of the rolling horizon model that includes uncertainties in the optimization process. Similarly to the SDDP, it involves solving a series of subproblems iteratively. However, SRHM uses a general-purpose optimization algorithm rather than a specific one like SDDP. [124]

### 5.2.4 Deterministic Models

In contrast to stochastic models, deterministic models assume the parameters included to be certain values. They apply average rates, not considering random variations in their parameters. The deterministic model can be categorized based on the complexity of the problem. As seen in Figure 5.1 the models are differentiated between linear and non-linear, and convex and non-convex programming. [125]

Mixed Integer Linear Programming (MILP) is a common modeling approach to solve complex optimization problems of conflicting objectives, where the potential trade-offs are identified. According to Gurobi[126], "*MILP problems are generally solved using a linear-programming based branch-and-bound algorithm*". However, as this method applies integers, it can become computationally heavy for large systems. [117]

### 5.2.5 Application in Power System and Operation

Various modified variations of the algorithms have been applied to obtain solutions to issues in power system operation and operation of power plants. Table Table 5.1 presents several examples showcasing the application of optimization techniques in wind and hydro operation, also including scenarios involving MOO and coordination of renewable energy systems.

In the field of power scheduling, as well as the sizing and cooperation of hybrid wind, solar, and hydro plants, researchers have explored various modified variants of the aforementioned optimization algorithms. Examples of such variants are provided in Table 5.1.

Combining different optimization algorithms is also a common practice as each method possesses its own advantages and drawbacks. An example of this is a study by Saxena et al. [127] using a method combining the PSO and GA algorithm for frequency regulation of a microgrid. Another hybrid approach is presented by Silvente et al.[128], combining MILP and SRHM to achieve optimal management of microgrids.

There are many other various types of algorithms being applied in recent research. As digitalization in the industry increases, the technology of efficient and precise optimization algorithms is becoming more and more relevant. Among the methods yet to be mentioned are the often applied Neural Network (NN) and Whale Optimization Algorithm (WOA).

## 5.3 Multi-Objective Optimization

When dealing with various optimization issues in the power system, there may be different objectives of multiple participants, including different non-economical objectives such as emissions and stability enhancement. This area is often referred to as MOO concerning problems with more than one objective to be optimized simultaneously. Identifying a single solution that fulfills the arbitrary preferences given by a decision maker, quantifying the trade-offs of the different objectives, or finding a representative set of Pareto optimal solutions are all possible objectives of the MOO. Pareto optimal solutions is a nondominated solution, meaning that no other solution can improve without worsening at least one other solution [129]. A Pareto optimal solution gives the best possible compromise between the conflicting objectives. The complete set of all the Pareto optimal solutions is represented by the Pareto front, being superior to other solutions in the search space. [100], [130]

Table 5.1 present some extensions of different optimization techniques applied to MOO in the literature. For example, methods using PSO and GA are commonly applied to obtain all the Pareto solutions of the Pareto front using an aggregative approach. However, as the number of Pareto optimal solutions can approach infinity, this type of approach can become computationally heavy. [100]

Gradient-based optimization algorithms can be applied to make the process more efficient. This type of approach uses the gradient of a function to find the local minimum or maximum of that function [131]. The weighted sum method and the $\epsilon$-constraint method are the most widely used approaches. Both achieve a more efficient optimization process by converting several objective functions into a single objective function. Using the $\epsilon$-constraint method, new solutions in the search space are found by adding different constraints to the objective function when applying the $\epsilon$-constraint method. On the other hand, the weighted sum method obtains this by changing the value of the weights of the conflicting objectives. However, one of the issues of the weighted sum method is the assumption of linear proportionality between the weights and the objective functions. This may not always be the case, as some of the different objectives may be dependent on each other resulting in a non-linear relation, limiting the method. [100]

Mavrotas [129] mentions three key issues with the implementation of the $\epsilon$-constraint method: *a) The calculation of the range of the objective functions over the efficient set, (b) the guarantee of efficiency of the obtained solution, and (c) the increased solution time for problems with several (more than two) objective functions.*

### 5.3.1 Lexicographic optimization

In order to efficiently obtain different solutions on the Pareto front, some initial solutions that define the search space are needed. One approach is lexicographic optimization, aiming to define a range that includes only Pareto optimal solutions. This method considers one objective function at a time, while the remaining functions are employed as constraints that limit the feasible region in the objective space. The step-wise process of the lexicographic optimization is illustrated in Figure 5.2, using an example of a two-objective minimization problem. [100]

In steps 1 and 3 of the process, the aim is to determine the optimal values for objective 1 and objective 2, respectively, through the utilization of single-objective optimization. These optimized values, $f_1^*$ and $f_2^*$, are subsequently employed as constraints in steps 2 and 4, while the other objective is being minimized. By employing this approach, the optimal value that can be attained by one objective without resulting in an increase in the objective being held at its optimal value is determined. The point where the minimized objective reaches its optimal value while the other objective is being constrained to its optimal value gives the worst possible optimal solution of this objective, referred to as the nadir point. [100]

The nadir values and the best possible solutions ($f_1^*$ and $f_2^*$) constitutes the lower and upper bound of each objective, which together may form a so-called pay-off table. Further, this can be utilized as a starting point to iterate towards new Pareto optimal solutions. [100]

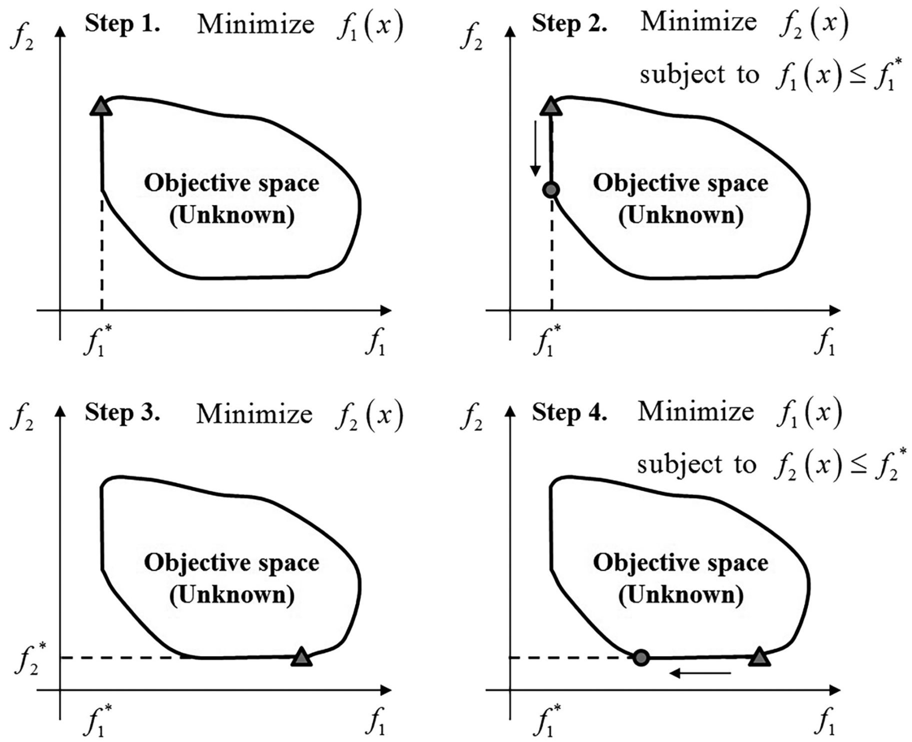



**Figure 5.2:** Step-wise process of lexicographic optimization for a minimization problem. [100]

### 5.3.2 Augmented Epsilon-Constraint Method

The AUGMECON algorithm is a novel version of the $\epsilon$-constraint method, developed for effective implementation of the standard $\epsilon$-constrain method in MOLP problems, by improving some of the drawbacks of the standard method. A major benefit is improved efficiency by avoiding re-evaluating solutions similar to those already evaluated. [129]

A flowchart giving an example of an iterative approach to the AUGMECON method is illustrated in Figure 5.3. A table, referred to as the payoff table, is used to divide the ranges of the different objectives. These ranges are obtained using the previously described method of lexicographic optimization. The set of solutions is found by only considering one objective function at a time while the other objective functions act as constraints to define the feasible region in the search space [100]. The AUGMECON version of the $\epsilon$-constraint method to efficiently obtain Pareto optimal solutions are presented in the following equation system. [129]

$$\max \quad f_1(x) + eps \cdot (s_2 + s_3 + ... + s_p)) \tag{5.1}$$
$$\text{subject to:} \quad f_2(x) - s_2 = e_2 \tag{5.2}$$
$$f_3(x) - s_3 = e_3 \tag{5.3}$$
$$... \tag{5.4}$$
$$f_p(x) - s_p = e_p \tag{5.5}$$
$$x \epsilon S \ and \ s_i \epsilon R^+ \tag{5.6}$$

The different objective functions are represented by $f_i(x)$, where $x$ represents the vector of different variables and $S$ is the feasible region. The objective functions being applied as constraints are all partitioned into a given number of grid points, forming intervals between the nadir point and the optimal value. Each simulation corresponds to an epsilon value, $e$, representing a single grid-point value, which is incorporated as a binding constraint in Equations (5.2)-(5.5). Consequently, the resulting solution data represents a Pareto front, covering all proposed solutions that fall within the predefined ranges established by the payoff table. A slack variable, $s$, represents the amount by which the constraint is relaxed or violated [**p.99**,

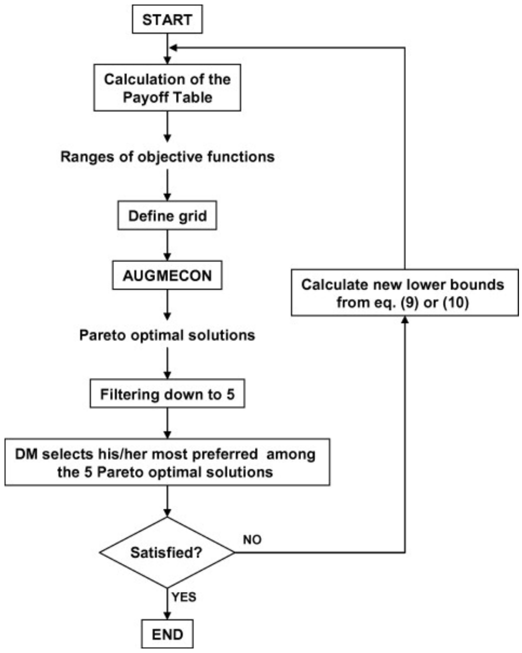



**Figure 5.3:** Flowchart of an interactive process using AUGMECON. [129]

91]. By including the slack, each constraint is converted into equality constraints. A parameter, $eps$, is set to a low number, usually between $10^{-3}$ and $10^{-6}$, in order to add slack variables to the objective function that are secondary to the objective function. As the constraint all now are binding, weakly efficient solutions are avoided in the resulting Pareto front. [129]

Recently a Python framework for multi-objective linear optimization under uncertainty (AUGMECON-Py) has been developed. Forouli et al. [132] describe the construction of the MOLP algorithm using AUGMECON-Py to solve complex and large problems under uncertainty. Figure 5.4 presents the architecture of the implementation of the software. Further, an open-source step-by-step implementation and requirements of the AUGMECON-based multi-objective optimization solver for Pyomo have been released in Github by Bles and Paterakis [133].

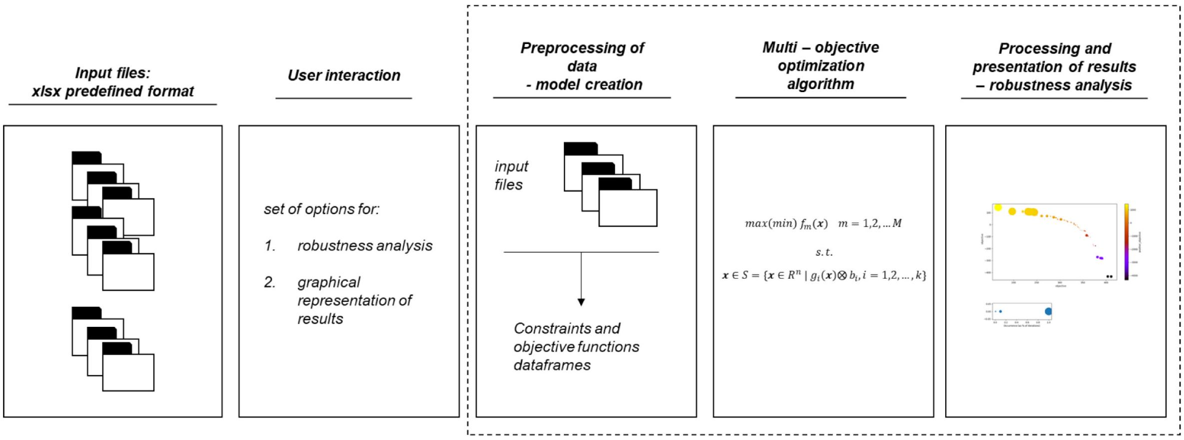



**Figure 5.4:** AUGMECON-Py architecture of the software. [132]

## 5.4 Decision Making

The solutions obtained in the Pareto front are all considered equally good from a neutral point of view. However, as different objectives can be more significant to the decision maker, a decision-generating algorithm can be required. The decision maker is looking for the most preferred solution from the Pareto front, considering the subjective weights of the different objectives.

### 5.4.1 Fuzzy Algorithm

A common approach involves utilizing a Fuzzy Decision Maker (FDM), which leverages a membership function to handle the imprecision and uncertainty present in various parameters, including the decision maker's desired level of achievement for the objectives [134]. The FDM is a computational tool that is used to make decisions, in a "fuzzy" environment, based on uncertain or imprecise information. Recently, the FDM algorithm has also been seen applied to aid meta-heuristic optimization algorithms such as the PSO and ACO [135]. [136]

In a fuzzy decision maker, the decision process is modeled as a set of rules that specify how the decision should be made based on the values of the input variables. There are many different approaches to implementing fuzzy logic [136]. A general incorporation of the fuzzy process can be explained by the following steps.

