# Strategic participation of coalitions of wind power producers in electricity markets

Michiel Kenis

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**Promotor:**
Prof. dr. ir. Erik Delarue

**Assessoren:**
Prof. dr. ir. Johan Meyers
Dr. ir. Hakan Ergun

**Begeleider:**
Dr. ir. Kenneth Bruninx

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Voorafgaande schriftelijke toestemming van de promotor is eveneens vereist voor het aanwenden van de in deze masterproef beschreven (originele) methoden, producten, schakelingen en programma's voor industrieel of commercieel nut en voor de inzending van deze publicatie ter deelname aan wetenschappelijke prijzen of wedstrijden.

# Preface

Almost 80 pages, the final result of an intense but fascinating year. This asks for some words of gratitude. First, I would like to thank professor Delarue, my promotor, for the provision of the thesis topic, the freedom in developing this thesis and the guidance whenever needed. Secondly, a great word of thanks is in place for Kenneth, my mentor. His always optimistic mindset and unconditional support truely inspired me throughout the entire year. On top of that, his accessability to discussions has brought a tremendous added value to this thesis. Finally, I would like to thank professor Meyers and Doctor Ergun for their valuable feedback after my intermediate presentation.

More than in only one year, this thesis is also a milestone in my life after five years of studies at KU Leuven, including a one semester exchange at KTH Stockholm and my activities in the Board of European Students of Technology (BEST). The road that I have taken so far would never have been possible without my family and friends. Therefore, mama, papa en Andries, een onwaarschijnlijk welgemeende bedankt voor alles. Besides, the true value of friendship is only captured in times when you least expect it. Therefore, a massive thanks goes to the greatest friends in the world, with a special mention for Merel and Michiel A. Finally, I'm eagerly looking forward to the future, wherein the frequently asked question 'How is it going with your thesis?' will switch to 'How is it going with your Ph.D.?'.

*Michiel Kenis*

# Contents

# Abstract

In order to reach the goals, set by the European Union, concerning the penetration of renewable energy sources (RES) into the European power system, an analysis on the optimal facilitation of wind power into the market is useful. This thesis researches the impact of a framework in which wind power producers (WPP's) can make their individual wind power forecasts available to other market participants. On top of that, it incorporates the provision of an independent aggregate wind power forecast by the transmission system operator (TSO). Specifically, it offers a model that is intended as a tool for WPP's to optimise their strategic behavior on the Day-Ahead (DA) electricity market on the one hand, and for policy makers to validate the possible allowance of such a framework on the other hand.

In a first part, this thesis develops a model using a Bi-Level (BL) structure which determines the strategic participation of market participants on the DA market through quantity and price bids. Furthermore, the model allows the strategic market participant to include the objective of the Market Operator (MO) to maximise social welfare when clearing the DA market. The BL structure allows to construct a Mathematical Problem with Equilibrium Constraints (MPEC) and an Equilibrium Poblem with Equilibrium Constraints (EPEC), in which multiple Stackleberg games are considered between a price-maker and its price-takers in order to reach a Nash equilibrium between price-making strategic market participants. The EPEC model is used in a context where the extent, to which market participants possess information on the wind power forecasts of the WPP's, differs. Specifically, each strategic participant solves an EPEC model according to the information, available to the strategic participant on the other market participants. In that regard, the realised DA market clearing and its consequences can be assessed.

A second part of this thesis performs a case study on a fictitious power system. The results allow to justify the applicability of the proposed EPEC in all cases, except for the 'no information sharing' case in which is opted for an MPEC. Moreover, it shows the results for multiple levels of demand in which both two extreme levels of information sharing and an intermediate level are compared. It is seen that strategic market participants with perfect information on the individual forecasts of WPP's lead to a perfect estimation and manipulation of the DA market outcome, which increases the WPP's profits. Besides, it shows a strategic behavior of withholding capacity by WPP's, leading to a decreased social welfare. Finally, the sensitivity is tested by varying the uncertainty on the wind power output of WPP's, by including risk-averse behavior and by imposing an incorrect aggregate wind power forecast.

# Samenvatting

Een analyse rond de optimale facilitatie van windenergie is nuttig, gegeven de (inter)nationale doelstellingen omtrent hernieuwbare energiebronnen (HEB) in de elektriciteitsmarkt. Deze thesis onderzoekt de impact van een kader waarin windenergieproducenten (WEP's) hun individuele windenergievoorspellingen beschikbaar kunnen stellen voor andere marktspelers. Daarbij wordt ook een onafhankelijke geaggregeerde windenergievoorspelling, voorzien door de transmissienetbeheerder (TNB), beschouwd. Specifiek bouwt deze thesis een model dat enerzijds gebruikt kan worden door WEP's om hun strategisch gedrag op de Day-Ahead (DA, Engels) groothandelsenergiemarkt te optimaliseren, en anderzijds voor beleidsmakers om de overweging van een dergelijk kader te faciliteren.

Ten eerste ontwikkelt deze thesis een Bi-Level (BL, Engels) structuur dat de strategische deelname van spelers op de DA markt voorstelt via hun volume -en prijsbod. Daarbij laat het de strategische speler toe om het objectief van de Markt Operator (MO), die de sociale welvaart maximaliseert bij het bepalen van het marktevenwicht, in rekening te nemen. Hieruit wordt een Mathematical Problem with Equilibrium Constraints (MPEC, Engels) en een Equilibrium Problem with Equilibrium Constraints (EPEC, Engels) geformuleerd. Meerdere Stackelbergspelen worden daarbij voorgesteld tussen een prijsmaker en de prijsnemers om vervolgens een Nash evenwicht te bereiken tussen de prijsmakende spelers. Het EPEC model wordt gebruikt in een context, waarin de hoeveelheid informatie van een marktspeler over de individuele windenergievoorspellingen van de WEP's, varieert. Elke strategische speler lost daarbij een EPEC op volgens de informatie die hij tot zijn beschikking heeft over de andere marktspelers. Dit laat toe om de marktuitkomst te analyseren.

Ten tweede past deze thesis het model toe op een fictief electriciteitssysteem. De resultaten rechtvaardigen het gebruik van het EPEC model in alle gevallen, behalve in het extreme geval waar spelers geen informatie over elkaar bezitten waar een MPEC model aangewezen is. Daarnaast toont het resultaten voor verschillende vraagcurves waarin zowel twee extreme gevallen van informatie-uitwisseling als tussenliggende gevallen vergeleken worden. Strategische spelers, met perfecte informatie over de windenergievoorspellingen van alle individuele WEP's, kunnen de marktuitkomst perfect inschatten en manipuleren. Dit leidt tot verhoogde winsten voor de WEP's, maar ook tot een daling van de sociale welvaart door het strategisch inhouden van windenergie in het bod op de DA markt. Tot slot wordt de sensitiviteit van de resultaten getest door het verkleinen van de onzekerheid in de windenergievoorspellingen, het beschouwen van risico-avers gedrag en van een incorrecte windenergievoorspelling.

# List of Figures and Tables

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# List of Abbreviations and Symbols

## Abbreviations

| | |
|---|---|
| RES | Renewable Energy Sources |
| WPP | Wind Power Producers |
| GenCo | Conventional Generator |
| IS | Information sharing |
| TSO | Transmission System Operator |
| DA | Day-Ahead |
| ID | Intra-Day |
| BL | Bi-Level |
| MO | Market Operator |
| OPcOP | Optimisation Problem constrained by another Optimisation Problem |
| MPEC | Mathematical Problem with Equilibrium Constraints |
| EPEC | Equilibrium Problem with Equilibrium Constraints |
| UL | Upper-Level |
| LL | Lower-Level |
| MILP | Mixed Integer Linear Programming |
| KKT | Karush-Kuhn-Tucker |
| CVaR | Conditional Value at Risk |

## Sets and indices

| | |
|---|---|
| i $\epsilon$ I | Set of GenCo's |
| k $\epsilon$ K | Set of WPP's |
| k $\epsilon$ K' | Subset of WPP's of which information on their wind power forecast is available |
| s $\epsilon$ $S_1$ | Set of scenarios representing the wind power output |
| q $\epsilon$ $S_2$ | Set of scenarios representing the market clearing |
| r $\epsilon$ $S$ | Set of scenarios representing both the wind power output and the market clearing |
| $\Delta^{UL}$ | Set of primal variables of the Upper-Level problem |
| $\Delta^{LL}$ | Set of primal and dual variables of the Lower-Level problem |

## Parameters

| | |
|---|---|
| $G_i$ | Capacity of a GenCo [MW] |
| $P_i^g$ | Marginal operational cost of a GenCo [€/MWh] |
| $w_k^{cap}$ | Capacity of a WPP [MW] |
| $P^d$ | Marginal utility of demand [€/MWh] |
| D | Aggregate inelastic demand [MW] |
| $p_s$ | Probability related to wind power output scenario s [-] |
| $p_q$ | Probability related to market clearing scenario q [-] |
| $\gamma$ | CVaR weighting factor [-] |
| $\beta$ | CVaR parameter [-] |

## Variables

### Primal Variables

| | |
|---|---|
| $\alpha_i^g$ | Price bid of a GenCo [€/MWh] |
| $g_i^b$ | Quantity bid of a GenCo [MW] |
| $g_{i,q}^c$ | Cleared quantity of a GenCo [MW] |
| $\alpha_i^w$ | Price bid of a WPP [€/MWh] |
| $w_{k,q}^c$ | Cleared quantity of a WPP [MW] |
| $w_{k,q}^b$ | Quantity bid of WPP [MW] |
| $d_q$ | Covered aggregate demand [MW] |
| $\lambda_q^{bal}$ | Imbalance penalty [€/MWh] |
| $\eta_q$ | CVaR auxiliary variable 1 [-] |
| a | CVaR auxiliary variable 2 [-] |

## Dual Variables

| | |
|---|---|
| $\lambda_q$ | Dual variable related to the DA market power balance - DA market clearing price [€/MWh] |
| $\underline{\delta}_{i,q}$ | Dual variable related to the lower bound constraint on the cleared quantity of a GenCo [€/MWh] |
| $\bar{\delta}_{i,q}$ | Dual variable related to the upper bound constraint on the cleared quantity of a GenCo [€/MWh] |
| $\underline{\xi}_{k,q}$ | Dual variable related to the lower bound constraint on the cleared quantity of a WPP [€/MWh] |
| $\bar{\xi}_{k,q}$ | Dual variable related to the upper bound constraint on the cleared quantity of a WPP [€/MWh] |
| $\underline{\epsilon}_q$ | Dual variable related to the lower bound constraint on the covered demand [€/MWh] |
| $\bar{\epsilon}_q$ | Dual variable related to the upper bound constraint on the covered demand [€/MWh] |

# Symbols

| | |
|---|---|
| $\mathcal{L}(x)$ | Lagrangian |
| h(x) | Generic inequality constraint in the form of h(x) $>$ 0 |
| $\pi$ | Generic dual variable related to the general inequality constraint h(x) $>$ 0 |
| M | Generic large positive constant in the formulation of the big-M method |
| B | Generic binary variable in the formulation of the big-M method |
| $F_i$ | Normal distribution of the wind power forecast of WPP i |
| $F$ | Deterministic aggregate wind power forecast |
| $\mu_i$ | Average in the wind power forecast of WPP i |
| $\sigma_i$ | Standard deviation in the wind power forecast of WPP i |

# Chapter 1

# Introduction

Section 1.1 describes the context and motivation of this thesis to justify its relevance. Secondly, Section 1.2 explicitly states and explains the research questions together with the summarised contributions. Furthermore, Section 1.3 gives a brief overview of the results. Finally, Section 1.4 introduces the structure in this thesis.

## 1.1 Context and motivation

In recent history, a growing concern raises about climate change. There is a consensus that human activities are very likely the primary cause [5]. The impact of global warming of 1.5°C above pre-industrial levels is assessed by the Intergovernmental Panel on Climate Change in [5]. The raising $CO_2$ concentration is one of the major drivers. Therefore, policies are being developed both nationally and internationally, aiming for limited $CO_2$ emissions. In 2007, The European Commission has set a goal of reaching 20% less greenhouse gas emissions since 1990, 20% of EU energy from renewables and a 20% improvement in energy efficiency by 2020 [6]. On a long-term timeframe, the EU agreed in the Paris Agreement on the objective of limiting the global temperature increase to 2°C, with clear efforts to limite it to 1.5°C [7]. When looking outside of Europe, China stated the goal of reaching a 15% share of non-fossil energy in its energy consumption by 2020, being 8.6% in 2010 [8].

