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Storage, Transmission, and Renewable Interactions in the Nordic Grid

Farzad Hassanzadeh Moghimi

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Abstract

The deep decarbonisation of the power sector emphasises the urgent need for the increased integration of variable renewable energy (VRE) sources such as wind and solar power. While VRE provides emission-free and cost-effective energy in its operations, its intermittent production necessitates the utilisation of variation-management mechanisms, such as storage, transmission, and demand-side response. In this context, the Nordic countries aim for strategic leadership in navigating the complexities of the sustainable-energy transition by leveraging existing flexible capacities, particularly hydro reservoirs.

However, flexible producers, such as hydro capacities, may have incentives that differ from those of society in a deregulated electricity industry such as that of the Nordic region. Large power companies may have enough flexible capacity to manipulate electricity prices through their own generation output. Empirical analyses of the Nordic electricity market based on data from 2011 to 2013, for instance, have identified signs of market power exercised by hydro and fossil-fuelled producers in Swedish price zones. This market power could increase in a future power system with higher VRE output that needs more flexibility. Furthermore, the dynamics introduced by CO2 pricing, combined with the emergence of prosumers, who are agents engaged in both electricity consumption and generation, may bolster firms' scope for strategic behaviour, thereby exacerbating unfavourable economic and environmental outcomes.

Simultaneously, policymakers face the formidable challenge of integrating intermittent output from VRE, even in a well-functioning power sector with flexible generation. Focusing on transmission planning is critical for integrating VRE effectively. Proactive transmission expansion allows transmission system operators (TSOs) to balance supply and demand across regions with complementary VRE profiles, reducing reliance on hydropower producers who might exert market power. However, the misalignment of incentives between producers and society, compounded by political constraints that prevent the accurate pricing of CO2 emissions according to social costs, complicates the challenging landscape of decarbonisation. Therefore, transmission planning must be proactively recalibrated to account for economic and environmental distortions to mitigate welfare losses from imperfect competition and incomplete CO2 pricing.

This thesis utilises a game-theoretic framework to capture the behavioural dynamics of agents and the optimal transmission-expansion strategy in a VRE-dominated power system. Such an approach reflects the complex interactions between firms' strategic incentives and climate-policy imperatives, thereby en- abling a thorough understanding of the complex challenges of transitioning to a decarbonised power system.

Keywords: *Electricity markets, Environmental policy, Game theory, Hydropower, Market power, Transmission planning.*

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To my family.

Abstract

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between firms' strategic incentives and climate-policy imperatives, thereby enabling a thorough understanding of the complex challenges of transitioning to a decarbonised power system.

Sammanfattning

En utfasning av fossila bränslen i energisektorn leder till ett behov av ökad proportion av förnybara energikällor (VRE – variable renewable energy) som vindkraft och solkraft. Sådana energikällor erbjuder utsläppsfri och kostnadseffektiv energi men har en så kallad intermittent energiproduktion vilket kräver mekanismer för hantering av produktionsvariationer och effekt i form av lagring, överföring och efterfrågerespons. I detta sammanhang strävar de nordiska länderna efter strategiska angreppsätt för att navigera i de komplexa utmaningarna som övergången till hållbar energi skapar genom att utnyttja befintliga flexibla energikällor och då särskilt vattenkraftreservoarer som är en reglerbar energikälla. Flexibla producenter med tillgång till i synnerhet vattenkraft kan därmed ha incitament som skiljer sig från samhällets i en avreglerad elmarknad som den nordiska i form av att stora elbolag kan ha möjlighet att styra över tillräckligt med flexibel kraftproduktion för att manipulera elpriser genom sin egen produktionsvolym. Empiriska analyser av den nordiska elmarknaden, baserade på data från 2011 till 2013, har till exempel identifierat tecken på sådan marknadsmakt som utövats av vattenkraft- och fossildrivna producenter i svenska prisområden. Denna marknadsmakt kan då öka i ett framtida elsystem med högre andel VRE-produktion som kräver mer flexibilitet. Vidare kan dynamiken som introduceras av CO_2-prissättning, i kombination med framväxten av så kallade prosumenter – aktörer som både konsumerar och producerar el – öka företagens möjligheter till ett marknadsbeteende som förvärrar negativa ekonomiska och miljömässiga effekter. Samtidigt står beslutsfattare inför den betydande utmaningen att integrera intermittent produktion i en fungerande energisektor med flexibel produktion, där planering av överföringsnät är avgörande för att effektivt integrera intermittent produktion från förnybara energikällor. Proaktiv utbyggnad av överföringskapacitet gör det möjligt för systemoperatörer (TSO:er) att balansera utbud och efterfrågan mellan regioner med kompletterande VRE-profiler, vilket minskar beroendet av vattenkraftproducenter som kan utöva marknadsmakt. Emellertid kompliceras landskapet för dekarbonisering av missanpassningen mellan producenternas och samhällets incitament, i kombination med politiska begränsningar som förhindrar korrekt prissättning av CO_2-utsläpp enligt dess samhällskostnader. Därför måste planeringen av överföringsnät proaktivt kalibreras för att hantera ekonomiska och miljömässiga snedvridningar och minimera välfärdsförluster till följd av ofullständig konkurrens och ofullständig CO_2-prissättning. Denna avhandling adresserar detta genom att tillämpa ett spelteoretiskt ramverk för

att fånga aktörernas beteendedynamik och den optimala strategin för utbyggnad av överföringskapacitet i ett VRE-dominerat elsystem. Ett sådant tillvägagångssätt speglar de komplexa interaktionerna mellan företagens strategiska incitament och klimatpolitiska målsättningar, vilket möjliggör en djupgående förståelse av utmaningarna i övergången till ett koldioxidfritt elsystem.

Acknowledgements

Completing this dissertation has been an extraordinary journey, one that would not have been possible without the incredible support and encouragement I have received along the way.

First and foremost, I would like to express my deepest gratitude to my main supervisor, Afzal S. Siddiqui, for his invaluable guidance, encouragement, and unwavering support throughout my PhD journey. His insightful advice, patience, and belief in my potential have been instrumental in shaping both this dissertation and my development as a researcher. I am also sincerely grateful to my second supervisor, Aron Larsson, whose thoughtful guidance and constant support have significantly contributed to the success of this research.

I would also like to extend my heartfelt thanks to my co-authors, Trine K. Boomsma, Yihsu Chen, Lina Reichenberg, and Hanna Ek Fälth, for their collaboration and valuable contributions to my work. Their ideas and shared expertise have enriched this research and helped me grow as an academic.

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To my family and my friends, thank you for your unwavering support, patience, and belief in me. Your encouragement kept me grounded during challenges, and your presence, whether through practical help, honest conversations, or simply being there, gave me the resilience to keep moving forward. This achievement belongs to all of us, shaped by your quiet strength and endless generosity.

To everyone who has stood by me and contributed to this journey in ways big and small, thank you. This dissertation is a reflection of the guidance, support, and love I have been fortunate to receive.

List of Papers

The following papers, referred to in the text by their numbers, are included in this thesis.

Paper P1: **Climate Policy and Strategic Operations in a Hydro-Thermal Power System**
Farzad Hassanzadeh Moghimi, Hanna Ek Fälth, Lina Reichenberg, Afzal S. Siddiqui, *The Energy Journal*, v. 44, no. 5, pp. 67–94, 2023,
DOI: https://doi.org/10.5547/01956574.44.4.fmog

Paper P2: **Aggregator-Enabled Prosumers' Impact on Strategic Hydro-Thermal Operations**
Farzad Hassanzadeh Moghimi, Yihsu Chen, Afzal S. Siddiqui, *Proceedings of the 56th Hawaii International Conference on System Sciences*, pp. 2693–2702, 2023,
DOI: https://hdl.handle.net/10125/102963

Paper P3: **Flexible Supply Meets Flexible Demand: Prosumer Impact on Strategic Hydro Operations**
Farzad Hassanzadeh Moghimi, Yihsu Chen, Afzal S. Siddiqui, *Computational Management Science*, v. 20, no. 1, art. 23, 2023,
DOI: https://doi.org/10.1007/s10287-023-00455-1

Paper P4: **Transmission Planning in an Imperfectly Competitive Power Sector with Environmental Externalities**
Farzad Hassanzadeh Moghimi, Trine K. Boomsma, Afzal S. Siddiqui, *Energy Economics*, v. 134, art. 107610, 2024,
DOI: https://doi.org/10.1016/j.eneco.2024.107610

Author's Contribution

Paper P1: **Climate Policy and Strategic Operations in a Hydro-Thermal Power System**

- Farzad Hassanzadeh Moghimi: As the lead author, Hassanzadeh Moghimi developed the Nash-Cournot model used in the study to analyse the strategic operations. He conducted the simulations, analysed the results, and wrote the manuscript, offering key insights into the implications of climate policy on hydro-thermal power systems.
- Hanna Ek Fälth: Fälth contributed to the development of the model and scenario analysis, particularly in relation to the integration of variable renewable energy (VRE) sources. She played a crucial role in reviewing the manuscript and providing feedback on the economic modelling.
- Lina Reichenberg: Reichenberg assisted in the formulation of the model's technical aspects and contributed to the interpretation of the results, particularly regarding the market dynamics of the Nordic power system and the potential impacts of climate policy.
- Afzal S. Siddiqui: Siddiqui supervised the research and provided general guidance on the formulation of the study. He contributed to the interpretation of the results, particularly in terms of market power and climate policy.

Paper P2: **Flexible Supply Meets Flexible Demand: Prosumer Impact on Strategic Hydro Operations**

- Farzad Hassanzadeh Moghimi: As the primary author, Hassanzadeh Moghimi conceptualised the study and formulated the research questions. He developed the Nash-Cournot model and conducted the numerical simulations. He was responsible for analysing the results and drafting the manuscript.
- Yihsu Chen: Chen provided key insights into integrating VRE dynamics into the modelling framework and contributed to the review and editing of the manuscript.

- Afzal S. Siddiqui: Siddiqui contributed to the study's methodological development and supervised the overall research process. He reviewed the manuscript and provided critical feedback on its refinement.

Paper P3: **Aggregator-Enabled Prosumers' Impact on Strategic Hydro-Thermal Operations**

- Farzad Hassanzadeh Moghimi: Hassanzadeh Moghimi took the lead in formulating the mathematical model, implementing the computations, and designing the experimental scenarios. He collected the data, performed the analysis, and wrote the manuscript.
- Yihsu Chen: Chen assisted in refining the model and ensuring the inclusion of aggregator-enabled prosumers in the analysis. He contributed to the discussion and provided valuable feedback on manuscript drafts.
- Afzal S. Siddiqui: Siddiqui proposed the topic and supervised the research. He provided key feedback on the interpretation of the findings and helped refine the manuscript.

Paper P4: **Transmission Planning in an Imperfectly Competitive Power Sector with Environmental Externalities**

- Farzad Hassanzadeh Moghimi: Hassanzadeh Moghimi developed the Stackelberg model, conducted scenario analyses, and carried out the computational simulations. He was responsible for interpreting the results and drafting the manuscript.
- Trine K. Boomsma: Boomsma contributed to the design of the mathematical framework and offered feedback on the model formulation. She provided comments on the manuscript.
- Afzal S. Siddiqui: Siddiqui supervised the research, proposed the topic, and contributed to the interpretation of results in the context of policy and market dynamics. He reviewed and refined the manuscript.

Contents

Abbreviations

C&T	Cap and Trade
COG	Cournot Oligopoly in Thermal Generation
COR	Cournot Oligopoly in Reservoirs
DC	Direct Current
DER	Distributed Energy Resources
DR	Demand Response
DSR	Design-Science Research
EPEC	Equilibrium Problem with Equilibrium Constraints
ETS	Emissions Trading System
EU	European Union
FAIR	Findable, Accessible, Interoperable, and Reusable
GAMS	General Algebraic Modelling System
GTEP	Generation-and-Transmission-Expansion Planning
ISO	Independent System Operator
KKT	Karush-Kuhn-Tucker
LP	Linear Programming
MATLAB	Matrix Laboratory
MCP	Mixed-Complementarity Problem
MILP	Mixed-Integer Linear Programming
MIQP	Mixed-Integer Quadratic Programming
MPEC	Mathematical Program with Equilibrium Constraints
NLP	Non-Linear Programming
O&M	Operations and Maintenance
OECD	Organisation for Economic Co-operation and Development
OR	Operational Research
PC	Perfect Competition

PEV	Plug-in Electric Vehicle
QP	Quadratic Programming
RPS	Renewable Portfolio Standard
SDDP	Stochastic Dual Dynamic Programming
SFE	Supply-Function Equilibria
TSO	Transmission System Operator
VRE	Variable Renewable Energy

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1. Introduction

This chapter briefly introduces the thesis, starting with an overview of the power system's landscape and the rise of variable renewable energy (VRE). It outlines the motivations for studying VRE integration, including sustainability and climate-change concerns. The research aims, questions, and expected contributions are presented, followed by a brief discussion of the thesis's organisation.

1.1 Background

Motivated by the imperative to address climate change, numerous Organisation for Economic Co-operation and Development (OECD) governments are embracing energy and infrastructure initiatives often referred to as 'Green Deals', which generally include measures to support the decarbonisation of the power sector. For example, future climate packages foresee a rapid expansion of VRE capacity, viz., wind and solar, in European power systems, along with the electrification of heating and transport sectors. This trend is particularly pronounced in the Nordic region, where sustainability commitments are deeply rooted. Notably, Sweden has set a target for carbon neutrality by 2045 [1], aligning with the European Union's ambitious aim to achieve at least a 55% reduction in CO_2 emissions by 2030 relative to 1990 levels [2]. However, attaining these ambitious climate goals necessitates a transformation of the power sector.

Due to its intermittent nature (see Figure 1.1[1]), VRE necessitates variation management from storage, transmission, and demand-side response. While this observation applies to most industrialised countries [3], the Nordic region differs in one important aspect: a vast hydropower system comprising 96% and 46% of the power capacity in Norway and Sweden, respectively [4]. Consequently, the substantial hydro capacity, coupled with transmission interconnections, can potentially alleviate the impact of intermittent VRE output in the Nordic region.

The Nordic region possesses abundant fossil-free power capacity, viz., hydro, nuclear, and VRE, and zonal integration, making it well positioned to decarbonise its power sector. Consisting of Denmark, Finland, Norway, and Sweden, subdivided into distinct price zones like $DK1$–$DK2$, FI, $NO1$–$NO5$,

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[1] `https://skat.dk/skat.aspx?oid=2276646`

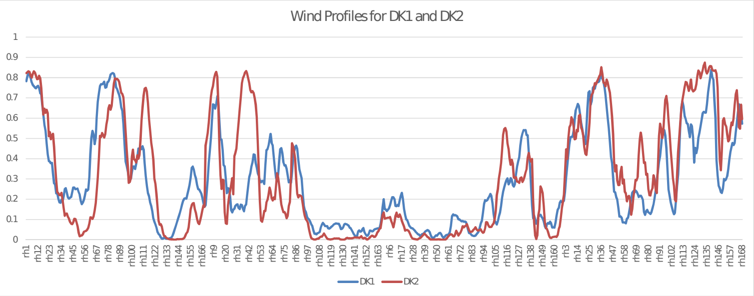

Figure 1.1: Wind Profiles in Representative Weeks of the Year 2018 for *DK*1 and *DK*2.

and *SE*1–*SE*4, respectively, all countries feature wind and solar capacities (see Figure 1.2).[2] From this perspective, meeting future climate targets by integrating VRE should be manageable for the Nordic region. Yet, despite the Nordic market being deemed well functioning according to [6], empirical studies [7; 8] reveal evidence of market power. The enhanced need for flexibility due to VRE penetration could bolster the leverage of firms with assets such as hydro.

The VRE capacities not only produce intermittent energy but also are often located far from consumption centres. As [5] highlights, the peak-to-average output ratios for VRE sources like solar and wind (often 3:1 or higher) significantly exceed those of nuclear plants (typically around 0.9:1). This discrepancy may increase the risk of VRE curtailment with generation-capacity expansion. Consequently, the current transmission infrastructure may be insufficient to support higher shares of VRE generation. While demand and supply flexibility can help balance the temporal intermittency of VRE, expanding the transmission capacity can address spatial imbalances and help absorb excess VRE output. Moreover, the fact that Sweden had a general CO_2 tax of €106/t in 2018,[3] while the EU emissions trading system (ETS) price was €15/t in the same year, indicates incomplete CO_2 pricing, i.e. the partial internalisation of the social cost of damage into market players' decision-making problems, in sectors covered by the EU ETS. This suggests that the higher Swedish CO_2 price in sectors not covered by the EU ETS is very likely to be a better indicator of the social cost of damage. From this perspective, a socially optimal transmission plan based on cost minimisation [9] matches the marginal benefits and marginal costs of transmission expansion.

Well-designed carbon pricing can guide economic decisions, prompting a

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[2] For instance, VRE comprises over 50% of the installed capacity in Denmark, while hydropower comprises 96% and 46% of the installed capacity in Norway and Sweden, respectively. Also, the aggregate reservoir volumes in Finland, Norway, and Sweden are 5,530 GWh, 82,224 GWh, and 33,758 GWh, respectively.

[3] `https://www.government.se/government-policy/swedens-carbon-tax/swedens-carbon-tax/`

shift towards renewables and curbing consumption to more efficiently allocate the existing resources. However, the distortion of CO_2 pricing in response to political pressure may derail incentives for decarbonisation and necessitate more proactive transmission planning [13]. Hence, despite its generally desirable characteristics, the Nordic region exhibits evidence of both imperfect competition and incomplete CO_2 pricing.

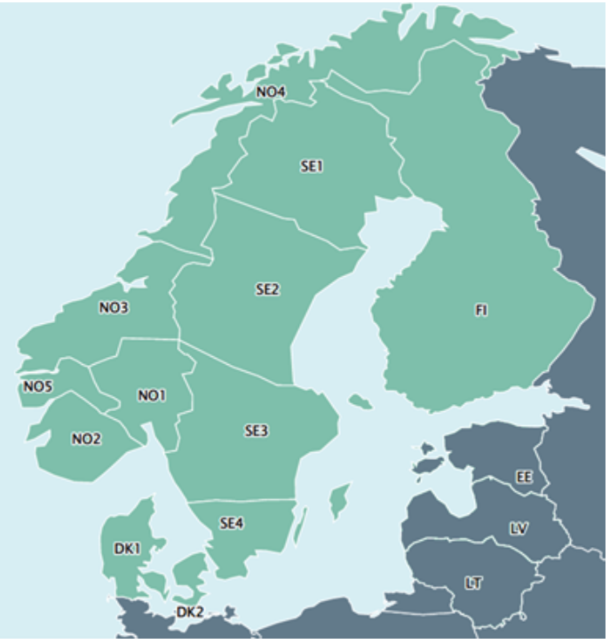

Figure 1.2: Map of the Nordic Pricing Zones.[4]

The deregulation of the electricity industry in most industrialised countries [10], such as the Nordic countries, implies that the investment and operational decisions of generation are driven by profit-maximising firms, in contrast to the regulated transmission system due to its natural-monopoly characteristics. Indeed, a transmission system operator (TSO) is responsible for welfare-maximising transmission expansion. As a result, these stakeholders' objectives may conflict, leading to distortions in market equilibrium and underscoring the importance of regulatory mechanisms. For instance, hydro reservoirs have been recognised as facilitators for integrating VRE capacity by redistributing energy from periods of surplus to periods of scarcity [12]. This perspective overlooks the dynamics of a deregulated power sector in which profit-maximising firms with substantial market shares could impact equilibrium prices through strategic operations, such as temporal arbitrage via hydro reservoirs. A stylised model has demonstrated that hydro producers who behave à la Cournot deploy more water in the off-peak period than price takers do [11]. In comparison to a perfectly competitive use of water, strategic use à la Cournot overproduces (underproduces) during off-peak (peak) periods, lowering (raising) the price.

In spite of the nature of the deregulated industry, power systems are still often analysed via single-agent cost-minimising models. These engineering-based models typically render system transition through VRE targets or CO_2 emission caps, assuming a centralised planner who allocates capacities in a socially optimal way [26; 27]. They assume perfect competition in the market, i.e. market equilibrium leads to social optimality. This assumption may overlook the technical and economic challenges of transitioning to a carbon-neutral power system by ignoring incentives. Moreover, externalities from CO_2 emissions are assumed to be either fully internalised as part of the CO_2 price or dealt with via proxy measures, e.g. renewable portfolio standards (RPSs). In reality, only part of the social cost of damage may be captured. Another subset of power-system models concentrates on economic considerations [25]. These models, however, simplify the technical and physical specifics of VRE, although recent work incorporates variability and resource heterogeneity [14; 28]. Hydro production is often modelled using availability factors [21] without directly representing reservoir operations [19]. Consequently, extant models are limited by focusing solely on either market or technical aspects.