Firstly, the decision-making problem needs to be identified, including establishing the input variables and goals and the different criteria and options based on the goals. Then the fuzzy sets and the membership functions are determined based on the input variables. This phase is identified as the "fuzzification", where the variables are transformed into linguistic variables, which define each variable's reliability rate. [136, 137]

The system's performance is determined by "If-then" conditions, constituting the rules for the design of the decision-making. The "if" part represents conditions that must be met, and the "then" part represents the following action to be performed. From this, the position of a particular variable is approved as a set. This phase is referred to as "fuzzy interference". [136, 137]

Further, the process of "defuzzification" is performed by transforming the fuzzy estimation of the output variable to numerical values in order to describe the outcome of the fuzzy computation. The "defuzzification" method combines the rules of the fuzzy set to obtain the final decision. Finally, the solutions need to be validated. Interpretation and verification can be obtained by testing the solutions in practice, ensuring their feasibility. [136, 137]

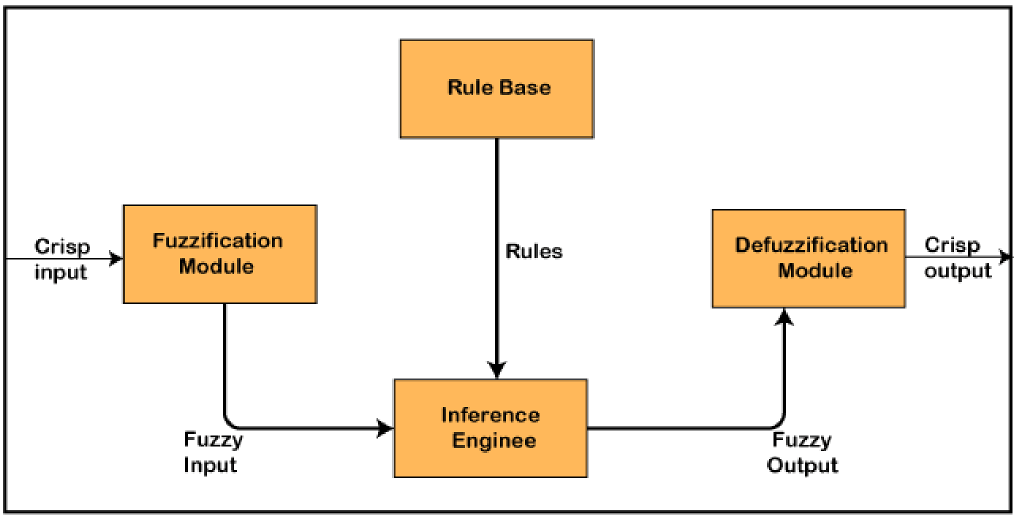



**Figure 5.5:** Fuzzy logic architecture. A crisp input/output is a precise, well-defined input that can be represented as a single value. [138]

### 5.4.2 Application of Fuzzy Logic in Multi-Objective Problems

Rezvani et al. [139] and Jamessen [15] utilize a linear membership function, where a utility value, $\mu_i^r$, is defined for each objective, based on their upper and lower bound. The membership function for an objective being minimized and maximized is shown in respectively Eq. 5.7 and 5.8. $F_i^r$ represents the objective value for objective $i$, while $F_i^{max}$ and $F_i^{min}$ are the respective maximum and minimum values possible for each objective.

$$\mu_i^r = \begin{cases} 1, & \text{if } F_i^r \leq F_i^{min}. \\ \frac{F_i^{max} - F_i^r}{F_i^{max} - F_i^{min}} & \text{if } F_i^{min} \leq F_i^r \leq F_i^{max} \\ 0, & \text{if } F_i^r \geq F_i^{max}. \end{cases} \tag{5.7}$$

$$\mu_i^r = \begin{cases} 1, & \text{if } F_i^r \geq F_i^{max}. \\ \frac{F_i^r - F_i^{min}}{F_i^{max} - F_i^{min}} & \text{if } F_i^{min} \leq F_i^r \leq F_i^{max} \\ 0, & \text{if } F_i^r \leq F_i^{min}. \end{cases} \tag{5.8}$$

From this, a total utility value, $\mu^r$, can be calculated for each Pareto optimal solution, by multiplying the resulting utility value, $\mu_i^r$, of every objective with its corresponding weight, $w_i$.

$$\mu^r = \frac{\sum_{i=1}^{p} w_i \cdot \mu_i^r}{\sum_{i=1}^{p} w_i} \tag{5.9}$$

# Chapter 6

# Methodology

A MOF for a wind-PHS system is building upon the incremental work of Stave and Jamessen. The prior development of the simulation and optimization model for a hybrid power system consisting of a hydro plant and wind farm can be found in the master thesis of Stave [18], with an additional published paper [16]. In the previous work, results of the model using NEM regulations and a bilateral power agreement are presented. Additionally, the impact of implementing Dynamic Line Rating (DLR) is further studied. [3]

The model is extended by Jamessen to include multiple objectives, separating the income of the two power plants, by implementing lexicographic programming, AUGMECON, and FDM. In addition to including a fixed speed pump to the hydro plant, making it a PHS system. The results from simulating a combined wind-PHS system using the developed MOF are found in the master thesis [17], with a published paper to it in [15]. [3]

This project aims to further extend and study the model for similar cases. The main extension to the model is the inclusion of wind farm control dynamics, using a damage-aware wind farm controller developed by Spyridon Chapaloglou at Sintef Energy. Another extension is the implementation of a variable speed pump and an analysis on its impact compared to the case using a fixed speed pump.

## 6.1 Overview of the Co-Simulation Framework

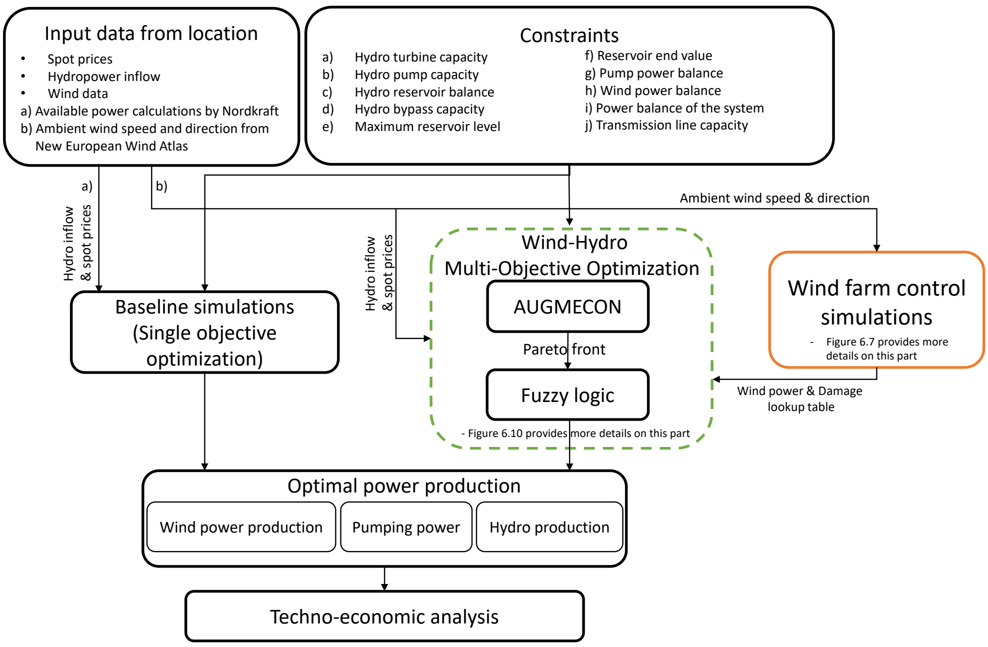



**Figure 6.1:** Overview of the methodology for the co-simulations framework. Extension from previous work by including wind farm control, is indicated by the orange box. The flowchart is based on the presented flowchart by Jamessen in [17].

Figure 6.1 presents an overview of the proposed methodology for the co-simulation framework, including different input data and constraints of the optimization program. The previous work of Stave [18] and Jamessen [17] are represented by black boxes in the figure. The extension of wind farm control, represented by the orange box, is included to provide a more realistic power generation from the wind farm. This control framework also considers the mechanical operation of the wind farm in more detail, adding a new objective to minimize wind turbine damage to the original optimization problem. The different elements of the framework will be described further in section 6.3 and section 6.4

## 6.2 Reference Case Study

The reference case builds on the study conducted by Stave [18], consisting of a single hydro plant with a capacity of 72 MW and a 96.6 MW wind farm. The power plants are located in Sørfjord in Northern Norway and share a single transmission line connecting to the grid with limited capacity, set to 140 and 200 MW for the purpose of this study. As with the case study conducted by Jamessen [17], a hydraulic pump is added to the hydro plant, resulting in a PHS system. Further, this case study differentiates by investigating a new wind farm consisting of 20 DTU 10 MW wind turbines [140]. As a result, the total wind power capacity is increased to 200 MW to achieve a more relevant case for this study. Moreover, in this study, the two power plants act as a hybrid coordinated system.

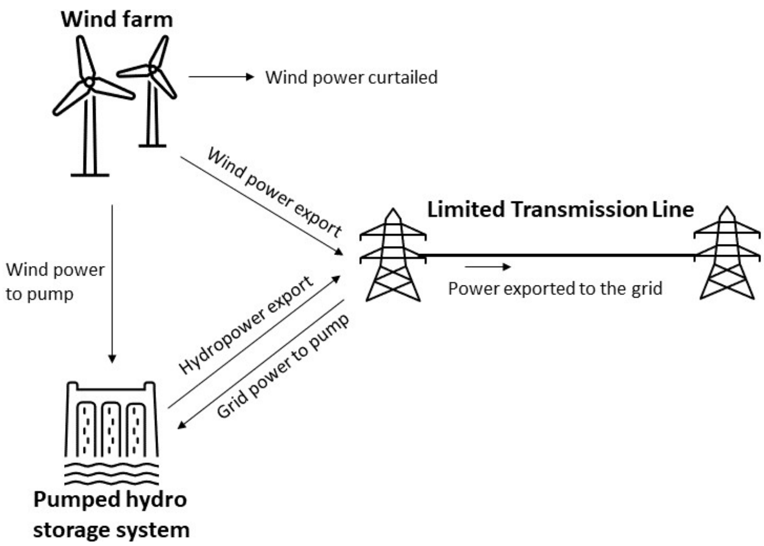



**Figure 6.2:** A wind farm and a PHS sharing a limited transmission capacity

The system's design and power exchanges are illustrated in Figure 6.2. The pump can import power from both the wind farm and the grid. It should be noted that power can only flow in one direction on the transmission line, meaning that power can not be exported to and imported from the grid simultaneously. Additionally, no PHS system is included in the current hydro plant as there is no suitable location for a downstream reservoir. Thereby, a virtual pump, which may be either a fixed- or variable-speed pump, is included to analyze its influence on the system. This makes the case study correspond to the design presented in Figure 6.2.

### 6.2.1 Data and Parameters

Data on the two power plants have been provided by Nordkraft. Including historical hydro inflow measurements from 2011-2015 and wind power potentials estimated by using weather measurements in combination with a power curve of the wind turbines. It should be noted that the wind farm control simulations require input ambient wind speed and direction. Thereby, data from New European Wind Atlas (NEWA) is utilized instead of wind power potentials from Nordkraft in these simulations. While the baseline simulations only utilize the wind power potentials, as presented in Figure 6.1. The parameters specifying the different attributes and capacities of the system are presented in Table 6.1.

**Table 6.1:** Parameters for the case study

| | Rating | Unit |
|---|---|---|
| **Wind farm** | | |
| Wind farm capacity | 200 | MW |
| Cut-in speed | 6 | m/s |
| Cut-off speed | 24 | m/s |
| **PHS system** | | |
| Turbine capacity | 72 | MW |
| Turbine efficiency | 95 | % |
| Pump capacity | 20 | MW |
| Pump efficiency | 85 | % |
| Max reservoir level | 97 020 | MWh |
| Bypass capacity of the reservoir | 67.74 | MW |
| **Grid** | | |
| Transmission capacity | 140/200 | MW |

The baseline and MOLP simulation are subject to different input wind data, with substantially higher wind power output for MOLP. Thereby, to ensure meaningful results for the case study, different transmission capacities are employed. Specifically, the baseline simulation adopts a transmission capacity of 140 MW, whereas the MOLP simulation utilizes 200 MW.

### Power prices

The spot prices are taken from Nordpools day-ahead prices in NO4. In recent years, the situation in the power market has been subject to considerable changes, further causing uncertainties about the validity of using historical power prices. As the power prices are trending towards higher variations as presented in section 2.4, historical power prices may not be representative for the future situation. Thereby, recent power prices from 2021 are used in this study. However, to exemplify the impact power prices have on the operation of the wind-PHS system, some simulations using spot prices from 2019 are also performed, as they historically present a typical "normal" year. The spot price throughout the year for 2019 and 2021 is presented in Figure 6.3, showing a major change in both its seasonal and short-term variations.

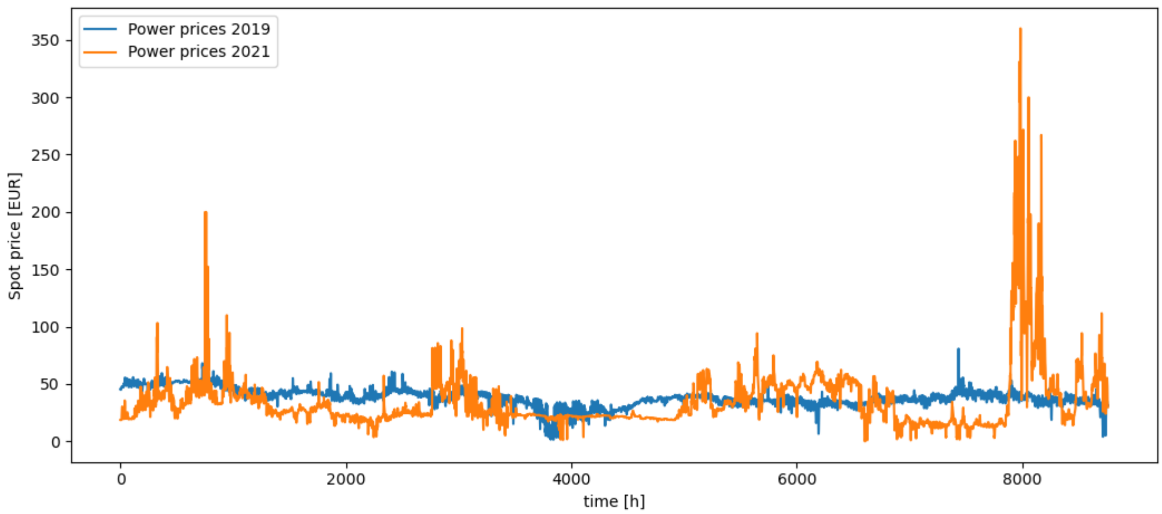



**Figure 6.3:** Spot prices from Nordpool in 2019 and 2021.

### Wind Farm Layout and Conditions

The layout of the wind farm consisting of 20 DTU 10 MW wind turbines is presented in Figure 6.4. The turbines have been strategically placed to minimize significant wake effects on downstream turbines while ensuring a realistic representation of a wind farm layout.