In this regard, the implementation of the aforementioned type of policies implies an increase of Renewable Energy Sources (RES) penetration in the power system. In parallel, the challenge of assuring a secure grid raises, mainly because one of the key characteristics of RES is their uncertainty and their variability [9]. Figure 1.1 illustrates this, as the wind power production in the Belgian wind farms between 21/04/2019 and 30/04/2019 are displayed. The orange line represents the actual measured power production, while the blue line gives the forecasted power production on a day-ahead basis. The wind power capacity of the Belgian wind farms amounts 3157.18 MW [10]. There is a clear discrepancy between both curves, representing the uncertainty of wind power, even on a day-ahead basis. During the time period, the maximum positive difference between the measured power and the forecasted power production is 301.6 MW on 26/04/2019. On the other hand, a maximum

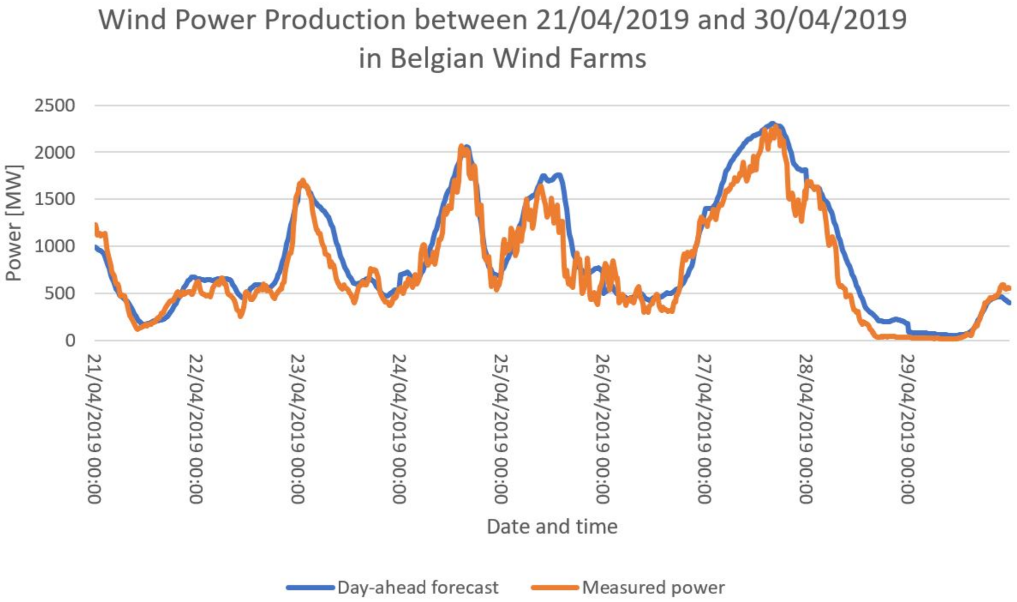

Figure 1.1: Aggregated wind power over all Belgian wind farms between 21/04/2019 and 30/04/2019. Both the actual production and the forecast production on day-ahead basis are displayed. Data are from Elia [10].

negative difference compared to the forecasted power production amounts 810.73 MW on 25/04/2019. In order to be able to correct these deviations, the Intraday (ID) market is in place. Power is traded based on the more recent and accurate wind power forecasts. After the ID market gate closure, the Market Operator (MO) relies on flexible market players in order to fill the last gap between supply and demand up until real-time delivery. Next to the uncertainty, the variability can also be noted on Figure 1.1. While on 29/04/2019, the measured wind power amounts 19.51 MW at some point, it amounts 2226.34 MW on 27/04/2019. Despite this relatively large difference, demand still needs to be met. Therefore, the MO again counts on flexibility providers in order to match demand and supply.

In order to meet the targets, set by governments and policy makers, a fluent and stimulated integration of RES into the electricity market is essential. The uncertainty and variability that Wind Power Producers (WPP's) face in this regard, is a challenge. A WPP behaves strategically on the electricity market, where his objective is to maximise his profit rather than bid his available capacity on the market. The European Commission recognises the need for an optimal penetration of wind power into the market, complementary with the effective wind power production. Therefore, the EU Commission stresses the importance of transparency. In this regard, Regulation (EU) No 543/2013 obliges the Transmission System Operators (TSO) of the EU member states to calculate and provide an aggregate forecast of the wind power production in the TSO's area for the relevant market participants [11]. Moreover, the integration of wind power into the electricity mix is expected to keep on increasing, so that the effects of a fluent integration of wind power into the market become more present.

Aiming for the optimal integration of RES into the electricity market, it demands a fluent facilitation of wind power producers by policy makers. This thesis investigates the influence of a framework in which WPP's can make their individual wind power forecasts available to other market participants. More specifically, it offers a model that is intented as a tool for WPP's to optimise their strategic behavior on the one hand, and for policy makers to validate the possible allowance of such a framework.

## 1.2 Research questions and contribution

This section aims to elaborate on the research questions that this thesis tackles. The research questions are divided in two main parts. While the first part is about the development of a model, the second part is on the consequences and application of the developed model. Both parts are essential for readers to fully understand the model and to make well-founded conclusions when applying the model. In the rest of this section, the two research questions are explicitly stated and explained.

**Research question 1 - How can the strategic behavior of a price-making WPP on the DA electricity market be modeled, considering the uncertain wind power production and variable information on the forecasts of other WPP's?**
This thesis develops a Bi-Level (BL) model that captures the strategic behavior of price-making market participants. The BL structure maximises both the profit of the strategic WPP and the social welfare as desired by the MO. Furthermore, the BL structure induces a hierarchical approach to model the strategic participation of the WPP on the market. The BL model implies an endogenous determination of the DA market clearing, in such a way that the price-making effect of the WPP is taken into account. Besides, the imbalance cost is taken into account via an endogenous formation of the balancing price.

However, the BL model does not take the reaction of other price-making strategic market participants into account. In order to model all market participants as being strategic and price-making generators, the BL model is integrated into the proposed EPEC model. Moreover, the proposed EPEC model incorporates the extent to which market players possess information on each other on the market. This degree of information sharing (IS) can exogenously be imposed.

BL models are widely used for a broad range of applications in the electricity market [1]. The strategic participation of market participants is often modeled in the DA electricity market, assuming price-taking behavior of other market participants [12, 13, 14, 15, 16, 17]. However, the most realistic market outcome will be achieved when modeling the behavior of all market participants as being strategic [18, 19, 20, 21, 22]. This thesis meets this requirement for a realistic market clearing, and aims to augment it by introducing the effect of (in)complete information on the market outcome.

Scientific literature closest to the work in this thesis, comes from Exizidis et al. [2] and aims to incorporate the effect of variable information on the market as well. However, the aspect of (in)complete information is put on the level between the MO and the market participants, while this thesis focuses on (in)complete information among market participants themselves. Besides, [2] takes the uncertain wind power production into account to only a limited extent, which could cause a bias in the bidding behavior of market players.

Furthermore, Exizidis et al. [3] construct an MPEC model which has large similarities with the referece case in this thesis, being the case in which no information is shared among market participants. However, [3] considers only price bids of generators on the DA market endogenously, while the model in this thesis also considers quantity bids. Consequently, the stochastic wind power output of the strategic WPP is again only considered to a limited extent as it only affects an imbalance penalty. Contrary, this thesis directly applies the uncertain wind power output in the determination of the strategic quantity bid, leading to a more realistic strategic behavior of market players. In [3], Exizidis et al. research the impact of an incorrect aggregate wind power forecast by using it similarly as in this thesis. However, this thesis obtains opposite results in case of an overestimation of the aggregate wind power forecast which is due to the aforementioned differences in the applied modeling approach.

**Research question 2 - What are the possible implications of one or more WPP's that share their wind power forecast(s) with other DA market participants?**
In a second contribution in this thesis, a fictitious power system is set up. Herein, the results of applying the developed model are analysed in order to reveal more insights into the model. Furthermore, the implicit assumptions become clear so that their impact can be analysed. Therefore, this part of the thesis can be split up into two contributions. On the one hand, the results are given and discussed for a base case in which the extent of IS is varied. On the other hand, the results are shown for two extreme cases of forecast sharing while the other parameters in the model are varied in order to receive a complete representation of the insights on the model.

Firstly, the results can be analysed from the perspective of the market participants. For example, this can done by looking at their profits. Secondly, the results can be analysed from the perspective of society, reflecting on the social welfare implications. Finally, from the perspective of policy markets, one can look into the RES penetration into the electricity market.

## 1.3 Summary of results

The results show increased profits for all WPP's in some cases due to an increased cleared DA market price. When strategic market players possess information on the wind power forecasts of WPP's, their price-making behavior is better estimated. Therefore, their expected market clearing corresponds to the ex-post market clearing more accurately. The increased cleared DA market price results from strategically withholding available capacity of strategic DA market participants.

A parallel effect is that social welfare decreases because of a lower wind power penetration into the DA market. The differences in WPP's profits (positive difference) and social welfare (negative difference) with the reference case, in which no player possesses information on any other player, are maximal when all players possess information on all other players. However, it should be noted that when market players possess information on only a part of the market players, it might cause a bias that leads to reverse results.

Furthermore, when lowering the uncertainty in the wind power forecasts of WPP's, a tipping point can be reached below which no impact of sharing information can be noted compared to the reference case. It results that a WPP faces a trade-off between investing in his own wind power forecast so that the related uncertainty decreases, or in buying information on the wind power forecasts of other WPP's in order to raise his profits.

Besides, risk-aversness of strategic players stimulates withholding the available capacity which can lead to a higher cleared DA market price more easily compared to the reference case. However, an important assumption is that all strategic players apply the same type of risk-aversness. When information on the type of risk-aversness, that any other player applies, is decoupled from the information on wind power forecasts, the aforementioned effects do not hold.

Finally, the reference case relies on the aggregate wind power forecast, provided by the TSO, in order to estimate the wind power production of the WPP's on which no information is available. Specifically, it subtracts the average of the own forecast from it, so that a deterministic forecast is obtained to represent all WPP's on which no information is available. Both an overestimation of 10% and an underestimation of 10% of the aggregate wind power forecast show significantly smaller differences with cases in which information is shared among players.

Concluding, the proposed EPEC model shows potential advantages for WPP's to share wind power forecasts amongst them. Despite that social welfare generally decreases in parallel, it could serve as an incentive for investors in wind power. However, it is important that a sufficiently large part of the WPP's in the DA market is sharing his wind power forecast in order to avoid reverse effects.

## 1.4 Structure

The following structure is maintained in this thesis. Chapter 2 aims to deliver essential background information concerning wind power forecasts. It delivers the necessary theoretical background upon which the BL model relies on. Moreover, it gives an overview of the current state-of-the-art concerning IS among market participants in scientific literature. Chapter 3 introduces the proposed model. It starts by giving a conceptual framework, which is thereafter translated into a mathematical problem. Furthermore, this BL problem is shaped so that it can be solved by a commercial solver such as Gurobi [23]. Chapter 4 aims to analyse the results of the proposed model on a fictitious power system. In a first stage, the results for base cases are extensively discussed; while in a second stage, several parameters are varied for which the results deliver significant insights as well. Finally, Chapter 5 gives a summary on all chapters and motivates suggestions for future research.

# Chapter 2

# Literature Study

This chapter discusses relevant information on wind power forecasts and the sharing thereof. Moreover, it provides the necessary theoretical background for the model that this thesis develops. Firstly, Section 2.1 introduces current practices concerning wind power forecasts. More specifically, it discusses how stochastic wind power forecasts are realised and presented. Furthermore, it introduces the spatial correlations that could exist between certain wind power forecasts. Finally, it gives a brief overview of the legal context of sharing and/or trading wind power forecasts. Secondly, 2.2 aims to present a broad electricity market modeling context, in which the model that this thesis develops is positioned. Consequently, it introduces the essential theory behind the equilibrium model in this thesis together with some existing models in literature. Thirdly, Section 2.3 adopts the state-of-the-art concerning the aspect of possessing information on other market participants and how it influences the bidding behavior of strategic generators. On top of that, it states how this thesis differs from and augments current literature. Finally, 2.4 gives a conclusion on this chapter.

## 2.1 Wind power forecasts

The prediction of wind power is defined as the estimation of the expected power output of wind turbines for a period of time in the future [24]. The forecast horizon can be both on a short term and a long term. On the one hand, the long term forecast horizon covers the period from a few months up to a few days before effective realisation and is useful for the planning of maintenance on the turbines [25]. On the other hand, the short term forecast horizon covers a few hours up to a day before realisation and is especially relevant for the DA dispatch of wind turbines. Several forecasting methods have been developed already [26, 27]. Lahouar et al. [24] make a general distinction between methods based on either a physical approach or a statistical approach. Physical approaches make directly use of the environmental conditions, being pressure, temperature, the wind farm construction and relief. Scientific literature [28] states that this method is not suited for short-term predictions on small areas, which is relevant in the framework of this thesis. Statistical approaches use historically measured wind realisations to make predictions on the future wind realisation [29]. For the sake of completeness, the autoregressive integrated moving average (ARMA) method [30], the autoregressive integrated moving average (ARIMA) method [31] and the persistence (PER) method [32] are mentioned. However, these classical statistical methods have a significant disadvantage compared to a model, based on an articifical neural network as the latter is able to learn from the past and adjust its algorithm endogenously [33, 34]. An additional difficulty is the conversion of the predicted wind speed into wind power through the usage of the power curve [35]. However, some models were developed to by-pass the power curve in order to predict the wind power directly [36, 37].