The incentives of market participants, as reflected in empirical studies [10; 11; 18], underscore the potential for the strategic manipulation of electricity prices by firms with substantial market shares. This strategic behaviour is often manifested through investment and operational decisions, exploiting hydro reservoirs for temporal arbitrage [20]. Moreover, the advent of prosumers, i.e. agents that both consume and produce electricity, introduces additional complexities, as these entities exert increasing influence over system operations and market dynamics [22–24]. Thus, there is a distinct need to capture both the spatio-temporal features of the power systems and the incentives of decision-makers in policy-enhancing models.

Insufficient accounting for such attributes may result in unrealistic policy recommendations in pursuit of climate goals. A real-world instance is the *Energiewende*, which has rapidly decarbonised the German power sector by replacing thermal generation with VRE [15]. However, the initial deficiency in the transmission capacity to link wind-rich sites in the north with load centres in the south [16] compelled support payments to gas-fired plants for flexibility [17]. From a societal perspective, such resource misallocation could distort price signals and hinder progress towards climate goals.

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[4] `https://www.energyexemplar.com/blog/nordic-power-market`

1.2 Research Gap

Given that most policy analyses of power systems rely on engineering-type models [30; 32], strategic behaviour may be overlooked in the derived conclusions. In fact, the industry is treated as perfectly competitive, thereby rendering market equilibrium as the social optimum. However, the power sector diverges from perfect competition in various aspects:

1. There are diverse agents with disparate objectives, e.g. profit-maximising firms that operate/invest in generation capacity and welfare-maximising TSOs in charge of transmission expansion [29; 33].
2. Flexible producers have the potential to exert market power [18], which may be increasingly leveraged in the future with high VRE penetration [31].
3. Strategic profit-maximising producers may cause capacity scarcity under high VRE penetration, necessitating support payments to the flexible plants they own [17].

While the Nordic electricity market is often upheld as an exemplar due to its day-ahead market-clearing prices, which are generally close to the marginal costs of generation [6], empirical analyses have shown signs of market power being exercised by hydro producers in Swedish price zones [31; 36]. These findings are based on 2011–2013 data without the explicit modelling of strategic operations. While some recent studies have focused on empirical analyses of electricity markets, such as [34], which examines the effects of wind power on the Swedish intraday market, there is a noticeable gap in research directly addressing the identification of market power through empirical methods. Game-theoretic frameworks are also employed in the literature to model strategic behaviour in the Nordic region. However, these studies often treat hydro as a generic flexible resource, overlooking the operational specifics of reservoirs. For example, [35] identifies how a flexible producer may create congestion in the balancing market to its advantage. Therefore, an explicit representation of both reservoir operations and strategic behaviour is required to support policy analyses in the Nordic region under current and future climate packages.

This research addresses these gaps by proposing a novel approach that integrates the engineering details of reservoir operations into game-theoretic models of strategic behaviour. This study aims to provide a better understanding of market dynamics and firm behaviour in the context of increasing VRE capacity. The key contributions include the following:

- Explicit representation of reservoir operations: Unlike models that treat flexibility generically, this approach incorporates hydro reservoirs' operational constraints and decision-making processes, enabling more realistic modelling of their operations in the market.

- Game-theoretic analysis of strategic behaviour: The proposed method employs game-theoretic techniques to model interactions between profit-maximising firms and the TSO, allowing a more detailed exploration of how strategic behaviour influences market equilibrium and pricing.
- Policy-relevant insights: By capturing both the engineering and economic aspects of the power system, this research generates practical insights for policymakers. This includes understanding how to account for potential market power while achieving climate goals.

In summary, the Nordic power system is dominated by hydro and nuclear plants, which account for 63.6% and 11.8% of the total capacity, respectively, while investments in VRE capacities increase the need for flexibility. Consequently, there is mounting potential for dominant firms to exercise market power, necessitating appropriate methods for analysis. Hence, the *specific research gap* that this thesis addresses is the incorporation of technical details into game-theoretic models to gain credible insights into the Nordic power system under future climate packages.

1.3 Research Aims

This thesis aims to address the strategic behaviour of power producers and the integration of VRE in the Nordic power system, focusing on the interactions among hydropower operations, market power, and the need for flexibility. In particular, the aims are as follows:

- Study of strategic behaviour in power-system models: Develop a model that integrates the strategic, profit-maximising behaviour of market participants, particularly flexible hydro producers. The aim is to capture how firms with significant market power might exploit hydro-reservoir operations for temporal arbitrage, thereby distorting electricity prices and market outcomes.
- Evaluate the impact of VRE integration on market power: Assess how the potential for market manipulation by hydro producers is affected by the integration of VRE and the overall decarbonisation goals in the Nordic power system. The study will explore how strategic behaviour may change the welfare and environmental metrics.
- Provide policy recommendations in the presence of market power: Based on the developed game-theoretic model, propose regulatory frameworks

and policies that reflect the impact of market power in the Nordic electricity market. The aim is to ensure that VRE integration proceeds without strategic manipulation that hinders progress toward decarbonisation. This includes enhancing the transmission capacity between regions to take into account firms' ability to exploit market power and addressing incomplete CO_2 pricing, as it can sustain the economic viability of fossil-fuelled plants, to ensure that fossil-fuelled plants do not undermine the benefits of increased VRE adoption.

Through these aims, this thesis seeks to bridge the gap between engineering and economic analyses by incorporating the strategic behaviour of market players into models that provide insights about the future of the Nordic power system under current and future climate policies.

1.4 Research Objectives and Questions

This thesis comprises a systems perspective of the Nordic electricity industry aimed at the provision of policy insights under decarbonisation. In particular, the main research question is the following:

- How do hydro storage and the transmission network influence power-system outcomes in future climate packages under both perfect and imperfect competition, as well as full or partially imposed CO_2 pricing?

In order to address this overarching objective, we need to bridge the gap between economic realism in game theory and physical realism in engineering-type system models in the power sector. Accordingly, we propose Models M1 and M2, which are defined as follows:

Model M1. *A detailed Nash-Cournot power-system model with the explicit representation of hydro constraints, the network topology, and VRE units.*

Model M2. *A bi-level model with industry features based on model M1, which enables the assessment of welfare-enhancing transmission-expansion decisions.*

By developing model M1, we tackle the following sub-research questions (RQs):

Research Question RQ1. *How are social welfare, reservoir operations, and CO_2 emissions affected by market power in the current Nordic power system?*

Research Question RQ2. *What will be the impact of the advent of prosumers with VRE capacity and flexible consumption on the potential for the exercise of market power by both hydro and thermal producers?*

Research Question RQ3. *What will be the impact of future climate policy comprising a high CO_2 price and expanded VRE capacity on the potential for the exercise of market power by both hydro and thermal producers with/without the presence of prosumers?*

Meanwhile, Model M2 will address the following:

Research Question RQ4. *What is the socially optimal transmission plan under both perfect and imperfect competition with full internalisation of the social cost of damage from CO_2 emissions?*

Research Question RQ5. *What are the socially optimal adaptations to transmission planning under both perfect and imperfect competition when the social cost of damage from CO_2 emissions is only partially internalised?*

1.5 Summaries of Papers and Their Contributions

Paper P1. *Climate Policy and Strategic Operations in a Hydro-Thermal Power System*

The Nordic power sector's decarbonisation necessitates substantial integration of VRE capacities. Despite the ability of Nordic hydro reservoirs to mitigate the intermittency of VRE output, there is a potential for strategic hydro producers to exploit the increased flexibility requirements, thereby exerting market power. Using a Nash-Cournot model, our analysis reveals that in the existing Nordic power system, large producers could achieve modest gains through strategic reservoir operations, even in the presence of regulations preventing the intentional increase of prices through water 'spilling'. Instead, strategic hydro producers could shift generation from peak to off-peak seasons. Such temporal arbitrage becomes more attractive under a climate package with a €100/t CO_2 price and doubled VRE capacity. Since the package increases generation variability, lowers average prices, and makes fossil-fuelled plants unprofitable, strategic hydro producers face lower opportunity costs in shifting output from peak to off-peak seasons and encounter muted responses from price-taking fossil-fuelled plants. Hence, a climate package that curtails CO_2 emissions may also bolster strategic hydro producers' leverage.

Paper P2. *Aggregator-Enabled Prosumers' Impact on Strategic Hydro-Thermal Operations*

Climate packages envisage the decarbonisation of the power system and the electrification of the wider economy via VRE. These developments foster the emergence of aggregator-enabled prosumers, thereby creating a demand for flexibility. By exploiting conducive geographic conditions, e.g. in the Nordic region, hydro reservoirs can mitigate VRE's intermittency. However, hydro producers may exploit the growing need for flexibility to wield market power through temporal arbitrage. Using a Nash-Cournot model, we examine how aggregator-enabled prosumers with endogenous loads and VRE capacity interact with other agents to alter market outcomes. Based on Nordic data, we observe that hydro producers bolster their market power by adjusting production away from periods when prosumers are net buyers and strategically 'dumping' their output during periods when prosumers become net sellers. Hence, jurisdictions that rely upon (hydro) storage to integrate VRE from prosumers will need to be wary of incumbent firms' incentives to manipulate prices.

Paper P3. *Flexible Supply Meets Flexible Demand: Prosumer Impact on Strategic Hydro Operations*

Ambitious climate packages promote the integration of VRE and the electrification of the economy. For the power sector, such a transformation means the emergence of so-called prosumers, i.e. agents that both consume and produce electricity. Due to their inflexible VRE output and flexible demand, prosumers will potentially add endogenous net sales with seasonal patterns to the power system. The Nordic region, endowed with extensive hydro reservoirs and robust transmission capacity, seems well prepared to manage intermittent VRE output. However, the increased requirement for flexibility may be leveraged by incumbent producers to manipulate prices. Applying a Nash-Cournot model that considers the spatio-temporal features and reservoir volumes of the Nordic region, our investigation explores how hydro producers may manipulate electricity prices through temporal arbitrage in the presence of (i) VRE-enabled prosumers and (ii) the combination of VRE-enabled prosumers and a high CO_2 price. We find that hydro reservoirs could exploit prosumers' patterns of net sales to conduct temporal arbitrage more effectively, viz., by targeting periods in which prosumers are net buyers (net sellers) to withhold ('dump') water. Moreover, a higher CO_2 price would further empower hydro reservoirs, as flexible, price-taking thermal plants would be unable to counter their strategy to exploit VRE intermittency. Hence, in spite of a flexible demand side to complement additional intermittent VRE output, strategic hydro producers may still exacerbate price manipulation in a future power sector via a more tailored exercise of market power.

Paper P4. *Transmission Planning in an Imperfectly Competitive Power Sector with Environmental Externalities*

The integration of intermittent VRE capacities poses a challenge to policymakers, as even in a well-functioning power sector with flexible generation, producers' incentives may not align with society's welfare-maximisation objective. Simultaneously, political pressures may keep policymakers from accurately pricing the damage caused by CO_2 emissions based on their social costs.

Transmission planning must be adjusted to account for economic and environmental distortions to facilitate decarbonisation. Using a Stackelberg model of the Nordic power sector, we find that a first-best transmission-expansion plan involves better resource sharing between Nordic zones, which actually reduces the need for some VRE adoption. Subsequently, when allowing for deviations from perfect competition, we identify an extended transmission-expansion plan under market power exerted by nuclear plants. By contrast, temporal arbitrage by hydro reservoirs does not require additional transmission expansion beyond that of perfect competition, as it promotes sufficient VRE adoption using existing lines. Meanwhile, incomplete CO_2 pricing under perfect competition requires an expanded transmission plan that matches hydro-rich zones with sites for VRE adoption. However, the economic viability of fossil-fuelled generation under incomplete CO_2 pricing diminishes the leverage of strategic producers, consequently necessitating less (more) extensive transmission expansion under market power exerted by nuclear (hydro) plants.

Table 1.1: Relation of Papers and Research Questions.

Paper	Focus	Relevant RQ(s)
*P*1	Climate policy, hydro operations, and VRE expansion	RQ1 & RQ3
*P*2	Prosumers and intra-seasonal arbitrage	RQ2
*P*3	Prosumers, climate policy, and inter-seasonal arbitrage	RQ2 & RQ3
*P*4	Transmission-expansion planning	RQ4 & RQ5

As indicated in Table 1.1, Papers P1–P4 contributed to answering the research questions. Paper P1, by utilising a Nash-Cournot model with a representation of the transmission network, intermittent VRE output, and reservoir constraints (Model M1), addresses RQ1 and RQ3. As for RQ1, we implement numerical examples for the year 2018 in which the firms are either price takers or Cournot competitors through their hydro-thermal generation output. We find that strategic firms with hydro capacities could shift their generation from peak to off-peak seasons to manipulate market prices to their benefit. RQ3 is addressed through a future scenario in which we impose a high CO_2 price of €100/t and increase the VRE capacity in the firms' existing portfolios. By doing this, changes to the supply side stemming from a future climate package that affect the leverage of strategic hydro-reservoir and thermal producers can be explored. The results show that such a climate package that curbs CO_2 emissions can also increase strategic behaviour, as it increases generation variability and makes fossil-fuelled plants unprofitable, thereby yielding greater impunity to flexible (hydro) producers to behave strategically.

Paper P2 extends Model M1, used in Paper P1, by including the impact of the structural changes to the demand side, viz., the advent of prosumers, on market power and system operations. In particular, to answer RQ2, it investigates how strategic hydro producers' ability to manipulate electricity prices through temporal arbitrage is affected by aggregator-enabled prosumers and a high CO_2 price. The model is implemented on a stylised test network using Nordic grid data to examine how intra-seasonal arbitrage by hydro producers is facilitated by prosumers. Paper P3 extends the analysis of RQ2 by using the full Nordic network and data in Model M1, with a detailed representation of the region's spatio-temporal features and reservoir volumes. We find that hydro reservoirs could exploit prosumers' patterns of net sales to conduct intertemporal arbitrage more effectively, while a higher CO_2 price would further enhance hydro reservoirs' market power (RQ3).

Paper P4 adopts a Stackelberg leader-follower, or bi-level, perspective to address welfare-enhancing 'designs', viz., transmission expansion in Model M2, thereby tackling RQ4 and RQ5. In terms of RQ4, numerical examples for the year 2018 are implemented, where firms act as either price takers or Cournot competitors in their hydro-thermal generation output, with the social cost of damage from CO_2 emissions fully internalised by the firms. We find that a socially optimal transmission plan, i.e. in a perfectly competitive market with full CO_2 pricing, leverages the higher ensuing electricity prices to curb consumption and permit more efficient sharing of generation resources. Also, imperfect competition in the presence of full CO_2 pricing has contrasting impacts on transmission expansion depending on the type of market power exerted. In the case of nuclear plants withholding output, aggressive transmission expansion is needed to improve hydro-resource sharing and boost VRE adoption. Meanwhile, temporal arbitrage with hydro reservoirs reduces flow on certain lines. Therefore, the transmission plan is the same as in the case of the perfectly competitive setting. To answer RQ5, Model M2 with incomplete CO_2 pricing explores the consequences of political pressures on transmission planning. Under perfect competition, the lack of a price signal to curb consumption hampers the efficient sharing of existing generation resources. This stands in contrast to the results with full CO_2 pricing, thereby necessitating a more proactive role for the TSO in alleviating environmental distortion by inducing VRE adoption. Since incomplete CO_2 pricing limits the scope for the exercise of market power, transmission plans under strategic behaviour by nuclear and hydro plants need to be tailored accordingly. In the case of the former (latter), less propensity to withhold (to conduct temporal arbitrage) means that less (more) transmission capacity is optimal than in the corresponding case with full CO_2 pricing.

1.6 Thesis Outline

The dissertation is organised into chapters as follows:

Chapter 1, Introduction, briefly introduces the research area of this work. It further presents the research problems and questions.

Chapter 2, Background and Related Work, provides context for related work on the topics of the included publications.

Chapter 3, Methodology, discusses the research approach and methods applied in this thesis.

Chapter 4, Summary of Papers, summarises and presents the main findings and contributions of the included publications.

Chapter 5, Concluding Remarks, discusses the results and limitations of this work. This chapter also presents the conclusions of the research and suggestions for future work.

2. Background and Related Work

This chapter reviews the literature on strategic hydro operations, prosumer dynamics, and transmission planning. We explore studies that demonstrate strategic behaviour in hydro operations and aggregator-driven demand-side flexibility. In addition, we examine research on incorporating renewable energy into transmission planning amidst climate imperatives. Combining these findings, we aim to identify gaps concerning analyses of climate policies and the power sector.

2.1 Strategic Hydro Operations

Future climate goals in OECD countries aim to slash CO_2 emissions in the power sector by primarily utilising VRE sources, specifically wind and solar power. The European Green Deal, for instance, targets a 55% decrease in total greenhouse-gas emissions by 2030 compared to 1990 levels [37], serving as a pivotal step towards a climate-neutral continent by 2050 through increased electrification of the heating and transport sectors. Implementing such a transformation of the power sector necessitates an unparalleled investment in flexible resources, such as storage and transmission capacity, to address spatial and temporal imbalances between supply and demand.

In the preceding three decades, the electricity industry has experienced deregulation in services like generation and retailing, while distribution and transmission have mostly remained regulated due to their natural-monopoly characteristics [10]. This restructuring could result in conflicts between power companies' profit-maximising behaviour and society's welfare-maximisation and climate goals. Policymakers must understand how market actors' incentives, such as strategic decisions, affect economic and environmental results.

Conflicts over the transition to renewable energy are widespread. For example, in California, the 'duck curve' phenomenon highlights the importance of flexibility. This curve illustrates the increase in solar power generation from 15,046 GWh in 2015 to 27,265 GWh in 2018 [38; 39]. Consequently, there is a notable spike in electricity demand during the evening hours (17:00–20:00), a trend that has intensified recently (see Figure 2.1). With an excess of solar energy during the day, electricity prices drop, thereby rendering gas-fired power plants unprofitable despite their potential to meet evening demand.

Energy storage, particularly current hydro reservoirs, could aid in the inte-

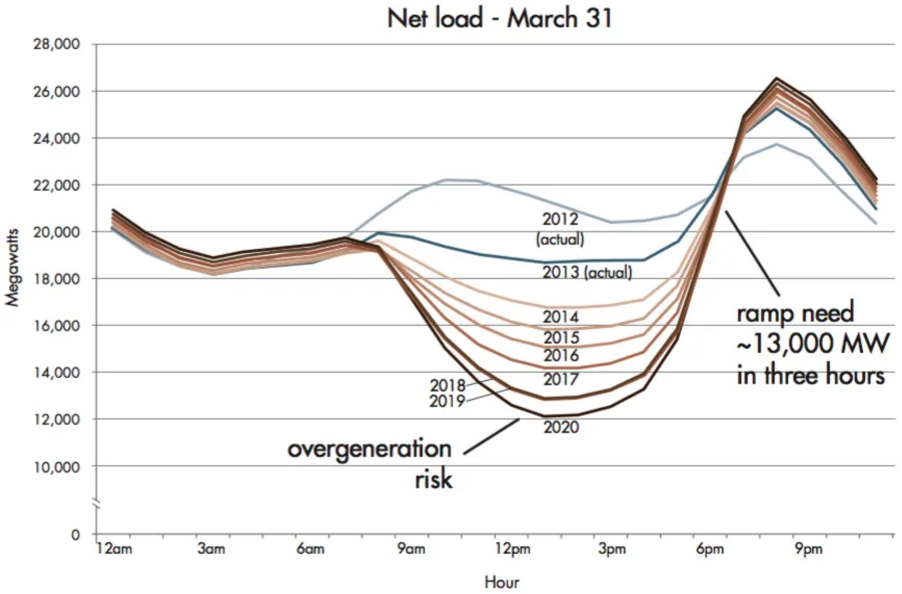

Figure 2.1: The Duck Curve Shows Steep Ramping Needs and Overgeneration Risk [39].

gration of VRE capacity [12] through temporal arbitrage, which decreases the necessity for peak-load generation capacity. Yet, this perspective from the era of vertically integrated regulated monopolies fails to acknowledge that companies with significant market shares may influence market prices through storage operations. The stylised model developed by [11] examines the Cournot-like behaviour of hydro producers in utilising their allocated water resources. The model specifically focuses on hydro reservoirs and shows that Cournot producers tend to use more water during off-peak periods compared to price takers. Both price-taking and Cournot hydro producers aim to maximise profit by managing generation in each period. However, a price-taking producer considers exogenous prices in each period, while a Cournot producer considers the effect of its production on the price in each period. This difference implies that price-taking producers aim to equalise prices across time periods to maximise profits, while Cournot producers focus on equalising marginal revenues (see Figure 2.2). Consequently, the Cournot outcome tends to decrease (increase) hydro production during peak (off-peak) periods, thereby resulting in lower (higher) prices during off-peak (peak) times. Cournot producers effectively reallocate water from periods of inelastic residual demand to periods of more elastic residual demand.