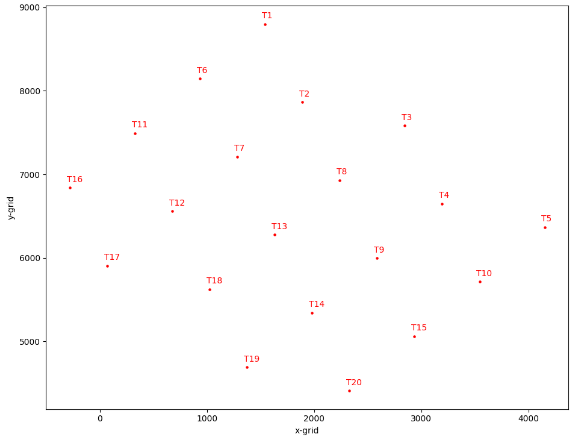



**Figure 6.4:** Wind farm layout

The wind farm simulations require input ambient wind conditions of wind speed and direction. This differentiates from the baseline simulations, where the wind power potentials provided by Nordkraft are being utilized directly. The ambient wind data from the location of the wind farm is collected from NEWA, providing a Meso-time-series for hourly data of wind speeds and directions. The wind data applied in this case study are historical weather data registered for the year 2013. The wind rose showing the frequency of different wind speeds and directions for the wind farm location throughout the year is presented in Figure 6.5. Further, Figure 6.6 presents the wind speeds throughout the year, illustrating the short and long-term variations.

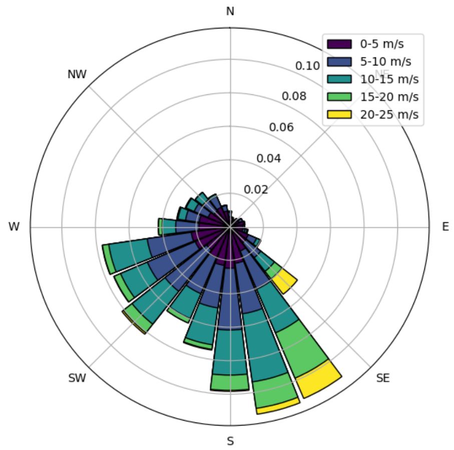



**Figure 6.5:** Wind rose for the wind farm throughout the year of simulations.

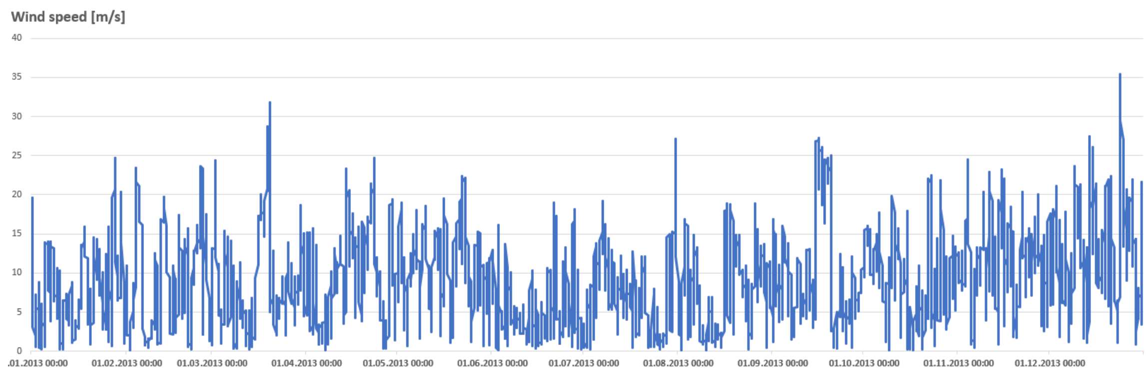



**Figure 6.6:** Wind speeds for the wind farm throughout the year of simulations.

## 6.3 Wind Farm Simulations

Several parts and components can be affected with drive-train components being some of the most important. To compensate for this, a damage-aware wind farm controller is employed in this study, capable of redistributing the de-rating commands among turbines such that those are damaged as uniformly as possible while satisfying the active power tracking requirement.

As presented in Figure 6.1, the multi-objective optimization uses an input lookup table of wind farm power output and damage accumulation for a given power reference and the ambient wind conditions at each time step. The process of the wind farm control simulations to generate this lookup table is presented in Figure 6.8. The lookup table consists of every hour throughout the year with options of 10 different power references ranging from 10-100 %. To illustrate the final output from the wind farm control simulations, an example from the output lookup table is presented in Figure 6.7, where the blue columns represent the input data while the yellow columns represent the resulting output data. Each of the 10 different power references has its own sheet in the output-file, similar to the one shown for the power reference of 100%.

| Hour | Wind Speed [m/s] | Wind Direction [deg] | Power Reference [%] | Accumulated Damage [-] | Power Output [MW] |
|---|---|---|---|---|---|
| 0 | 14.742453 | 179.68477 | 100 | 1.03874604 | 179.7855774 |
| 1 | 14.819081 | 180.42636 | 100 | 1.042715223 | 181.7007006 |
| 2 | 14.638902 | 179.58197 | 100 | 1.040921029 | 177.9228501 |
| 3 | 14.826732 | 181.76016 | 100 | 1.062441308 | 188.2998162 |
| 4 | 15.933663 | 185.41663 | 100 | 0.806397865 | 196.3580538 |
| 5 | 16.42432 | 185.88583 | 100 | 0.765601395 | 196.8285608 |
| 6 | 16.806677 | 185.31558 | 100 | 0.745758043 | 196.7251495 |
| 7 | 16.250029 | 180.47305 | 100 | 0.91442143 | 195.4272235 |
| 8 | 16.234726 | 172.3446 | 100 | 0.760249301 | 196.8119357 |
| 9 | 16.556967 | 171.72604 | 100 | 0.728412936 | 196.6839255 |
| 10 | 17.075418 | 171.11081 | 100 | 0.684732845 | 195.971196 |
| 11 | 17.308054 | 171.92578 | 100 | 0.681368855 | 196.5340395 |
| 12 | 18.366812 | 168.42279 | 100 | 0.632481714 | 197.0027037 |
| 13 | 18.793568 | 164.49133 | 100 | 0.621018043 | 197.1111517 |
| 14 | 19.238415 | 160.32242 | 100 | 0.609809515 | 197.1043826 |
| 15 | 20.812346 | 157.71059 | 100 | 0.624472202 | 198.3298609 |
| 16 | 20.450283 | 152.9649 | 100 | 0.579586241 | 197.0846265 |
| 17 | 21.410568 | 150.74193 | 100 | 0.564533137 | 196.967274 |
| 18 | 22.602749 | 148.80417 | 100 | 0.544814797 | 197.1069597 |
| 19 | 22.634956 | 146.57664 | 100 | 0.545875858 | 197.116896 |
| 20 | 23.68339 | 135.57637 | 100 | 0.52299681 | 196.8387088 |
| 21 | 23.841349 | 136.8401 | 100 | 0.521092707 | 196.7464234 |
| 22 | 19.707191 | 146.1406 | 100 | 0.606390022 | 197.0095686 |
| 23 | 17.188307 | 149.33585 | 100 | 0.676089809 | 196.7548168 |
| 24 | 16.705917 | 150.40634 | 100 | 0.700245251 | 196.8105117 |

**Figure 6.7:** Example of out lookup table from wind farm control simulations. Presenting the sheet of a power reference of 100 % for the first day of simulations.

From the ambient wind conditions, synthetic turbulence is generated using a set of wind field simulations. The tool used in this model is TurbSim.FASTFarm by National Renewable Energy Laboratory (NREL), a stochastic inflow turbulence tool [141]. This generates an output of a higher minutes-based resolution turbulent wind speed time series per turbine, represented by $\phi_{Ws,TI}$ in the flowchart. The resulting wind for each individual turbine will be different due to the turbulence, causing an individual power output and damage accumulation for each turbine. In the final steps, the resulting damage and power output are applied to a lookup table for each time step. The output power and damage are dependant on the power reference ($P_i$), the wind speed ($w_s$) and direction ($w_d$).

The effect of the wind farm controller is represented through a quasi-steady framework, suitable for integration in hourly-basis optimization setups for power systems and market analyses. This serves as a proxy function of the smaller sub-hourly time scales, when the actual power tracking and frequency restoration is happening, in between the discrete coordination instants. The active power control is modeled on a higher minutes-based resolution, including both high-frequency-farm-wide turbulent wind speed fluctuations [142] and slower dynamics (10-minutes averaged) from the changing wake patterns in the farm, due to the control actions.

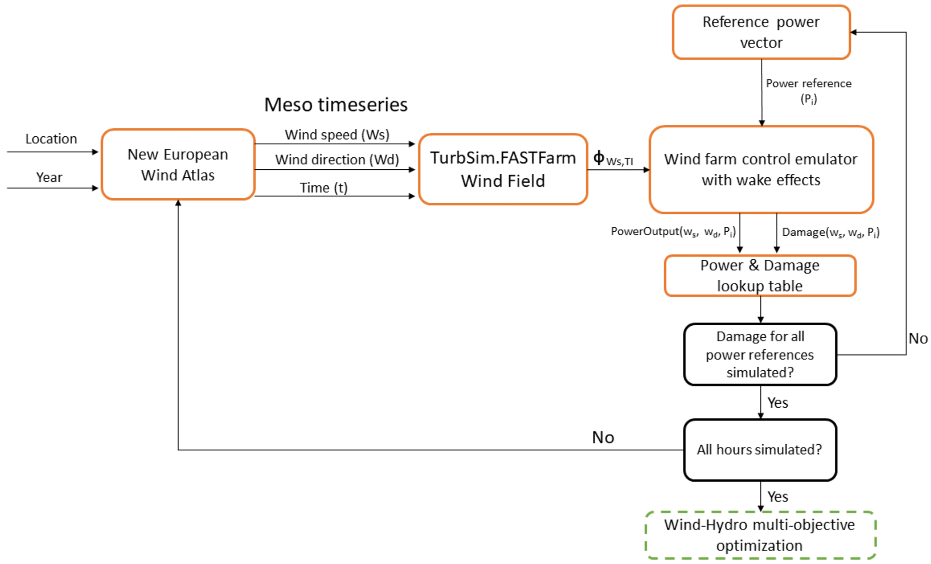



**Figure 6.8:** Flowchart of the wind farm control simulations

### 6.3.1 Example of Simulations Result for the Wind Farm

The turbulence interactions will cause the wind speed to be different at each turbine. This can be seen in the example for wind farm control simulations in Figure 6.9, showing the wind speed at each turbine throughout one hour while testing different ambient conditions. In the plot, each grey line represents each turbine, showing some significant difference in wind speeds from turbine to turbine. In the same plot, the measured power output from the wind farm throughout the simulations can be seen from the pink curve, where the power reference is set at maximum (100%) as shown by the green "Reference" curve.

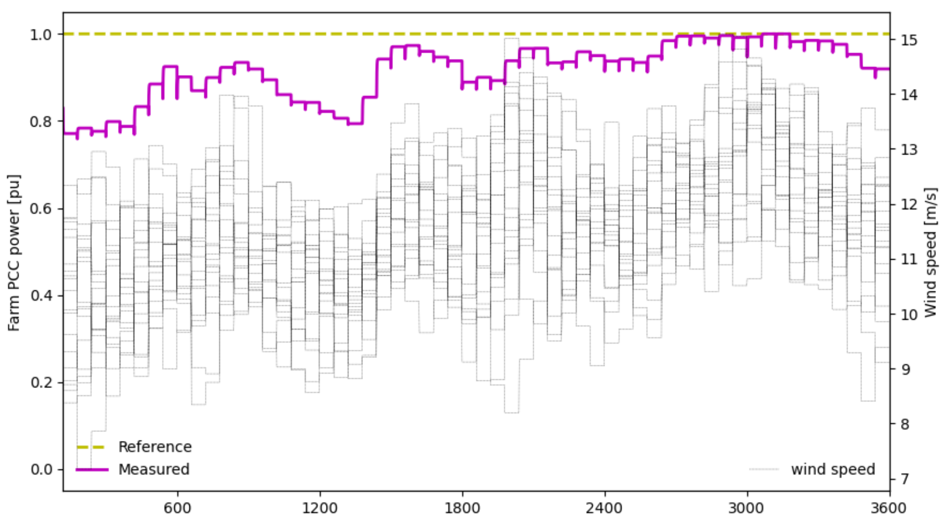



**Figure 6.9:** Wind farm wake simulations example

Furthermore, the variations in wind speed and turbulence intensity at each turbine lead to different power outputs and damage levels. Figure 6.10 illustrates an example of damage accumulation during one hour of simulation for each turbine, with a power setpoint of 100%. The results demonstrate significantly higher damage for the northern wind turbines, as wind is approaching from the north. However, when the power setpoint is reduced, as shown in Figure 6.11 using a setpoint of 60 %, a substantial reduction in damage can be observed for the northern turbines. Lowering the setpoint allows the controller to de-rate the turbines, reducing the load and mitigating damage.

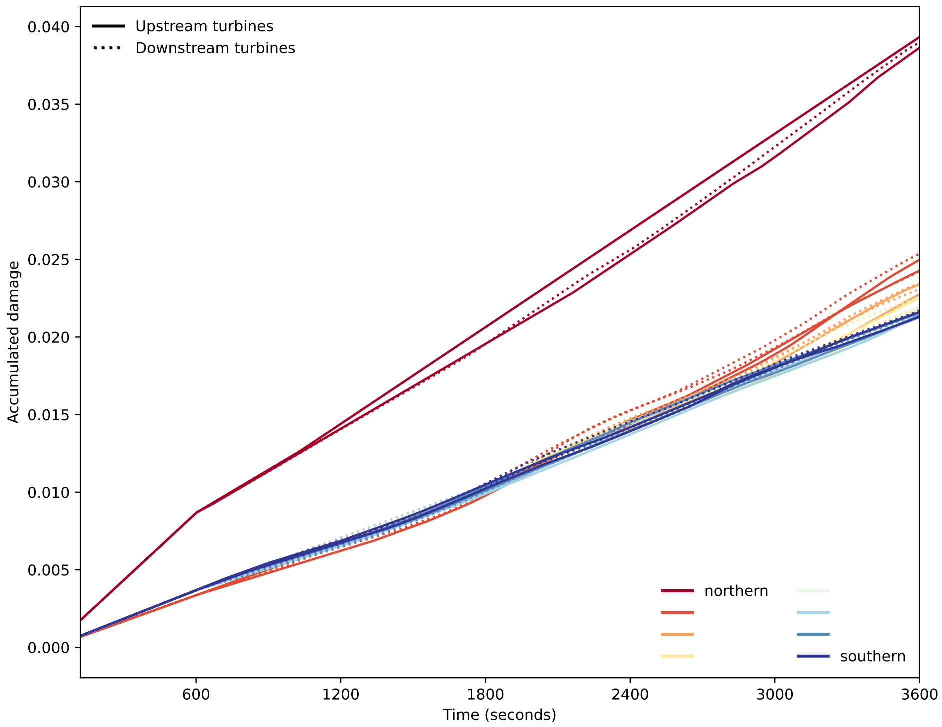



**Figure 6.10:** Damage accumulation at different turbines, with a power reference of 100 %

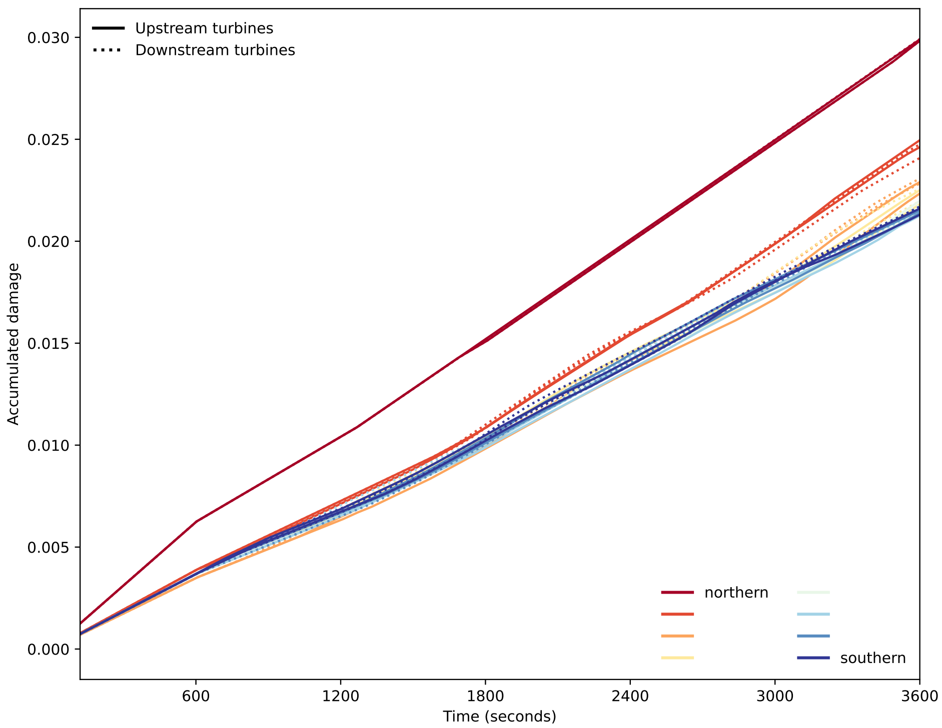



**Figure 6.11:** Damage accumulation at different turbines, with a power reference of 60 %

## 6.4 Multi-Objective Optimization Model

The multi-objective framework designed by Jamessen [17] is further developed and extended in this study in order to include all the objectives of the different entities accounted for in the case study. A flowchart of the existing process of solving the model using AUGMECON, lexicographic optimization and fuzzy logic is presented in Figure 6.12.