Anyway, a wind power forecast is a stochastic variable due to its characterisation by uncertainty. The uncertainty is implicit to the prediction, whereby one aims to limit it. In order to represent the uncertainty on a wind power forecast, a probability density is often assumed. A large part of literature assumes a normally distributed wind power forecast [38, 39]. However, applying a beta distribution to model the forecasts, shows some clear advantages over the Gaussian distribution as it is asymmetrical divided [40, 2, 41, 42, 43]. Next, Bruninx et al. [44] show a further improved performance via the introduction of the Levy $\alpha$-stable distribution. Besides, literature shows that modeling combinations of distributions may also increase the accuracy of the forecast, like Wu et al. [45] show for a combination of a normal distribution and a Laplace distribution. In this thesis, forecast timescales are fixed at a DA timeframe. Herein, beta distributions would deliver a sufficiently accurate forecast distribution [47]. However, this thesis aims to explore the insights of the bidding behavior of WPP's relatively to its wind power forecast. Therefore, for the simplicity of applying a symmetrically distributed forecast, this thesis opts for modeling wind power forecasts as a normal distribution.

One of the focus points in this thesis, is the variable extent to which market participants possess wind power forecast information on WPP's. Moreover, the option of possessing the wind power forecast on a WPP is binary. On the one hand, a market participant can exactly know the wind power forecast of a WPP. On the other hand, the contrary is true. When defining the situation of a market participant as having no information on a WPP, it implies that there is no useful information on this WPP available so that the market participant needs to rely on other information sources. This binary division is a simplification of realistic information flows. Specifically, the effect of spatial correlations between wind power forecasts is overlooked. Wind power forecasting methods exist that are based on these spatial correlations. Especially in combination with an approach, based on artificial neural networks, this method can deliver accurate results [27]. Obviously, the wind power forecast of a WPP has generally more similarities with the forecast of a neighbouring WPP than with the forecast of a remotely located WPP. As this potential source of information on WPP's is difficult to quantify with only a limited added value with regard to the research questions, this is not considered in this thesis.

Up until now, no initiative has been taken by the European Commission concerning the act of sharing wind power forecasts by WPP's [48]. Therefore, no framework is in place on both national or European level in order to regulate this practice. This thesis aims to support possible discussions in the future on the optimal penetration of wind power into the DA market.

## 2.2 Participation in the Day-Ahead Market

Depending on the time before the delivery of electricity, generators can participate in the forward and future market, the DA market and the ID market respectively [49]. Despite the limited revenue opportunities in the forward market[1] [50, 51], WPP's are mainly active in DA electricity markets [12, 13, 14, 15, 16, 17]. The ID market and the balancing market is rather an opportunity for WPP's to adjust their bids, made on the DA market, when having a more accurate wind power forecast at their disposal [52] during the ID time period. Therefore, the focus in this thesis is on the DA electricity markets. However, the expected imbalance costs are incorporated in the DA market through the endogenous formation of an imbalance penalty. This section aims to present both the context and the theoretical background of the model that this thesis develops. Section 2.2.1 classifies the proposed model in a broad electricity market modeling context. Next, Section 2.2.2 introduces the fundamental theory behind the applied techniques and applies these techniques to the context of this thesis.

### 2.2.1 Classification

Electricty market modeling knows a broad range of applications. Therefore, a variety of models have already been developed to simulate the behavior of market agents, where each model has its own scope, goal and assumptions [53]. In order to position the developed model in this thesis, the need for a structured classification arises. Delarue [4] proposes a framework in order to structure electricity market models in its context, driven by characteristics of and assumptions in the model. Table 2.1 situates the developed model, using this framework. The model considers the perspective of a market participant, maximising its profit. The market participant participates therefore in the DA market, which is considered to be oligopolistic. This implies that all DA market participants are price-makers, each of them aiming for the single objective of a maximised individual profit, making that the entire model considers multiple objectives. Furthermore, the electricity demand is modeled as behaving inelastically, which is close to reality [54]. Nevertheless, a constant marginal utility of demand is considered to represent the willingness-to-pay of customers. The applied time frame focuses on the short-term operation of market participants, as the focus of this thesis lays on the operational aspect less than on the investment decisions of market participants. Spatial constraints are neglected by representing the power system as a single node sytem therefore neglecting the grid. Finally, the strategic price-making behavior of market participants is optimised.

On top of the profit-maximising objective of each market participant, the MO's welfare-maximising objective also needs to be taken into account when each market

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[1] Wind power forecasts are not sufficiently reliable in the time frame of forward markets.

| | |
|---|---|
| Competition | Monopolistic<br>**Oligopolistic**<br>Perfectly competitive |
| Objectives | Single<br>**Multiple** |
| Demand | Elastic<br>**Inelastic** |
| Time frame | **Short term**<br>Long term |
| Spatial constraints | **Single node**<br>Trade based interconnections<br>DC load flow<br>Full AC load flow |
| Aim of the model | **Optimising behavior**<br>Simulating events |

Table 2.1: Classification of this thesis' model in a broad context of electricity market models using the framework, proposed by Delarue [4]. The specifications that apply for this thesis' model are put in bold letters.

participant models his expected market clearing, as further explained in Section 2.2.2. Consequently, this two-fold consideration allows for an application of the model in two perspectives. On the one hand, it can be used to analyse the profitability of the market participant, while it can also be used to analyse the implications for society on social welfare on the other hand. This clear set of classification properties urges for a specific modeling approach. The endogenous consideration of the MO's welfare-maximising objectives in the decision making process of the profit-maximising market participant leads to a hierarchical structure [1]. Similar settings considered in literature often lead to the same model structure, leading to BL modeling. This thesis follows this approach, on which is elaborated in the next section.

### 2.2.2 Bi-level models

An extensive introduction to BL modeling theory and some applications are presented in [1]. This section aims to present the key insights from Gabriel et al. [1], relevant to this thesis. This section is also inspired by Schillemans [55]. Next, this section discusses applications from literature that are related to the developed model.

#### Bi-level model theory

The concept behind a BL model is a Stackelberg game [56]. Herein, the leader aims to anticipate the followers' reactions to his actions. Specifically, the leader is aware of the reactions that are performed to his actions, while the followers will take the leader's actions only as given.

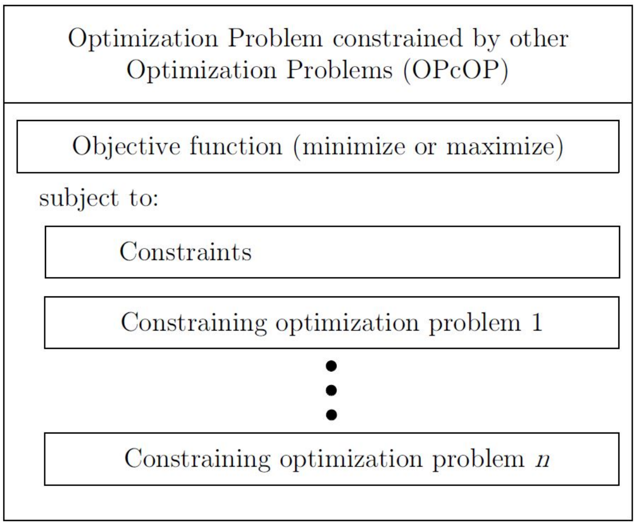


Figure 2.1: Representation of an OPcOP by Gabriel et al. [1]. The objective function, subjected to its constraints, represents the UL problem. The LL problem, which includes another optimisation problem, is a constraint for the UL problem.

A BL model is an Optimisation Problem constrained by other Optimisation Problems (OPcOP), in which the hierarchical structure of a BL model is expressed, as Gabriel et al. [1] argue. Specifically, the Upper-Level (UL) problem represents the leader's optimisation problem. It is constrained by the typical constraints of the leader on the one hand, and the followers' Lower-Level (LL) problems on the other hand. Both the UL and the LL problems have their decision variables in their respective optimisation problem. However, the LL problem's decision variables are also variables in the UL problem. Contrary, the UL problem's decision variables are parameters in the LL problem. Both optimisation problems in the OPcOP are solved simultaneously. The Stackelberg game can be recognised in the following interpretation. The leader determines his UL variables in order to optimise his UL objective function while knowing what LL variables will be determined by the followers, who optimise their LL objective function while the determined UL variables are known by the followers as parameters.

Figure 2.1 represents an OPcOP [1]. The objective function, subjected to its constraints, represents the UL problem. The LL problem, which includes another optimisation problem, is a constraint for the UL problem.

In order to solve the OPcOP properly, it is transformed into a Mathematical Problem with Equilibrium Constraints (MPEC). The LL problem is transformed into its Karush-Kuhn-Tucker (KKT) conditions, which are sufficient and necessary conditions to achieve optimality of the LL problem. It should be noted that the KKT conditions are only one option to transform the LL problem so that the OPcOP can be solved. Therefore, an MPEC is achieved, consisting of the UL optimisation problem, constrained by its typical constraints and the KKT conditions.

In order to expand the Stackelberg game towards a Nash equilibrium, in which there are multiple leaders of a Stackelberg game, an Equilibrium Problem with Equilibrium Constraints (EPEC) is constructed. In this case, the set of followers is identical for all leaders. An essential difference with an MPEC, is that the leaders' actions are also influencing the other leaders' problems. Specifically, an EPEC is an iteration over a set of MPEC's with a different leader but with the same LL problem until there is no leader that wishes to change his determined decision variables so that a Nash equilibrium is achieved. This thesis applies both an MPEC and an EPEC model.

### Application to WPP's and GenCo's in the DA market

This section aims to discuss applications of the BL model for DA market participants. This thesis focuses on the behavior of WPP's and GenCo's in the DA electricity market and are therefore the only considered market participants.

The strategic behavior of WPP's and GenCo's can be modeled through the usage of an MPEC model, in which the WPP or GenCo is considered as price-maker in the DA electricity market. The generator maximises his profit in the UL problem by deciding on a strategic quantity and price bid with which he participates in the DA market in a considered time step. The LL problem consists of the MO which clears the DA market by maximising the objective of social welfare. The quantity and price bids of the generator are parameters in the LL problem. The market clearing price, together with the cleared quantities of all generators, are the result of the LL problem and are used by the strategic generator in the UL problem. Herein, the strategic generator aims to influence the market clearing price through his strategic quantity and price bids. In this MPEC setting, the strategic generator is considered as the only price-maker in the DA market.

An additional dimension that enters the MPEC model when modeling the strategic behavior of a generator in a market that includes WPP's, is the aspect of uncertain wind power output. Section 2.1 argued on the stochastic representation of a wind power forecast. An uncertain wind power production leads to an uncertain DA market clearing, which is represented in scenarios. Therefore, the social welfare objective in the LL problem is a sum of the social welfare realisation in every scenario, weighted for the probabilities of the related scenarios. Moreover, in case the strategic generator is a WPP itself, the strategic generator faces also an uncertain power output. Similarly, the profit maximising objective in the UL problem is a sum of the profit realisation in every scenario, weighted for the probabilities of the related scenarios. The aspect of uncertainty can thus appear in both the UL and the LL problem, resulting in scenarios.

An MPEC model leads to an optimistic setting as seen from the strategic market participant. The BL structure in an MPEC model implies that the LL problem is considered not to be entirely independent from the UL problem. The LL problem optimises its social welfare objective, given the UL variables as parameters. However, when two or more equilibrium solutions for the LL problem exist, the UL problem can freely choose an equilibrium solution that is optimal to it own objective function.

Therefore, the MPEC model results in a upper limit for the profit that the strategic market participant can achieve. This will be elaborated upon in Chapter 4.

In scientific literature, there have been developed several MPEC models with a WPP or a GenCo being the strategic DA market participant [12, 13, 14, 2, 15, 22, 17]. However, each model applies its own bidding structure and constraints. Exizidis et al. [2] model the strategic behavior of WPP's. Their work serves as a useful introduction to the aspect of wind power forecast sharing as Section 2.3 argues. Hobbs et al. [12] include transmission constraints in an MPEC with a GenCo as strategic market participant. Ruiz et al. [13] add the aspect of an uncertain bidding behavior of the price-taking WPP's in the DA market. Furthermore, Baringo et al. [14] develop an MPEC with the strategic market participant being a WPP with an uncertain wind power production. Thesis thesis explicitly models uncertain wind power production, both for price-makers as for price-takers (which also leads to an uncertain market clearing). However, it does not consider transmission constraints.

It is useful to note that a (simplified) representation of the balancing market is essential in the modeling of the strategic behavior of WPP's. Given the nearly zero operational cost of WPP's, the main driver of the costs for a WPP is a possible imbalance settlement imposed by the TSO [57]. Therefore, an endogenous formation of the balancing market is more realistic than when exogenously assumed. This thesis adopts a compromise between these two extreme cases. In practice, the balancing price strongly correlates with the DA market price with a constant factor. Therefore, the balancing price is endogenously determined in the MPEC model by defining it as the DA market price, corrected by a constant factor of 1.3 without explicitly modeling the balancing market. The choice for a factor of 1.3 is inspired by the Croatian electricity market, in which an imbalance penalty of 40% on top of the DA market price is imposed [58]. Both Dai et al. [17] end Baringo et al. [16] apply the MPEC model for a WPP as the strategic market participant, taking the endogenous modeling of the balancing market into account.

Figure 2.2 visualises the strategic quantity bid of a WPP. On the one, a higher bid involves a higher expected imbalance cost. On the other hand, a lower bid involves lower expected revenues as its quantity is lower. An optimal choice needs to be made, according to the expected market clearing outcome and the expected power production. It is assumed that curtailment occurs when the realised wind power output is higher than the cleared bid, while an imbalance cost needs to be paid when the wind power output is lower.