This inclination was demonstrated in a case study of the California power system [18], despite the strategic hydro producers having to generate an equal amount of energy from their reservoirs over the entire duration of the study, as under perfect competition. The use of a Nash-Cournot model to analyse pumped-hydro storage operations in Germany revealed the possibility of welfare losses compared to a scenario without storage, particularly if strategic storage operators also possessed generation capacity [40]. The effects of storage operations on social welfare under different ownership structures are summarised using stylised equilibrium models in the presence of both perfect [41] and imperfect competition [42]. These ownership structures encompass a range of scenarios, including privately owned storage facilities, publicly owned storage facilities, and cooperative-owned storage facilities, as well as scenarios involving vertically integrated utilities with storage assets. By considering these diverse ownership arrangements, the studies provide insights into how market structure and ownership influence the efficiency and welfare implications of storage deployment in electricity markets.

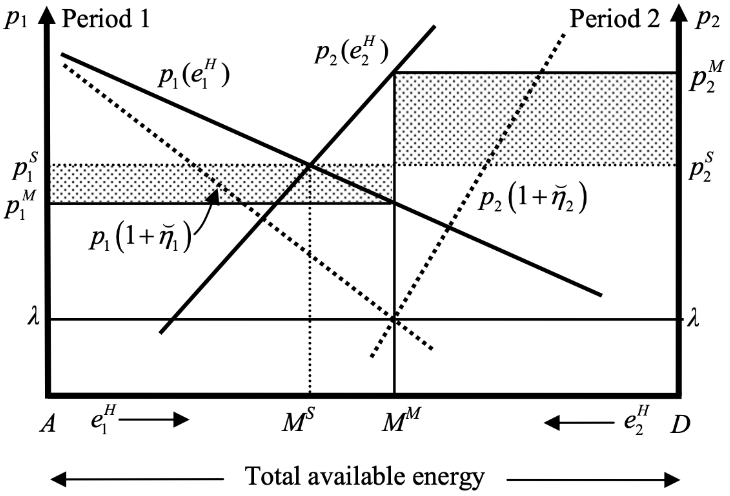

Figure 2.2: The Basic Bathtub Curve for Two Periods (Solution for Market Power Shown by Thin Dotted Lines) [19].

While the aforementioned literature investigates how strategic storage operations may distort strategic producers' incentives, it does not consider CO_2 emissions and VRE. More recent work accounts for the interaction between climate policy and strategic storage operations. The authors in [43] assess the uncertainty of VRE generation by analysing a transmission-constrained test network in Western Europe. They observe that when firms behave à la Cournot, they utilise their pumped-hydro storage to release excess output from their thermal plants that are limited by ramping, essentially holding back generation while avoiding the costs associated with ramping. In a Nash-Cournot analysis of the New York-Québec interconnection, [20] confirms the main finding of

[18], viz., the occurrence of temporal arbitrage by large hydro producers, even in the presence of a regulatory constraint that prohibits the release of excess water. Furthermore, the findings indicate that implementing stricter regulations that prevent strategic hydro producers from exporting their surplus generation (such as Québec's heritage pool [44]) can reduce temporal arbitrage through reservoirs. However, it can also exacerbate spatial arbitrage by pumped-hydro operators. According to [20], the implementation of a more stringent regional limit on CO_2 emissions is expected to result in a greater motivation for strategic actions, and this effect is anticipated to be even more pronounced in future climate policies. In a hypothetical power system that relies completely on VRE with storage, a study by [46] reveals that while the strategic spilling of storage-enabled VRE output by Cournot producers could have a more detrimental effect on social welfare than price manipulation through storage alone, regulators would have an easier time detecting intentional reductions in VRE generation when combined with storage. Additionally, the expansion of the storage capacity in the possession of strategic companies could exacerbate the negative effects on welfare. Similarly, the authors of [47] employ an equilibrium approach to evaluate the potential distortion of investment incentives and generation dispatch caused by market power exerted by storage operators. Their study highlights the necessity of competitive conditions in both the generation and storage sectors for optimal storage incentives. Furthermore, they underscore the importance of considering potential positive externalities of energy storage, such as enhanced supply security, further strengthening the case for implementing support mechanisms like storage capacity auctions.

Conversely, the Nordic region is perceived to be less affected by distortions resulting from market power exertion in hydro storage, as it is often praised as a model example due to day-ahead market-clearing prices that closely mirror marginal costs. In [6], it is argued that extensive hydro reservoirs and spatial integration in the Nordic region reduce the possibility of market power. Nevertheless, studies examining the Nordic electricity market, using data collected between 2011 and 2013, have provided empirical evidence indicating the market power of hydro producers in Swedish price zones [7], deliberate reporting of unit failures by gas- and oil-fired power plants [36], and system-wide withholding similar to the Cournot model [8]. Another branch of the literature that employs game-theoretic frameworks to analyse the motivations behind strategic behaviour in the Nordic region often considers hydro producers to be flexible assets and disregards reservoir operations. For example, [45] examines the impact of nodal versus zonal pricing, [21] assesses the strategic role of combined heat and power plants, and [35] identifies how a flexible producer may create congestion in the balancing market to its advantage. Therefore, the assessment of future climate packages lacks an explicit representation of reservoir operations [19] in game-theoretic policy analyses of strategic behaviour in the Nordic region.

2.2 Advent of Prosumers

Future decarbonisation pathways involve the electrification of the broader economy, potentially introducing prosumers that both produce and consume electricity. In contrast to the strategic operations of hydro producers, the limited generation capacities and market shares of small-scale prosumers render them unable to influence market prices significantly, which is why they are treated as price takers. Nevertheless, to fully exploit their capabilities, prosumers can be effectively represented by aggregators [51; 53]. In [48], the authors introduce an optimisation framework to enable demand-response (DR) aggregator participation in the market, where the aggregator maximises its payoff in the day-ahead market by offering consumers different contracts to curtail and shift their load. Furthermore, [49] presents an optimal bidding strategy for a microgrid that minimises the microgrid's expected net cost through a combination of stochastic and robust optimisation, considering exogenous forecasted prices. In addition, the optimal bidding strategy for the DR aggregator for day-ahead market participation is determined by incorporating demand flexibility in a stochastic programming model that aims to maximise the aggregator's expected profit [50].

Demand-side flexibility may be bolstered due to aggregators that can marshal the mobility and consumption patterns of plug-in electric vehicles (PEVs) [54] and building occupants [55]. While previous studies account for stochastic but exogenous prices, recent research in this field has analysed the effects of strategic behaviour by aggregators. For instance, [23] employs a bi-level model where a PEV aggregator at the upper level anticipates the lower-level market clearing while determining retail prices. Similarly, [22] investigates the incentive for a leader to manipulate electricity prices by 'spilling' output from a portfolio of distributed energy resources (DER). Moreover, another study [52] examines the impact of the increasing number of aggregator-enabled prosumers on the strategic behaviour of aggregators using a bi-level model. It has been demonstrated that increasing the aggregation of prosumers can significantly widen the disparity between strategic and non-strategic bidding. However, the model does not represent the strategic behaviour of incumbent agents, such as power companies with flexible generation assets capable of exploiting intermittencies in both VRE output and prosumers' net sales.

To examine a prosumer's behaviour in a standard transmission-constrained oligopoly [57], [24] introduces a prosumer with intermittent DER, a backup generator, and a gross-benefit function that values its consumption. With all other entities acting as price takers, the prosumer gains no advantage in exerting market power, as demonstrated in a 24-node test network. This framework can be extended by considering the prosumer as a Stackelberg leader rather than a Cournot player [56]. In contrast to the Cournot approach, Stackelberg leadership allows the prosumer to influence market dynamics by preemptively determining consumption levels actively, thereby gaining advantages such as the ability to alter prices in its favour.

The extant literature primarily examines either (i) the strategic actions taken by prosumers or (ii) optimal decisions by prosumers under uncertainty given exogenous electricity prices. What is missing is how flexible incumbent producers, such as those with large hydro reservoirs, could exploit the presence of prosumers with inflexible VRE output and endogenous consumption. Therefore, aggregator-enabled prosumers in a hydro-dominated power system, such as the Nordic one, could alter power companies' leverage, and the extent of this has not been studied.

2.3 Transmission Planning under Climate Policy

In response to the urgent need to tackle climate change, many OECD governments are implementing energy and infrastructure initiatives[1] known as 'Green Deals'. These packages attempt to help decarbonise the power industry and electrify related sectors such as heating, industrial processes, and transport. In recent years, support schemes such as feed-in tariffs and RPSs have significantly reduced the levelised costs of VRE, specifically solar and wind power, to near parity with that of gas-fired turbines (see Figure 2.3). Furthermore, implementing cap-and-trade (C&T) protocols, such as the EU's ETS, has further reduced fossil-fuelled generation. For instance, from 2019 to 2020, Sweden slashed electricity-generation emissions by 12%, using a 6.6 TWh boost in hydro capacity and a 2.9 TWh drop in thermal generation.[2] Therefore, the future power system will heavily rely on VRE output that is complemented by flexibility in both demand, e.g. by coupling with other energy sectors, and supply, e.g. from hydropower and other forms of energy storage.

At the same time, the expansion of the transmission system to accommodate additional VRE capacity is vital due to the intermittent output of both solar and wind facilities, often located far from consumption centres. Consequently, the current transmission network may need to be reinforced to manage the increased integration of VRE capacities. In addition, while flexibility in demand and supply can temporarily offset the intermittent nature of VRE outputs, transmission capacity can help to alleviate spatial imbalances. From this perspective, a socially optimal transmission plan based on cost minimisation [9] matches the marginal benefits and marginal costs of transmission expansion.

Recent engineering and operational research (OR) work has expanded the scope of the generation-and-transmission-expansion planning (GTEP) problem to include the spatial and temporal characteristics of power systems. For

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[1] `https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en`

[2] `https://www.eea.europa.eu/publications/the-eu-emissions-trading-system-2`

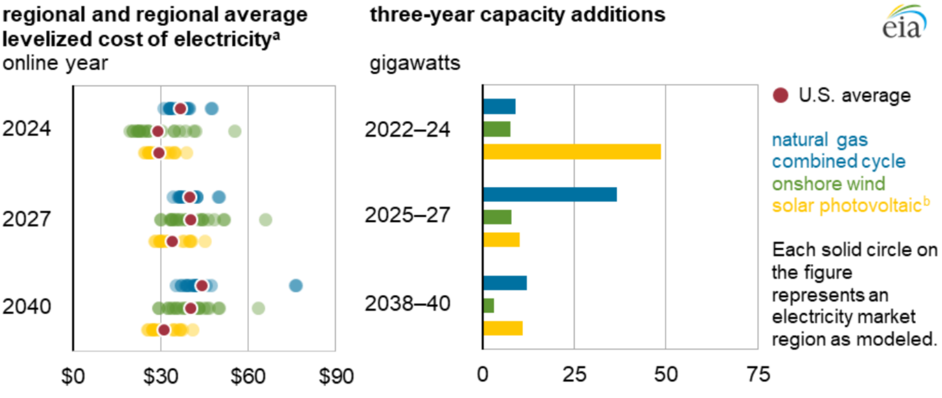

Figure 2.3: Levelised Cost of Electricity by Region and Total Incremental Capacity Additions for Selected Generating Technologies Entering into Service in 2024, 2027, and 2040.[3]

example, [3] devises a multi-year GTEP for north-eastern North America that takes hydro operations into account, while [58] conducts robust-optimisation GTEP for the Nordic region that focuses on short-term uncertainties in demand and VRE output. In an effort to enhance the methodology for large-scale GTEP, [59] develops computational algorithms, while [60] proposes clustering procedures for an accurate representation of demand and VRE output. Such analyses assume that all decisions are undertaken by a single cost-minimising (or welfare-maximising) entity, which could lead to a first-best guideline for transmission expansion [61]. The centralised approach, however, fails to consider the deregulated nature of the power sector in the majority of OECD countries [10]. Indeed, this sector comprises various decision-makers who may have conflicting objectives that may not be in line with welfare maximisation.

Departures from central planning assume a welfare-maximising TSO that anticipates the generation-capacity adoption and operations of profit-maximising power companies. These studies employ bi-level models, i.e. a Stackelberg leader-follower framework, to account for the game-theoretic nature of interactions between transmission and generation investment [25]. The lower level involves a Nash-Cournot game with power companies deciding on profit-maximising generation investment and output, an independent system operator (ISO) determining welfare-enhancing power flows, and the upper-level TSO maximising transmission expansion. Power companies can either operate as price takers [62] or exert market power [63]. The latter model includes three levels, with competition among power companies unfolding in investment and operations. Rather than explicitly solving the tri-level model, the authors evaluate the generation-expansion-and-operations game for selected transmission

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[3] `https://www.eia.gov/outlooks/archive/aeo22/pdf/electricity_generation.pdf`

proposals and assess the impact of ignoring the firms' responses on social welfare. Such a reactive transmission plan is inferior to a proactive transmission plan that anticipates these responses, and the welfare reduction is found to be about 17%.

In terms of environmental considerations, the engineering/OR literature addresses game-theoretic problems in the power sector but often overlooks the social cost of damage from CO_2 emissions or represents them only indirectly, such as through RPS targets. For example, bi-level papers on transmission expansion examine VRE adoption [26], RPS targets [27], and energy storage [72], but they do not explicitly delve into the economic implications of CO_2 emissions. Despite the relevance of explicitly representing externalities for policymakers and regulated entities to grasp the tradeoffs between economic and environmental attributes, the literature often bypasses this aspect. Indeed, [64] advises against using proxy indicators such as RPS targets.

By contrast, the literature on environmental economics [71] directly tackles the policy issue of decarbonisation by incorporating the social cost of damage from CO_2 emissions and formulating optimal policies [65] by balancing pollution reduction's marginal benefits and costs. For example, it may prioritise reducing consumption as a first-best strategy for mitigating the more costly damages from CO_2 emissions before considering a transition to VRE [66]. This strand of the literature allows for closed-form solutions suitable for comparative statics, such as policy under uncertainty [67] or market power [69]. In transmission planning, [68] employs a Nash game with a single line and two strategic firms to demonstrate a paradox stemming from carbon taxation. Without a CO_2 tax, the node with coal generation transmits power to the node with a gas-fired plant. This action congests the line and enables the plants to act as local monopolies. Once the CO_2 tax is imposed, the gas-fired plant displaces the coal plant. Consequently, the equilibrium with the CO_2 tax alleviates congestion on the line and leads to a duopoly, thereby increasing the CO_2 emissions. Using a single-line transmission system and endogenous transmission expansion in a Stackelberg game, [70] highlights the inability of countervailing transmission expansion to offset welfare losses from incomplete CO_2 pricing under perfect competition. It is also suggested that partial CO_2 pricing under Cournot competition may be optimal, which generalises the result of [69]. However, such analytical tractability comes at the price of simplifications of the power system's spatio-temporal characteristics, and the findings may be limited in reality.

As previously stated, the engineering/OR literature provides only a cursory examination of environmental externalities, while environmental economics overlooks the spatio-temporal aspects of the power system. Between the two strands of the literature, we find a research gap in how transmission planning should be adapted in a power system that has high VRE adoption and the possibility for economic/environmental distortions.

2.4 Summary

Critical gaps in research emerge that necessitate comprehensive research efforts across the domains of strategic hydro operations, the advent of prosumers and prosumers' dynamics, and transmission planning under climate policy. While insights into strategic behaviour in Nordic hydro operations are apparent, the omission of a detailed representation of reservoir dynamics in the deregulated power sector and climate policy [11; 18; 19] limits our grasp of its full impact on the market. Similarly, the existing literature lacks an examination of how flexible incumbent producers, such as those with large hydro reservoirs, could exploit the presence of prosumers with inflexible VRE output and endogenous consumption [54–56]. Finally, as the engineering/OR literature typically does not directly tackle environmental externalities [26; 27; 72] and environmental economics simplifies the representation of the power system's spatio-temporal attributes [69–71], we find a research gap in how transmission planning should be adapted in a power system that has high VRE adoption and the possibility for economic/environmental distortions.

In response to these research gaps, this thesis proposes a novel approach that integrates the engineering details of reservoir operations into game-theoretic models of strategic behaviour. This study aims to provide a better understanding of market dynamics and firm behaviour in the context of increasing VRE capacity. The key contributions include the following:

- Explicit representation of reservoir operations: Unlike models that treat flexibility generically, this approach will incorporate hydro reservoirs' operational constraints and decision-making processes, enabling more realistic modelling of their operations in the market.

- Game-theoretic analysis of strategic behaviour: The proposed method employs relevant game-theoretic techniques to model the interactions between profit-maximising firms and the TSO. This allows a more detailed exploration of how strategic behaviour influences market equilibrium and pricing.

- Policy-relevant insights: By capturing the power system's engineering and economic sides, this research aims to generate practical insights for policymakers. This includes understanding how to account for potential market power while achieving climate goals.

This thesis specifically addresses the research gap by developing a comprehensive modelling framework that integrates technical and strategic factors, ultimately providing more credible insights for the Nordic power system under future climate packages.

3. Methodology

This chapter outlines the methodological principles behind the study in this thesis. It starts by looking into the chosen research strategy, the methodological background, and an overview of the research methods used. Finally, it concludes with alternative approaches and ethical concerns for the study.

3.1 Choice of Research Strategy

Design-science research (DSR) is about both the creation of artefacts and answering questions about them and their environments. As research can have many goals and characteristics, any research strategy or method may be valuable and can be used in DSR. In large DSR projects, it is customary to use different research methods, as each method can answer a specific type of question. For instance, an experiment or quantitative analysis may be the best choice for the evaluation of artefacts [73]. Accordingly, a DSR perspective is taken in this work, as the models, i.e. artefacts, can be evaluated using quantitative input data in order to address counterfactual policy and technological developments. These are the foci of the aforementioned RQ1–RQ5. In more detail, the DSR framework comprises the following steps:

1. Problem explication: The challenges in evaluating counterfactual policy and technological developments in the energy sector are clearly defined.

2. Requirement definition: The results of each scenario are identified and analysed using the relevant metrics.

3. Artefact design and development: The artefacts are the Nash-Cournot power-system model (M1) and the Stackelberg (bi-level) investment model (M2).

4. Artefact demonstration: Real-world data are used to implement the artefact and to calibrate it in different scenarios and cases, viz., Models M1 and M2.

5. Artefact evaluation: The artefact's performance is evaluated using both quantitative and qualitative analysis in different scenarios and cases. Consequently, the results are used for informing policy decisions.

The specific strategy within the DSR framework that is used is simulation, which 'imitates the behaviour of a real-world process or system over time' [73]. As an alternative strategy, the case-study approach, 'which investigates an instance of a phenomenon in depth' [73], could have been utilised. However, in addition to the difficulties of generalising the results from case studies, the necessity of studying the problem instance in its 'natural setting' was not suitable for addressing the RQs because they require the assessment of counterfactuals that stem from future climate packages.

In particular, we rely upon operational research, which is defined as a quantitative framework for assessing how to operate and design systems optimally by efficiently allocating resources [75]. From the operational research toolkit, we adopt a game-theoretic approach to simulate operations and market interactions in the Nordic grid during a transition to a decarbonised power sector that addresses RQ1–RQ5.

3.2 Methodological Background

3.2.1 Optimisation and Game Theory

Mathematical modelling plays a crucial role in investment and operational decision-making in the energy sector. These models are widely used to simulate the complexities of power systems, analyse the impacts of policy dispensations, forecast demand and supply, and optimise power-system operations. In particular, optimisation is a foundational pillar in the deregulated electricity industry, ensuring the system's efficiency and cost-effectiveness [74].

Before the deregulation of the electricity industry, operations and investment in the power system used to be under a single centralised decision-making agent, typically aiming at minimising costs or maximising system reliability [25]. However, this landscape has changed dramatically through the deregulation of the electricity industry such that the market participants' interaction with their own distinct objectives yields the market outcome. In response to the critical need for the use of mathematical frameworks that can capture the complexities of the new system, game theory has emerged as a powerful tool for modelling strategic interactions among market participants, allowing analysts to explore various equilibrium outcomes, anticipate the implications of different strategies, and gain a deeper insight into the behaviour of market participants [77].