The method is further improved by adding a tailored software extension by Bles and Paterakis [133], pyAUGMECON, using a Python and Pyomo-based implementation of AUGMECON and lexicographic optimization to obtain an approximation of the exact Pareto front.

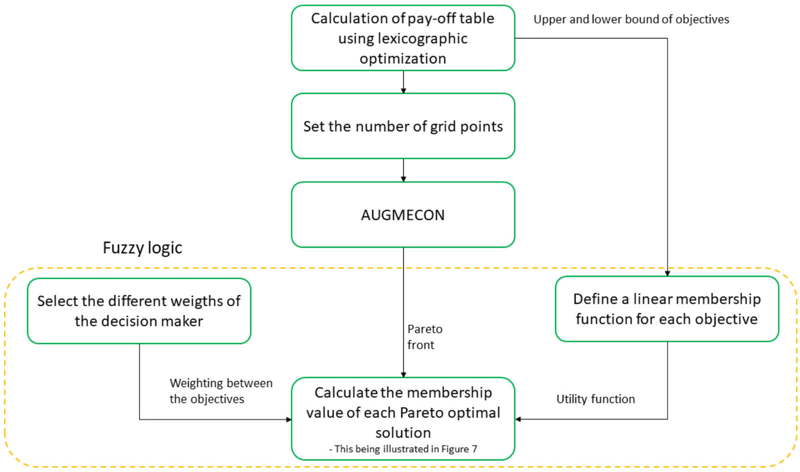



**Figure 6.12:** Flowchart of the multi-objective optimization process

First, the pay-off table is required to be calculated, this is done using lexicographic optimization, as described in subsection 5.3.1. From this the ranges, upper and lower bounds of each objective are obtained. These ranges are further used to obtain the Pareto optimal solutions, for the given number of grid points, resulting in a Pareto front. Additionally, the ranges are used to define the linear membership function (Equation 5.7 and Equation 5.8) of the objectives in the fuzzy logic part for decision-making (represented by the yellow box).

Further, five different weights are used to present different trade-offs, $w_d/w_r$, between the two objectives in fuzzy decision-making. Where $w_d$ represents the weight of the damage objective and $w_r$ the weight of the revenue objective. The trade-offs applied to the case study are presented in Table 6.2, where the ratio of 1/9 means that the revenue objective is granted a much higher priority than damage for the decision maker. Correspondingly, a ratio of 9/1 grants greater priority to the damage objective.

**Table 6.2:** Different weights of the decision maker

| | Weight 1 | Weight 2 | Weight 3 | Weight 4 | Weight 5 |
|---|---|---|---|---|---|
| $w_d/w_r$ | 1/9 | 1/4 | 1/1 | 4/1 | 9/1 |

Finally, the total utility value for each of the Pareto optimal solutions is obtained through Equation 5.9. This is calculated for every weight given by Table 6.2. Providing the decision maker with different options depending on the priority of each objective.

## 6.5 Multi-Objective Linear Programming Model

The different objectives of the MOLP to maximize the total revenue of the hybrid plant and minimize the accumulated damage to the wind turbines are given by respectively Eq. 6.1a and 6.1b. The optimization constraints are formulated in equations from Eq. 6.1c to 6.1r, which are represented in the constraint box in Figure 6.1. These constraints apply to every hour of the simulation throughout the year, except for Eq. 6.1i, which ensures that the reservoir level remains unchanged from the initial level at the end of the simulation.

These equations include operating conditions for the PHS system, including hydro production capacity (Eq. 6.1d), maximum reservoir level (Eq. 6.1h), maximum bypass water (Eq. 6.1g) and reservoir balance (eq. 6.1f). The pump may be set to either fixed speed or variable speed (Eq. 6.1e). The pumping power may come directly from the wind farm or be imported from the grid (Eq. 6.1j). Then it must be ensured that no power is exported to and imported from the grid simultaneously, which is done in Eq. 6.1q.

**Table 6.3:** Nomenclature of all parameters and variables in the model

| | |
|---|---|
| **Sets** | |
| T | All the time steps, t, of the simulations |
| R | All the power references of the simulations |
| **Parameters** | |
| $t_{max}$ | Total number of hours for the simulation [-] |
| $P_{w,pot,t}$ | Available power for the wind farm at time step t [MW] |
| $P_{w,r,t}$ | Power output wind farm for power reference, r, at time step t [MW] |
| $D_{r,t}$ | Damage accumulated for power reference, r, at time step t [-] |
| $\gamma_t$ | Spot price in the day-ahead market at time step t [EUR/MWh] |
| $E_{inflow,t}$ | Inflow to the hydro reservoir at time step t [MW] |
| $Cap_{res}$ | Maximum capacity of the hydro reservoir [MWh] |
| $Cap_{ht}$ | Production capacity of the hydro turbine [MW] |
| $Cap_{pump}$ | Production capacity of the hydro pup [MW] |
| $\eta_{ht}$ | Efficiency of the hydro turbine [%] |
| $\eta_{pump}$ | Efficiency of the pump [%] |
| $E_{res,init}$ | Initial reservoir level [MWh] |
| $Cap_{flood}$ | Maximum flood of the reservoir [MW] |
| $Cap_{line}$ | Maximum power flow of the transmission line [MW] |
| **Variables** | |
| $P_{imp,t}$ | Imported power from the gird to pump at time step t [MW] |
| $P_{w,prod,t}$ | Produced power from the wind farm at time step t [MW] |
| $P_{w,exp,t}$ | Exported wind power at time step t [MW] |
| $P_{w,curt,t}$ | Wind power being curtailed at time step t [MW] |
| $P_{w,toPump,t}$ | Wind power exported to the hydro pump at time step t [MW] |
| $P_{h,exp,t}$ | Exported hydropower at time step t [MW] |
| $P_{pump,t}$ | Power of the hydro pump at time step t [MW] |
| $P_{h,loss,t}$ | Hydropower bypassed due to spillage at time step t [MW] |
| $P_{tot,exp,t}$ | Total exported power from the hybrid system at time step t [MW] |
| $E_{res,t}$ | Reservoir level at time step t [MWh] |
| **Variables - Binary** | |
| $\alpha_{exp,t}$ | Stating if power is exported to the grid at time step t |
| $\alpha_{imp,t}$ | Stating if power is imported to the grid at time step t |
| $\beta_t$ | Stating if the power pump is active or inactive at time step t |
| $\delta_r, t$ | Stating if power reference, r, is active at time step t |

Further, the wind production is selected at each hour from the lookup table obtained from wind farm simulations (Eq. 6.1c). Eq. 6.1r is included in order to ensure that only one power reference is used at each time step. The wind farm can export its power to the grid and directly to the pump (Eq. 6.1k). Further, the wind power curtailed is given by the difference between the maximum power output form the wind farm and its actual production (Eq. 6.1m)

The total exported power from the hybrid system can not exceed the transmission capacity, this is ensured in Eq. 6.1p, where total exported power is the sum of power export from the hydro plant and the wind farm (Eq. 6.1o). Finally, the power balance of the whole system is defined in Eq. 6.1n.

The objectives and constraints marked with blue color are exclusively utilized by the MOLP approach and not by the single-objective baseline simulations. While the constraints marked with red are exclusively utilized by the baseline simulations. Furthermore, in the MOLP simulation, the reservoir level changes are multiplied by 9 as the simulation only considers every 9th hour throughout the year. This adjustment is made to ensure that the limitations of reservoir capacity appropriately influence the results. Additionally, the objective results are multiplied by 9 to approximate values for a complete year. For the baseline simulation, this is not an issue as input data for all hours throughout the year is included in the optimization.

$$\max \quad \sum_{t \epsilon T} (P_{w,exp,t} + P_{h,exp,t} \cdot \eta_{ht} - P_{imp,t}) \cdot \gamma_t \cdot 9 \tag{6.1a}$$

$$\min \quad \sum_{t \epsilon T} (\sum_{r \epsilon R} D_{r,t} \cdot \delta_{r,t}) \cdot 9 \tag{6.1b}$$

subject to

$$P_{w,prod,t} = \sum_{r \epsilon R} P_{w,r,t} \cdot \delta_{r,t} \tag{6.1c}$$

$$P_{h,exp,t} \leq Cap_{ht} \tag{6.1d}$$

$$P_{pump,t} \leq Cap_{pump}$$

$$P_{pump,t} = Cap_{pump} \cdot \beta_t \tag{6.1e}$$

$$E_{res,t} = E_{res,t-1} + 9 \cdot (E_{inflow,t} + P_{pump,t} \cdot \eta_{pump} \cdot \Delta t)$$

$$- P_{h,exp,t} \cdot \Delta t - P_{h,loss,t} \cdot \Delta t \tag{6.1f}$$

$$P_{h,loss,t} \leq Cap_{flood} \tag{6.1g}$$

$$E_{res,t} \leq Cap_{res} \tag{6.1h}$$

$$E_{res,t_{max}} = E_{res,init} \tag{6.1i}$$

$$P_{pump,t} = P_{w,ToPump,t} + P_{imp,t} \cdot \alpha_{imp,t} \tag{6.1j}$$

$$P_{w,prod,t} = P_{w,exp,t} + P_{w,ToPump,t} \tag{6.1k}$$

$$P_{w,pot,t} = P_{w,exp,t} + P_{w,ToPump,t} + P_{w,curt,t} \tag{6.1l}$$

$$P_{w,curt,t} = P_{w,r,t,max} - P_{w,prod,t} \tag{6.1m}$$

$$P_{tot,exp,t} \cdot \alpha_{exp,t} - P_{imp,t}$$

$$= (P_{w,exp,t} + P_{h,exp,t}) - (P_{pump,t} - P_{w,ToPump,t}) \tag{6.1n}$$

$$P_{tot,exp,t} = P_{h,exp,t} \cdot \eta_{ht} + P_{w,exp,t} \tag{6.1o}$$

$$P_{h,exp,t} \cdot \eta_{ht} + P_{w,exp,t} \leq Cap_{line} \tag{6.1p}$$

$$\alpha_{exp,t} + \alpha_{imp,t} \leq 1 \tag{6.1q}$$

$$\sum_{r \epsilon R} \delta_{r,t} \leq 1 \tag{6.1r}$$

## 6.6 Shortcommings and Assumptions

The current framework and case study has certain shortcomings and assumptions that are worth noting. The optimization assumes perfect information on input parameters (spot price, ambient wind conditions, and hydro inflow), but in reality, input data is subject to stochastic environments. This has a significant impact on the decision-making process. Nevertheless, the optimization can still illustrate the potential benefits of wind-hydro coordination and wind farm control.

Regarding the MOLP simulation, modeling issues enforced limitations on the amount of input data that could be processed in the optimization. Additionally, performing wind farm control simulations for an entire year is computationally demanding. As a solution, every 9th element of the input data for a whole year is employed in these simulations. It is important to acknowledge that this approach may affect the results, as the distinct variations typically observed throughout each day are no longer fully represented in the simulations.

Moreover, there are some specific shortcomings observed in the wind farm control simulations conducted in this study:

- Due to computational efforts, the operator may only choose between 10 different power references for operating the wind farm, where each power represents the percentages from 10-100% with a step size of 10 %. Ideally, there should be more options.
- Due to modeling issues, a cut in speed of 6 m/s for the ambient wind conditions is required for the wind turbines to operate. In reality, the farm operator would be aware of the effects inside the farm,

so the operating limit is different compared to a single turbine.

Additionally, certain limitations of the PHS system are worth noting as they could potentially impact the practical outcomes.

- In the current model, the hydro pump is able to operate at any speed. However, a minimal operating point for the pump may be required for practical application.
- The operating point is set to be equal at any power reference and reservoir level. In reality, this may vary depending on those. The variable speed may better adjust to the conditions, resulting in better efficiency.
- The scheduling of the hydro plants' power production is in reality based on water value calculations. However, in this study, such stochastic modeling is not included.
- In this model, the lower reservoirs are assumed to have unlimited water capacity, allowing unrestricted pumping. However, in practical scenarios, lower reservoirs often have limited water availability constraints may impose restrictions on water extraction.
- Further, the PHS system may be subject to environmental constraints, mentioned in section 4.5, which may limit the flexible operation of the PHS.

# Chapter 7

# Results

The simulation results from the case study are divided into two main sections; differentiating between results using the baseline single-objective model and results obtained for the multi-objective co-simulation framework.

The design of the system and the power flows are illustrated in Figure 6.2. The objectives and constraints presented in section 6.5 have been applied using the data and parameters presented in subsection 6.2.1. At the same time, different significant assumptions and shortcomings considered for the simulations are presented in section 6.6. The results presented within this chapter are derived from applying the described methodology in Figure 6.1 to the designated case study presented in Section 6.2.

## 7.1 Baseline Single-Objective Simulations

In the baseline approach, the wind farm control simulations are excluded, using the potential wind power directly, as presented by the flowchart in Figure 6.1. Thereby, the revenue of the hybrid system is the only objective considered in the optimization. These results are based on work performed in the project work [3].