The MPEC model inherently considers only one price-making market participant and assumes all other market participants to be price-takers. This can cause a bias in the representation of realistic DA markets. The EPEC model, however, allows to analyse the interaction between multiple price-making strategic market participants facing the same LL problem. The implementation of an EPEC model demands an iteration over MPEC's in which the considered price-making generator changes every iteration until a Nash equilibrium is reached. In scientific literature, some EPEC models exist concerning the strategic behavior of multiple WPP's and GenCo's [22, 3] in the DA electricity market. Banaei et al. [22] compare multiple bidding structures in their EPEC setting. Furthermore, Exizidis et al. [3] also introduce the

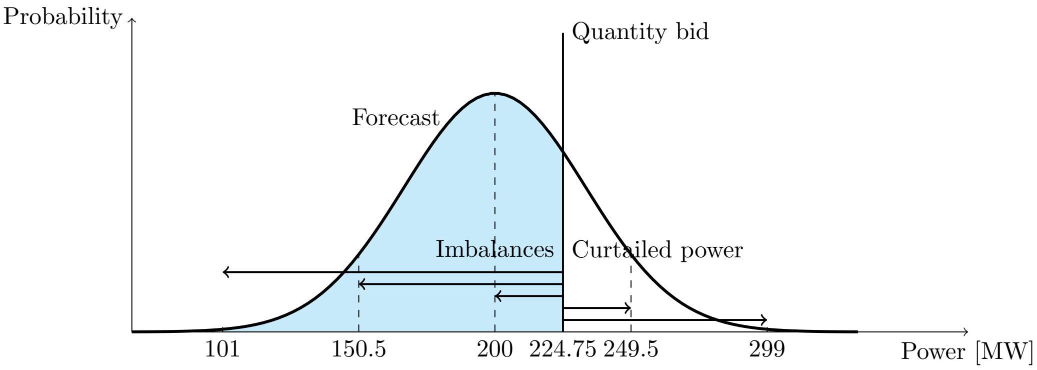


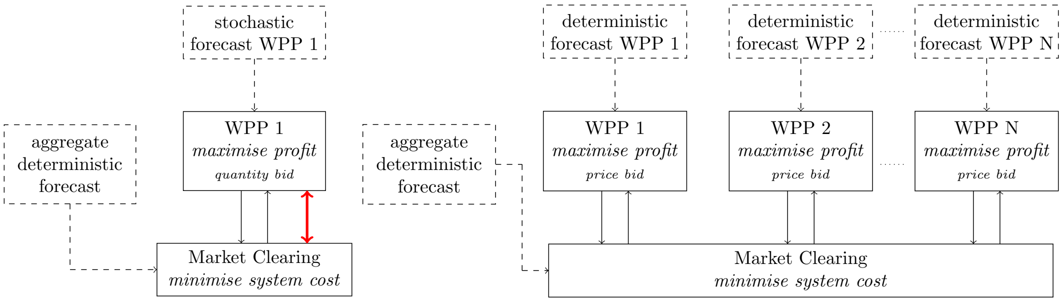
Figure 2.2: Visualisation of the decision process of a strategic WPP. On the one hand, there is a risk for a lower expected revenue. On the other hand, there is a risk for a higher expected imbalance cost. The optimal bid depends on the expected market clearing.

same imbalance penalty for WPP's as adopted in the EPEC model that this thesis develops.

## 2.3 Sharing forecasts: state-of-the-art

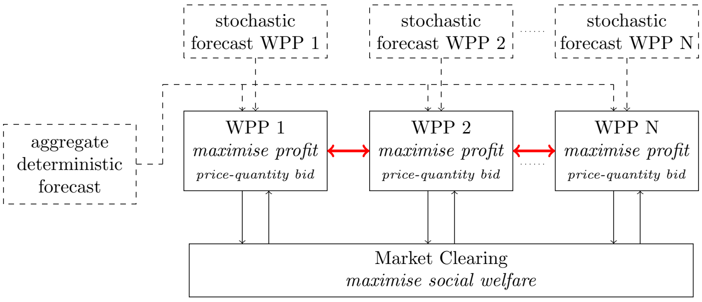
Figure 2.3 visualises the aforementioned different approaches between [2], [3] and this thesis. The dashed lines indicate the information flow in a reference case, while the red lines indicate the act of IS.

Exizidis et al. [2], [3] were the first one to address the issue concerning the impact of the practice of sharing wind power forecasts aiming at the DA electricity market. In [59], one proposes a competitive framework that gives the necessary incentives so that the interests of wind power producers and the system operator would be more aligned. While WPP's wish to place both quantity and price bids on the electricity market in order to maximise their profit with a determined risk of not being able to deliver their cleared quantity, the system operator whishes to limit the system costs (e.g. imbalance stresses in the power system) for the grid. It proposes the introduction of an aggregate wind power forecast by an independent agent, being the TSO. The MO, who is responsible for clearing the DA market, will use this aggregate wind power forecast aiming to clear the DA market with the objective of minimising the expected system costs. Herein, the expected system costs are a weighted sum over the system costs in each scenario. Therefore, excessive penetration of wind power in the DA market with respect to the system costs is limited so that the stability of the grid is ensured. In other words, the MO protects the power system from high imbalance stresses by incorporating an aggregate wind power forecast which is independent from the bidding behavior of the market participants. It should be noted that in the EU, the DA market is cleared, entirely based on the bids and offers from the market particpants disregarding an independent forecast of the MO. As noticed before, publishment of an aggregate wind power forecast by the TSO,



(a) Exizidis et al. [2]

(b) Exizidis et al. [3]



(c) This thesis

Figure 2.3: Main differences between the approach of Exizidis et al. [2, 3] and this thesis. The dashed lines indicate the information flows, while the red lines indicate the information sharing (IS). Firstly, in this thesis, the market clearing happens independently from the aggregate wind power forecast as happens in the EPEC spot market. Secondly, multiple strategic WPP's are considered. Thirdly, the aspect of IS is put among WPP's themselves. Fourthly, the uncertainty in wind power output is explicitly taken into account via strategic quantity and price bids.

is mandatory for EU member states [11]. In Belgium for example, this is indeed performed by Elia [10]. In this thesis, this aggregate wind power forecast, generated by an independent agent, is used to model the strategic behavior of market players in case the market participants have no other information on the competing market participants to rely on.

In [2], Exizidis et al. take this practise, where the MO clears the market based on its minimised expected system costs using an aggregate wind power forecast, into account. His work shows potential benefits of sharing wind power forecasts among market agents in the DA electricity market. However, the aspect of sharing information is put here between a market participant and the MO. 'Sharing wind power forecasts' means here that two individual forecasts, one from the WPP and one from the MO, are summed into a common forecast with an equal weight for both probability distributions related to their forecasts. This common forecast is used by the WPP to determine his strategic bid on the DA market, while it is also used by the MO to clear the DA market. This results in advantages for both agents: higher profits for the WPP and lower system costs for the MO as a more informed decision is made by the two agents using a shared wind power forecast. However, the difference between the results of either the 'non-sharing' case and the 'sharing' case are limited when a normal distribution is assumed in both the forecast of the WPP and the MO. In Belgium, the DA electricity market is organised as the EPEX spot DA market [60]. In contrast to [2], the market clearing by the MO happens, based entirely on the quantity and price bids of the market participants and independently of the aggregate wind power forecast. Hereby, the MO maximises social welfare. In that regard, this thesis adopts the same market clearing practice as the EPEX spot DA market. Moreover, the aspect of sharing wind power forecasts shifts from the exchange between a market participant and the MO to the exchange between market participants as the MO does not use the aggregate wind power forecast. Furthermore, [2] considers only a quantity bid in the strategic participation, while this thesis' model also includes price bids.

As a follow-up, Exizidis et al. [3] investigate the influence of the accuracy of the independent aggregate wind power forecast, using the same approach to model the market clearing as in [2]. Specifically, one compares the aggregate forecast with the sum of the averages of the associated individual wind power forecasts of every WPP. These two measures should equal eachother in order to avoid causing a bias in the representation of the non-strategic market participants. It shows that the aggregate wind power forecast results in a lower DA electricity price in the case of underforecasting (meaning that the aggregate forecast is lower than the sum of the individual averages) so that sowial welfare is favoured, while the profits for WPP's decrease. The opposite effect is true (decreasing social welfare and increasing profits for WPP's) for overforecasting, meaning that the aggregate forecast is higher than the sum of the individual averages.

The underlaying model [3] is for a great part similar to the reference case in this thesis, in which there is no sharing of wind power forecasts by WPP's. However, [3] only considers price bids of market players on the DA market endogenously, while the model in this thesis also considers quantity bids. Consequently, the stochastic wind power output of the strategic WPP is only considered to a limited extent. Contrary, this thesis directly applies the uncertain wind power output in the determination of the strategic quantity bid, leading to a more realistic strategic behavior of market players.

Moreover, this thesis focuses on the aspect of available information for market players on top of the aforementioned aggregate wind power forecast. Similarly as in this thesis, [3] also researches the impact of an incorrect aggregate wind power forecast. Because of the limited considered strategic behavior of market participants in [3], the results differ with this thesis. Similarly as in [3], profits of WPP's decrease while the realised social welfare increases in case of an overestimation. In case of an underestimation, however, this thesis finds that the same effects occurs as in case of an overestimation which is contradictory with [3]. This is due to the aforementioned differences in the applied modeling approach.

## 2.4 Conclusion

This chapter discussed scientific literature giving essential information that is relevant to this thesis. Firstly, it looked into wind power forecasts. It showed the wide range of approaches to predict the wind power on multiple timescales. Herein, it seemed that artificial neural networks offer a great potential to set up a wind power prediction on DA basis. Moreover, the representation of a wind power forecast as a probability distribution showed accuracy differences between modeling approaches. It seemed that beta distributions are more suitable than gaussian distributions to represent wind power forecasts. However, this thesis develops a model based on gaussian distributed wind power forecasts for its symmetrical properties. Next, an abstraction of spatial correlations between wind power forecast is motivated. Finally, research showed that there is no legal framework in place in the EU in order to share or trade indivual forecasts between DA market participants.

Secondly, this chapter introduces the modeling of the participation of generators on the DA electricity market. This thesis' model is first positioned in a generic framework of modeling approaches. Thereafter, BL models are introduced. A BL model depicts a hierarchical structure in which a Stackelberg game between a leader and its followers is represented. When having translated the BL model mathematically into an MPEC model, an EPEC model can be constructed consequently. Herein, a Nash equilibrium in which multiple leaders participate is modeled. Furthermore, several examples from literature in which these types of models are developed, are presented. This thesis applies both MPEC and EPEC models.

In a final part, this chapter gave a brief overview of the current state-of-the-art in scientific literature concerning the act of sharing wind power forecasts. Only little research has been performed on this topic so far. On the one hand, this thesis builds on the provision of an aggregate wind power forecast by the TSO. On the other hand, it shifts the focus towards the act of sharing forecasts between market participants themselves, compared to literature.

# Chapter 3

# Model formulation

This chapter formulates both an EPEC and MPEC model that represents the strategic participation of both price-making WPP's and Genco's in the DA electricity market, considering the uncertain wind power production and variable information on the forecasts of other WPP's. Firstly, this chapter elaborates on the aspect of IS and how it is used in the model, by defining three levels of forecast sharing. First of all, two extreme cases of sharing wind power forecasts are discussed: perfect IS and no IS. Thereafter, an intermediate case of partial IS is discussed as well and put into a context between the two extreme cases. The second section aims to give a conceptual framework that depicts the model. Herein, a BL problem as part of the EPEC model is described. In the next contribution of this chapter, the mathematical formulation of the model in the form of an MPEC is performed. Section 3.4 performs the conversion of the MPEC into a Mixed Integer Linear Programming (MILP) problem. Finally, Section 3.5 concludes on the chapter.

## 3.1 Levels of IS

The developed model explicitly focuses only on the DA energy market, in which the market participants are either WPP's or GenCo's. The model assumes that the generation capacities and marginal costs of GenCo's are known by all market participants at all times. The act of sharing a wind power forecast is defined as a WPP that makes his individual wind power forecast available, in the form of normal distribution with an average and a standard deviation, to all other market participants in the DA market. The level of wind power forecast sharing can be split up into three categories as depicted in Figure 3.1. Two extreme cases can be identified. On the one hand, the 'perfect IS' case considers that all WPP's share their individual wind power forecast with all market participants, being the other WPP's and all GenCo's. On the other hand, the 'no IS' case considers that no single WPP shares his individual wind power forecast wind with any other market participant. Herein, the only information that each market participant possesses on

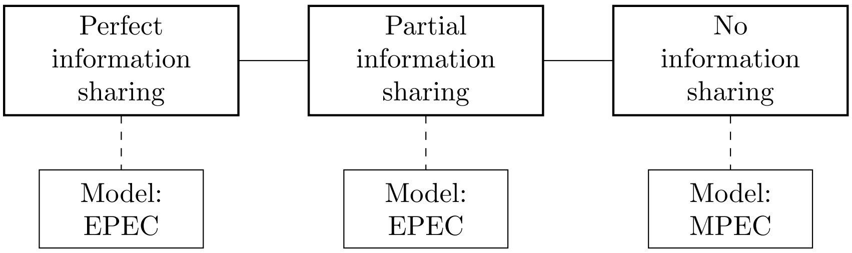


Figure 3.1: Three levels of wind power forecast sharing with their associated modeling approach. The ‘perfect IS’ case considers an EPEC model, while the ‘no IS’ case considers an MPEC model. The intermediate ‘partial IS’ case uses an EPEC.

the (other) WPP’s is the aggregate wind power forecast[1], independently provided by the TSO. This aggregate forecast is deterministically considered as perfectly accurate, as argued in Section 1.1. Contrary to the two extreme cases, the intermediate ‘partial IS’ case is not unambiguously defined and positions itself between the two extreme cases. This case is defined as the situation where at least one WPP and maximum all except one WPP makes his individual wind power forecast available to all other market participants. It is modeled as an EPEC, but with aspects included from both extreme cases. Section 4.2 motivates why the considered models are appropriate for their level of IS. It should be noted that the model assumes that the act of sharing information happens with integrity and honesty, so that no wrong information is shared among the market participants.