In traditional economic theory, perfect competition arises in a context where market participants behave as if they cannot impact market prices through their individual actions [76]. This framework posits that all actors contribute to market equilibrium, and their interactions may be reformulated as a single optimisation problem aimed at maximising social welfare [25]. However, the practical application of perfect competition often diverges from its theoretical idealism. Real-world market dynamics frequently involve strategic behaviour among participants, leading to influence over prices, known as market power. Market power, or strategic behaviour, can be studied through game theory, offering more profound insights into market interactions. For instance, producers may manipulate market prices by independently determining production levels, a so-called Cournot game. Here, market prices become a function of players' strategic decisions. Moreover, some market participants may leverage their anticipation of others' decisions to their advantage, as seen in the leader-follower Stackelberg game. In this setup, the Stackelberg player makes decisions prior to others, influencing prices in their favour. To model such strategic behaviour accurately, it becomes imperative to employ mathematical models [76] using optimisation. By integrating game theory into market analysis, market dynamics and the impact of strategic behaviour on market outcomes can be better understood.

The crucial role of optimisation is obvious, as it became the core tool to model and solve such problems. A mathematical optimisation problem, or just an optimisation problem, comes in the following form:

$$\begin{aligned} \underset{x}{\text{Minimise}} \quad & f(x) \\ \text{subject to} \quad & h(x) = 0, \\ & g(x) \leq 0, \end{aligned} \tag{3.1}$$

where $f(x)$ is the objective function that is being minimised over the decision variable x [78], $h(x)$ is the function for the equality constraints, and $g(x)$ is the function for the inequality constraints. Generally, optimisation problems can be classified by their particular forms of objective and constraint functions [78]. For instance, a convex optimisation problem has both objective and constraint functions that satisfy the inequality below:

$$f(\alpha x^1 + (1-\alpha)x^2) \leq \alpha f(x^1) + (1-\alpha) f(x^2), \tag{3.2}$$

for all $x \in \mathbb{R}^n$, $\alpha \in \mathbb{R}$, and $\alpha \geq 0$ (see Figure 3.1). Also, linear programming (LP), quadratic programming (QP), non-linear programming (NLP), and mixed-integer linear or quadratic programming (MILP/MIQP) are some other forms of optimisation problems, depending on the natures of their objective and constraint functions.

In situations characterised by multiple concurrent optimisation problems, we encounter an equilibrium setup that can be effectively tackled by employing Karush-Kuhn-Tucker (KKT) conditions for ensuring global optimality, particularly when these problems are convex (see Figure 3.2). To grasp the KKT conditions, it is crucial to understand the Lagrangian function. In the simple optimisation problem (3.1), the Lagrangian function $\mathcal{L} = f(x) + \lambda^T h(x) +$

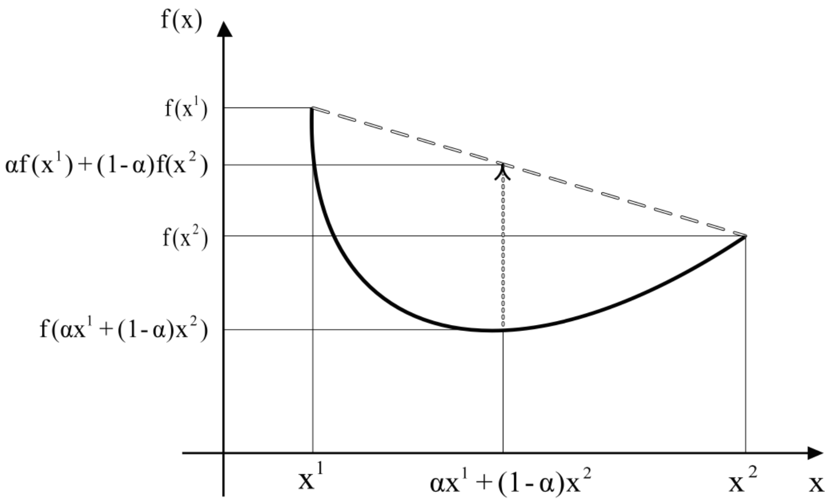

Figure 3.1: Geometric Illustration of Convex Function [25].

$\mu^T g(x)$ is formed by combining the objective function, $f(x)$, with the product of Lagrange multipliers, λ and μ, and constraints, $h(x)$ and $g(x)$. $f(x)$, $h(x)$, and $g(x)$ are continuously differentiable in the feasible region ($x \in \{x \mid h(x) = 0, g(x) \leq 0\}$). The KKT conditions of the problem (3.1) can be defined as follows:

$$\begin{aligned} &\nabla_x f(x) + \lambda^T \nabla_x h(x) + \mu^T \nabla_x g(x) = 0, \\ &h(x) = 0, \\ &g(x) \leq 0, \\ &\mu^T g(x) = 0, \\ &\mu \geq 0, \end{aligned} \tag{3.3}$$

where λ and μ are Lagrange multipliers, and ∇_x denotes the gradient with respect to x [25].

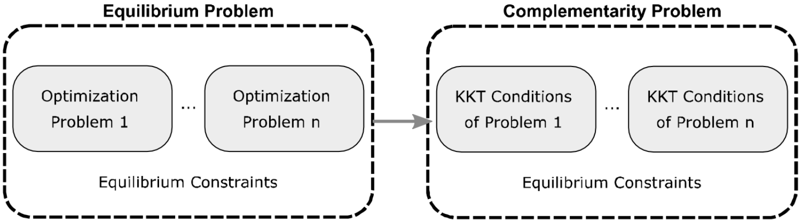

Figure 3.2: Reformulation of an Equilibrium Problem Using KKT Conditions [79].

The yielded KKT conditions encompass four main types of conditions:

stationarity, primal feasibility, dual feasibility, and complementary slackness. First, stationarity, $\nabla_x f(x) + \lambda^T \nabla_x h(x) + \mu^T \nabla_x g(x) = 0$, ensures that at the optimal solution, the gradient of the Lagrangian function with respect to the decision variables is zero. This implies that the solution is at a critical point, where further movement does not improve the objective. Second, primal feasibility, $h(x) = 0$ and $g(x) \leq 0$, requires that the equality and inequality constraints are satisfied, ensuring that the solution lies within the feasible region defined by these constraints. Third, dual feasibility, $\mu \geq 0$, ensures that the Lagrange multipliers associated with the inequality constraints remain non-negative. This reflects the fact that the corresponding constraints either have no impact or contribute positively to the objective. Finally, complementary slackness, $\mu^T g(x) = 0$, dictates that if a constraint is active, meaning that it influences the solution, its corresponding Lagrange multiplier must not be zero. This condition captures the idea that either the constraint binds with equality or its associated multiplier vanishes [25]. Mixed-complementarity problems (MCPs) extend optimisation modelling by incorporating equality conditions through KKT conditions, which is particularly useful for representing scenarios like equilibrium conditions.[1]

Multi-level problems appear when decision-making is necessary through several levels, e.g. the Stackelberg leader-follower game. Bi-level problems (see Figure 3.3) [77] pose significant mathematical challenges due to the interplay between upper- and lower-level decisions, where the feasible space is usually non-convex. One solution is to recast a bi-level problem as a mathematical program with equilibrium constraints (MPEC) (see Figures 3.3 and 3.4). Solving these reformulated versions of the problems is also difficult, mainly due to the non-convexity of the lower-level problem's KKT conditions caused by the complementary slackness condition, i.e. $\mu^T g(x) = 0$ for the problem (3.1). Several bi-level problems can likewise be reformulated as an equilibrium problem with equilibrium constraints (EPEC).

Nevertheless, various strategies exist to tackle these challenges. One such strategy involves reformulating MPECs using disjunctive constraints for the lower-level KKT conditions. This approach introduces new binary variables for each constraint, resulting in a mixed-integer linear or quadratic program (MILP/MIQP) [25]. Bi-level problems can also be tackled through reformulation, as a mathematical program with primal and dual constraints (MPPDC) [29]. The MPPDC presents the lower-level market equilibrium via its primal and dual constraints and the LP or QP strong-duality condition, which serves to convert the problem into a convex one (see Figure 3.3). It may also require another reformulation as a mixed-integer quadratically constrained quadratic program (MIQCQP) to resolve the non-linearities of the strong-duality condition.

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[1] For details, refer to [78] and [25].

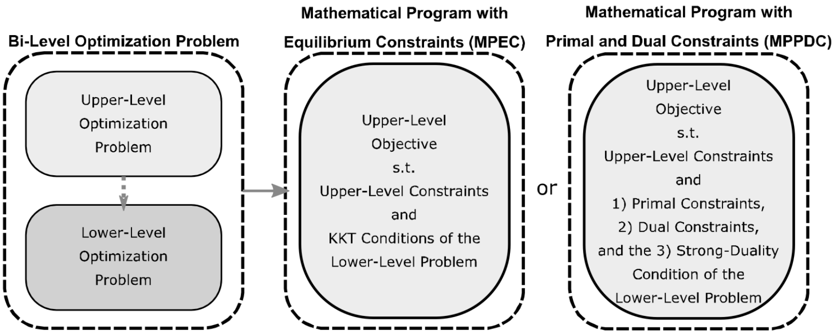

Figure 3.3: Reformulation of a Bi-level Optimisation Problem into an MPEC or MPPDC [79].

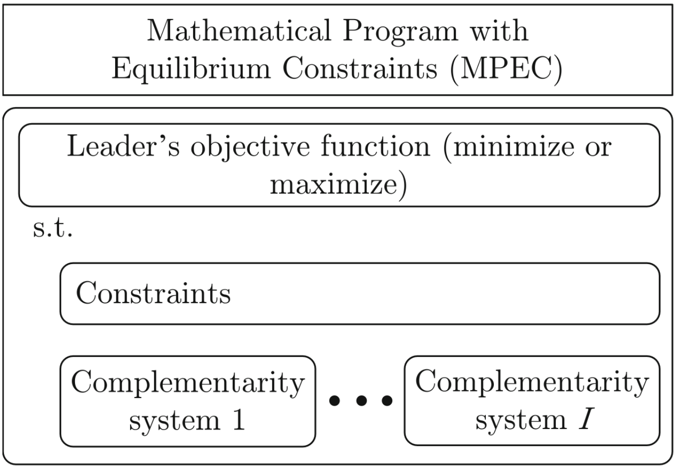

Figure 3.4: Framework of an MPEC [80].

3.2.2 Nash-Cournot Power-System Model

Model M1 (see Figure 3.5), which simulates power-system operations through the representation of the transmission network, hydro constraints, and VRE intermittency [28] to address the first two aims of the thesis, that is, the study of strategic behaviour and the impact of market power on VRE integration, as well as RQ1–RQ3, has been developed using a spatially constrained Nash-Cournot[2] model [57] with three types of agents, viz., profit-maximising firms, aggregator-enabled prosumers, and a surplus-maximising ISO. We represent consumers passively by a linear inverse-demand function at each node and in each time period [81]. The nodes are connected by transmission lines, which may be either AC or DC lines. A DC load-flow[3] approximation models the AC portion of the network.

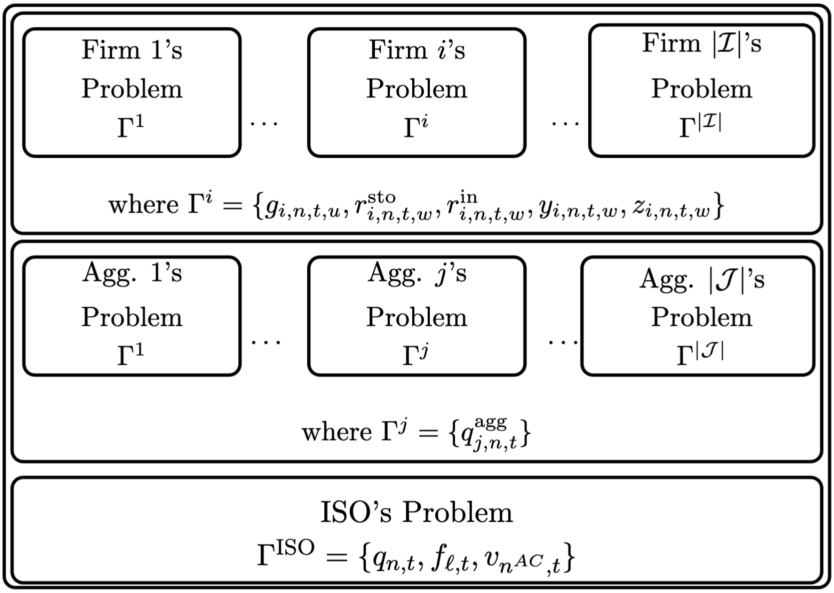

Figure 3.5: Framework of Model M1.

Each firm maximises its profit (as its objective) via its decisions, which concern the operation of its fleet of thermal, hydro, and VRE plants. The model also includes the impact of aggregator-enabled prosumers on market interactions and the operations of the system. In effect, each aggregator-enabled prosumer maximises its profit from market interactions and benefits from its endogenous consumption [24]. Finally, the surplus-maximising ISO's deci-

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[2] The Nash-Cournot assumption is when firms independently choose their production level (quantity), considering the production levels (quantities) of other firms as given.

[3] The DC load flow is a simplified method in power-systems engineering for calculating steady-state conditions by assuming constant voltage and ignoring reactive power, focusing solely on active power flows.

sions concern the operation of the transmission network and the balancing of nodal net demand (Figure 3.6).

$\mathit{Maximise}_{\Gamma\mathrm{i}}$ Revenue from Net Electricity Sales - Cost of Thermal Generation
- Cost of CO_2 Emissions
s.t. Capacity Limit on Thermal Generation
Ramp Limit on Thermal Generation
Hydro-Reservoir-Balance Constraint
Operational Limits of Hydro Generation
Annual Hydro Regulation

$\mathit{Maximise}_{\Gamma\mathrm{j}}$ Revenue from Net Market Interaction
+ Gross Benefit from Electricity Consumption

$\mathit{Maximise}_{\Gamma\mathrm{ISO}}$ Gross Consumer Surplus
s.t. Energy-Balance Constraint
Transmission System Limits

Figure 3.6: Problems of Firm *i*, Aggregator *j*, and ISO in Model M1.

Decisions are modelled over a representative year via the open-loop approach.[4] To reduce the computational burden, a clustering technique is employed in Model M1 to handle the VRE units' output, hydro inflows, and electricity consumption. In contrast to [57], we include a representation of hydro reservoirs and VRE intermittency, along with the CO_2 price. The operations of hydro reservoirs encompass the installed hydro capacity, reservoir volumes, and exogenous inflows to plants. Meanwhile, VRE intermittency is captured through historical time series that reflect generation relative to the installed capacity. Instead of using a cap on CO_2 emissions [82], we incorporate the EU ETS CO_2 permit price as an exogenous charge on fossil-fuelled generation. This is justified by the fact that CO_2 emissions from Nordic power and heat generation for 2017 were 35.1 Mt, which is a fraction of the nearly 1,755 Mt of CO_2 emissions in the entire EU ETS for the same year [85]. Transfers

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[4] All decisions are treated as if they were made at the same time. In contrast to the closed-loop approach, the open-loop approach ignores the dynamic nature of operational decisions, e.g. hydro plants may adapt their output to stochastic inflows [83].

with zones outside of the four Nordic countries are treated as exogenous net imports.[5]

The standard approach for the numerical resolution of open-loop Nash-Cournot problem instances [25] is to replace each agent's optimisation problem with its KKT conditions for optimality, which are both necessary and sufficient as long as each problem is convex. Thus, the equilibrium problem underpinning Model M1 is recast as an MCP, which can be readily tackled by the PATH[6] solver. Alternatively, the equilibrium problem may be reformulated as an equivalent single-agent QP problem that maximises a quadratic objective function and incorporates Cournot behaviour by making use of an extended-cost function to capture the exercise of market power in its objective function. This transformation is due to the fact that the inverse-demand curve in the model is linear and transport costs are proportional to the distances travelled [86]. QP problem instances can be handled by the CPLEX[7] solver.

However, recent advancements offer alternative approaches. The work in [84] demonstrates how many MCPs, particularly in oligopolistic markets, can be restructured as convex optimisation problems based on [57] and [86]. This approach avoids the need for PATH by eliminating the requirement to derive KKT conditions, leading to significantly faster solutions. By including market-power considerations in an optimisation framework, their method offers a more efficient alternative to traditional MCP solvers, allowing larger, more complex problem instances to be solved in a fraction of the time.

The QP model, as represented in [25], provides an adequate framework for optimising strategies within energy markets. The QP model can have a unique solution, which can be confirmed by analysing the Hessian matrix. Specifically, when the Hessian matrix associated with the QP model is positive definite at the optimal solution, this indicates that the solution is both locally stable and unique. This implies that small perturbations around the equilibrium will converge back to the same point, reinforcing the model's reliability in predicting outcomes. Such stability properties are particularly significant in the context of oligopolistic competition, where strategic interactions among firms can lead to complex dynamics. The insights derived from the Hessian matrix analysis are further supported by the research of [84] and [57].

3.2.3 Bi-level Investment Model

In contrast to the single-level open-loop Nash-Cournot operational model that underpins Model M1, a Stackelberg leader-follower, or bi-level, perspective is taken to handle welfare-enhancing 'designs' such as transmission-expansion plans in Model M2; this addresses the third aim of the thesis, that is, provid-

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[5] `https://www.nordpoolgroup.com/historical-market-data/`

[6] `https://pages.cs.wisc.edu/~ferris/path.html`

[7] `https://www.ibm.com/analytics/cplex-optimizer`

ing policy recommendations for adapting to market power, as well as RQ4 and RQ5 (see Figure 3.7). Our investment-modelling approach is static, focusing on a one-year timeframe, while operational dynamics are modelled with an hourly resolution. The TSO and ISO are responsible for the network's investment decisions for upgradable transmission lines and flow management, respectively. Conversely, individual nodes can accommodate multiple firms, and firms may own plants across various nodes. These firms' portfolios encompass various technologies, including VRE, hydro reservoirs, and thermal generators.

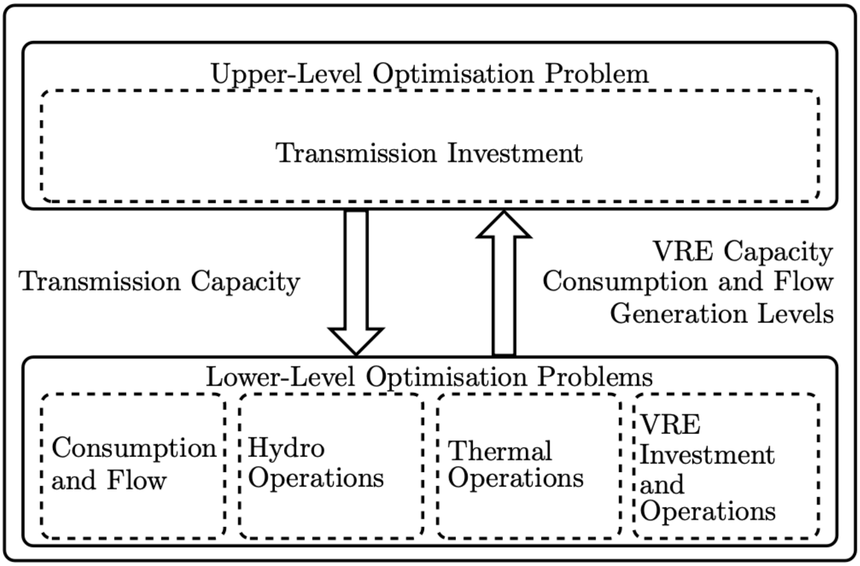

Figure 3.7: Framework of Model M2.

The upper level of Model M2 (see Figure 3.8) comprises a welfare-maximising TSO that determines transmission investment. The damage-cost function for CO_2 emissions is assumed to be linear, which is supported by the empirical evidence in [87] for a linear relationship linking regional damages and cumulative global emissions. The TSO adopts a transmission capacity at mutually exclusive discrete levels, which increases line susceptances with capacity, based on the model in [26; 27]. As a Stackelberg leader, the TSO anticipates lower-level followers' decisions about generation-capacity expansion, generation output, consumption, and power flows when making its transmission-capacity investment decisions. Thus, the TSO is constrained by the lower-level problems of the firms and the ISO.