### 7.1.1 System Simulations

The model provides output data of optimal hourly power production throughout the year. An illustration of this is presented in Figure 7.1 and Figure 7.2, where the wind power being curtailed and the reservoir level at each hour is also visualized. As there is limited transmission capacity, the wind farm is forced to curtail some of its potential power. However, for some operating hours, the wind farm and hydro plant can be observed to not fully utilize the transmission capacity to export power to the grid. Hence, there is potential to enhance grid utilization by leveraging flexibility options.

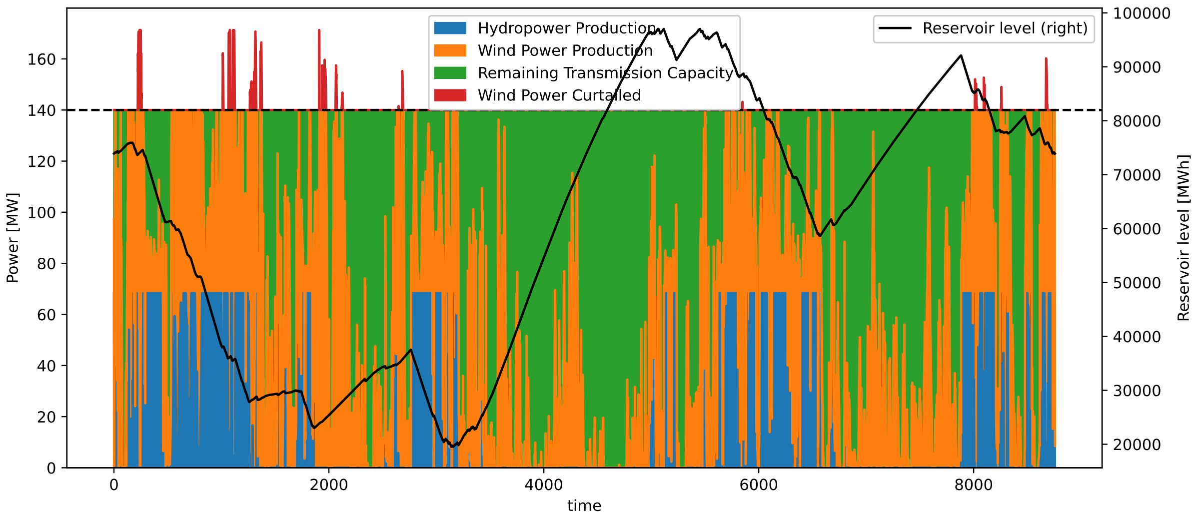



**Figure 7.1:** Power prices from 2021 - Variable speed pump

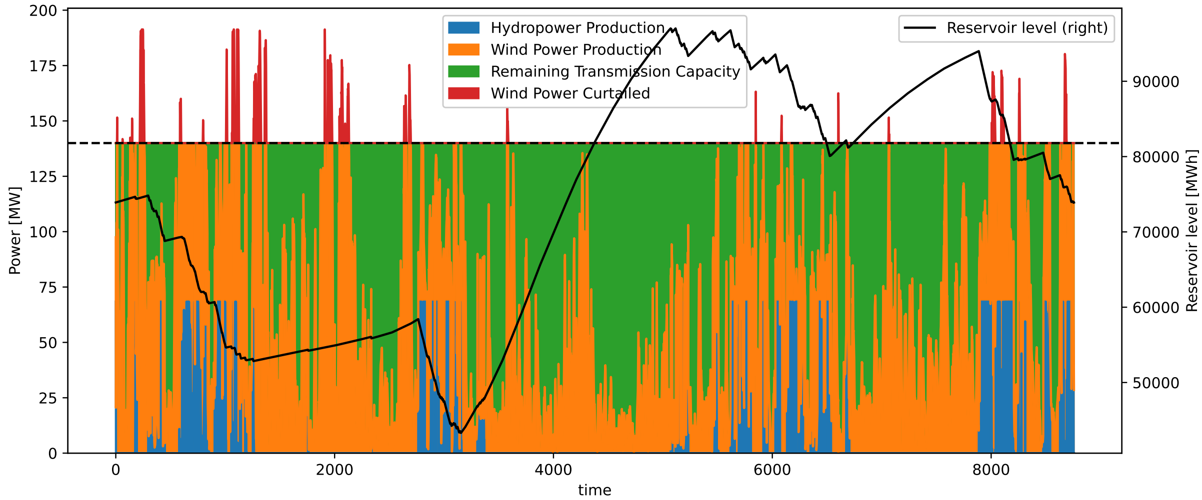
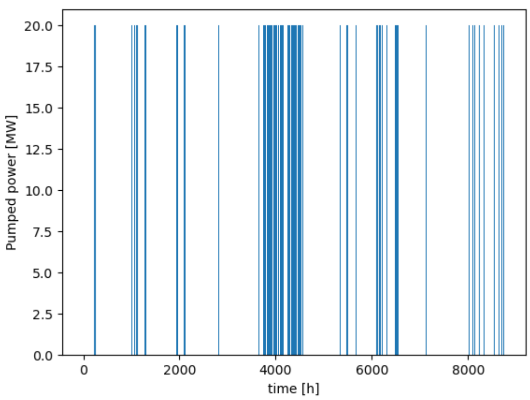



**Figure 7.2:** Power prices from 2021 - With no PHS system

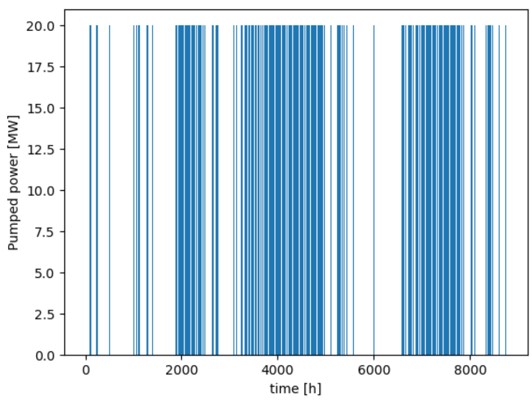
A significant difference can be observed, regarding hydropower production and wind curtailment, when comparing the results using a PHS system and the results with no PHS system installed. The utilization of a PHS system with a variable speed pump leads to an increase in hydropower production from 106.12 GWh to 177.48 GWh compared to the results when no pump is utilized. This indicates a substantial reduction in available hydropower when the reservoir is not being charged by a pump. Furthermore, the pump effectively utilizes surplus wind power to transfer water to the reservoir, resulting in a decrease in wind curtailment when employing a PHS system. Another observation from comparing Figure 7.1 and Figure 7.2 is that the full range of the hydro reservoir level is more utilized with a PHS system.

### 7.1.2 Hydro Pumping Power

The pumping power throughout the year is presented in Figure 7.3 and Figure 7.4, demonstrating the different operations for the variable speed pump compared to the fixed speed pump. As seen in Figure 7.3, the fixed speed pump is either not operating or pumping at maximum capacity, which is the only option of the fixed speed pump. Additionally, it can also be observed that the pump is substantially more utilized in 2021 than in 2019, which can be expected as it operates to benefit from varying power prices. Another observation is that the pump is highly active in the summer months, which is expected due to the generally lower demand for power and lower power prices during that period. This creates incentives for storing power in the reservoir during the summer months.



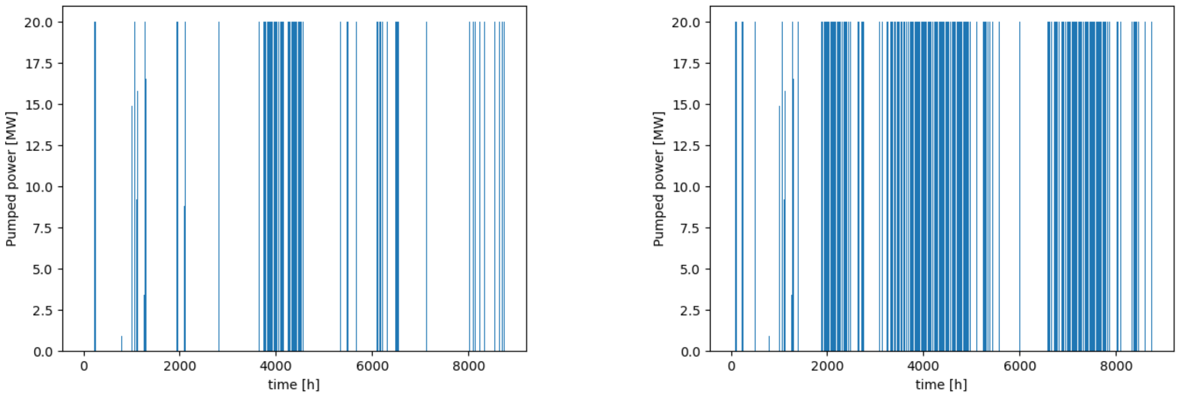

**(a)** Power prices from 2019




**(b)** Power prices from 2021

**Figure 7.3:** Pumping power using a fixed speed pump

The pumping power results using a variable speed are similar to the ones obtained using a fixed pump. However, there can be observed some operation below the maximum rating of the hydro pump in Figure 7.4.




**(a)** Power prices from 2019 **(b)** Power prices from 2021

**Figure 7.4:** Pumping power using a variable speed pump

### 7.1.3 Impact of Implementing a PHS System

Simulations to compare the outcome from using a variable speed pump, a fixed speed pump and no pumped hydro storage have been conducted in this study. The resulting revenue, pumping power, wind curtailment and grid utilization for the different cases is presented in Table 7.1 and Table 7.2, respectively using power prices from 2019 and 2021.

**Table 7.1:** Comparison of results for fixed vs. variable speed pump using power prices from 2019.

| | No PHS | Fixed Speed Pump | Variable Speed Pump |
|---|---|---|---|
| Grid utilization [%] | 40.649 | 40.996 | 41.018 |
| Wind power curtailed [MWh] | 10 153 | 3680 | 3644 |
| Total pumping power [MWh] | - | 37 480 | 36 251 |
| Revenue hydro plant [MEUR] | 5.111 | 5.245 | 5.251 |
| Revenue wind farm [MEUR] | 15.384 | 15.645 | 15.647 |
| Combined revenue [MEUR] | 20.495 | 20.890 | 20.898 |

**Table 7.2:** Comparison of results for fixed vs. variable speed pump using power prices from 2021.

| | No PHS | Fixed Speed Pump | Variable Speed Pump |
|---|---|---|---|
| Grid utilization [%] | 40,644 | 40.911 | 40.927 |
| Wind power curtailed [MWh] | 10 214 | 3 730 | 3705 |
| Total pumping power [MWh] | - | 89 240 | 88 370 |
| Revenue hydro plant [MEUR] | 7,167 | 8,093 | 8,096 |
| Revenue wind farm [MEUR] | 14,532 | 14,811 | 14,813 |
| Combined revenue [MEUR] | 21,699 | 22,904 | 22,910 |

The results from 2019 and 2021 simulations show great benefit from utilizing a PHS, with major improvements of reduced wind curtailments and increased income of the combined system. The PHS system can achieve revenue improvements of up to 5.6% and reduce wind curtailments to approximately 36% compared to the case without PHS. However, when comparing the results using a variable speed pump compared to a fixed speed pump, only small deviations are observed for pump utilization and wind curtailment. Thereby, employing a variable speed pump does not yield a significant increase compared to a fixed speed pump in the combined income of the hydro plant and wind farm (with increases of only 0.0365% and 0.0241% for 2019 and 2021, respectively).

A more significant impact can be seen from different input power prices. Simulations in 2021 resulted in greater use of the hydro pump, causing some of the income to shift from the wind farm to the hydro plant. The combined income of the two power plants experienced a significant increase of 9.63% in 2021 compared to 2019 when a variable speed pump was utilized. However, it is worth noting that the income of the wind farm decreased in this scenario.

Furthermore, the advantage of utilizing PHS in terms of total revenue becomes more significant when power prices are subject to greater variability in 2021. The rise in revenue, when comparing a fixed speed PHS to the scenario without a pump, has increased from 1.93% in 2019 to 5.56% when using the power prices from 2021. However, arguably unexpected, the difference between the fixed speed and variable speed pump results for combined revenue and wind curtailment is relatively higher in 2019 compared to 2021.

## 7.2 Multi-Objective Simulations

In this section, the extensions of wind farm control simulations, presented in section 6.3, are included. The following results are obtained using the co-simulation framework presented in Figure 6.1. The optimization model aims to provide appropriate options for the decision maker considering two objectives; total revenue for the hybrid system, and the damage accumulation to the wind turbines of the wind farm.

### 7.2.1 Pay-off Table

The resulting pay-off table in the case study for the two objectives is presented in Table 7.3, providing the ranges for the Pareto front and utility functions. Note that the damage accumulation is just represented by a damage index representing physical damage of various components of the drivetrain.

**Table 7.3:** Pay-off table

| | **Damage [-]** | **Revenue [MEUR]** |
|---|---|---|
| Min Damage | 0 | 9.03 |
| Max Revenue | 4045.66 | 35.19 |

Zero damage is achieved when fully minimizing the damage objective. However, this comes at the cost of no power being produced from the wind farm. Further, resulting in a major decrease in revenue for the hybrid system, with only 25.7% of the maximum value attained under this condition.

### 7.2.2 Pareto Front

The obtained Pareto front from the multi-objective optimization is presented in Figure 7.5, showing the Pareto optimal solutions for 50 grid points. As the damage increases from smaller values, a significant relative increase in income can be observed. However, as the accumulated damage reaches higher levels, the additional revenue generated from further damage increases becomes considerably less.

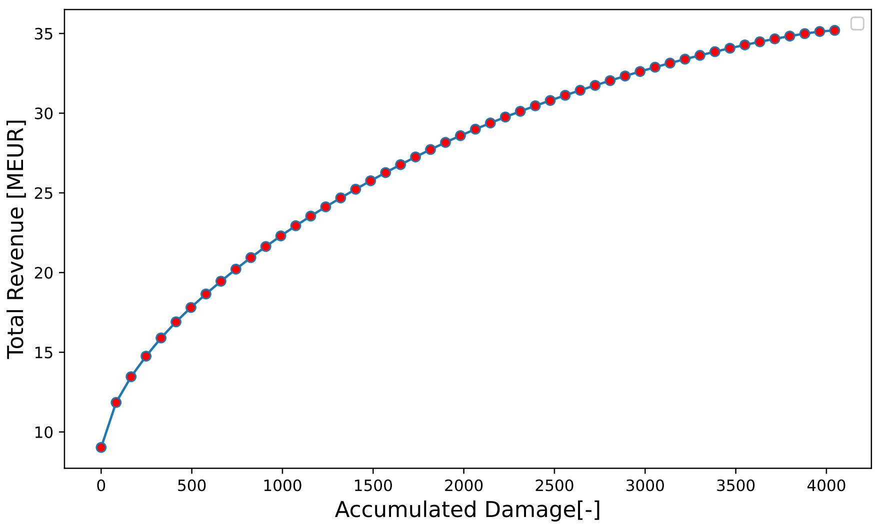



**Figure 7.5:** Pareto front for 50 grid points

### 7.2.3 Fuzzy Utility Value

Figure 7.6 presents the utility value for every Pareto optimal solution given in Figure 7.5, indexed from 0-49, using the different weights from Table 6.2.