An overview of the available information for all market participants is depicted in Table 3.1, depending on the level of forecast sharing. The level of information that a market participant has on the other market players influences his view on the market participants. The following reasoning applies for the ‘partial IS’ case, but can intuitively be extended towards both extreme cases of levels of IS. When a market participant knows the wind power forecast $F_k$ of a WPP, it can make reasonable assumptions on the strategic behavior of this WPP and therefore models this WPP as being an independent strategic price-making market participant. When a market participant has no information on a WPP, it is implicitly not aware of the market participation of this WPP. However, the market participant can still rely on the aggregate wind power forecast F, provided by the TSO. The market participant will subtract the averages $\mu_k$ of all wind power forecasts $F_k$ it knows of[2], from the aggregate wind power forecast F. The resulting value $F_X$ is an indication for the market participant what the sum of the average forecasts of the WPP’s, on which it has no information, amounts. Therefore, the remaining WPP’s of which their wind power forecasts are unknown, are represented by the market participant as one separate single WPP X, using a deterministic wind power forecast[3] $F_X$. This

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[1] If the considered market participant is a WPP, it also possesses his own individual wind power forecast at all times.

[2] This includes the wind power forecast of the market participant himself as well, in case it is a WPP.

[3] A deterministic wind power forecast is a forecast on which no uncertainty is considered.

| | Available information on WPP's |
|---|---|
| Perfect IS | $\mathrm{F}_k \sim \mathrm{N}(\mu_k,\sigma_k)\ \forall k \epsilon K$<br>$\mathrm{F} = \sum_{\forall k \epsilon K} \mu_k$ |
| No IS | $\mathrm{F} = \sum_{\forall k \epsilon K} \mu_k$ |
| Partial IS | $\mathrm{F}_k \sim \mathrm{N}(\mu_k,\sigma_k)\ \forall k \epsilon K' < K$<br>$\mathrm{F} = \mu_X = \sum_{\forall k \epsilon K} \mu_k \quad \rightarrow \quad F_X = \mathrm{F} - \sum_{\forall k \epsilon K'} \mu_k$ |

Table 3.1: Overview of the available information on WPP's, depending on the level of IS. $F_k$ is the wind power forecast of WPP k of which the uncertainty is normally distributed, with average $\mu_i$ and standard deviation $\sigma_i$. F represents the aggregate wind power forecast, while $F_X$ is the forecast that is assumed to represent the forecasts of all WPP's on which no information is available. K' is a subset of K, representing all WPP's of which their forecasts are known.

deterministic forecast thus amounts the difference between the aggregate wind power forecast and the averages in the wind power forecasts that are known by the market participant.

This paragraph clarifies the previous reasoning with an illustrative example. Figure 3.2 supports the associated reasoning. Imagine a DA market with 12 market participants at the considered moment of time, of which 8 WPP's (WPP 1 up to WPP 8) and 4 GenCo's (GenCo A up to GenCo D). Every WPP has his individual wind power forecast, defined by a normal distribution with an average and a standard deviaton. In addition, every GenCo is defined by his generation capacity and operational cost. On the one hand, the upper part of Figure 3.2 depicts the real set-up of market participants. On the other hand, the lower part of Figure 3.2 depicts the set-up of market participants as seen by a market participant that has the wind power forecasts of WPP 1, WPP 2, WPP 3 and WPP 4 to his disposal. These four WPP's can therefore be represented as individual market participants as their wind power forecasts are known. Contrary, the wind power forecasts of WPP 5, WPP 6, WPP 7 and WPP 8 are not known. Therefore, they are presented as a single WPP X with a deterministic forecast. The deterministic forecast of WPP X amounts the deterministic aggregate wind power forecast subtracted by the averages of the known wind power forecasts $\mu_1$, $\mu_2$, $\mu_3$ and $\mu_4$. The capacities and marginal operating costs of the GenCo's are generally known by each market participant. Using this set-up of the market, the strategic behavior of the market participant to which the forecasts of WPP 1, WPP 2, WPP 3 and WPP 4 are made available can be optimised using the appropriate model. The illustrative example can be assigned to the 'partial IS' case. Note that in the 'perfect IS' case, all WPP's share their forecasts; while in the 'no IS' case, no WPP shares his forecast.

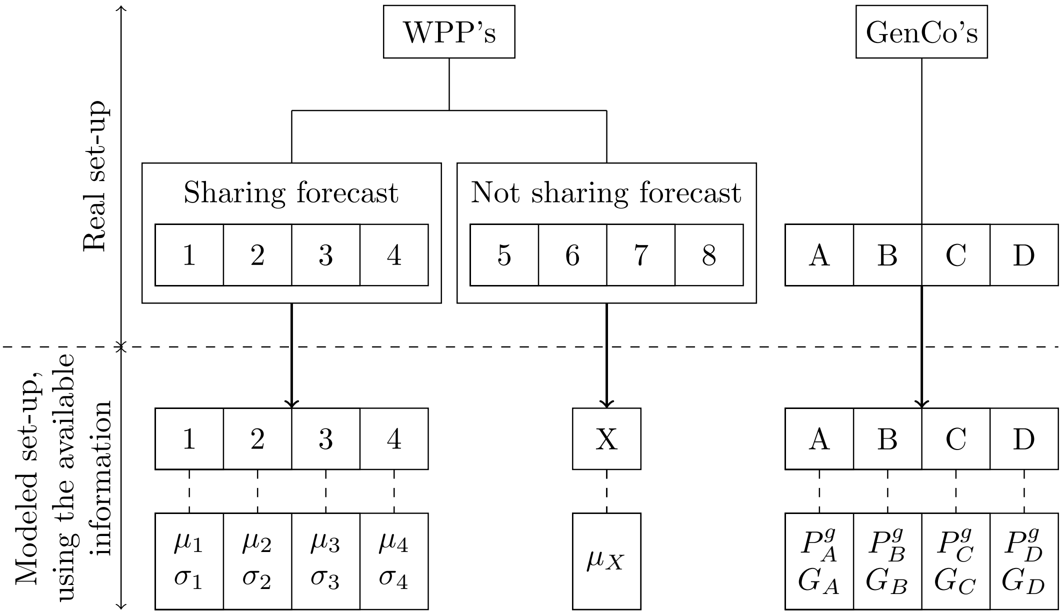

Figure 3.2: An illustrative example representing how the market participants are modeled, depending on the extent to which WPP share their wind power forecasts. WPP 1, WPP 2, WPP 3 and WPP 4 share their forecast, while WPP 5, WPP 6, WPP 7 and WPP 8 do not. The WPP's on which no information is available are modeled as a single WPP, applying a determinisitic forecast.

## 3.2 Conceptual framework

Both an *MPEC and an EPEC model* are developed, depending on the level of IS. However, an EPEC model can be considered as a set of MPEC's as argued in Section 2.2. An EPEC considers multiple strategic market participants sharing the same market clearing problem, while an MPEC considers only one strategic market participant with a market clearing problem. Figure 3.3 illustrates this relation by showing an EPEC in which multiple MPEC models can be recognised. The EPEC model consists of solving the MPEC models sequentially. An iteration over all MPEC's with their associated strategic market participants[4] is performed until a Nash equilibrium is reached. In what follows, the MPEC model is put forward first, after which the EPEC model is discussed.

### 3.2.1 MPEC model

Section 2.2.2 discussed the theoretical background behind BL modeling so that it can be used to represent the participation of agents in the DA market. Applying the theory on this thesis' model, Figure 3.4 concisely depicts the strategic market participation of either a WPP or a GenCo.

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[4] The strategic market participants can be either WPP's or GenCo's.

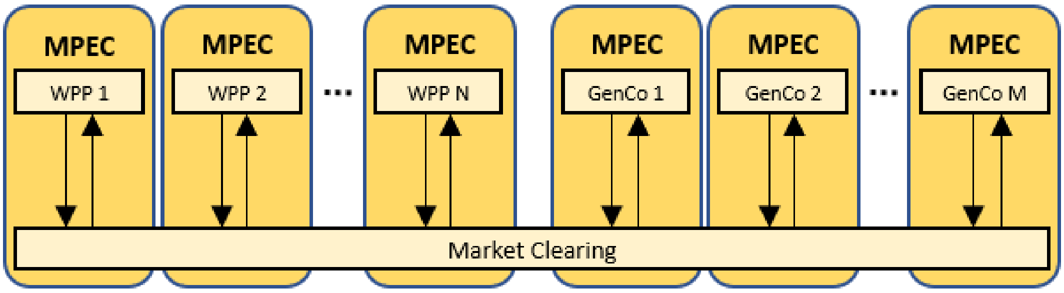

Figure 3.3: The structural representation of an EPEC model in which the relation with an MPEC model is highlighted. The model considers N WPP's and M GenCo's who are all price-making strategic players. An iteration over MPEC's is performed until a Nash equilibrium is reached in which no strategic market participants wishes to change his bid to the DA market.

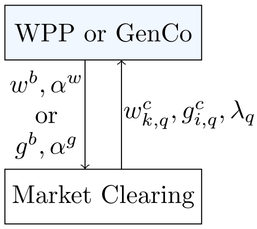

Figure 3.4: Structure of an MPEC model, applied on this thesis' model. The decision variables of the UL problem are the quantity bid and price bid of which the notation depends whether the strategic participant is a WPP or a GenCo, while the decision variables of the LL problem are the cleared quantities and the cleared price.

The DA market participants are either WPP's or GenCo's, potentially producing an amount of energy $w_k$ and $g_i$ respectively. The MO clears the DA market in order to meet demand D [MWh], given the bids and offers of the market participants. The market clearing DA price $\lambda$ determines how generating units are paid out, while WPP's and GenCo's face an operational cost of zero and $P_i^g$ respectively. Furthermore, imbalance costs are implicitly taken into account through a simplified representation of the balancing market. Reserve procurement is not considered. A uniform balancing penalty $\lambda^{\text{bal}}$ represents the imbalance price, defined as $1.3 \times \lambda$. The choice for a factor of 1.3 is inspired by the Croatian electricity market, in which an imbalance penalty of 40% on top of the DA market price is imposed [58].

In the *UL problem*, the WPP or GenCo maximises his expected profit from the DA market by formulating a quantity bid $w^b$ or $g^b$ and a price bid $\alpha^w$ or $\alpha^g$ respectively. These bids consider feasible realisations for a specific time step, considering the technical limitations of the concerned WPP or GenCo. The WPP formulates its strategic bid based on its uncertain wind power production forecast as an imbalance penalty needs to be paid by the WPP in case the real production of the WPP does not meet the cleared quantity. The GenCo formulates its strategic bid based on its available generation capacity and its non-zero marginal cost, which are both deterministically defined.

In the *LL problem*, the strategic WPP or GenCo represents his belief on how the market will be cleared, assuming bids and offers of others are known. The clearing maximises social welfare, which represents the sum of the producers' and consumers' surplus realised by the DA market in the considered time step. It results in the energy scheduling for all market players. The MPEC model assumes that other market participants do not behave strategically. The MO clears the market assuming the bids of every market player are known. When there is uncertainty on the bids of one or more market participants, modeled through scenarios, the MO clears the market for all these scenarios. Its objective function is then a sum of social welfare realisations in all these scenarios, weighted for the probability related to these scenarios. It should be noted that applied EPEC model does not consider market clearing uncertainty explicitly, as it models the WPP's as seperate strategic participants that consider the uncertainty in their UL problem. However, market clearing uncertainty is applied in Section 4.2 in an MPEC model, which is why it is included in the formulated model. In case of scarcity in the DA market, the MO must shed load. The model assumes no congestion, ramping constraints nor costs.

Furthermore, the MPEC model is formulated while incorporating *risk-averse behavior* of the strategic player through the usage of the Conditional Value at Risk (CVaR) [61]. It considers a modified UL objective for the risk-averse strategic player. Specifically, risk-aversness allows to give a stronger weight to the worst case UL objective scenarios, as Höschle [61] introduces. Herein, two parameters are exogenously imposed. Firstly, there is the CVaR parameter, that determines which worst case scenarios should be considered. For example, a CVaR parameter $\beta$ of 0.8 considers the 80% of the scenarios that results in the lowest profits for the strategic player. Secondly, the CVaR weighting factor $\gamma$ imposes the extend to which the risk-averse consideration of the UL objective should be taken into account. Therefore, the actual upper level objective is a weighted sum of the pessimistic UL objective (weighted by $\gamma$) and the originally expected profit (weighted by (1-$\gamma$)). A straight-forward inclusion of the mathematical formulation of risk-aversness is included by making use of two auxiliary variables a and $\eta$ as introduced by scientific literature [61].