Based on Model M1, the lower level includes profit-maximising power companies that decide upon generation investment and operations, as well as a surplus-maximising ISO that controls power flows. Under the Nash supposition, each firm maximises profit by taking the decisions of the ISO, every other firm, and the TSO's transmission-capacity expansion as given. However, the upper-level decision-maker must anticipate the responses of lower-level decision-makers when determining transmission investment [27; 29]. In maximising its profit, each firm decides how to operate its fleet of thermal generators, VRE capacity, and hydro reservoirs, assuming that plants' capacities are made available by paying the operations and maintenance (O&M) cost while also expanding VRE capacity. It is also assumed that the private costs of CO_2 taxes imposed on industry differ from the social cost of damage from CO_2 emissions. More specifically, the private costs depend on the specific fraction of the damage-cost rate that is internalised to the firms' problems.

Maximise Gross Consumer Surplus
- Cost of Thermal Generation
- Amortised Cost of Generation Investment
- Amortised Fixed O&M Cost
- Amortised Cost of Transmission Investment
- Social Cost of CO_2 Emissions

s.t.

Discrete Transmission Capacity

> Maximise Gross Consumer Surplus
> - Cost of Thermal Generation
> - Amortised Cost of Generation Investment
> - Amortised Fixed O&M Cost
> - Extended Cost
> - Private Cost of CO_2 Emissions
>
> s.t.
>
> Energy-Balance Constraint
> Capacity Limit on Transmission
> DC Load-Flow Constraints
> Constraints on Thermal Generation
> Constraints on VRE Generation
> Constraints on Hydro Generation
> Annual Hydro Regulation

Figure 3.8: Bi-level Problem of Model M2.

As is common in detailed power-system models of (hydro) storage operations [18; 20; 46; 89] and bi-level transmission planning with generation-capacity expansion [27; 72; 88], we take an open-loop perspective at the lower level. This means that, given the transmission-expansion plan, all operational and generation-capacity availability and expansion decisions are treated as if they were made simultaneously. We distinguish between the operational and generation-capacity decisions by letting the former be adapted to each time period, whereas the latter are not, i.e. there is a single generation-capacity availability and expansion decision for each plant of a firm. Considering the transmission-expansion decisions of the TSO, the lower-level open-loop Nash-Cournot game among the firms and the ISO may be reformulated as a single optimisation problem, viz., a QP problem [57; 86; 90]. The bi-level problem is solved via implicit enumeration over all possible transmission-expansion combinations.

3.3 Other Relevant Methods

Depending on the specific research questions, alternative methods could have been utilised. For instance, supply-function equilibria (SFE) could be an accurate method for including auction rules and enabling players to exploit both price and quantity offers. In SFE, it is assumed that the amount of energy a company is willing to supply to the market depends on the market price through its supply function. Thus, the decision variables of each firm are neither the price nor the quantity but the parameters of its supply function [76]. However, computing SFE can be a demanding task to perform, as it has been mentioned in [18] that in a hydro-thermal power system with several capacity-constrained heterogeneous firms, the optimal slope of a supply function at a given quantity may depend on the slopes at other quantities. In this context, [18] opts for a Nash-Cournot model due to its simplicity and suitability for modelling quantity decisions in hydro production. The Cournot assumption works well for power systems because hydro production is primarily a quantity decision. SFE models, though accurate, require solving differential equations that depend on the partial derivatives of residual demand functions, making them computationally challenging for hydro-thermal systems [18]. Consequently, the Nash-Cournot model works well due to its simplicity and suitability for quantity-based decisions in hydro production. Additionally, Cournot models allow the inclusion of system constraints like transmission congestion and hydro-reservoir operations, which are key features in hydro-dominated systems, such as those in the Nordic region [20]. This choice aligns with previous studies that have utilised Nash-Cournot frameworks to derive policy insights from various power markets [20; 40; 46; 47; 89].

Moreover, dynamic decisions could have been incorporated through a closed-loop model to tackle uncertainty in seasonal hydro inflows. It is plausible that each producer adjusts operational decisions seasonally, considering inflows and other producers' reaction functions. Nevertheless, this setup results in an EPEC, thereby making it challenging to find Nash equilibria. The theory does not guarantee existence and uniqueness [92; 93], which would lead to ambiguity in interpreting numerical results. As a result, policy analyses often rely on the more common open-loop Cournot model [18; 20; 40; 46; 89]. In a similar vein, stochastic dual dynamic programming (SDDP) can be employed to solve problems with realistic test networks, like the study in [91]. However, such an analysis assumes that the power system is operated by a single welfare maximiser and neglects strategic behaviour. This attribute is instead incorporated by [94] in an SDDP model and by [83] in an infinite-horizon game between strategic hydro and thermal producers. In particular, the latter model is solved numerically for Markov perfect equilibria by approximating the expected value functions in the hydro producer's Bellman equation. Although the open-loop approach used in this research overlooks the dynamic decision-making related to uncertainty, it can capture the system's main features, viz., heterogeneous ownership of assets, seasonal variations, and transmission congestion, at the expense of accounting for uncertainty.

3.4 Research Ethics

This research does not involve any human participation in either modelling or data collection. Most of the data are available from public sources. Moreover, licences for GAMS solvers were purchased through my *doktorandpott*, and I used the available MATLAB student licence. Some of the figures in the publications were drawn using a licenced version of Microsoft Office. Otherwise, the freely available LaTeX software was used for document preparation, with the TikZ package being used to render illustrations. Stockholm University's Overleaf licence was used to facilitate collaboration.

The research is conducted in line with the FAIR principles (Findable, Accessible, Interoperable, and Reusable), as mentioned in [95]. The data and results are easy to find and use for other similar studies, as the resources, assumptions, and final results are described in detail in my publications (or manuscripts). Finally, the collected dataset will be curated in line with Stockholm University's data-management policy.[8]

3.5 Summary

This chapter presents the methodological approach and research methods used in this study. The chapter began by detailing the DSR framework. It highlighted the chosen modelling method, effectively addressing complex research questions related to policy and technological developments in the Nordic power sector. Furthermore, the chapter discussed how comparing this method with alternative approaches can validate the research questions. By contrasting the Nash-Cournot model with other methodologies, such as supply-function equilibria, the chapter highlighted the advantages of using a framework that captures strategic interactions while remaining computationally tractable. This comparative analysis enhances the credibility of the findings and provides a better understanding of the methodologies employed. Finally, the chapter briefly touched on the ethical considerations involved in this research. By ensuring that all data sources were publicly available and aligning with the FAIR

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[8] `https://www.su.se/staff/researchers/research-data.`

principles, the research guarantees that its findings are accessible and reusable for future research.

4. Summary of Papers

This chapter provides an overview of the papers included in this thesis. Section 4.1 discusses the contributions of Paper P1, which explores strategic hydro operations. Section 4.2 presents the contributions of Papers P2 and P3, which examine the advent of prosumers. Finally, Section 4.3 focuses on Paper P4, addressing transmission planning and its relationship with climate policy.

4.1 Climate Policy, Hydro Operations, and VRE Expansion

In this section, strategic hydro operations under climate policies in the Nordic power sector are studied. This is in response to this thesis's RQ1 and RQ3, which are related to the impact of market power and climate policy on the hydro operations of the Nordic power system.

4.1.1 Motivation

Embarking on the path to a sustainable and decarbonised future necessitates a thorough understanding of the complex dynamics of the power sector. As climate packages in the OECD countries aim for significant decarbonisation, integrating societal goals with private market participants' goals becomes increasingly difficult, particularly in the context of a deregulated power sector. The European Green Deal's ambitious goals, such as a 55% reduction in greenhouse gas emissions by 2030, require substantial investments in flexible resources such as storage and transmission capacity. Real-world examples, such as Germany's Energiewende and California's 'duck curve', demonstrate the necessity of strategic planning in ensuring the success of sustainable-energy transitions. The integration of energy storage, particularly exploiting existing hydro reservoirs, appears as a critical solution to the issues faced by intermittent renewable energy output. However, recent research has highlighted potential distortions caused by the exercise of market power in hydro-storage operations, emphasising the importance of careful analysis and strategic planning in the pursuit of sustainable-energy goals.

In the Nordic region, the study identifies processes by which future climate regulations may unintentionally intensify strategic behaviour by hydro reservoirs, thereby emphasising the importance of policy adaptations to ensure that the transition aligns with societal goals. This study, by filling the identified gap, contributes significantly to our understanding of the difficulties at the junction of market dynamics, regulatory incentives, and environmental sustainability in the pursuit of a greener future. The route to a green future is about more than just adopting renewable energy; rather, it is about navigating the complex framework of economic interests, environmental sustainability, and social welfare.

4.1.2 Design of Experiment

We investigate two *scenarios* to answer RQ1 and RQ3. The first is the current baseline, and the other is a future scenario that gradually allows VRE adaptation and higher CO_2 taxation:

- Base2018: Generation and transmission capacities are at 2018 levels (see Figure 4.1 and Tables 4.1, 4.2, and 4.3).[1,2]
- 2030CV: It is the same as Base2018, but with increases in the VRE capacity and CO_2 tax.

In each scenario, we consider the following three *cases* with varying degrees of competition:

- Perfect competition (PC): All firms are price takers.
- Cournot oligopoly in thermal generation (COG): Selected firms with large capacities, e.g. Vattenfall at $SE3$ and Fortum at both $SE3$ and FI, withhold generation from nuclear plants to manipulate prices.
- Cournot oligopoly in reservoirs (COR): Selected firms with strategic reservoirs, e.g. Vattenfall at $SE1$ and Statkraft at $NO4$, exercise market power in hydro-reservoir generation to manipulate prices.

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[1] We use $i1$ to $i17$ to refer to Vattenfall, E.ON, OKG, Fortum, TVO, PVO, HELEN, Kemijoki, Ørsted, Statkraft, Norsk Hydro, Sira-Kvina, Agder Energi, BKK, E-CO Energi, Sydkraft, and Skellefteå Kraft, respectively.

[2] Information about the operational parameters, including CO_2 emission rates [in t/MWh] and ramp rates as proportions of installed capacities [unitless], is based on data available from firms' websites, relevant databases, and relevant authorities (e.g. `https://data.open-power-system-data.org/conventional_power_plants/` and `https://energia.fi/en/newsroom/publications/district_heating_statistics.html`).

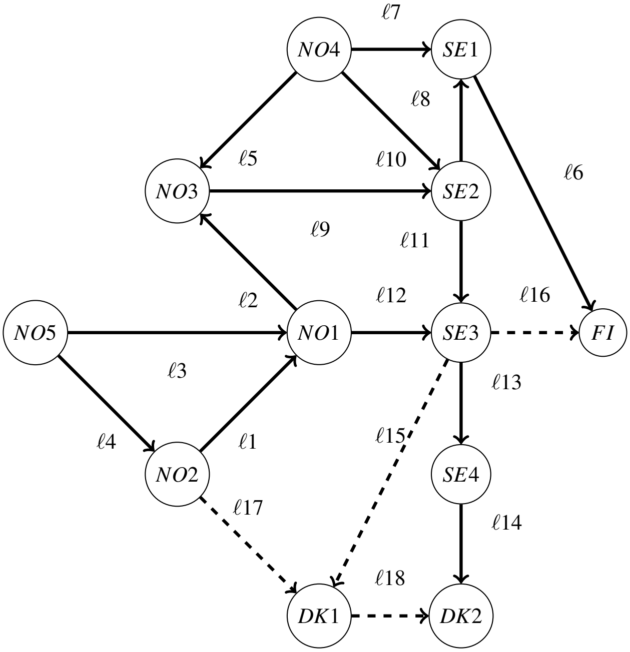

Figure 4.1: Stylised Nordic Test Network.

Table 4.1: Firms' Hydro Reservoir Volumes by Node for Strategic Reservoir (SRS), Non-Strategic Reservoir (NRS), Strategic Pumped-Hydro (SPH), and Non-Strategic Pumped-Hydro (NPH) Types (GWh).

Nodes	Firm	SRS	NRS	NPH	SPH
$SE1-SE4$	$i1$	12210	4668		
	$i4$		5952		
	$i10$		2533		
	$i16$		4105		
	$i17$		1626		
	$i18$		2457		
FI	$i6$		1268		
	$i8$		4262		
$NO1-NO5$	$i10$	17707	15508	2823	
	$i11$	99	5406		
	$i12$		4328	681	
	$i13$	276	4506	95	
	$i14$	2016	1331		130
	$i15$	4646	4746		421
	$i21$		26234	701	

Table 4.2: Thermal Generation Costs $C_{i,n,t,u}$ (€/MWh), Emission Rates $P_{i,n,u}$ (t/MWh), and Ramp Rates R_u^{up} (–).

Unit	$C_{i,n,t,u}$	$P_{i,n,u}$	R_u^{up}
Coal $u1$	32	0.83	0.2
Gas $u2$	65	0.50	0.5
CCGT $u3$	48	0.37	0.5
Oil $u4$	67	0.72	0.7
Biomass $u5$	59	0.00	0.2
Nuclear $u6$	21	0.00	0.1
Peat $u7$	22	1.09	0.1
Waste $u8$	22	0.94	0.1
CHP Coal $u9$	37	0.83	0.1
CHP Waste $u10$	22	0.94	0.1
CHP Gas $u11$	57	0.50	0.1
CHP Oil $u12$	33	0.72	0.1
CHP Peat $u13$	22	1.09	0.1
CHP Biomass $u14$	27	0.00	0.1

Table 4.3: Firms' Installed Capacities by Node and Unit (GW).

Nodes	Firm	$u1$	$u2$	$u3$	$u4$	$u5$	$u6$	$u7$	$u8$	$u9$	$u10$	$u11$	$u12$	$u13$	$u14$	Wind	Solar	Hydro
$SE1-SE4$	$i1$	–	–	–	–	–	4.9	–	–	–	0.1	–	–	–	0.1	0.3	–	7.5
	$i2$	–	–	–	–	–	0.7	–	–	–	–	–	–	–	0.1	0.2	–	–
	$i3$	–	–	–	–	–	0.8	–	–	–	–	–	–	–	–	–	–	–
	$i4$	–	–	–	–	–	1.4	–	–	–	0.1	–	–	0.2	0.1	0.1	–	3.5
	$i10$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.1	–	1.1
	$i16$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.2
	$i17$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.5
	$i18$	–	0.4	–	1.8	–	–	–	–	–	–	–	–	–	0.1	5.6	0.2	1.6
FI	$i4$	0.3	–	–	–	–	1.5	–	–	0.1	–	0.3	–	–	0.1	–	–	1.5
	$i6$	0.3	–	–	–	–	1.0	–	–	–	–	–	–	–	0.4	–	–	0.4
	$i7$	–	–	–	0.1	–	–	–	–	0.2	–	0.7	–	0.2	–	–	–	–
	$i8$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.4
	$i19$	–	–	–	1.2	–	0.3	–	–	0.7	0.2	0.9	0.1	2.1	–	1.9	0.2	0.7
$DK1-DK2$	$i1$	0.4	–	–	–	–	–	–	–	–	–	–	–	–	–	0.8	–	–
	$i9$	1.4	0.7	1.2	–	0.1	–	–	–	–	–	0.3	–	–	1.6	0.4	–	–
	$i20$	0.4	–	0.3	–	–	–	–	–	–	–	–	–	–	–	4.4	0.9	–
$NO1-NO5$	$i2$	–	0.2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	$i4$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.1	–	–
	$i10$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.2	–	9.5
	$i11$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.3
	$i12$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3.9
	$i13$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2.0
	$i14$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.8
	$i15$	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4.4
	$i21$	–	0.8	0.1	–	–	–	–	0.1	–	–	–	–	–	–	1.7	0.1	12.4

In addition to the Base2018 scenario with a CO_2 price of €15/t, we investigate all three cases under a hypothetical 2030 scenario called 2030CV that has a CO_2 price of €100/t, which is in line with Sweden's CO_2 tax[3] of €110/t, and doubled nodal VRE capacities in each firm's 2018 portfolio, which is based on recent projections.[4] The purpose of the 2030CV scenario is to examine how a restructured supply side due to climate policy affects market power, i.e. RQ3. As such, this scenario keeps demand functions fixed at 2018 levels in order to focus on the supply side. This is a reasonable assumption because overall electricity consumption in OECD countries is projected to grow at about 1% per annum between 2020 and 2030 [96]. In addition, since the VRE capacity is exogenous, its capital costs will be excluded from the results because fixed costs affect neither the operational decisions nor the differences in surpluses between cases. All problem instances can be solved to optimality in a few seconds with GAMS 35.1.0 using CPLEX 20.1.0.1 on an Intel Core i7-8650U CPU@1.90GHz quad-core processor with 16.0 GB of RAM. Also, we report the following key metrics: social welfare (SW), consumer surplus (CS), firm surplus (FS), merchandising surplus (MS), government revenue (GR), and CO_2 emissions (EM).

4.1.3 Summary of Main Findings and Contributions

The main contribution of the paper can be summarised as the development of a Nash-Cournot model to evaluate how climate policies could influence strategic behaviour by hydro producers in the Nordic power market. We specifically focus on temporal shifts in production and their impact on market outcomes under varying CO_2 prices and VRE capacity.

Regarding the impact of market power within the current Nordic power system (RQ1), we utilise 2018 data in a base scenario to examine potential Bushnell (2003)-like behaviour, i.e. the strategic behaviour of hydro producers, as they could shift generation from peak to off-peak seasons to conduct temporal arbitrage, by large reservoir owners [18]. A summary of the numerical findings in Table 4.4 for 2018 highlights the welfare loss when market power is permitted under either COG or COR, resulting in a transfer of welfare from consumers to producers.[5] Also, the comparison of the PC and COR results reveals that the latter provide a more accurate representation of price

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[3] `https://www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax/`

[4] `https://www.iea.org/articles/renewables-2020-data-explorer?mode=market&region=Denmark&product=Total`

[5] To calibrate and verify the results' credibility, we used the PC case results and made a comparison with the existing data: total generation of 400 TWh (vs 398 TWh in 2018), total net-hydro generation of 212 TWh (vs 213 TWh in 2018), average electricity price of €39.32/MWh (vs €42.04/MWh in the representative weeks), and total CO_2 emissions of 31.5 Mt (vs 35.1 Mt for both power and heat generation in 2017).

variability compared to the PC results. While the PC model captures average price levels with a low standard deviation (€4.89/MWh), it struggles to reflect price variation. In contrast, COR captures both diurnal and seasonal price patterns more effectively, with a higher standard deviation (€10.81/MWh), which better aligns with real-world fluctuations. Additionally, the COR model improves accuracy in reservoir-level tracking, where the modelled reservoir levels better follow the actual data.

Under COG, there is a significant increase in CO_2 emissions, likely due to the withholding of nuclear capacity. Throughout the year, Vattenfall is able to decrease its total nuclear generation from 43.27 TWh to 7.86 TWh, allowing higher-cost fossil-fuelled plants to operate at capacity more often and increase the equilibrium price, as well as Vattenfall's FS by about 31%. In terms of temporal arbitrage under COR, Figure 4.2 demonstrates how Vattenfall at $SE1$ can shift water from the peak winter and fall seasons to the off-peak spring season to influence prices (see Figure 4.3), despite annual net-hydro generation being regulated to remain the same as under PC. In this way, Vattenfall can increase its FS by about 2%. The ability to manipulate electricity prices through temporal arbitrage without 'spilling' water is more subtle than a conventional strategy of capacity withholding by nuclear plants, which would be more easily detectable by market inspectors. Concerning RQ1, it is apparent that hydro capacities' generation output could be adjusted strategically to engage in temporal arbitrage, thereby manipulating market prices.

Table 4.4: Numerical Results for Base2018 Scenario (in Billion € Unless Otherwise Indicated).