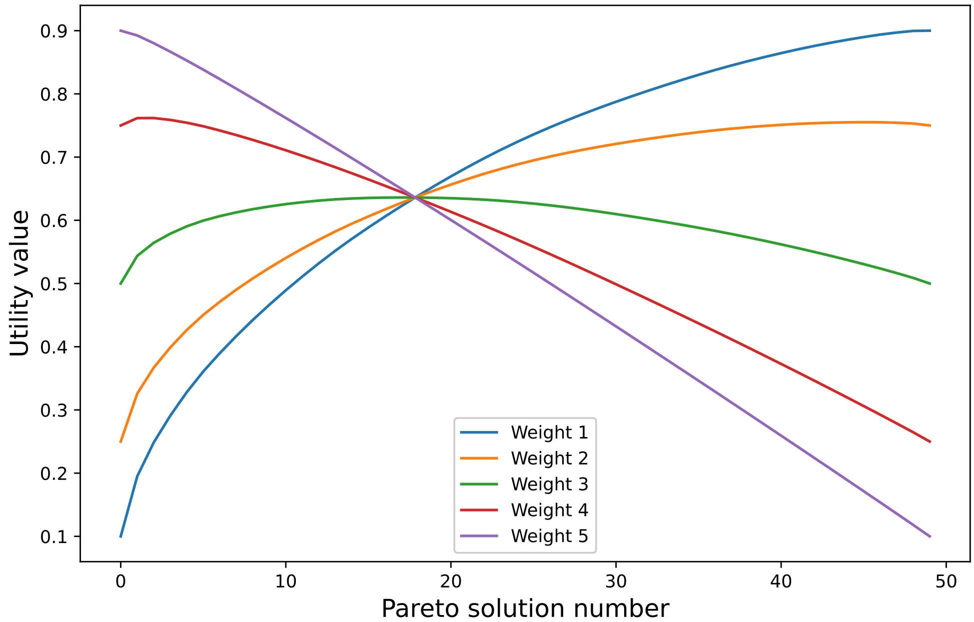



**Figure 7.6:** Utility value for the different weights, using fuzzy logic.

Evidently, when the revenue is granted most of the priority in Weight 1, the Pareto solution number 49, with the highest revenue and damage, obtains the greatest utility value. While Pareto solution number 0 obtains the greater total utility when applying weight 5, granting the damage a much higher priority. Moreover, with equal weighting, the optimum solution is found closer to the mid-point at Pareto solution 18. The results for the two objectives obtained from each solution using different weights are presented in Table 7.4.

**Table 7.4:** Results on objectives from different weights

| | Weigth 1 | Weight 2 | Weigth 3 | Weight 4 | Weigth 5 |
|---|---|---|---|---|---|
| Pareto solution number | 49 | 45 | 18 | 2 | 0 |
| Revenue [MEUR] | 35.19 | 34.66 | 25.76 | 13.47 | 9.03 |
| Damage [-] | 4045.66 | 3715.40 | 1486.16 | 165.13 | 0 |

### 7.2.4 System Simulations

The resulting system simulations for each optimal solution are visualized in Figures 7.7 through 7.10. When giving full priority to wind turbine damage mitigation, all wind power is curtailed, despite the availability of surplus transmission capacity, as illustrated in Figure 7.7. As the focus gradually shifts towards the revenue objective, less wind power is curtailed, and a greater portion of the transmission capacity is utilized. It is worth noting that the transmission capacity has been increased to 200 MW, as explained in Section 6.2.1.

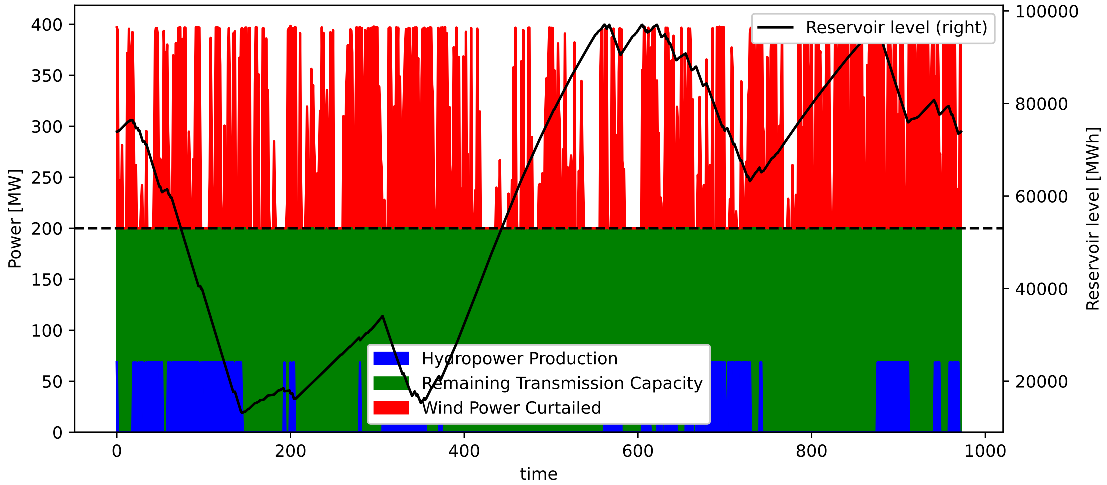



**Figure 7.7:** Resulting system simulation for Pareto solution 0 - Weight 5.

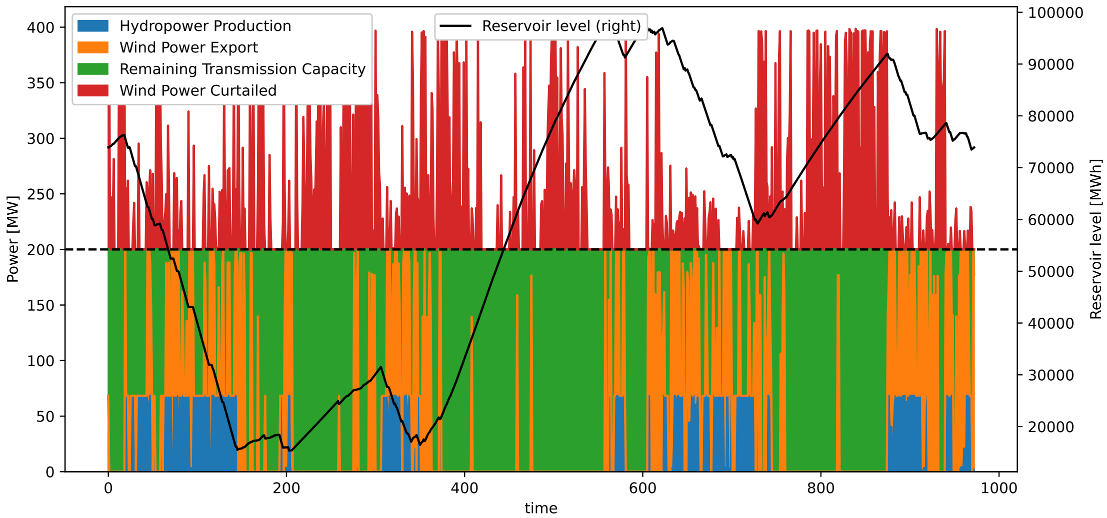



**Figure 7.8:** Resulting system simulation for Pareto solution 18 - Weight 3.

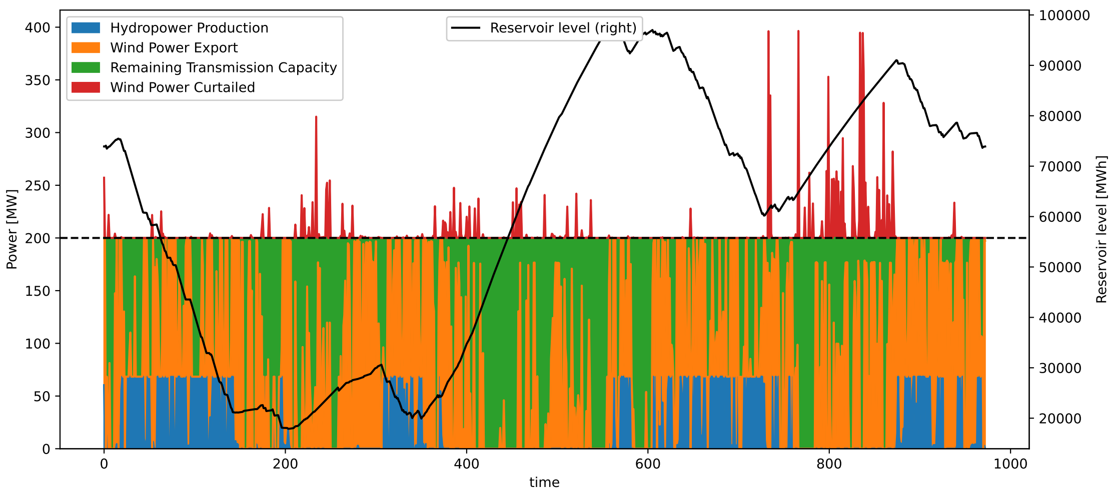



**Figure 7.9:** Resulting system simulation for Pareto solution 45 - Weight 2.

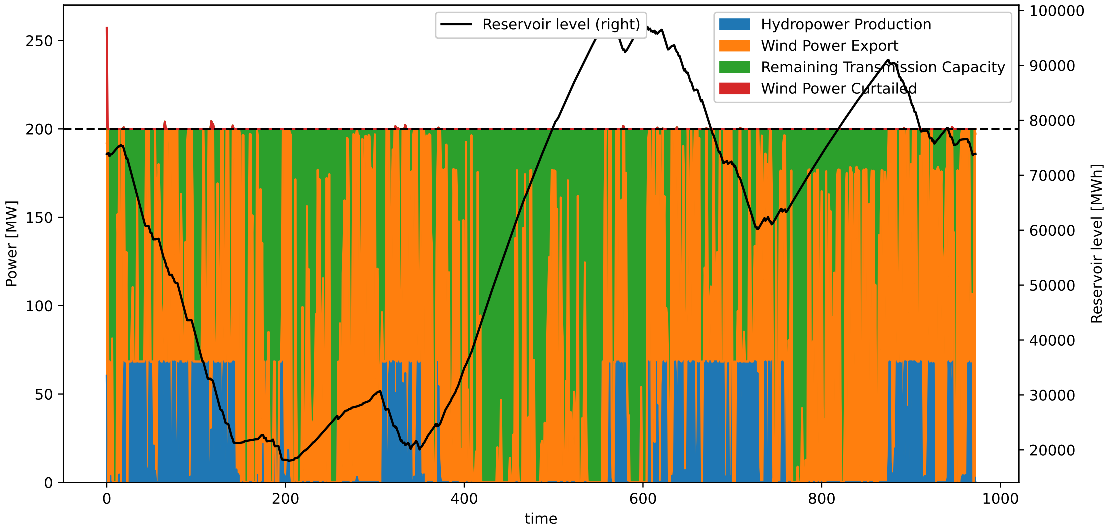



**Figure 7.10:** Resulting system simulation for Pareto solution 49 - Weight 1.

Figure 7.11 displays the resulting power references used for the optimal solution of Weight 1. The power reference demonstrates significant variability throughout the simulation. Similarly, for the optimal solution with an equal weight between objectives (Weight 3), the applied power reference also varies, as shown in Figure 7.12. However, it is observed that power production is more often not initiated, as this causes high damage. It should be noted that during certain hours, the wind speed is outside of the operating range of the wind turbine, resulting in no wind power generation across all scenarios.

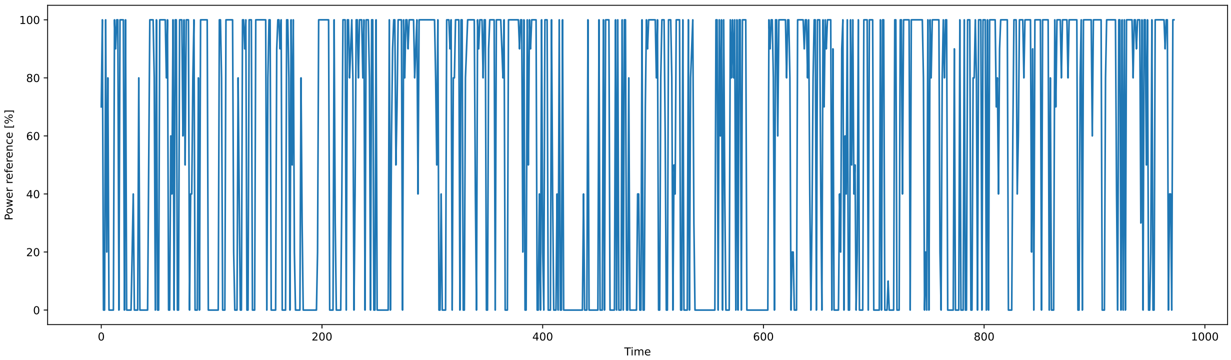



**Figure 7.11:** Power reference throughout simulation for Pareto solution 49 - Weight 1.

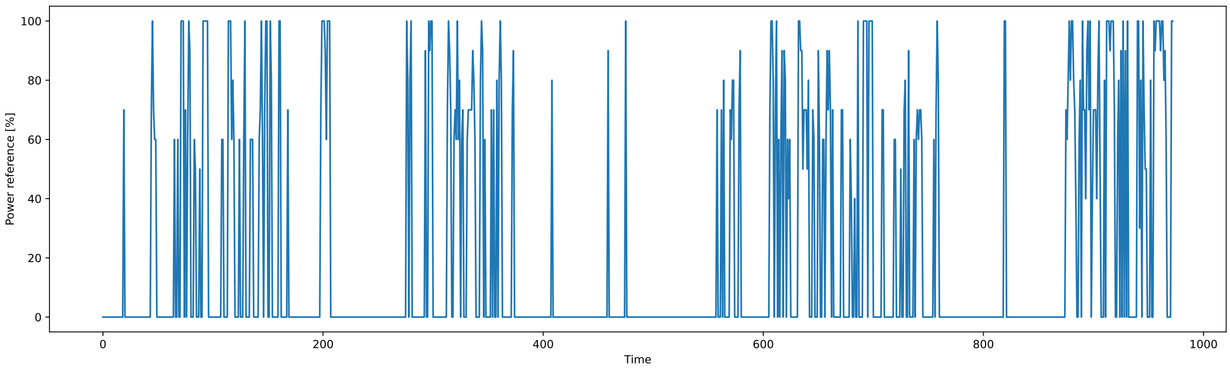



**Figure 7.12:** Power reference throughout simulation for Pareto solution 18 - Weight 3.

### 7.2.5 Relative Comparative Analysis

In Figure 7.13 the Pareto solution achieving the highest total utility value is chosen for every weight, and its relative outcome on the two different objectives is presented. Where Pareto solution 0 is used as a reference point for the other candidates, optimizing the total revenue, resulting in revenue of 35.19 MEUR and 4045.66 damage.

| | Weight 1 | Weight 2 | Weight 3 | Weight 4 | Weight 5 |
|---|---|---|---|---|---|
| **Relative damage** | 0.0 % | -8.2 % | -63.3 % | -95.9 % | -100.0 % |
| **Relativ revenue** | 0.0 % | -1.5 % | -26.8 % | -61.7 % | -74.3 % |

**Figure 7.13:** Relative results of different candidates

Based on this comparative analysis, different trade-offs between total revenue for the hybrid system and damage accumulation for the wind turbines can be presented to the decision-makers. The results from Weight 2 show that a significant improvement in the damage objective (8.2%) can be achieved with a relatively minor decrease in revenue (1.5%). Similarly, shifting from Weight 5 to 4 yields a substantial increase in revenue (12.6%) for a relatively modest increase in damage (4.9%).