It should be noted that the market clearing in the MPEC model happens to be optimistically with respect to the strategic market participant. Consequently, situations in which the MO is indifferent, will be handled in favour of the strategic WPP as the act of market clearing is inherently under control of the strategic market participant.

### 3.2.2 EPEC model

Section 3.1 explained that the representation of the market participants in the DA market depends on the level of IS. Every market participant uses the available information from (1) the WPP's that share their wind power forecasts, (2) the

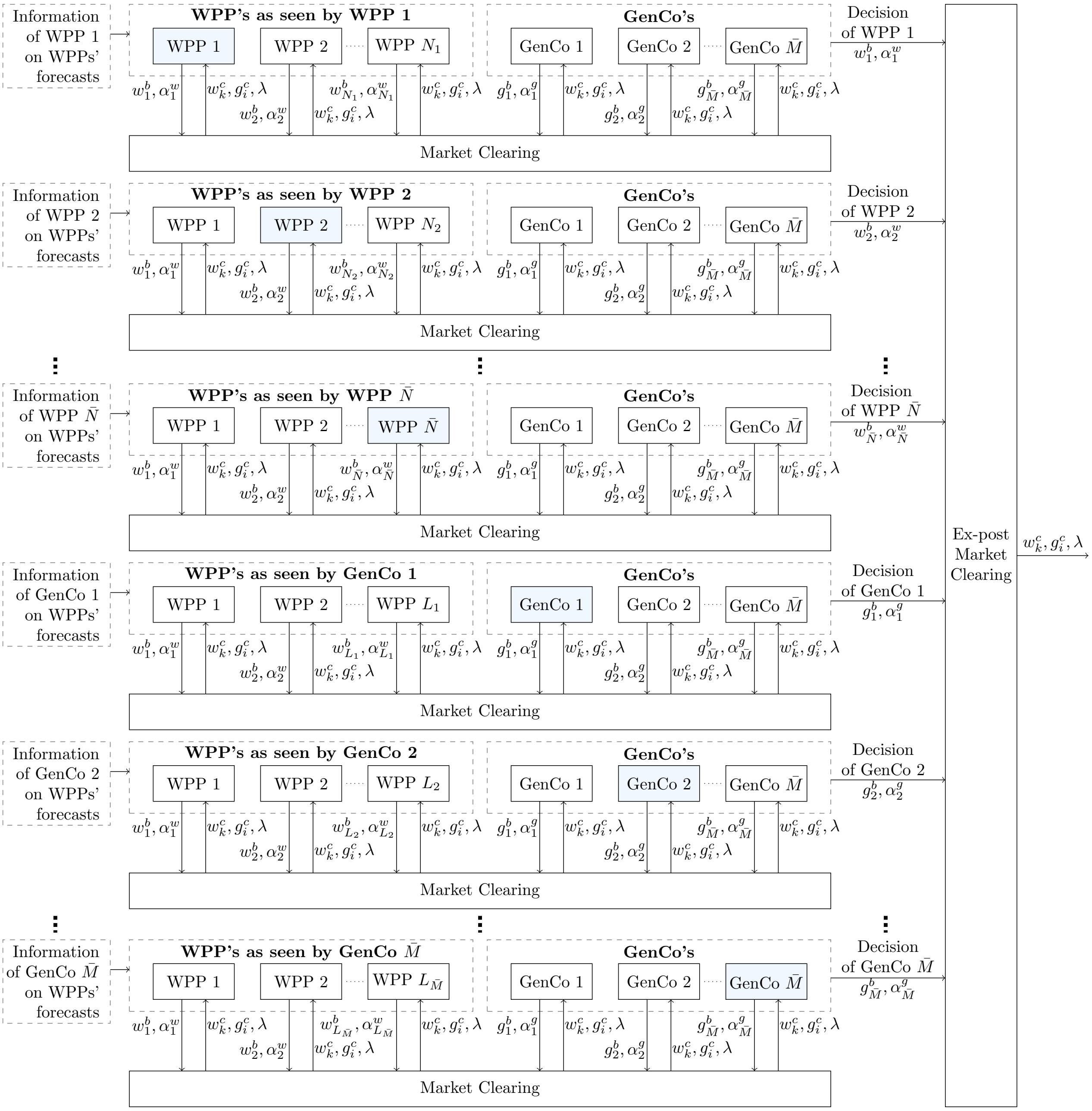

Figure 3.5: Schematic overview of the EPEC model. Each decision-making market participant solves an EPEC, in which all market participants - as represented by the decision-making market participant according to his available information - behave as strategic price-makers. When all market participants established a decision in the form of a quantity and price bid on the DA market, an ex-post market clearing is performed.

information[5] on itself, (3) the information on all GenCo's and possibly (4) the aggregate wind power forecast. Therefore, every market participant may have a different view on the set-up of market participants and thus the market clearing problem. As, on the one hand, an EPEC model inherently considers only one market clearing problem and, on the other hand, all market participants consider different market clearing problems, every market participant solves an EPEC model in which the market clearing problem is represented according to his view, based on his available information. The strategic player, setting up all market participants in order to solve the EPEC model so he can make his strategic decision, is named as the *decision-making market participant* among all market participants in the considered EPEC setting.

Figure 3.5 gives a schematic overview of the model. Using Figure 3.3, the MPEC models can be recognised in Figure 3.5. Specifically, WPP 1 considers $N_1$ WPP's in the DA market according to his available information, WPP 2 considers $N_2$ WPP's etc. Similarly, GenCo 1 considers $L_1$ WPP's, GenCo 2 $L_2$ WPP's etc. By solving the EPEC model, all market participants - as represented by the decision-making market participant - will be considered to behave strategically as *price-makers*. This way, the considered decision-making market participant can anticipate on strategic reactions of the other players.

Finally, when an EPEC is solved for every market participant to determine their associated quantity and price bid, an *ex-post market clearing* is necessary. Indeed, the market clearing problem, as seen by the decision-making market participants, may differ from the actual market clearing problem as argued earlier. The resulting market clearing is established equivalently to the LL problem in the MPEC model where social welfare is maximised.

The procedure according to which the EPECs are solved, is presented concisely in Figure 3.6, in which all iteration processes are depicted. The outer loop describes the iteration over all decision-making market participants, indicated with the index i. Before solving the EPEC model, all market participants are represented according to the information available to player i. Consequently, the EPEC model is solved. Herein, the inner loop can be recognised as an iteration over MPEC's. The MPEC's face the same unique market clearing problem - depending on the set-up of the decision-making market participant -, but consider a different strategic player. Every strategic player considers the quantity and price bids from the other market participants as exogenously given. Note that a Stackelberg game can be recognised in every MPEC, as described in Section 2.2.2. The iteration over the MPEC's stops when the changes in the bidding behavior of all market participants with the previous iteration is smaller than the convergence tolerance $\epsilon$, wich is exogenously imposed. In that case, a *Nash equilibrium* between all price-making players is reached. When the EPEC is solved for every decision-making market participant, the procedure ends by an ex-post market clearing using the determined quantity an price bids of

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[5] The information includes a wind power forecast if the market participant is a WPP, while it includes the generation capacity and the marginal operational cost if the market participant is a GenCo.

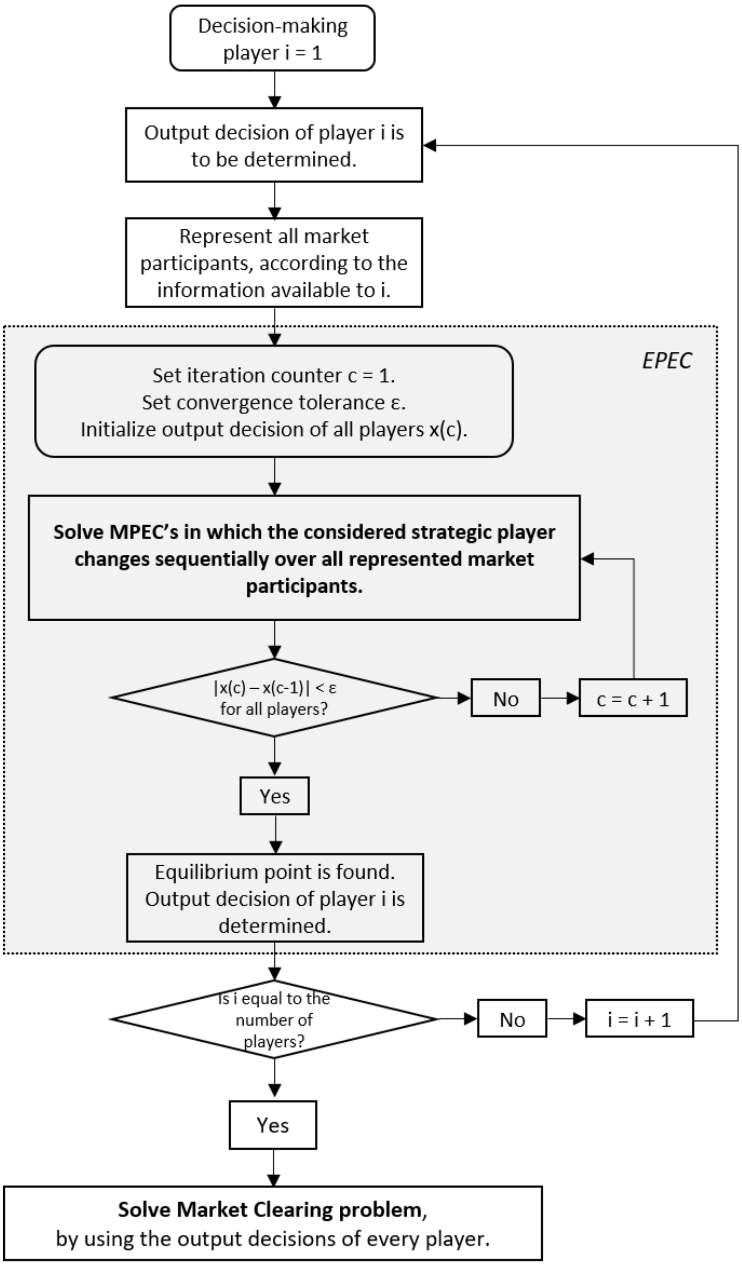

Figure 3.6: The overall procedure in order to solve the overall model. The outerloop represents the iteration over all decision-making market participants i with their associated EPEC's, while the inner loop represents the solving of one EPEC by iterating over MPEC's. In every MPEC, another strategic market participant but the same market clearing problem is faced, depending on the market set-up by the decision-making market participant i. When a Nash equilibrium is reached, the EPEC for the next decision-making market participant can be performed. When all market participants solved an EPEC model, leading to a quantity and price bid on the DA market, an ex-post market clearing is performed.

every decision-making market participant.

## 3.3 Mathematical formulation of an MPEC

The high-level model structure that is put forward in Section 3.2, is translated into a mathematical problem. An UL problem for both a WPP and a GenCo is formulated, followed by a formulation of the LL problem which is identical for both a WPP and a GenCo. The formulated model considers uncertainty on both the wind power production of the strategic WPP in the UL of the WPP, and on the market clearing problem, caused by the uncertain bids of the price-taking WPP's.

### 3.3.1 Upper-level problem for a WPP

The strategic WPP is represented as being player k=1, while all non-strategic WPP's are k>1. The aim of the UL problem is the profit maximisation for the considered strategic WPP. The UL variables are $\Delta^{UL} = \{\ w^b_{k=1},\ \alpha^w_{k=1},\ imb\ \}$.

$$\max_{\Delta^{UL} U \Delta^{LL}} (1-\gamma)\Big[\sum_{q \epsilon S_2} p_q \lambda_q w^c_{q,k=1} - \sum_{s \epsilon S_1} p_s \lambda^{bal} imb_s\Big] + \gamma\Big[a - \frac{1}{\beta}\sum_{r \epsilon S} \eta_r \cdot p_r\Big] \tag{3.1}$$

subject to

$$w^B \leq w^{cap} \tag{3.2}$$

$$imb_s \geq 0 \quad \forall s \epsilon S_1 \tag{3.3}$$

$$imb_s \geq \sum_{q \epsilon S_2} p_q (w^c_{q,k=1} - w_s) \quad \forall s \epsilon S_1 \tag{3.4}$$

$$\eta_r \geq a - (\lambda_r w^c_{r,k=1} - \lambda^{bal}_r imb_r) \tag{3.5}$$

$$\eta_r \geq 0 \tag{3.6}$$

where $\lambda_q$, $\lambda^{bal}$ and $w^c_q \ \epsilon$ arg {LL problem}.

Objective (3.1) maximises the profit, consisting of the revenues minus the imbalance costs. The revenue is a sum of the products of the DA market price $\lambda_q$ and the cleared quantity $w^c_{q,k=1}$ for the strategic WPP in every market clearing scenario q, weighted for the probabilities related to these scenarios $p_q$. The imbalance cost is a sum of the products of the imbalance penalty $\lambda^{bal}$ and the imbalance $imb_s$ for the strategic WPP in every wind power scenario s, weigthed for the probabilities $p_s$ related to these scenarios. The scenario set $S_1$ is defined by the scenarios that indicate the potential wind power production of the strategic WPP. The scenario set $S_2$ is defined by the market clearing scenarios, caused by the uncertainty on the bids of the non-strategic players.