Metric \ Case	PC	COG	COR
SW	142.29	140.69	142.21
CS	129.46	117.46	128.94
FS	12.01	21.70	12.20
MS	0.35	0.71	0.59
GR	0.47	0.82	0.48
EM (Mt)	31.46	54.70	32.26
Vattenfall FS	2.01	2.63	2.05

To investigate RQ3, we introduce a 2030CV scenario featuring a €100/t CO_2 price and an exogenous doubling of VRE capacity to explore the potential impact of future climate policies on market power and hydro operations (see Table 4.5). The substantial increase in VRE capacity notably improves social welfare, resulting in decreased average prices under PC. However, our analysis reveals that such a transformation in the power sector could facilitate market power for several reasons: (i) reduced average prices diminish forgone revenues from shifting production away from peak seasons; (ii) the necessity

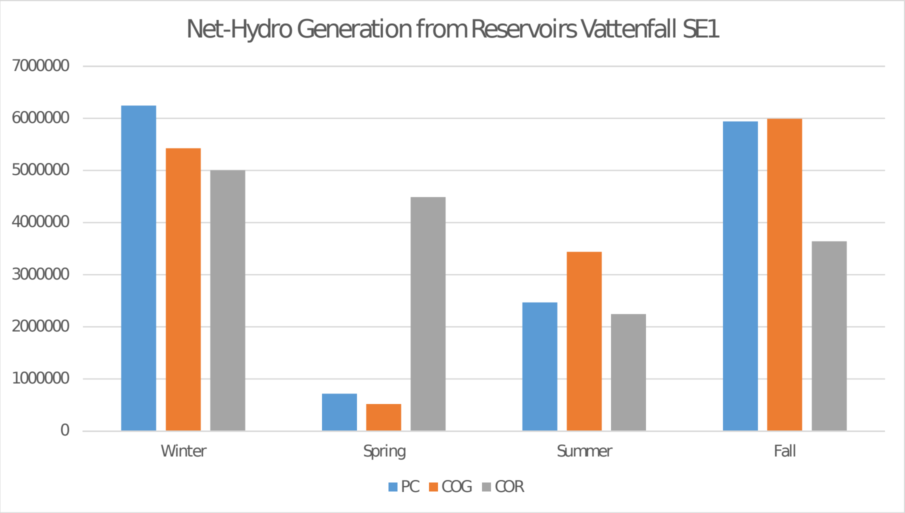

Figure 4.2: Vattenfall's Net-Hydro Operations from Reservoirs at $SE1$ (in MWh).

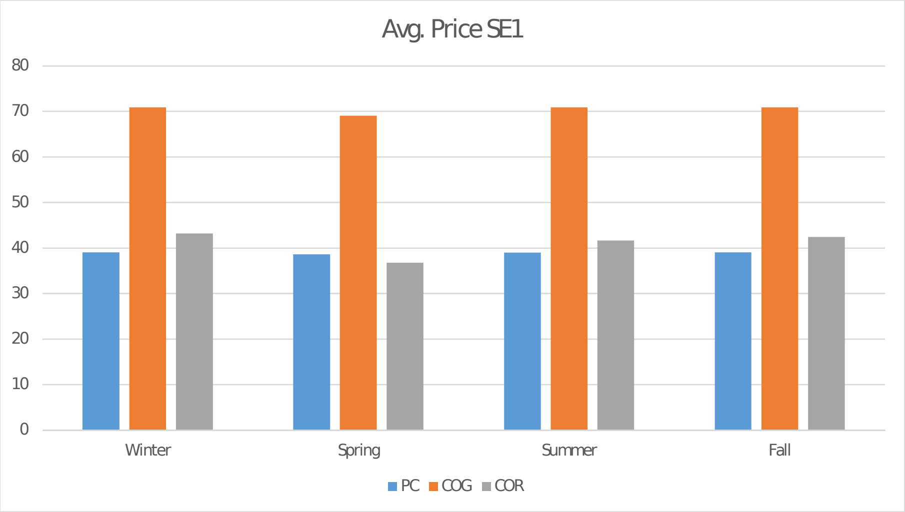

Figure 4.3: Seasonal Average Prices at $SE1$ (in €/MWh).

of balancing intermittent VRE output may lead to the export of 'excess' hydro production during off-peak seasons; and (iii) flexible price-taking fossil-fuelled plants, subjected to a high CO_2 price, may become economically unviable in responding to price increases induced by strategic manoeuvres. It can be seen that under COG, Vattenfall strategically withholds its nuclear capacity to boost its FS by 196%. Under COR, Vattenfall takes advantage of volatile prices to increase its FS by 11.9%. This increase is facilitated by the increased deployment of VRE and the lack of response from price-taking fossil-fuelled plants. Consequently, the growing demand for emission-free and flexible resources, driven by increased VRE penetration, could potentially be exploited by strategic firms (see Figure 4.4). Regarding RQ3, our results suggest that increased CO_2 prices and the adoption of VRE capacities could encourage hydro producers to enhance their strategic behaviour.

Table 4.5: Numerical Results for 2030CV Scenario (in Billion € Unless Otherwise Indicated).

Case / Metric	PC	COG	COR
SW	142.80	141.73	142.77
CS	130.00	111.04	129.23
FS	10.07	27.84	10.61
MS	2.39	2.14	2.58
GR	0.34	0.71	0.34
EM (Mt)	3.43	7.07	3.43
Vattenfall FS	1.09	3.23	1.22

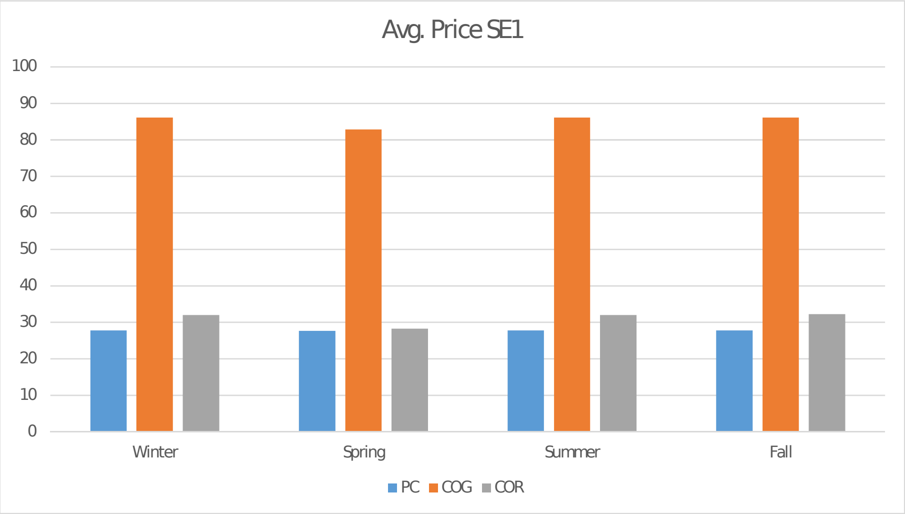

Figure 4.4: Seasonal Average Prices at $SE1$ in the 2030CV Scenario (in €/MWh).

4.2 Advent of Prosumers and Intra-Inter-Seasonal Arbitrage

In this section, the advent of prosumers and intra- and inter-seasonal arbitrage in the Nordic power sector are studied. This is in response to this thesis's RQ2 and RQ3, which are related to the impact of prosumers and climate policy on the hydro operations of the Nordic power system.

4.2.1 Motivation

Climate policies, exemplified by the commitment to carbon neutrality in Nordic countries and the European Union's ambitious targets for CO_2 reduction, necessitate a transformative approach to power sectors. This paradigm shift involves substantial investments in VRE capacities like wind and solar power, which are crucial for achieving decarbonisation goals. The intermittent nature of VRE demands flexible resources, such as storage and demand response, for integration into power systems. Despite the Nordic region's apparent suitability for accommodating VRE with its hydro reservoirs and transmission links, the evolving landscape, marked by increased flexibility needs and the rise of prosumers, introduces complexities. This study scrutinises the potential impact on Nordic hydro producers' market power, specifically their ability to manipulate electricity prices through temporal arbitrage, considering the influence of prosumers and a high CO_2 price. It is focused on structural changes to the demand side, as opposed to the structural changes to the supply side in Section 4.1. The analysis is set against the backdrop of deregulated electricity industries, recognising the inherent challenges of market power by strategic producers. This research contributes to the relevant research questions by shedding light on the interplay among market power, VRE integration, and evolving demand-side flexibility in the Nordic context.

4.2.2 Design of Experiment

In this part of the study, we employ two setups to address RQ2 and RQ3. Initially, we explore the impact of aggregator-enabled prosumers on intra-seasonal hydro operations using two scenarios: NA, which serves as the baseline without aggregator-enabled prosumers, and Agg100, where one aggregator-enabled prosumer with 100 MW of exogenous wind capacity and endogenous demand for electricity is introduced. We use limited Nordic data in a three-node test system (Figure 4.5) with 10-MW capacity transmission lines, employing demand parameters and VRE profiles from 2018 for Nordic zones $NO4$, $DK2$, and $DK1$ for nodes $n1$–$n3$, respectively. Subsequently, we extend the analysis to investigate the impact of aggregator-enabled prosumers on inter-seasonal hydro operations. In this extended study, we consider three scenarios. The first serves as a baseline without aggregator-enabled prosumers, while the other two represent future scenarios that gradually introduce aggregator-enabled prosumers and higher CO_2 taxation. In this part, we utilise full Nordic data. The scenarios are as follows:

- Part 1

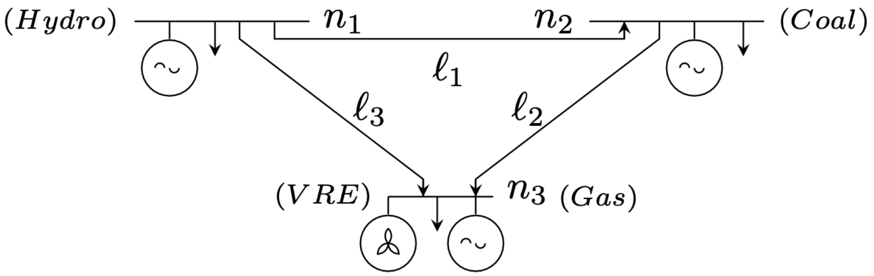

Figure 4.5: Three-Node Test System.

  - NA: It is a reference scenario without aggregator-enabled prosumers in order to establish a baseline using limited Nordic data from the year 2018.
  - Agg100: It is the same as NA, but with the addition of an aggregator-enabled prosumer with 100 MW of wind capacity and a gross-benefit function.

  Each problem instance takes a few seconds to solve to optimality with GAMS 35.1.0 using CPLEX 20.1.0.1 deployed on an Intel Core i7-8650U CPU@1.90GHzquad-core processor and 16.0 GB of RAM.

- Part 2

  - Base2018: Generation and transmission capacities are at 2018 levels.
  - FutureAV: It is the same as Base2018, but with the presence of a price-taking aggregator-enabled prosumer at each node with its own demand function and VRE capacity.
  - FutureAVC: It is the same as FutureAV, but with a higher CO_2 tax.

Similar to the previous section, in each scenario, we consider the following three *cases* with varying degrees of competition:

- Perfect competition (PC): All firms are price takers.
- Cournot oligopoly in thermal generation (COG): Selected firms with large capacities, e.g. thermal capacity at $n2$ and $n3$ in Part 1, and Vattenfall at $SE3$ and Fortum at both $SE3$ and FI in Part 2, withhold generation to manipulate prices.
- Cournot oligopoly in reservoirs (COR): Selected firms with strategic reservoirs, e.g. hydro producer at $n1$ in Part 1, and Vattenfall at $SE1$ and Statkraft at $NO4$ in Part 2, exercise market power in hydro-reservoir generation to manipulate prices.

Each problem instance takes a few seconds to solve to optimality with GAMS 35.1.0 using CPLEX 20.1.0.1 deployed on an Intel Core i7-8650U CPU@1.90GHz quad-core processor and 16.0 GB of RAM. Since the aforementioned test cases (PC, COG, and COR) are utilised to investigate strategic behaviour through thermal and hydro units, we have a total of nine problem instances.

We report the following key metrics: social welfare (SW), consumer surplus (CS), firm surplus (FS), prosumer surplus (PS), merchandising surplus (MS), government revenue (GR), and CO_2 emissions (EM).

4.2.3 Summary of Main Findings and Contributions

The contributions include examining the impact of aggregator-enabled prosumers on strategic hydro operations using a Nash-Cournot model. They explore how prosumers' behaviour and a high CO_2 price affect hydro producers' ability to manipulate market prices through temporal shifts.

In Part 1, we investigate the intra-seasonal impact of the aggregator-enabled prosumers by utilising limited data from the Nordic power system to address RQ2 and RQ3. It can be seen from the results that strategically withholding thermal generation under COG significantly reduces system emissions by over 50% (see Table 4.6). However, it leads to higher average prices compared to PC, shifting the surplus from consumers to firms (see Figure 4.6). Similarly, the strategic use of hydro storage under COR slightly decreases social welfare and consumer surplus but allows temporal arbitrage, resulting in increased profitability for hydro producers. Compared to PC, hydro production is withheld during the peak periods and increased during the off-peak periods, resulting in higher prices during peak periods and lower prices during off-peak periods (see Figures 4.6 and 4.7).

Table 4.6: NA Results (in k€ Unless Otherwise Indicated).

Case Metric	PC	COG	COR
SW	1164.28	822.98	1162.55
CS	714.28	202.36	707.68
FS	199.93	552.93	204.91
GR	128.37	60.08	128.31
MS	121.69	7.62	121.65
EM (kt)	8.56	4.01	8.55
Firm $i1$ FS	114.02	142.22	116.43
Firm $i2$ FS	85.91	412.41	88.48

In Agg100, SW is higher vis-à-vis NA (see Table 4.7), as the aggregator at $n3$ adds VRE output plus its own consumption. In fact, prices are not uniformly

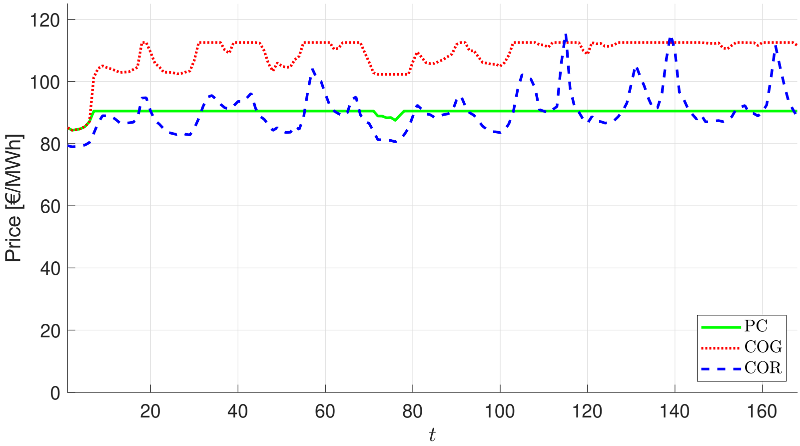

Figure 4.6: Node $n1$ Prices in NA (in €/MWh).

affected by the aggregator's VRE output, resulting in slight price increases at nodes $n1$ and $n2$ due to higher average consumption. However, a moderate increase in CS overall is mainly driven by higher CS at node $n3$. Additionally, CO_2 emissions decrease due to the integration of VRE.

Under COG, prices rise across all nodes compared to PC, and the prosumer benefits from these higher prices and transitions to a net seller (see Table 4.7 and Figure 4.9). Under COR, hydro production mirrors patterns observed in NA but exploits VRE output intermittency (see Figure 4.8). This enables the hydro producer to adjust its production, maximising sales when the aggregator is a net seller and withholding water when it becomes a net buyer, as shown in Figures 4.7 and 4.8. Consequently, the prosumer's intermittent net sales enable the hydro producer to increase FS by 2.25% under COR compared to PC, versus 2.11% in NA.

Table 4.7: Agg100 Results (in k€ Unless Otherwise Indicated).

Case Metric	PC	COG	COR
SW	1566.43	1245.54	1563.81
CS	725.43	327.55	723.80
FS	199.23	362.28	200.23
PS	391.99	450.65	390.77
GR	120.13	43.11	119.95
MS	129.65	61.96	129.05
EM (kt)	8.01	2.87	8.00
Firm $i1$ FS	115.55	138.22	118.15
Firm $i2$ FS	83.68	224.06	82.09

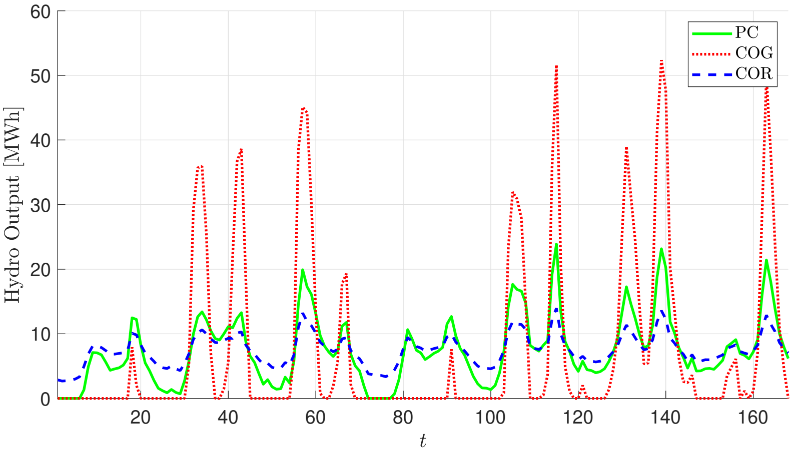

Figure 4.7: Hydro Production in NA (in MWh).

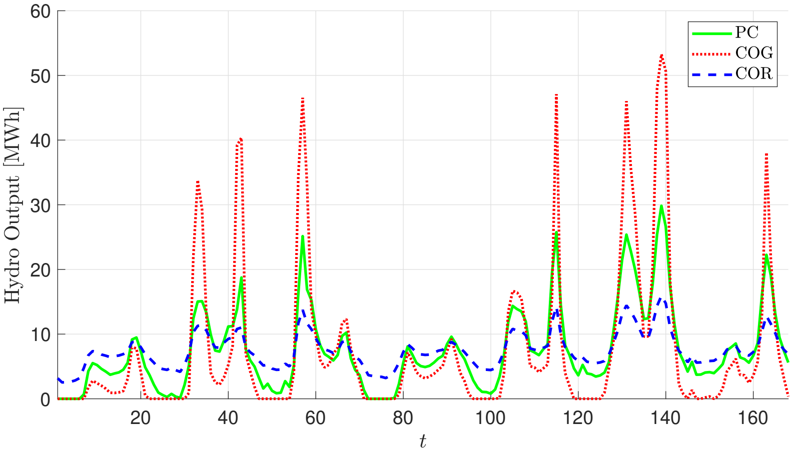

Figure 4.8: Hydro Production in Agg100 (in MWh).

In Part 2, we expand the investigation of the inter-seasonal impact of the prosumers by incorporating full Nordic data. In addition to the Base2018 scenario (Table 4.8), which aligns with findings from previous literature, we explore the implications of future changes in demand driven by aggregator-enabled prosumers for market-power exertion and hydro-reservoir operations within the Nordic grid to address RQ2 and RQ3. The summarised numerical results of the FutureAV scenario are presented in Table 4.9. Our analysis reveals that the aggregator-enabled prosumers, through their VRE output, lead to a decrease in overall average prices (see Figure 4.10) and a slight increase in CS. However, the aggregator's price impact varies across different periods due to its endogenous consumption. VRE availability peaks during spring and

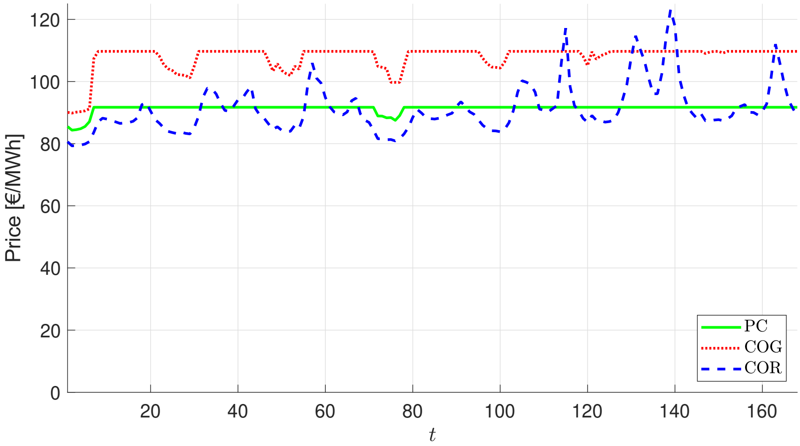

Figure 4.9: Node $n1$ Prices in Agg100 (in €/MWh).

fall (see Figure 4.11), while conventional consumer demand peaks during winter and fall (see Figure 4.12). Furthermore, aligned with VRE availability, the aggregator's net sales at $SE1$ under PC are highest during spring and fall (see Figure 4.13). Consequently, the hydro producer can exploit the aggregator's net-sales pattern to amplify the impact of hydro's temporal arbitrage compared to scenarios without aggregator-enabled prosumers. Regarding strategic behaviour involving thermal generation, the influence of market power under COG is constrained due to aggregators typically transitioning to net suppliers across all seasons (see Figure 4.13). Consequently, Vattenfall's endeavour to withhold nuclear capacity to encourage more price-taking thermal generation at full capacity is tempered. This is evidenced by the smaller increase in EM from PC to COG in the 2030AV scenario compared to the Base2018 scenario, along with Vattenfall's FS increase of 15.76%, which is lower than that in the Base2018 scenario at 30.84% (see Tables 4.8 and 4.9).