# Chapter 8

# Discussion

The flexibility and reliability of power generation is a reoccurring theme in recent literature, as the energy sector is going through a transition of renewable energy sources replacing conventional power plants. In this matter, utilizing the flexibility that hydropower can provide through technologies such as PHS, as well as optimizing the coordination of the VRES are vital factors. Additionally, efficient control of the power plants optimizing their production, and providing stable and reliable power are important aspects for the power producers and system operators. [3]

This section provides a discussion of the results from applying the proposed framework to the case study and the literature review conducted on the power grid and market, wind power, hydropower, and optimization techniques. The subsequent sections will answer the questions outlined in the problem description, section 1.2, in relation to the potential benefits and drawbacks considering relevant technical and business aspects.

## 8.1 Business Aspects for Power Producers

The results obtained from both the analysis on the inclusion of a PHS system and the multi-objective analysis with wind farm control dynamics showcase the potential benefit of optimal coordination between different power plants in congested areas. The optimization in the conducted case study assumes a common owner for the power plants, treating it as a hybrid system. However, power plants often have different stakeholders with different incentives in their decision-making. This makes the process of optimal overall coordination and operation of the power plants a challenging task in real-case applications. The different interests and objectives of stakeholders can be difficult to quantify, making it challenging to find appropriate compensation that satisfies all parties involved.

Large power producer companies may have ownership of several power plants within the congested area, making the process of coordination easier to put into practice. However, the power plants do often have different owners. This also instigates issues concerning the prioritization of transmission capacity and settling on a price for wind power utilized directly by the pump.

The application of the multi-objective framework in this study can facilitate the decision-making process by presenting the decision-makers with various optimal options corresponding to different weighting of objectives. As shown in Figure 7.5 and Figure 7.6, different solutions can be applied based on the priority of the decision-makers. Further, by analyzing the outcomes derived from various strategies/weights, as demonstrated in Figure 7.13, it becomes possible to establish suitable trade-offs and compensations between different objectives among the involved parties.

## 8.2 Stability and Balancing Issues from VRES

The literature underlines the need for coordination and provision of flexibility in order to facilitate the increasing penetration of VRES. This is causing a high innovation in the field of flexible operation, providing ancillary services and power storage technologies. Among these are options of control, digitalization and hydro storage mentioned in section 4.2. [3]

As the VRES', in most cases, is decoupled through power converters, they are usually unable to provide inertia or load-frequency control. This results in a reduction of system inertia, causing a faster frequency drop rate during load events. Hydropower plants constitute a key part of the transition towards a higher share of renewable sources in the energy sector. Norway holds a unique position due to its primary reliance on hydroelectric power as the main source of electrical energy, granting significant flexibility to the system. However, as the share of VRES' like wind and solar power are increasing, issues of balancing may need more consideration. Furthermore, Norway is progressively establishing more interconnections with wind-dominated continental Europe, wherein hydropower functions to a certain extent as a vital energy storage mechanism or "battery" for the broader continental European grid. In the preparation for this, the optimal coordination and control of power production play a significant role. [3]

## 8.3 Coordination of Power Operation and Market Possibilities

The market serves well to obtain optimal coordination between the various participating power producers to satisfy the demand. However, when there is congestion within a price area, applying measures for optimal coordination becomes a relevant topic.

The current NEM legislation grants existing power plants prioritization of transmission in areas with limited transmission capacity. New power plants may have to wait for upgrades of necessary transmission capacity to be able to produce without any concerns of congestion, only using the remaining capacity from the prior power plants. In Norway, the newly established power plants primarily consist of wind farms, while the majority of the existing plants are hydropower plants. Consequently, in accordance with NEM regulations, hydropower plants are granted transmission priority, which results in the potential flexibility offered by hydropower not being fully utilized. Due to their dependence on ambient conditions and limited options to store energy, wind farms lack the same degree of flexibility, potentially leading to the curtailment of surplus energy.

Furthermore, the VRES may need external flexibility options due to unpredictable power production from varying ambient conditions. This may be done through the balancing markets as described in subsection 2.3.2. Another option is to make agreements of balancing power between different power plants. UPPAs, presented in subsection 2.3.3 serve as an option for this, forming a contract where a third party takes upon the balancing responsibility of a VRES.

The market may also serve additional possibilities for the power producers to achieve higher revenues, as the intraday- and balancing markets are becoming more influential in the power market. The NBM aims to enable a more market-based and automated approach to the balancing process, which may attract more investments to increase flexibility. Participating in the balancing markets for the hybrid system may be economically attractive. However, the market possibilities may be subject to some limitations in this case, as the current model concerns power plants sharing a limited transmission capacity. [3]

## 8.4 Benefits of Utilizing a PHS

The coordination between power plants and the integration of a PHS can result in substantial economic benefits from the enhanced flexibility it may offer. The power prices have been varying a lot in recent years and are predicted to vary even more as the share of VRES continues to increase. A PHS may utilize the daily and hourly variations in the power prices by operating the pump at times of relatively low power prices. Further, seasonal variations can be utilized by pumping and storing water during the low-demand season, and subsequently utilizing the stored water from the reservoir for power generation during the high-demand season. The increased flexibility from PHS significantly enhances the system's capability to participate in the mentioned intra-day and balancing markets, thereby potentially resulting in higher revenues.

In this study, the use of a PHS system is investigated. The findings presented in section 7.1 demonstrate a significant benefits from utilizing a PHS. The pump is actively used to store energy and shift the power production to times of high prices following the high demand periods. This results in a higher income for the power plant. The wind energy curtailment is also reduced by using the PHS, as the hydro pump is able to utilize some of the surplus wind power potentials. The extent of this is highly dependent on the limiting transmission capacity. However, the impact on grid utilization is relatively limited. One of the primary factors contributing to this may be the energy losses associated with pumping water to the upper reservoir. [3]

In order to be fully able to utilize the hourly and daily variations in power prices, a variable speed pump can be used, providing additional flexibility to the PHS. Still, the results of the case study only showed slight economic benefits when using a variable speed pump in comparison to a fixed speed pump. However, it is worth mentioning that the simulations do not take into account the potential benefit of a variable speed pump in terms of controlling the speed towards the turbine's optimal efficiency point. Thereby, the variable speed pump will increase the operating efficiency and lifetime of the turbine, resulting in economic benefits to be made. Additionally, it may have great value for the system operator, providing additional flexibility and enhancing the provision of ancillary services. [3]

## 8.5 Wind Farm Control Strategies

There are several relevant objectives to consider when designing a control system, some of these have been presented in section 3.3. In this study, only the revenue and damage are considered in the optimization, as the operator is provided different options of power references with a corresponding power output and damage. The power output and damage are dependent on the ambient conditions for wind speed and direction. Further, the turbulence impacts the resulting wind at each wind turbine. This is being affected by the wakes from other upstream turbines, which again is influenced by the wind farm layout and the control settings. One option is to de-rate the wind turbines to reduce the total damage accumulation of the wind farm. However, the results presented in Figure 7.13 show that this causes a substantial reduction in the total revenue, as potential wind power is being curtailed.

The extent of accumulated damage is mainly determined by wind speed, turbulence intensity, and active power control. In order to mitigate the load of the wind farm, the control strategy has a tendency to derate the upstream turbines to a greater extent than the downstream turbines to achieve the reference power output. This is to mitigate the higher damage potential at upstream turbines compared to downstream turbines caused by the wake velocity deficit that dominates the wake-induced turbulence.

Greater flexibility in the various control options aiming to mitigate and minimize turbine damage is achieved when the power reference for the wind farm is reduced below the available power determined by the current wind conditions. The example from wind farm control simulations in Figure 6.10 and 6.11 supports this. The flexibility provides options for the operator to select the optimal power setpoint, taking into consideration their preferences and priorities at the time. The optimal decision at each time step can differ due to the varying benefits associated with the two conflicting objectives, which are influenced by factors such as varying power prices and ambient wind conditions. Furthermore, the limiting set of capacities in the system can impact the optimal power reference, as the optimization process takes into account relative long-term scenarios. This is exemplified in Figure 7.11, which displays the varying applied power references at each time step.

## 8.6 Appropriate trade-offs between damage and revenue objectives

There are several benefits achieved by reducing the damage accumulation in wind turbines. Among them are, a longer operational lifetime of the wind turbines, reduced maintenance costs, reduced outages and better long-term operational efficiency. However, these may be hard to quantify. Additionally, the benefits may not be apparent before a long time has passed. As the investors may want fast returns on their investments and are concerned with liquidity, the revenue from the current power production is likely to be granted a greater priority.

However, the results presented in Figure 7.5, 7.6 and 7.13 demonstrate the significant relative benefits that can be achieved by looking into the Pareto optimal solutions and selecting a preferred weight. The candidates presented in Figure 7.13 can assist decision-makers in identifying appropriate trade-offs between the two objectives.

## 8.7 Optimization Techniques for Power Operation and Coordination

In order to obtain the optimal operation and coordination of generating units, different techniques of optimization may be utilized. As the complexity and size of the problem can become very high for large power grids and long-term analyses, optimization algorithms finding an appropriate solution fast is essential. In the literature, various versions of the different optimization techniques are researched, some of the main ones are presented in section 5.2. These are deterministic, stochastic, and AI-based models. Extensive research has been conducted on the application of these methodologies across various domains, including optimization for wind and hydropower operations, as well as coordination in renewable energy systems. However, their practical use in the industry is more limited. Each optimization technique possesses its own set of advantages and drawbacks, which concerns the types of problems they can address, the computational time required for simulations, simplicity of method application, the precision of the obtained solutions, and flexibility and reliability for various scenarios. [3]

MILP and the stochastic models SDDP and SRHM are mostly applied in the planning and scheduling phase of wind and hydropower. Machine learning algorithms may also be applied for this purpose, in addition to the operation of the power plants. Moreover, MILP and machine learning algorithms have also been applied to solve multi-objective problems. [3]

The model considers a quite small system. However, the model simulates every hour of the year, making it computationally heavy. This is a major concern for the wind farm control part of the simulations, as simulations for various ambient wind speeds and directions that occur throughout the year are required. The inherent nature of the MOO problem described in section 6.5 causes few problems in obtaining linearity. However, some binary variables have been included to ensure one-directional power flow, and to determine the power reference at each time step. As a result, the model experiences a substantial increase in computational time. [3]

There are several possible extensions for the co-simulation framework. The model can be modified for a larger system, increasing the size and complexity of the problem. Among the other potential extensions is to also include different control options for the hydropower plant. Further implementing a more realistic power flow study, where an objective of power fluctuations/ ancillary services may be included in the MOO. this will also cause a substantial increase in the computation effort required. Furthermore, the optimization may include the uncertainties for the different input parameters using stochastic programming with water value calculations. Then, it becomes important to minimize the complexity of the model and identify efficient algorithms. [3]

## 8.8 Influence of Input Data

The input data of wind conditions, hydro inflow, and power prices are highly stochastic. The major influence this may have on the operation of the power plants is showcased by the different results using power prices from 2019 and 2021. As presented in Figure 7.3, the hydro pump is much more active when there are large variations in the power prices throughout the year. Further, this causes a higher income for the hydro plant as they have the possibility to store energy for times of higher power demand.

The hydro inflow and ambient wind data remain consistent across all simulations. However, this can vary from year to year, affecting the operational pattern. Periods of low inflow of water to the hydro plants have historically shown a significant impact on the power prices in Norway. In this case study the hydro inflow is represented by an average time-series based on historical data from 2011-2015. One consequence of this approach is that extreme scenarios from years characterized by either very high or very low inflow are not analyzed, which could potentially yield valuable insights into different situations that may arise.

Moreover, the input ambient wind data utilized by the wind farm control simulations are only based on historical data from one year. An alternative option would be to use average values obtained from historical data spanning several years. However, this would not present the full range of wind speeds that typically occurs during a year. Simulating the entire range of wind speeds, including both low and high magnitudes, throughout the year is an important factor in this study.

Climate changes can greatly impact wind conditions for the wind farms and inflow to the hydro reservoir. More extreme weather may increase the variations in available production. Further, increasing the need for energy storage, making options for enhancing flexibility more beneficial. However, this poses challenges in accurately predicting ambient conditions, thereby complicating the operation and coordination of power plants. Furthermore, the increasing share of RES in the market can cause higher variations in power prices as they are highly dependent on these conditions. This substantiates the significant need for accurate forecasting, along with the enhanced flexibility attained through the optimization of coordination and control strategies, as well as the utilization of energy storage technologies like PHS.

# Chapter 9

# Conclusion and Further Work

The results highlight the importance of coordinated operation and control strategies for maximizing the benefits of the power system. The results underline this with achieved improvements in revenue and curtailed energy. As well as illustrating the potential increase in the overall satisfaction of conflicting objectives by implementing the co-simulation multi-objective framework. The coordinated operation of wind and hydropower optimization strategies, supported by appropriate control strategies, is projected to deliver significant techno-economic advantages to Norwegian power market stakeholders such as the transmission system operator, and wind and hydropower plant operators.

The power market and grid constantly evolve, presenting challenges and opportunities for power producers and system operators. As the demand for power continues to grow and more power producers seek to connect to the grid, grid utilization and energy storage developments will be key factors in ensuring a reliable and cost-effective power system. New technologies and optimization techniques may also emerge, providing better control and flexibility options.

The installment of a PHS system greatly benefits the power plants' overall revenue and energy curtailment, with a resulting increase of 1.93% and 5.56%, respectively, using 2019 and 2021 power prices. The analysis has also demonstrated the impact of the input parameters, especially the ambient conditions of wind and hydro inflow. Moreover, the spot prices are evidently highly influential on the results, where the more varying price in 2021 shows a clear increase in the profitability of a hydro pump, with improvements reaching 9.63% compared to 2019 prices. Although the results of the simulations did not show a substantial economic benefit from using a variable speed pump, it is essential to acknowledge that the model did not take into account all factors that could influence the cost-effectiveness of its inclusion.