The conditional value at risk is implemented in the objective function. Herein, $\gamma$ is the CVaR weighting factor. $\beta$ is the considered CVaR parameter. However, both $\gamma$ and $\beta$ are exogenously imposed to represent the risk-averse behavior of the strategic WPP. $a$ and $\eta$ are auxiliary variables to compute the CVaR.

Equation (3.2) states that the maximum quantity bid of the strategic WPP cannot exceed its technical capacity. Equations (3.3) and (3.4) define the imbalance of the strategic WPP. It can only be positive, as curtailment would occur in case of a negative imbalance. If positive, it is equal to the weighted difference between the cleared quantity for the strategic WPP and the actual wind power production, which is scenario dependent. Therefore, the imbalance is scenario dependent.

### 3.3.2 Upper-level problem for a GenCo

Similarly, the strategic GenCo is represented as player i=1, while the non-strategic GenCo's are i>1. The aim of the UL problem is the profit maximisation for the considered strategic GenCo. The UL variables are $\Delta^{UL} = \{g^b_{i=1},\, \alpha^g_{i=1}\}$.

$$\max_{\Delta^{UL} U \Delta^{LL}} (1-\gamma)\Big[\sum_{q \epsilon S_2} p_q g^c_{q,i=1}(\lambda_q - P^g_{i=1})\Big] + \gamma\Big[a - \frac{1}{\beta}\sum_{q \epsilon S_2} \eta_q \cdot p_q\Big] \tag{3.7}$$

subject to

$$g^b \leq G \tag{3.8}$$

$$\eta_q \geq a - (\lambda_q(g^c_{q,k=1} - P^g_{i=1})) \tag{3.9}$$

$$\eta_q \geq 0 \tag{3.10}$$

where $\lambda_q$ and $g^c_q \,\epsilon$ arg {LL problem}.

Objective (3.7) maximises the profit, consisting of the revenues minus the operation costs. The revenue is a sum of the products of the DA market price $\lambda_q$ and the cleared quantity $g^c_{q,i=1}$ for the strategic GenCo in every market clearing scenario q, weighted for the probabilities related to these scenarios $p_q$. The operation cost is a sum of the products of the marginal cost $P^g_{i=1}$ and the cleared quantity $g^c_{q,i=1}$ for the strategic GenCo in every market clearing scenario q, weighted for the probabilities related to these scenarios $p_q$. The conditional value at risk is identically implemented as in Section 3.3.1. Finally, Equation (3.8) states that the maximum quantity bid of the strategic GenCo cannot exceed its generation capacity.

### 3.3.3 Lower-level problem

The aim of the lower level problem is social welfare maximisation. The LL variables are $\Delta^{LL} = \{d,\, w^c_k,\, g^c_i,\, \lambda,\, \lambda^{bal},\, \underline{\delta}_i,\, \bar{\delta}_i,\, \underline{\epsilon}_q,\, \bar{\epsilon_q},\, \underline{\xi}_k,\, \bar{\xi}_k\}$, while the UL variables are considered as parameters.

$$\forall q \epsilon S_2 \Big\{ \qquad \max_{\Delta^{LL}} P^d d_q - \sum_{i \epsilon I} \alpha^g_i g^c_{i,q} - \sum_{k \epsilon K} \alpha^w_k w^c_{k,q} \tag{3.11}$$

subject to

$$\sum_{k \epsilon K} w^c_{k,q} + \sum_{i \epsilon I} g^c_{i,q} = d_q \qquad : \lambda_q \tag{3.12}$$

$$0 \leq g^c_{i,q} \leq g^b_i \qquad \forall i \epsilon I \qquad : \underline{\delta}_{i,q}, \bar{\delta}_{i,q} \tag{3.13}$$

$$0 \leq w^c_{k,q} \leq w^b_{k,q} \qquad \forall k \epsilon K \qquad : \underline{\xi}_{k,q}, \bar{\xi}_{k,q} \tag{3.14}$$

$$0 \leq d_q \leq D \qquad : \underline{\epsilon_q}, \bar{\epsilon_q} \tag{3.15}$$

$$\left. \lambda^{bal}_q = 1.3\lambda_q \qquad \right\} \tag{3.16}$$

Objective (3.11) maximises social welfare, which is defined as the sum of the consumer surplus and the producer surplus. Specifically, the integral of the difference between the willingness-to-pay curve of the customers on the one hand, and the aggregate supply curve[6] of the producers on the other hand is calculated, over a domain of zero up to the covered demand.

Equation (3.12) represents the electricity balance. It is enforced that the total scheduled generation equals the energy demand at all times. This implies that load shedding can occur if necessary. The induced dual variable $\lambda_q$ represents the cleared market price.

Equation (3.13) states that the cleared quantity of a GenCo cannot exceed the quantity bid of the GenCo. This holds for every GenCo participating in the DA market. Moreover, the cleared quantity of a GenCo can differ among the considered market clearing scenarios, caused by the uncertain bidding behavior of WPP's.

Similarly, Equation (3.14) imposes that the cleared quantity of a WindCo cannot exceed the quantity bid of the WPP. Again, this holds for all WPP's. The quantity bids of the non-strategic WPP's are exogenously imposed. However, they can occur in the form of scenarios causing the market clearing scenarios. Therefore, the cleared quantity of a WPP can also differ among the considered market clearing scenarios. Note that a strategic market participant will place only one quantity and price bid as his strategic decision, without making use of scenarios.

An inelastic demand D is considered in combination with a maximum willingness-to-pay $P^d$, which is the marginal utility of demand. As load shedding can occur, the inelastic demand D imposes only an upper limit for the demand that is met through the market clearing. This is stated in Equation (3.15).

Finally, Equation (3.16) defines the imbalance penalty that is imposed on market participants when their actual output does not meet their cleared quantity. It is endogenously constructed, being 30% higher than the cleared DA price. There is no penalty mechanism in place for actual energy productions that exceed the cleared quantity as curtailment is imposed in that situation.

In Equations (3.12), (3.13), (3.14) and (3.15), dual variables are defined for each (in)equality constraint. These dual variables are used in Section 3.4 to complete the conversion to a MILP problem.

## 3.4 Conversion to a MILP problem

This section converts the MPEC to a MILP poblem. A commercial solver, like Gurobi [23], can solve the MILP problem. The section starts by defining the KKT

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[6] The supply curve is ordered according to increasing price bid.

conditions which replace the LL problem. The KKT conditions consist of both stationary conditions and complementary slackness conditions [62]. Finally, Section 3.4.2 linearises both the KKT conditions and the UL objective function.

### 3.4.1 KKT conditions for the LL problem

The KKT conditions are defined according to the procedure described by Gabriel et al. [1]. KKT conditions replace the LL problem and can be split up into two groups: the stationarity conditions and the complementary slackness conditions, whereby the dual variables are used.

The stationarity conditions are found when the gradient of the Lagrangian of the LL problem equals zero. Equation (3.17) defines the Lagrangian.

$$\begin{aligned}\mathcal{L}(d_q, g^c_{i,q}, w^c_{k,q}, \lambda_q, \underline{\delta}_{i,q}, \bar{\delta}_{i,q}, \underline{\epsilon}_q, \bar{\epsilon}_q, \underline{\xi}_{k,q}, \bar{\xi}_{k,q}) = & \\ & P^d d_q - \sum_{i\epsilon I} \alpha^g_i g^c_{i,q} - \sum_{k\epsilon K} \alpha^w_k w^c_{k,q} \\ & + \lambda_q \big( \sum_{k\epsilon K} w^c_{k,q} + \sum_{i\epsilon I} g^c_{i,q} - d_q \big) \\ & + \underline{\delta}_{i,q}(g^c_{i,q} - g^b_i) + \bar{\delta}_{i,q}(-g^c_{i,q}) \\ & + \underline{\epsilon}_q(d_q - D) + \bar{\epsilon}_q(-d_q) \\ & + \underline{\xi}_{k,q}(w^c_{k,q} - w^b_{k,q}) + \bar{\xi}_{k,q}(-w^c_{k,q})\end{aligned} \tag{3.17}$$

Equations (3.23), (3.24) and (3.25) represent the stationarity conditions. They are obtained by differentiating the Lagrangian with relation to $d_q$, $g^c_{i,q}$ and $w^c_{k,q}$ respectively.

The complementarity slackness conditions are induced by the inequality constraints (3.13), (3.14) and (3.15) in the LL problem. Each inequality constraint results in three complementarity slackness constraints. First, the primal inequality constraints are maintained (Equations (3.19), (3.20), (3.21) and (3.22)). Secondly, the associated dual variables are imposed to be non-negative (Equation (3.32)). Thirdly, every inequality constraint in the LL problem is imposed to be orthogonal to its related dual variable (Equations (3.26), (3.27), (3.28), (3.29), (3.30) and (3.31)). Introducing a generic representation of an inequality constraint in the LL problem as $h(x) \geq 0$ with an associated dual variable $\pi$, the three complementarity slackness conditions, resulting from this inequality constraint, can be represented as Equation (3.18) in its most generic form.

$$0 \leq \pi \perp h(x) \geq 0 \tag{3.18}$$

$$\sum_{k\epsilon K} w^c_{k,q} + \sum_{i\epsilon I} g^c_{i,q} = d_q \qquad \forall q \epsilon S_2 \tag{3.19}$$

$$0 \leq g^c_{i,q} \leq g^b_i \qquad \forall i \epsilon I, \forall q \epsilon S_2 \tag{3.20}$$

$$0 \leq d_q \leq D \qquad \forall q \epsilon S_2 \tag{3.21}$$

$$0 \leq w^c_{k,q} \leq w^b_{k,q} \qquad \forall k \epsilon K, \forall q \epsilon S_2 \tag{3.22}$$

$$P^d - \lambda_q + \underline{\epsilon}_q - \bar{\epsilon}_q = 0 \qquad \forall q \epsilon S_2 \tag{3.23}$$

$$-\alpha^g_i + \lambda_q + \underline{\delta}_{i,q} - \bar{\delta}_{i,q} = 0 \qquad \forall i \epsilon I, \forall q \epsilon S_2 \tag{3.24}$$

$$-\alpha^w_k + \lambda_q + \underline{\xi}_{k,q} - \bar{\xi}_{k,q} = 0 \qquad \forall k \epsilon K, \forall q \epsilon S_2 \tag{3.25}$$

$$\bar{\delta}_{i,q}(g^b_i - g^c_{i,q}) = 0 \qquad \forall i \epsilon I, \forall q \epsilon S_2 \tag{3.26}$$

$$\underline{\delta}_{i,q} g^c_{i,q} = 0 \qquad \forall i \epsilon I, \forall q \epsilon S_2 \tag{3.27}$$

$$\bar{\epsilon}_q(D - d_q) = 0 \qquad \forall q \epsilon S_2 \tag{3.28}$$

$$\underline{\epsilon}_q d_q = 0 \qquad \forall q \epsilon S_2 \tag{3.29}$$

$$\bar{\xi}_{k,q}(w^b_{k,q} - w^c_{k,q}) = 0 \qquad \forall k \epsilon K, \forall q \epsilon S_2 \tag{3.30}$$

$$\underline{\xi}_{k,q} w^c_{k,q} = 0 \qquad \forall k \epsilon K, \forall q \epsilon S_2 \tag{3.31}$$

$$\underline{\delta}_{i,q}, \bar{\delta}_{i,q}, \underline{\epsilon}_q, \bar{\epsilon}_q, \underline{\xi}_{k,q}, \bar{\xi}_{k,q} \geq 0 \qquad \forall i \epsilon I, \forall k \epsilon K, \forall q \epsilon S_2 \tag{3.32}$$

### 3.4.2 Linearisation

Two non-linearities are present in problem. On the one hand, the complementarity slackness conditions are non-lineear, while on the other hand, the non-linear terms $\lambda \cdot w^c$ and $\lambda \cdot g^c$ are present in the UL objective functions of both a WPP and a GenCo. In order to obtain a MILP problem, linearisation is necessary.

#### KKT conditions

The non-linear KKT conditions need to be linearised, being the complementary slackness conditions in Equations (3.26), (3.27), (3.28), (3.29), (3.30), (3.31) and (3.32). The big-M method can be used to perform the linearisation [63]. Using the generic form that Equation (3.18) introduced, the big-M method transforms the complementarity slackness condition into Equations (3.33), (3.34) and (3.35). The big-M method introduces a large positive constant M and a binary variable B.

$$h(x) \leq M \cdot B \tag{3.33}$$

$$\pi \leq M \cdot (1 - B) \tag{3.34}$$

$$\pi, h(x) \geq 0 \tag{3.35}$$

When B equals one, the dual variable $\pi$ becomes zero, while $h(x) \leq M$. When B equals zero, the inequality becomes an equality as $h(x)$ equals zero, while $\pi \leq M$. The constant M should be chosen large enough so that its value at least equals the maximum attainable value of $h(x)$ and $\pi$. However, large values for M typically entail high calculation times. Therefore, a strategic choice as the value for M can have large computational advantages. Taking the complementarity slackness condition, represented by Equations (3.20), (3.26) and (3.32) as an example, the linearisation results in Equations (3.36), (3.37) and (3.38).

$$\bar{\delta}_{i,q} \leq M_{\bar{\delta}i,q} u_{\bar{\delta}i,q} \tag{3.36}$$

$$(g_i^b - g_{i,q}^c) \leq M_{\bar{\delta}i,q}(1 - u_{\bar{\delta}i,q}) \tag{3.37}$$

$$(g_i^b - g_{i,q}^c), \bar{\delta}_{i,q} \geq 0 \tag{3.38}$$

The optimal value of $M_{\bar{\delta}i,q}$ equals $G_i$, representing the generation capacity of GenCo i. When applying this value, the induced additional computational time is reduced.