Continuing our investigation, we introduce a high CO_2 price of €100/t to assess the implications of a prospective climate package on market-power dynamics alongside aggregators within the 2030AVC scenario. This elevated CO_2 price results in a reduction of emissions by nearly 90% compared to the PC case in the 2030AV scenario (see Table 4.10). Notably, there is a marginal decrease in social welfare, accompanied by a transfer of wealth from consumers to firms and aggregator-enabled prosumers, primarily driven by the rise in average electricity prices (see Figure 4.15). Consequently, the aggregator at $SE1$ predominantly functions as a net seller (see Figure 4.16), a trend observed across all aggregators. Exploring strategic behaviour under COG, the substantially elevated electricity prices induced by carbon policy further incentivise net sales by aggregators (see Figure 4.16). Moreover, the inability of price-taking flexible plants, such as gas-fired plants, to react to heightened

Table 4.8: Numerical Results for the Base2018 Scenario (in Billion € Unless Otherwise Indicated).

Metric \ Case	PC	COG	COR
SW	142.29	140.69	142.21
CS	129.46	117.47	128.94
FS	12.01	21.70	12.20
PS	–	–	–
MS	0.35	0.70	0.59
GR	0.47	0.82	0.48
EM (Mt)	31.46	54.70	32.26
Vattenfall FS	2.01	2.63	2.05

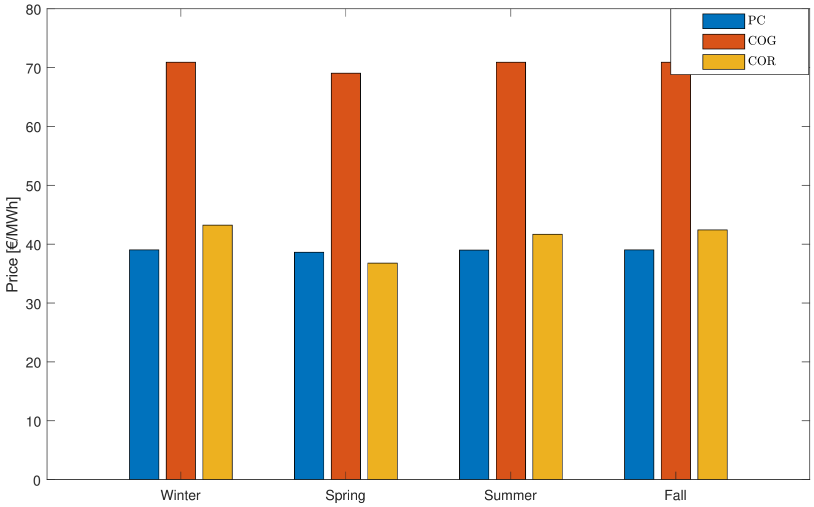

Figure 4.10: Seasonal Average Prices at $SE1$ for the Base2018 Scenario (€/MWh).

Table 4.9: Numerical Results for the 2030AV Scenario (in Billion € Unless Otherwise Indicated).

Metric \ Case	PC	COG	COR
SW	147.08	145.37	146.99
CS	129.33	119.41	128.81
FS	12.03	19.54	12.23
PS	4.69	4.78	4.69
MS	0.56	0.85	0.77
GR	0.47	0.78	0.48
EM (Mt)	31.59	51.84	31.96
Vattenfall FS	2.03	2.35	2.08

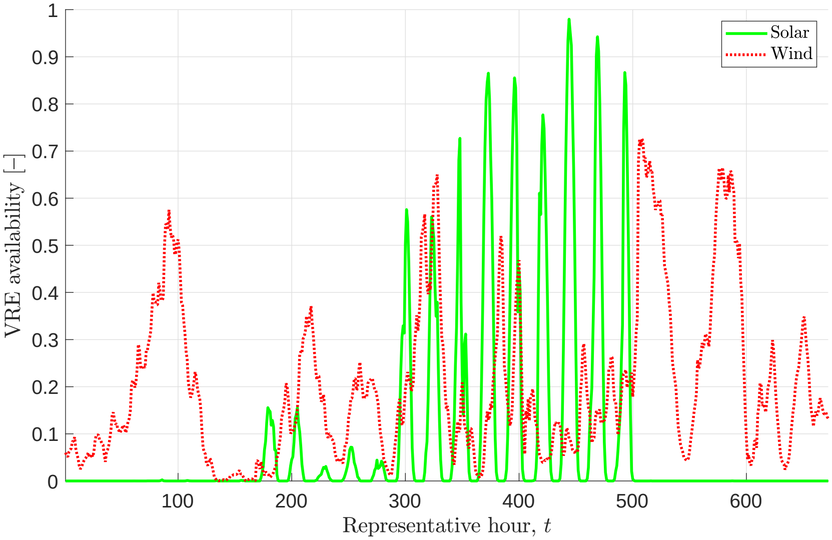

Figure 4.11: VRE Availability in Representative Weeks at $SE1$ (–).

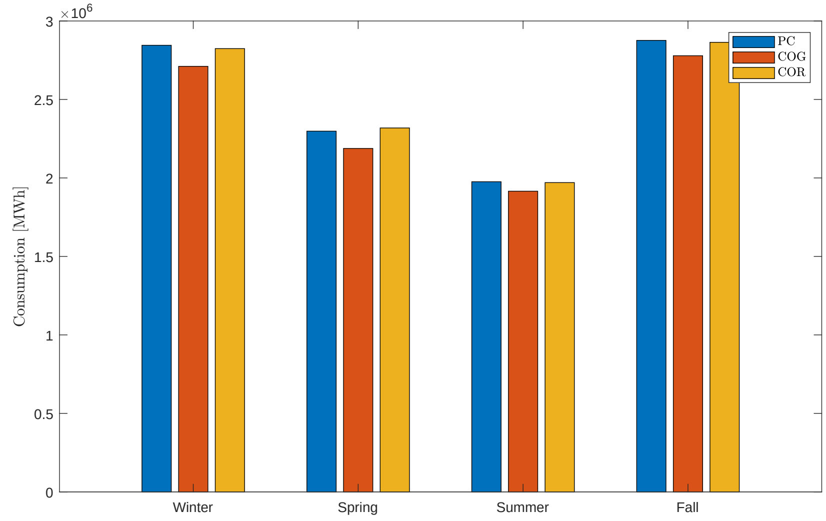

Figure 4.12: Consumption at $SE1$ in 2030AV (in MWh).

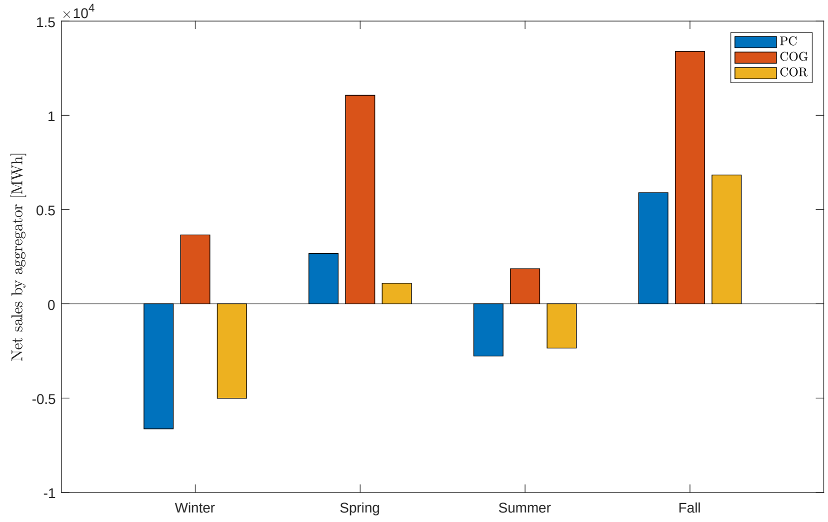

Figure 4.13: Net Sales by the Aggregator at $SE1$ in 2030AV (in MWh).

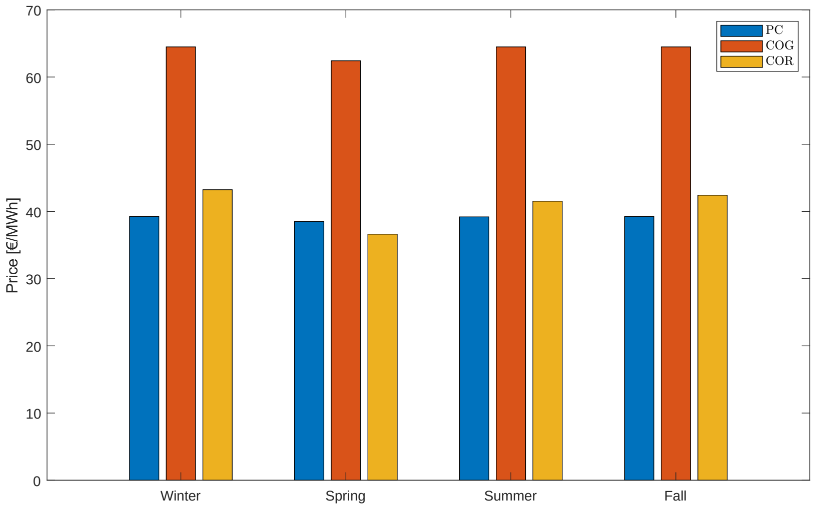

Figure 4.14: Seasonal Average Prices at *SE*1 in 2030AV (in €/MWh).

prices relative to the 2030AV scenario empowers Vattenfall to exert market power through its nuclear plants, allowing it to increase its FS by 19.41% under COG. For instance, Vattenfall may opt to withhold output to force otherwise idle thermal plants to set the market-clearing price.

Under COR, the effectiveness of market-power exertion via hydro reservoirs is heightened by a high CO_2 price (see Table 4.10). While the aggregator consistently acts as a net seller under COR in the 2030AVC scenario, Vattenfall's net-hydro generation at *SE*1 is more evenly distributed across seasons under PC in the 2030AVC scenario (see Figure 4.17) compared to the 2030AV scenario. This is attributed to limited generation from price-taking flexible units, like gas-fired plants elsewhere in the Nordic region, thereby amplifying Vattenfall's ability to exploit VRE generation intermittency despite the aggregator's counteractive flexibility in net sales. Thus, Vattenfall's leverage under COR is bolstered in the 2030AVC scenario relative to the 2030AV scenario, as evidenced by its FS increasing by about 3%, which is higher than in the 2030AV scenario.

Concerning RQ2, our study illuminates the impact of aggregator-enabled prosumers and a high CO_2 price on the strategic manipulation of electricity prices by hydro producers through temporal arbitrage. By analysing a stylised test network with Nordic grid data, we first unveil how aggregator-enabled prosumers influence the intra-seasonal arbitrage of hydro producers. Specifically, we find that the aggregator's net-sales pattern can be exploited by hydro producers to enhance their temporal arbitrage's effectiveness. Furthermore, our extended analysis using the full Nordic network also highlighted how hydro reservoirs could leverage aggregator-enabled prosumers' net-sales patterns for more effective arbitrage. Finally, we observe that a higher CO_2 price amplifies the market power of hydro reservoirs, addressing RQ3.

Table 4.10: Numerical Results for the 2030AVC Scenario (in Billion € Unless Otherwise Indicated).

Metric \ Case	PC	COG	COR
SW	146.21	144.38	146.11
CS	121.16	108.10	120.38
FS	18.18	28.67	18.64
PS	4.77	5.24	4.78
MS	1.68	1.38	1.90
GR	0.42	0.99	0.41
EM (Mt)	4.16	9.91	4.10
Vattenfall FS	3.09	3.69	3.18

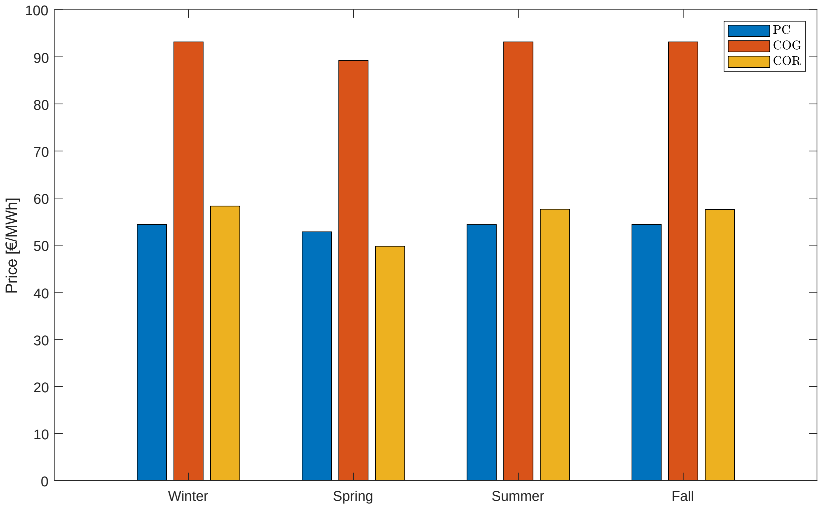

Figure 4.15: Seasonal Average Prices at *SE*1 in 2030AVC (€/MWh).

4.3 Transmission Planning and Climate Policy

In this section, transmission planning and climate policy in the Nordic power sector are studied. This is in response to this thesis's RQ4 and RQ5, which are related to Nordic power-system transmission planning considering the climate imperatives.

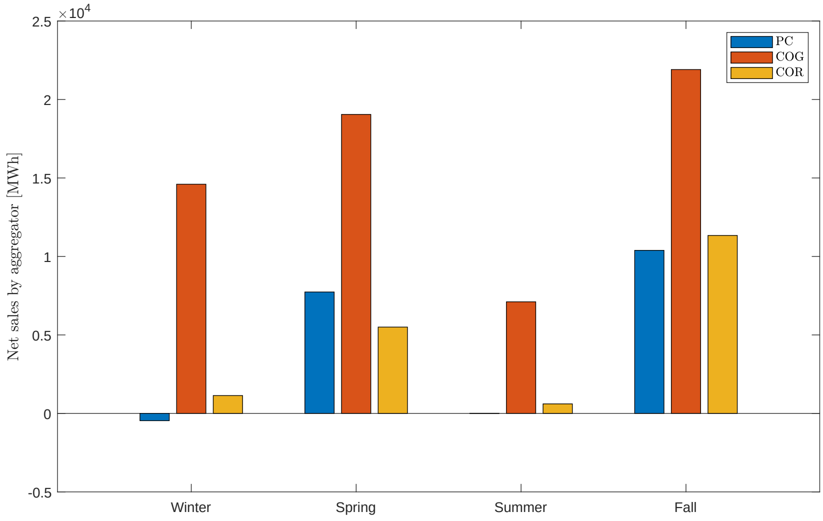

Figure 4.16: Net Sales by the Aggregator at $SE1$ in 2030AVC (MWh).

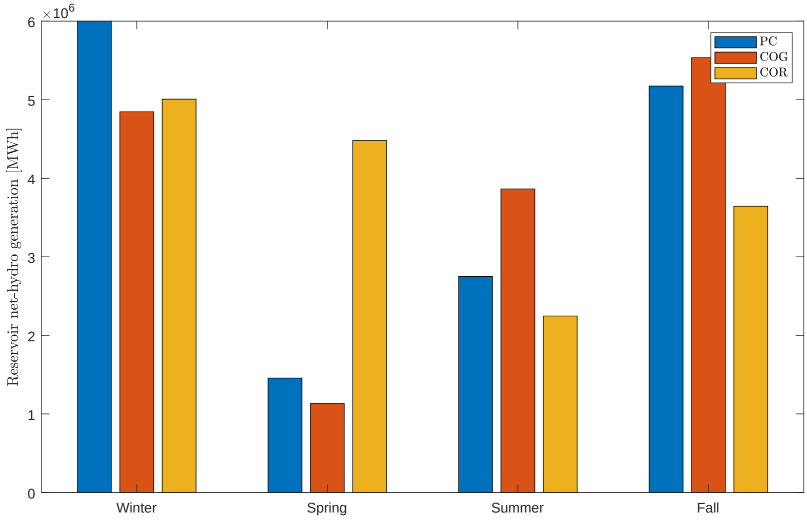

Figure 4.17: Net Hydro-Reservoir Generation by Vattenfall at $SE1$ in 2030AVC (MWh).

4.3.1 Motivation

Effectively integrating VRE capacities into power sectors amidst the challenges posed by electricity-market deregulation necessitates adaptive policy-making. The transition towards sustainability, exemplified by initiatives like the Green Deals in OECD countries, demands a comprehensive understanding of the power sector's difficulties and market participants' divergent interests. Deregulation presents difficulties, as power companies' interests may not coincide with social welfare, thereby necessitating transmission planning to adopt energy storage, particularly through hydro reservoirs, which appears to be a significant solution to address spatio-temporal imbalances. However, recent research has uncovered distortions and market-power issues associated with hydro storage, underscoring the importance of careful planning in sustainable-energy transitions. Recognising the impact of imperfect competition and incomplete carbon pricing, which reflects a situation in which political currents militate against the perceived costs of sustainability measures [13], on transmission planning is crucial within the Nordic context.

4.3.2 Design of Experiment

We investigate four *scenarios* to answer RQ4 and RQ5 (see Table 4.11). The first is the current baseline and the following three are future scenarios that gradually allow a higher social-cost rate of damage from CO_2 emissions, VRE adoption, and transmission investment:

- Base2018: Generation and transmission capacities are at 2018 levels, assuming a social-cost rate of damage from CO_2 emissions of €15/t.
- FutureC: It is the same as Base2018, except that the social-cost rate of damage from CO_2 emissions is €100/t.
- FutureCV: It is the same as FutureC, except that VRE expansion[6] is allowed by firms at nodes at which they own VRE capacity.
- FutureCVT: It is the same as FutureCV, except that transmission expansion is allowed on selected lines.

The candidate lines for investment are selected by conducting a congestion analysis on the Nordic network (see Figure 4.1). Table 4.12 lists the proportion of representative hours during which the lines are congested in either direction for lines that are congested for at least 40% of the hours. Upgrades to capacities of either 400 MW or 800 MW are allowed for each of these four lines at an amortised annual capital cost of €200/MW-km. Table 4.13 indicates the incremental susceptance (for AC lines only) and annual amortised cost from

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[6] We do not allow the expansion of fossil-fuelled, hydro, and nuclear technologies because of environmental, siting, and lead-time restrictions, respectively.

undertaking a 400 MW upgrade to the lines. For example, a 400 MW increase in the capacity of line $\ell 6$ increases its total susceptance by 141 S and costs €49.44 million. Likewise, an 800 MW increase in the same line's capacity increases its total susceptance by 282 S and costs €98.88 million.

In a similar manner, in each future scenario, we consider the following three *cases* with varying degrees of competition:

- Perfect competition (PC): All firms are price takers.
- Cournot oligopoly in thermal generation (COG): Selected firms with large capacities, e.g. Vattenfall at $SE3$ and Fortum at both $SE3$ and FI, withhold generation from nuclear plants to manipulate prices.
- Cournot oligopoly in reservoirs (COR): Selected firms with strategic reservoirs, e.g. Vattenfall at $SE1$ and Statkraft at $NO4$, exercise market power in hydro-reservoir generation to manipulate prices.

We finally analyse each of the nine aforementioned future scenario/case combinations under the following two *regimes*:

- Complete carbon pricing ($H = 1$): The future social-cost rate of damage from CO_2 emissions of €100/t is fully internalised.
- Incomplete carbon pricing ($H = 0.15$): The CO_2 price (or tax) perceived by the industry remains at the Base2018 rate of €15/t.

Table 4.11: Design of Experiment.

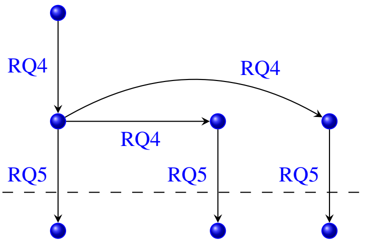
Regime	Case Scenario	PC	COG	COR
$H = 1$	Base2018			
	FutureCVT			
$H = 0.15$	FutureCVT			

Table 4.12: Congestion Analysis.