Currently, wind turbine damage is not widely considered for the daily operation of wind farms in the industry. By taking wind farm control dynamics into account, the accumulated damage to the wind turbines can be considered in the wind farm's operation. The decision-makers in this case study are presented with different optimal candidates depending on the multi-objective solutions provided by the co-simulation framework. By fully prioritizing the wind turbine damage, the total revenue is decreased by 74.3 % from its optimum value. As decision-makers often prefer fast returns on their investments, this option is likely to be unacceptable. A solution with weights favoring the revenue objective may be more applicable, resulting in a reduction of 8.2% from the maximum damage and only a reduction of 1.5% from the maximum total revenue.

Overall, the study highlights the importance of considering both technical and business aspects when optimizing the coordinated operation of RES. Further research is needed to fully understand the potential benefits and limitations of the model, and to identify strategies for improving its efficiency and application to real-world scenarios.

**Further work**

A more comprehensive study on relevant data for the wind farm and hydro plant can be performed. Especially considering the environmental aspects. Including restrictions on ramp-up rate, minimum level of the reservoir, and minimum and maximum discharge of water in the model. Environmental impact can also be included in the multi-objective function. However, an implementation using environmental constraints seems the most reasonable, as violating the restrictions can have severe consequences on the ecosystem. Additionally, a more comprehensive study on the stochastic nature of the input data used in the model can be considered. A possibility is to use average values of the power prices or predictive data, although accurate predictions are hard to obtain due to various unpredictable factors influencing the results. [3]

As the scheduling of power production is subject to uncertainties, this is a stochastic process. The current model considers perfect information. However, it can be interesting to explore the implementation of a more realistic model for both short-term and long-term scheduling of the PHS system. Furthermore, the forecast errors and their impact may be investigated. Additionally, the correlation between the hydro inflow, wind, and power prices is a relevant topic for the scheduling and forecasting of power plant operations. [3]

In order to reduce the computational efforts of the simulations, different measures may be applied. Different optimization techniques using machine learning applied in wind- and hydro operation can be further developed and extended with other common algorithms to obtain an appropriate optimal solution faster. Further, parallelized runs for the different wind conditions may be implemented to faster obtain the lookup table from wind farm control simulations. Moreover, the damage accumulation in the MOO may be represented by a function using interpolation or other methods in order to avoid many binary variables in the optimization.

Different control strategies for the wind farm may be investigated and compared to analyze the influence of each strategy on different objectives. Furthermore, control options for the PHS system can be included in further studies. Where performing a more comprehensive analysis on the provision of ancillary services may become relevant. This may be highly relevant for the system operators, further contributing options for different stability-enhancing objectives to the simulation model.

A power flow study may be implemented to analyze the interactions and impact between the hybrid system and the grid. This will also make an analysis regarding power system services and stability enhancement more applicable, considering fluctuations in voltage, frequency and power. Additionally, it can be considered to implement DLR of the transmission into the model, making the rating dynamically dependent on external factors such as weather conditions. Further, it may also be very interesting to investigate the DLR's correlation with hydro inflow, wind conditions and power prices.

The power plants may consider participating in other markets like the balancing market. The current case only considers the day-ahead market. But as other markets are becoming larger and more influential, adding this to case studies may improve the potential revenue of the power plants. [3]

A more comprehensive study of the economics involved can be made in order to better justify decisions on investments for the power producers and system operators. Especially considering the potential OPEX cost resulting from ware on the wind turbines. Furthermore, a sensitivity analysis can be performed to investigate the impact of input ambient conditions such as wind speed, wind direction, and inflow to the hydro plant, as well as power prices in the market. Additionally, the sensitivity of various limiting capacities and attributes within the system can be analyzed.

The case study could incorporate a local load in the area, which could be a flexible load. In industry and research, the production of "green" ammonia and hydrogen is emerging as a potential addition for remote areas. This may be used to utilize surplus energy, further serving as an alternative to expensive and time-consuming grid investments.

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# Chapter 10

# Appendix

## 10.1 A: MOLP Results

### 10.1.1 System simulations

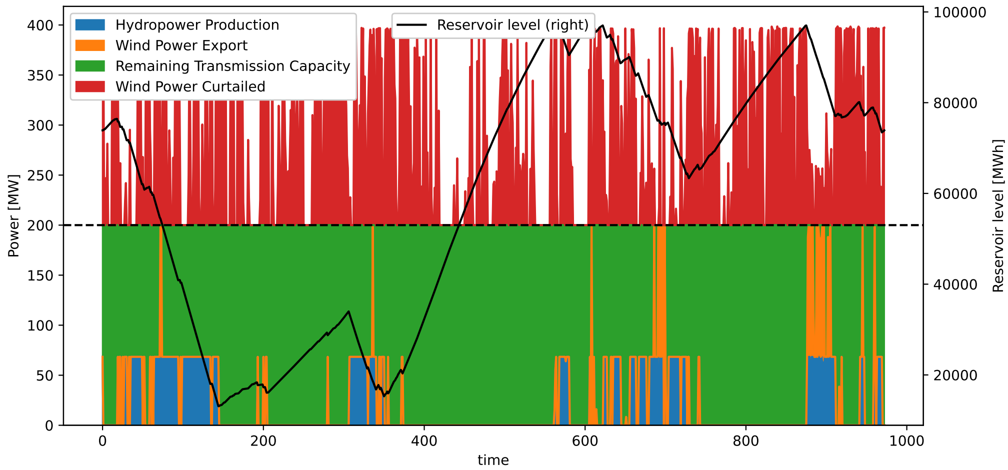


**Figure 10.1:** Resulting system simulation for Pareto solution 2 - Weight 4.

### 10.1.2 Pumping power

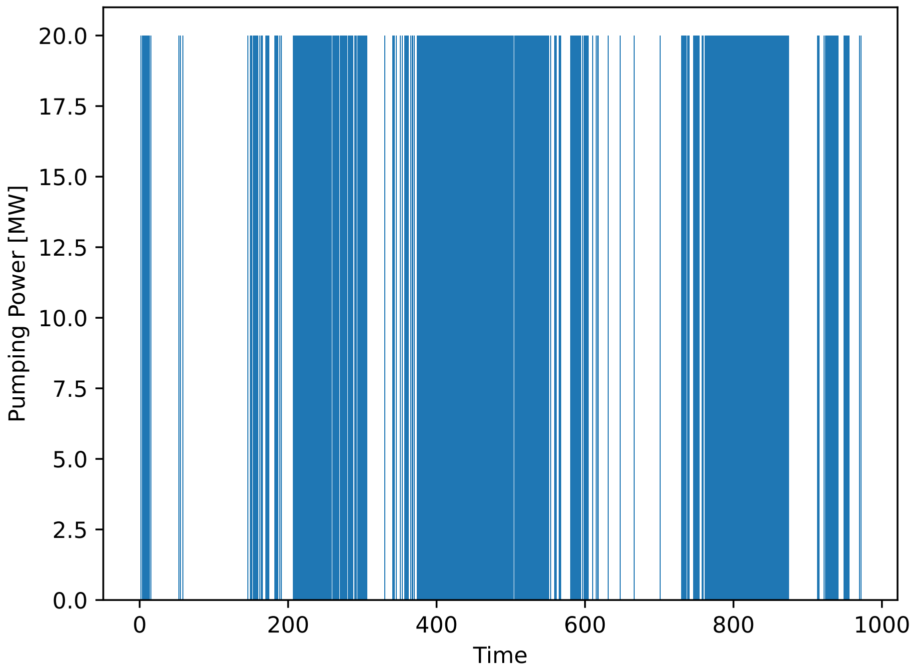


**Figure 10.2:** Resulting system simulation for Pareto solution 0 - Weight 5.

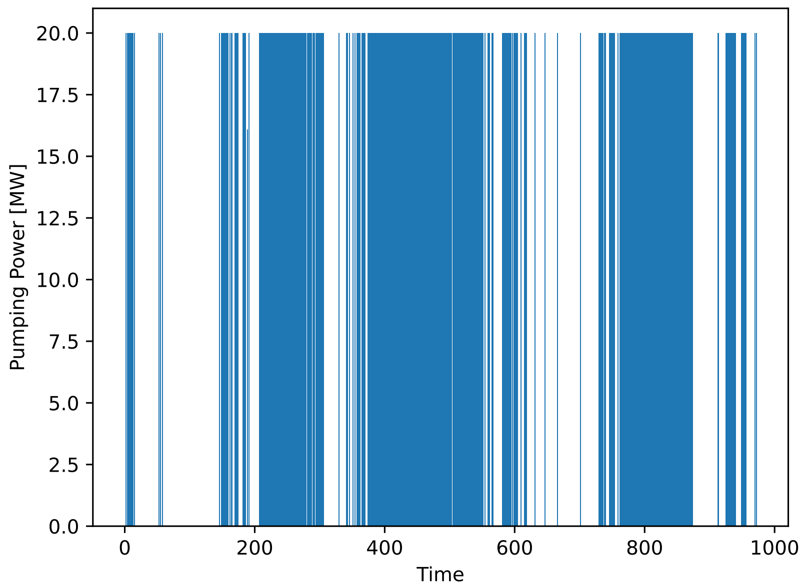


**Figure 10.3:** Resulting system simulation for Pareto solution 2 - Weight 4.

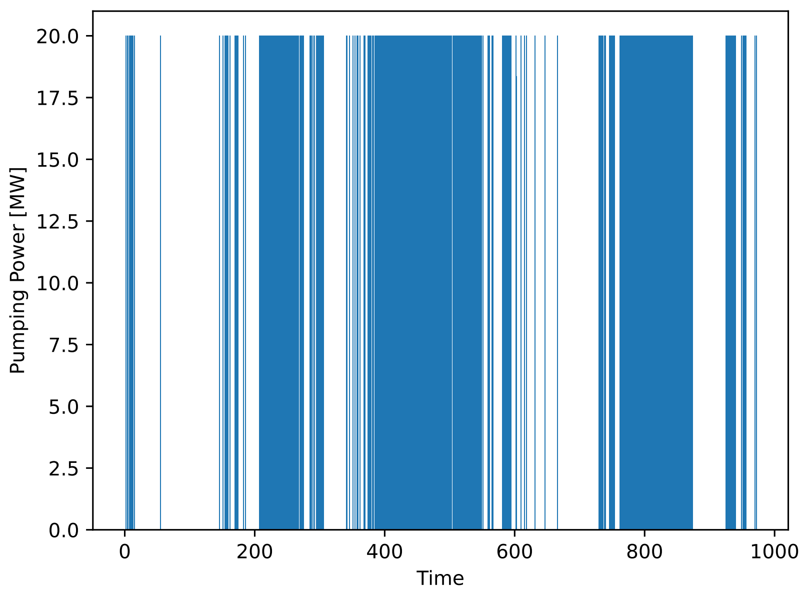


**Figure 10.4:** Resulting system simulation for Pareto solution 18 - Weight 3.

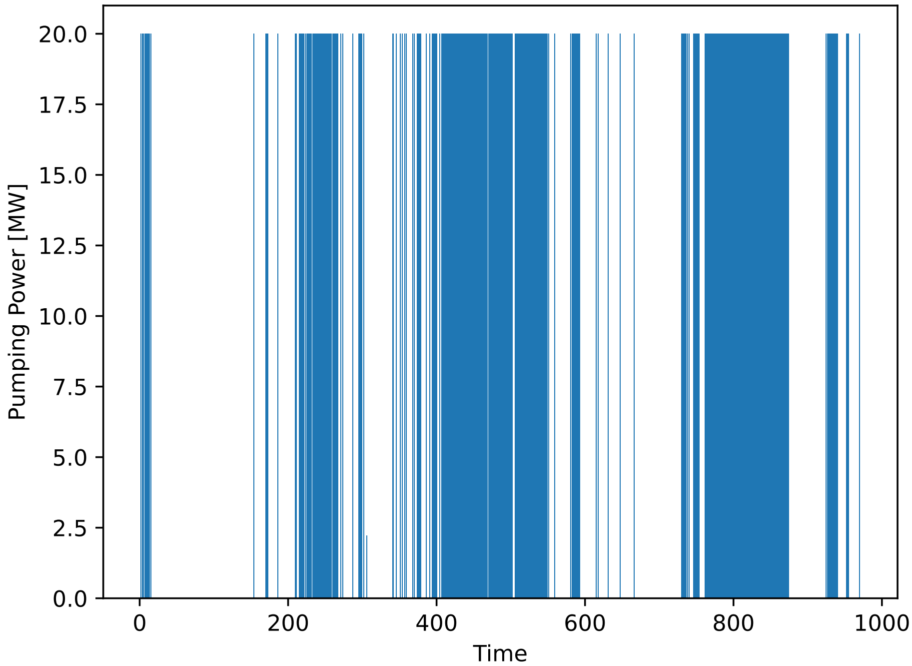


**Figure 10.5:** Resulting system simulation for Pareto solution 45 - Weight 2.

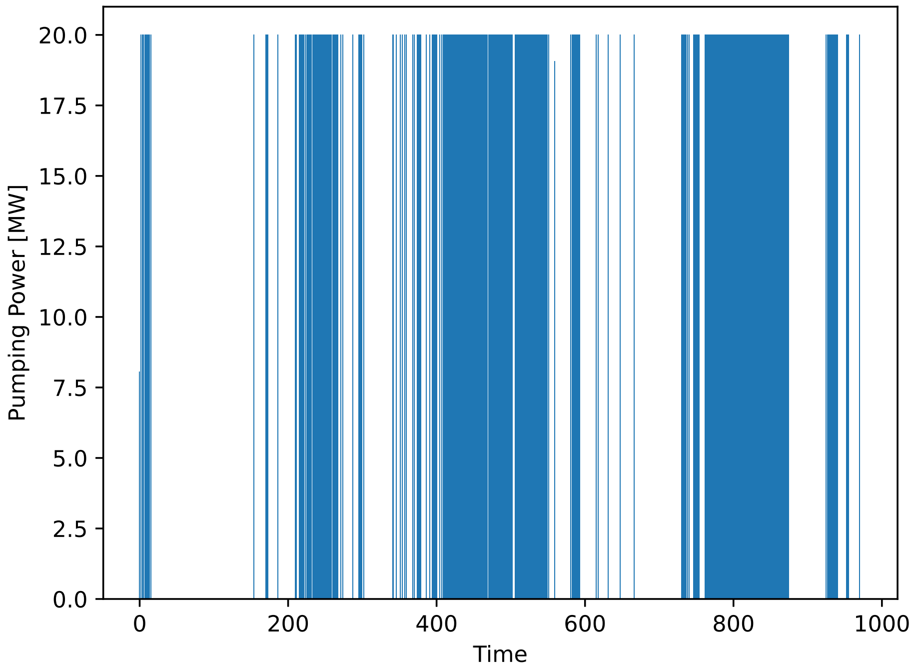


**Figure 10.6:** Resulting system simulation for Pareto solution 49 - Weight 1.

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