Line	$\ell 4$	$\ell 16$	$\ell 2$	$\ell 7$	$\ell 6$	$\ell 15$	$\ell 17$	$\ell 18$
Proportion of Hours Congested	0.923	0.732	0.686	0.646	0.570	0.525	0.488	0.441

We solve all problem instances in GAMS 40.3.0 using CPLEX 22.1.0.0 deployed on an Intel(R) Core(TM) i7-1280P processor with 32.0 GB of RAM. The cases in the Base2018, FutureC, and FutureCV scenarios can be solved

Table 4.13: Increase in Transmission-Line Susceptance $B_{j,\ell^{AC}}$ (in S) and Amortised Cost $C^{trn}_{j,\ell}$ (in Million €) from 400 MW Capacity Upgrade.

Line	$\ell 6$	$\ell 7$	$\ell 15$	$\ell 16$	$\ell 18$
$B_{j,\ell^{AC}}$	141	213	–	–	–
$C^{trn}_{j,\ell}$	49.44	37.76	45.60	31.92	12.48

to optimality in between 70 and 116 seconds, using only the lower-level QP problem. However, each case in the FutureCVT scenario takes approximately 2 hours since enumeration requires solving the lower-level QP problem $3^4 = 81$ times. Also, we report the following key metrics: social welfare (SW), consumer surplus (CS), firm surplus (FS), merchandising surplus (MS), government revenue (GR), the social cost of damage from CO_2 emissions (DC), and the cost of transmission investment (TC). Additional metrics include CO_2 emissions (EM), the Nordic average price (AP), investment in generation capacity (GC), and investment in transmission lines (TL).

4.3.3 Summary of Main Findings and Contributions

This paper contributes by using a Stackelberg model to analyse how transmission planning is affected by market power and incomplete CO_2 pricing in the Nordic power sector. It addresses optimal transmission planning under various market scenarios and policy frameworks.

In addressing RQ4 and RQ5, our study employs a calibrated model of the Nordic power sector to derive key policy implications. To effectively address RQ4, we conduct a thorough comparison between the findings from the PC case in the FutureCVT scenario in the $H = 1$ regime and those from earlier scenarios, as well as those from other cases within the FutureCVT scenario. We find that a socially optimal transmission plan under PC, achieved in a perfectly competitive market with the full internalisation of CO_2 emissions' social costs, utilises higher electricity prices to reduce consumption and facilitate more efficient sharing of generation resources. This includes freeing up existing generation capacity, such as nuclear plants in $SE3$, to be utilised by the more fossil-fuel-dependent FI zone (see Figure 4.18). Consequently, less adoption of VRE capacity is needed in FI compared to scenarios without transmission expansion, thereby revealing the tradeoff between consumption reduction and VRE adoption even without economic and environmental distortions (see Tables 4.14 and 4.15[7]).

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[7] The final row of the table indicates additions to the transmission-line capacity (TL) of the candidate lines. For example, the value of TL in the PC case is [0 0 0 2], which corresponds to an 800 MW increment to line $\ell 16$ and no increments to other candidate lines.

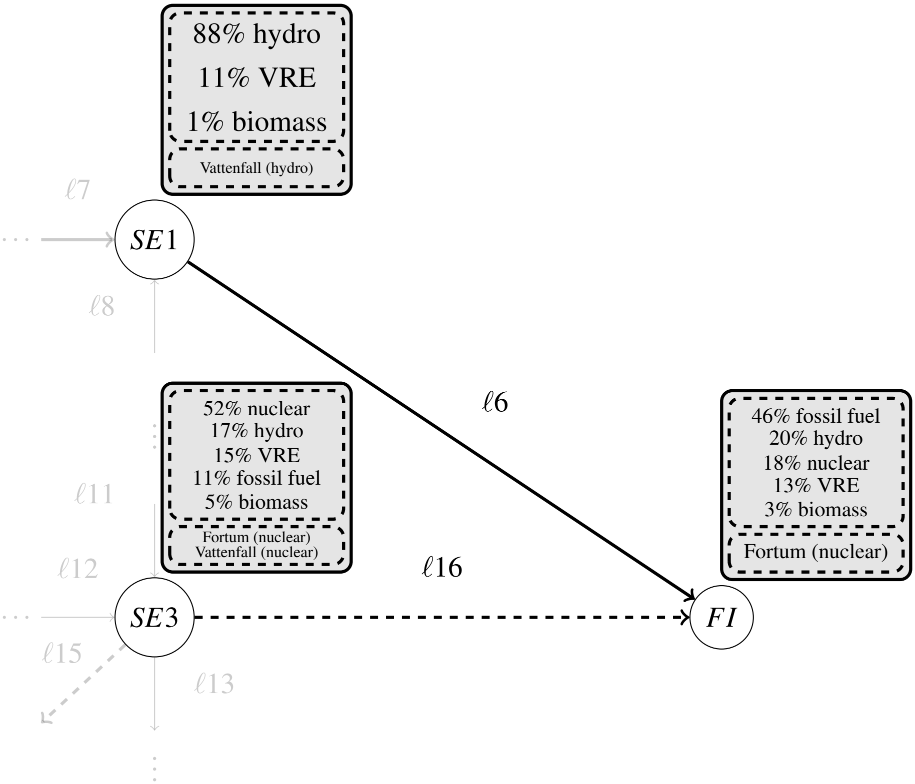

Figure 4.18: Network Map of Zones $SE1$, $SE3$, and FI with 2018 Generation-Capacity Mixes and Strategic Firms.

Focusing on strategic behaviour, we observe differing impacts on transmission expansion under imperfect competition and the full internalisation of CO_2 emissions' social costs, depending on the type of market power exerted. For instance, additional transmission expansion is necessary to compensate for restricted nuclear output under COG in which generation withholding by nuclear plants is involved. Conversely, temporal arbitrage by large reservoirs leads to higher electricity prices during seasons with high wind availability, encouraging VRE adoption. As a result, the transmission plan from PC suffices to integrate VRE due to reduced power flows on existing lines (see Tables 4.15 and 4.16, along with Figure 4.19).

The partial internalisation of social costs associated with CO_2 emissions highlights the impact of political pressures on transmission planning. In order to effectively respond to RQ5, we conduct a comparative analysis of FutureCVT scenarios between the two regimes, $H = 1$ and $H = 0.15$. Under PC without a price signal to curb consumption, i.e. with $H = 0.15$, the inefficient sharing of existing generation resources requires the TSO to actively reinforce transmission lines between $SE1$ and FI to induce VRE adoption (see Table

Table 4.14: Summary Results in the FutureCV Scenario (in Billion € Unless Otherwise Indicated).

Metric \ Case	PC	COG	COR
SW	138.913	137.829	138.797
CS	129.291	124.742	128.176
FS	8.550	11.238	9.533
MS	1.073	1.849	1.088
GR	0.105	0.342	0.096
DC	0.105	0.342	0.096
EM (Mt)	1.053	3.420	0.958
Vattenfall FS	1.049	1.372	1.190
AP (€/MWh)	37.151	48.746	39.933
GC (GW)	9.916	39.190	11.035

4.17). This is in marked contrast to how the TSO adds transmission capacity only to line $\ell 16$ in the $H = 1$ regime to reduce the VRE capacity at FI. Simply put, the limited price signal to curb CO_2 emissions necessitates a transmission capacity that can use additional hydro resources from $SE1$ to compensate for an insufficient curb on consumption at FI. Indeed, hydro resources are better able to balance the (intermittent) VRE output adopted at FI. Consequently, incomplete carbon pricing triggers the TSO to support higher seasonal flows from $SE1$ to FI vis-à-vis $H = 1$ (cf. Tables 4.18 and 4.16). An exception is during spring, which experiences an increase in the flow in the opposite direction. Since the incomplete internalisation of CO_2 emissions' social costs leaves fossil-fuelled generation economically viable, firms' exercise of market power is checked under both COG and COR. Accordingly, tailored transmission plans are required for strategic behaviour by nuclear and hydro plants. For example, withholding by nuclear plants under COG requires less transmission expansion than under the full internalisation of CO_2 emissions' social costs, while temporal arbitrage by hydro reservoirs under COR yields insufficient incentives for VRE adoption, prompting more transmission expansion vis-à-vis the full internalisation of CO_2 emissions' social costs (see Table 4.17).

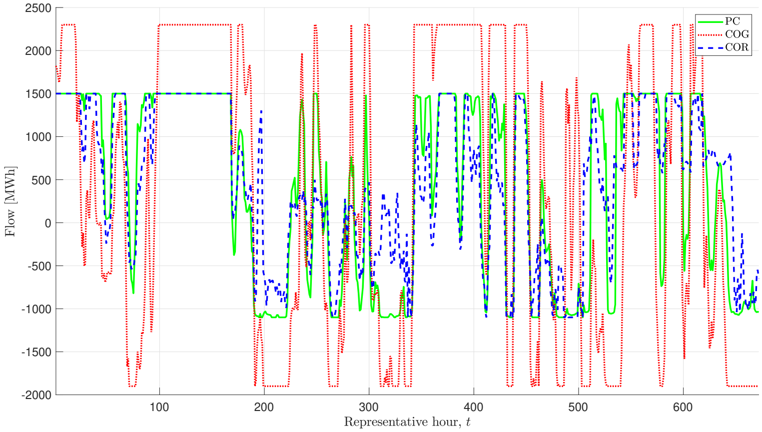

Figure 4.19: Hourly Flows on Line $\ell 6$ in the FutureCVT Scenario (in MWh).

Table 4.15: Summary Results in the FutureCVT Scenario (in Billion € Unless Otherwise Indicated).

Metric \ Case	PC	COG	COR
SW	138.938	137.902	138.825
CS	129.658	125.177	128.780
FS	8.397	11.052	9.128
MS	0.947	1.837	0.980
GR	0.074	0.204	0.066
DC	0.074	0.204	0.066
TC	0.064	0.163	0.064
EM (Mt)	0.736	2.035	0.659
Vattenfall FS	1.068	1.391	1.175
AP (€/MWh)	36.953	48.413	39.074
GC (GW)	10.000	39.860	11.282
TL (–)	[0 0 0 2]	[2 0 0 2]	[0 0 0 2]

Table 4.16: Seasonal Flow on $\ell 6$ and $\ell 16$ (in TWh), Seasonal AP for $SE1$, $SE3$, and FI (in €/MWh), and Annual NI for $SE1$, $SE3$, and FI (in TWh) in the FutureCVT Scenario.

Metric \ Case	PC	COG	COR
$\ell 6$ Flow	[2.897 -0.842 0.668 1.044]	[2.452 -1.098 2.326 -0.680]	[2.639 -0.309 0.208 1.482]
$\ell 16$ Flow	[0.490 -0.336 2.779 0.542]	[-0.414 0.072 1.998 -0.143]	[0.223 -0.169 2.930 -1.231]
$SE1$ AP	[40.407 29.931 30.141 33.603]	[52.440 39.401 40.919 43.855]	[44.076 26.152 32.476 40.883]
$SE3$ AP	[51.172 29.969 29.855 38.374]	[85.020 40.145 46.825 46.474]	[53.332 28.804 29.120 43.049]
FI AP	[72.835 26.835 35.128 39.034]	[80.574 30.810 55.492 41.248]	[71.999 25.296 35.671 42.237]
$SE1$ $SE3$ FI NI	[-9.929 -4.355 7.241]	[-10.083 13.696 4.514]	[-9.877 -4.029 5.774]

Table 4.17: Summary Results in the FutureCVT Scenario with $H = 0.15$ (in Billion € Unless Otherwise Indicated).

Case / Metric	PC	COG	COR
SW	138.365	136.197	138.150
CS	130.083	126.540	129.935
FS	8.594	10.790	8.505
MS	0.424	0.957	0.551
GR	0.116	0.355	0.131
DC	0.771	2.364	0.870
TC	0.081	0.081	0.102
EM (Mt)	7.713	23.639	8.704
Vattenfall FS	1.162	1.320	1.123
AP (€/MWh)	37.368	46.457	37.288
GC (GW)	7.824	34.309	8.638
TL (–)	[1 0 0 1]	[1 0 0 1]	[0 1 0 2]

Table 4.18: Seasonal Flow on $\ell 6$ and $\ell 16$ (in TWh), Seasonal AP for $SE1$, $SE3$, and FI (in €/MWh), and Annual NI for $SE1$, $SE3$, and FI (in TWh) in the FutureCVT Scenario with $H = 0.15$.

Case / Metric	PC	COG	COR
$\ell 6$ Flow	[3.675 -1.262 1.191 1.312]	[1.435 -0.628 1.588 -1.146]	[2.993 -0.951 0.499 2.557]
$\ell 16$ Flow	[-0.342 0.702 2.974 1.001]	[-1.155 -1.589 0.411 -1.326]	[-0.328 0.717 3.369 -2.069]
$SE1$ AP	[44.151 32.928 33.560 37.014]	[52.715 39.912 41.495 42.750]	[44.620 32.150 34.948 39.656]
$SE3$ AP	[48.278 32.565 32.682 37.649]	[69.508 41.064 43.412 46.355]	[48.233 29.587 29.813 40.704]
FI AP	[49.251 30.800 34.185 37.431]	[60.432 30.335 41.223 41.062]	[49.134 29.004 33.884 40.127]
$SE1$ $SE3$ FI NI	[-9.980 -5.508 9.252]	[-10.103 24.390 -2.409]	[-9.974 -5.314 6.847]

5. Concluding Remarks

This chapter discusses the contributions of this dissertation, which addresses all of the research questions through four papers. This chapter revisits the research objectives and reflects on the achievements of the dissertation. The chapter concludes by proposing future research directions.

5.1 Discussion and Conclusion

Future climate packages envision a substantial increase in the utilisation of VRE capacities in European power systems, viz., wind and solar, alongside the electrification of other sectors like heating and transport. Dealing with the highly intermittent output of VRE is a well-known challenge in power-system operations. However, the Nordic power system has the potential, from its vast hydro capacities, to compensate for the intermittent output of VRE.

The conventional view of power-system operations is mainly based on the engineering aspects of the power system and overlooks the market dynamics in a deregulated sector. In such an environment, profit-maximising firms can strategically exploit prices using hydro reservoirs, thereby potentially distorting market outcomes. Another subset of power-system models delves into economic considerations and market dynamics to address incentives and externalities. However, these models often overlook the technical and physical aspects of the power system. Real-world examples emphasise the need for models that account for both engineering constraints and market realities. Despite its transparent market structure, signs of market power have emerged in the Nordic region, necessitating the explicit consideration of reservoir operations and game-theoretic models.

The main research objective of this thesis is to investigate how both hydro-storage operations and the transmission network can impact power-system outcomes as part of future climate packages under perfect/imperfect competition. To address this overarching objective, the thesis aims to bridge the gap between economic realism in game theory and physical realism in engineering-type models in the power sector.

In Paper P1, to address RQ1, our study revealed that firms with significant hydro capacities could strategically adjust their generation output to conduct temporal arbitrage that can manipulate market prices in their favour. Also, in response to RQ3, our findings indicate that future climate policies, notably higher CO_2 prices and VRE adoption, may further incentivise hydro producers to engage in strategic behaviour.

In Papers P2 and P3, to address RQ2, our study demonstrated how aggregator-enabled prosumers and a high CO_2 price impact strategic hydro producers' ability to manipulate electricity prices through temporal arbitrage. Via an analysis conducted on a stylised test network using Nordic grid data, we revealed the impact of prosumers on the intra-seasonal arbitrage of hydro producers. We found that an aggregator-enabled prosumer reduces overall average prices with its VRE output. However, its pattern of net sales can be exploited by the hydro producer to enhance the impact of hydro's intra-seasonal arbitrage. Furthermore, our extended analysis using the full Nordic network highlighted how hydro reservoirs could leverage prosumers' net-sales patterns for more effective inter-seasonal arbitrage. Additionally, we found that a higher CO_2 price amplifies hydro reservoirs' market power, which addresses RQ3.

In Paper P4, to address RQ4, our findings suggest that optimal transmission plans utilise higher electricity prices from the full internalisation of the social cost of damage from CO_2 emissions in a perfectly competitive market to manage consumption efficiently. In this context, efficient resource sharing involves optimising available energy resources, particularly nuclear and hydro capacities, to achieve a reliable and cost-effective power supply. With the full internalisation of the costs of CO_2 emissions, optimal transmission expansion would be enabled to facilitate better sharing of nuclear resources between zones and reducing the reliance on VRE adoption. However, under imperfect competition and full CO_2 pricing, transmission expansion impacts can differ depending on the market-power type. In the case of nuclear plants withholding output, aggressive transmission expansion is needed to improve hydro-resource sharing and boost VRE adoption. Meanwhile, temporal arbitrage with hydro reservoirs reduces flow on certain lines. Therefore, the transmission plan is the same as the one for a perfectly competitive market. Addressing RQ5, efficient resource sharing is hindered in the case of perfect competition without CO_2 price signals, which requires the TSO to reinforce the line to mitigate the environmental distortion by inducing VRE adoption. Furthermore, incomplete CO_2 pricing limits the exercise of market power, requiring tailored transmission plans for strategic behaviour by nuclear and hydro plants. In the case of the former (latter), less propensity to withhold (to conduct temporal arbitrage) means that less (more) transmission capacity is optimal compared to the corresponding case with full CO_2 pricing.

One significant area to explore in future work is the incorporation of stochastic hydro inflows and VRE output into the analysis. Doing this would allow us to assess how uncertainties in the energy supply impact temporal arbitrage and the strategic decisions made by producers [83]. Moreover, the role of prosumers is an important consideration. Investigating their impact on market equilibrium can yield insights into how their behaviour affects supply and demand under conditions of uncertainty [56]. Further, examining capacity-investment and decommissioning decisions through a leader-follower framework could explain how strategic firms respond to climate targets. This analysis might also determine whether transmission expansion by a welfare-maximising entity could act as a countervailing measure against market power [63]. Lastly, expanding research to consider the coupling of sectors, particularly in the electrification of heating and transport, is crucial for developing comprehensive policy recommendations. Integrating uncertainties into these models will enhance our understanding of their implications under future climate policies [4].

5.2 Limitations and Future Work

Mathematical modelling plays a crucial role in decision-making processes in the energy sector, especially regarding investment and operational strategies for transitioning towards carbon neutrality. Adapting to VRE capacities involves addressing capacity fluctuations, which can be managed through stochastic programming [98]. It is also essential to consider the electrification of the economy[1] in these modelling approaches. However, managing computational burdens and complex solution approaches remains a challenge, as there is a delicate balance between accurately representing reality and ensuring that the model is computationally tractable. For instance, while a closed-loop Cournot model could incorporate more realistic dynamic decisions to address uncertainty in hydro inflows, it introduces computational challenges and may lack uniqueness in equilibrium solutions [92; 93]. Therefore, despite its limitations, an open-loop Cournot model is deemed more practical for policy analyses. Furthermore, the SDDP approach could be an efficient computational tool for analysing realistic networks. Nevertheless, incorporating strategic behaviour into SDDP models can be achieved only with added complexity and computational demands [83]. Ultimately, the chosen modelling approach prioritises policy relevance and computational feasibility while capturing the essential features of the Nordic power sector.

Future research should also aim to develop models that integrate market dynamics with technical constraints, including methods that account for strategic behaviour from power producers [92]. Additionally, models that incorporate quadratic objective functions are essential for capturing the nonlinear impacts of strategic behaviour and CO_2 pricing [63]. Solution approaches such as branch-and-bound, decomposition, and parametric programming are critical to explore to address the complexity of the models [83; 97]. Exploring Cournot competition within these frameworks can provide insights into optimising resource allocation and mitigating market-power effects [100].

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[1] `https://www.norden.org/en/declaration/declaration-nordic-carbon-neutrality`

The papers within this thesis sequentially build upon each other, extending previous research with future potential to assess alternative energy policies. In Paper P1, the model includes fixed capacities for generation and transmission, an absence of the endogenous determination of VRE capacities, and a lack of consideration for fossil-fuel-plant decommissioning. These simplifications could be enhanced by incorporating dynamic capacity adjustments, endogenising VRE expansion, and simulating fossil-fuel-plant decommissioning in the model [63]. In Papers P2 and P3, the emergence of prosumers and their impact on market dynamics are covered. Those studies could benefit from including the impact of strategic behaviour by prosumers [24]. The study in Paper P4, apart from carbon pricing, could explore subsidies and other support mechanisms, e.g. in the context of regional trade in the Middle East and North Africa [99]. Moreover, our approach could be used to study the market power exerted by fossil-fuelled plants in interconnected regions with contrasting emission policies and measure the implications for carbon leakage [100]. If socially optimal transmission plans for the Nordic region are devised, further integration of power sectors between neighbouring regions would warrant a cooperative game-theoretic approach to determine how to allocate benefits and costs from shared resources such as transmission interconnections [101].

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