### UL objective function of a WPP

Non-linearity of the UL objective function can be found in the term $\lambda_q \cdot w_{k=1,q}^c$. The strong duality theorem [64] is used, which reads as Equation (3.39). Subsitution of the stationarity condition (3.25) and the complementary slackness conditions (3.31) and (3.30) into (3.39) leads to Equation (3.40). The right-hand side of (3.40) depicts a linear representation for $\lambda_q \cdot w_{k=1,q}^c$.

$$P^d d_q - \sum_{i \epsilon I} \alpha_i^g g_{i,q}^c - \sum_{k \epsilon K} \alpha_k^w w_k^c = \sum_{i \epsilon I} g_i^b \bar{\delta}_{i,q} + D\bar{\epsilon}_q + w_{k=1,q}^b \bar{\xi}_q + \sum_{k \epsilon K \backslash (k=1)} w_{k,q}^b \bar{\xi}_{k,q} \tag{3.39}$$

$$\lambda_q w_{k=1,q}^c = \sum_{i \epsilon I} g_{i,q}^c \alpha_i^g + P^d d_q - \sum_{i \epsilon I} g_i^b \bar{\delta}_{i,q} - D\bar{\epsilon}_q + \sum_{k \epsilon K \backslash (k=1)} w_{k,q}^b \bar{\xi}_{k,q} \tag{3.40}$$

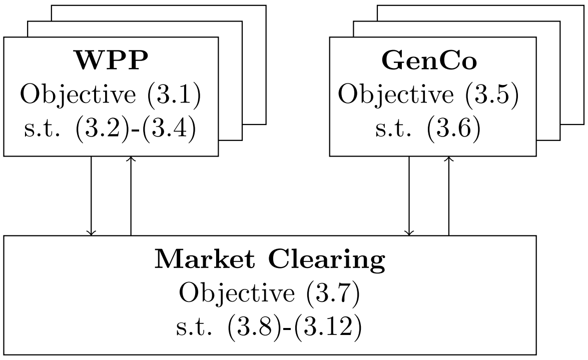
### UL objective function of a GenCo

The objective function of a GenCo consists of the non-linear term $\lambda_q \cdot g_{i=1,q}^c$. Similarly as in the UL objective function of WPP, the term is linearised using the strong duality theorem. Substitution of the stationarity condition (3.24) and the complementary slackness conditions (3.27) and (3.26) into (3.39) leads to Equation (3.41). The right-hand side of (3.41) depicts a linear representation for $\lambda_q \cdot g_{i=1,q}^c$.

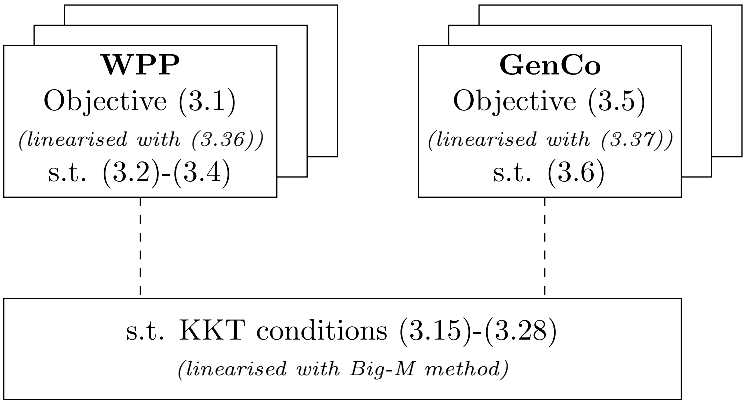
$$\lambda_q g_{i=1,q}^c = \sum_{k \epsilon K} w_{k,q}^c \alpha_k^w + P^d d_q - \sum_{k \epsilon K} w_k^b \bar{\delta}_{k,q} - D\bar{\epsilon}_q + \sum_{i \epsilon I \backslash (i=1)} g_{i,q}^b \bar{\xi}_{k,q} \tag{3.41}$$

## 3.4.3 Implementation

The final MILP problem is presented in Figure 3.7. It consists of the maximisation of the UL objective function, which is dependent on whether the considered strategic player is a WPP or a GenCo. It is subject to both its own constraints and the KKT conditions, of which the latter is commonly defined for each strategic player in the EPEC model.



(a) EPEC as a set of MPEC's



(b) EPEC as a set of MILP's

Figure 3.7: Implementation of the EPEC model as a set of MPEC's, converted into MILP's. In the MILP problem, the LL problem is replaced by a set of KKT conditions. An overview of the equations is depicted. The mathematical formulation applies for the MPEC or MILP problem of one strategic player, but is extended to an EPEC model by iterating over all market participants as the strategic player.

The model is implemented using Julia Jump [65] as the programming language. Moreover, the EPEC and MPEC models are solved via the MILP problems using the Gurobi solver [23].

## 3.5 Conclusion

This chapter formulated an EPEC model, as a set of MPEC's, that represents the strategic participation of multiple price-making WPP's and GenCo's in the DA electricity market, considering the uncertain wind power production. The chapter started by declaring the aspect of possessing information on other strategic participants. Three levels of wind power forecast sharing exist: the extreme cases of 'perfect IS' and 'no IS' on the one hand, and the 'partial IS' case as an intermediate level on the other hand. Depending on the information available to a decision-making market participant, the market is set up. Consequently, an EPEC or MPEC model is solved by each decision-making market participant. Finally, an ex-post market clearing occurs.

Section 3.2 provided a conceptual framework in which the general solution strategy was explained, depending on the information available to the strategic market participants. Furthermore, Section 3.3 formulated the associated mathematical problem of an MPEC. Finally, 3.4 completed the conversion of an MPEC problem towards a MILP problem so that it can be solved using Gurobi as a solver.

Chapter 4 applies the developed model in a fictive power system so that the applicability of the model is proven on the one hand, and conclusions on the act of sharing wind power forecasts can be made on the other hand.

# Chapter 4

# Results' discussion

This chapter applies the developed EPEC and MPEC model to a fictitious power system. In Section 4.1, the considered case study is introduced. More specifically, the input data are provided together with two simplifcations in the proposed model. Moreover, a stability analysis is performed on the proposed model, considering a discrete amount of scenarios to represent the uncertain wind power output. Section 4.2 motivates and justifies the applicability of the model. Herein, it is argued why an EPEC model fits the 'perfect and partial IS' cases the best and why an MPEC model suits the 'no IS' case better, facilitated by numerical results. Furthermore, Section 4.3 and Section 4.4 compare the 'perfect IS' case and the 'partial IS' case respectively with the 'no IS' case. Herein, some insightful conclusions are made.

The following three sections discuss the sensitivity of the results with regard to some parameters. Section 4.5 varies the considered standard deviations in the wind power forecasts. Next, Section 4.6 introduces risk-averse behavior by the strategic WPP's. Furthermore, Section 4.7 considers an incorrect aggregate wind power forecast. Finally, Section 4.8 concludes.

## 4.1 Modus operandi

This section aims to present the setting in which the results are captured. It starts by providing the full set of input data that the chapter consistently applies throughout the chapter, unless explicitly mentioned. Besides, it presents the assumptions that are consistently applied. Next, it introduces the measures that allow comparing different solutions of the model. Finally, a stability analysis is presented that shows the convergence of the solution of the model when representing the uncertainty through a set of scenarios.

### 4.1.1 Input data

A fictive power system is set up to illustrate the model's functioning. Parameters are inspired by real-world situations, such as the marginal operational cost of GenCo's. However, there is no intention to rigorously represent any real-world power system

| Player | WPP 1 | WPP 2 | WPP 3 | WPP 4 | |
|---|---|---|---|---|---|
| $w^{cap}$ [MW] | 1000 | 1000 | 1000 | 1000 | |
| Player | GenCo 1 | GenCo 2 | GenCo 3 | GenCo 4 | GenCo 5 |
| G [MW] | 500 | 450 | 300 | 240 | 235 |
| $P^g$ [$\frac{€}{\text{MWh}}$] | 30 | 32 | 35 | 50 | 60 |
| Player | GenCo 6 | GenCo 7 | GenCo 8 | GenCo 9 | |
| G [MW] | 150 | 100 | 50 | 50 | |
| $P^g$ [$\frac{€}{\text{MWh}}$] | 80 | 110 | 150 | 200 | |

Table 4.1: Parameters describing the generation capacity and the marginal operation costs for the market participants in the DA market. The marginal operation costs for WPP are neglected.

| Player | Average $\mu$ [MW] | Standard Deviation $\sigma$ [MW] |
|---|---|---|
| WPP 1 | 200 | 33 |
| WPP 2 | 200 | 66 |
| WPP 3 | 200 | 5 |
| WPP 4 | 100 | 33 |

Table 4.2: Parameters describing the normally distributed wind power forecast of each individual WPP.

and its related DA market. The power system is considered in a single time step as there are no intertemporal constraints. The fictive power system consists of only one node, to which 4 WPP's, 9 GenCo's and all customers are connected. The customers are treated in an aggregated way, so they are not specified. Table 4.1 show the parameters that indicate the generation capacity and the marginal operational costs of the considered market players. Hereby, the operational cost of a WPP is neglected. Furthermore, Table 4.2 describes the individual wind power forecast of each WPP through the average and standard deviation in the gaussian distribution. 33 equidistant samples are taken from the continuous distribution in order to obtain scenarios that describe the wind power output. It can be noted that the deterministic aggregate wind power forecast amounts 700 MW, as being the sum of the averages in the individual forecasts.

The aggregate demand of the customers, off-taking electricity from the node, is modeled as being perfectly inelastic as Section 4.1.2 visualises. This implies that the market clearing price does not impact demand until a price is reached that equals the customers' marginal utility of demand $P^d$. For a market clearing price of $P^d$, demand is modeled as being perfectly elastic, meaning that customers are indifferent on being cleared in the market as long as the clearing price equals $P^d$. The marginal utility of demand is set at $P^d = 300\ \frac{€}{\text{MWh}}$, while the inelastic demand is a priori set at D = 2500 MW. However, Section 4.3 also considers demand levels of D = 1500

MW and D = 2000 MW. Moreover, no risk-averse behavior is considered (CVaR weighting factor $\gamma$ equals zero) unless explicitly stated.

Two important simplifications in the EPEC model, rigorously introduced as a set of MPEC models in Chapter 3, are considered. Firstly, the price bids of the market participants are exogenously imposed instead of endogenously determined as part of the strategic participation. Their values are set equal to the marginal operation costs of the considered market participants, which are zero in the case of WPP's. The reason lays in the optimistic character of the market clearing problem that is considered by a strategic market participant. In an EPEC model, it has been encountered that all strategic market participants[1] will equalise their price bid to the market clearing price. However, every market participant has his own optimistic view on the expected market clearing, meaning that each market participant will consider himself as being cleared in the market. Consequently, the ex-post market clearing is indifferent on which market participants are cleared into the market, resulting in a random ex-post market clearing. This inherent flaw in the model is avoided when only allowing strategic behavior from the market participants through quantity bids.

The second simplification is made on the strategic behavior of GenCo's. In this setting, it has been encountered that the strategic behavior of the GenCo's results in quantity bids that are equal to the generation capacities of the strategic GenCo's. This situation implies that the price-making strategic behavior of the GenCo's equals the price-taking non-strategic behavior of GenCo's in case the quantity bids amount the generation capacities. Therefore, this chapter considers GenCo's as price-taking non-strategic market participants.

### 4.1.2 Measures

The ex-post market clearing allows to calculate numerous properties of the power system in the DA market. This thesis aims to discuss these results both from the perspective of the individual WPP's on the one hand, and the perspective of policy makers on the other hand.

Figure 4.1 visualises the market clearing in which the WPP's bid their average wind power forecast and the GenCo's bid their generation capacity. Firstly, the supply curve of the producers (WPP's and GenCo's) can be recognised, in which the WPP's are indicated in red and the GenCo's are indicated in yellow. The total wind power that is bid on the DA market amounts 700 MW, leading to a maximum supply possibility of 2775.0 MW. When every WPP would bid one standard deviation of his wind power forecast less than his average, the total wind power that is bid on the DA market would be 561.5 MW leading to a maximum supply possibility of 2636.5 MW. When every WPP would bid one standard deviation of his wind power forecast more than his average, the total wind power that is bid on the DA market would amount 838.2 MW leading to a maximum supply possibility of 2913.2 MW. However, there is always a risk for an imbalance penalty or curtailment, in case the cleared quantity cannot be delivered at real-time, that is taken into account when

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[1] All WPP's and only the GenCo's with a marginal operational cost lower than or equal to the market clearing price.

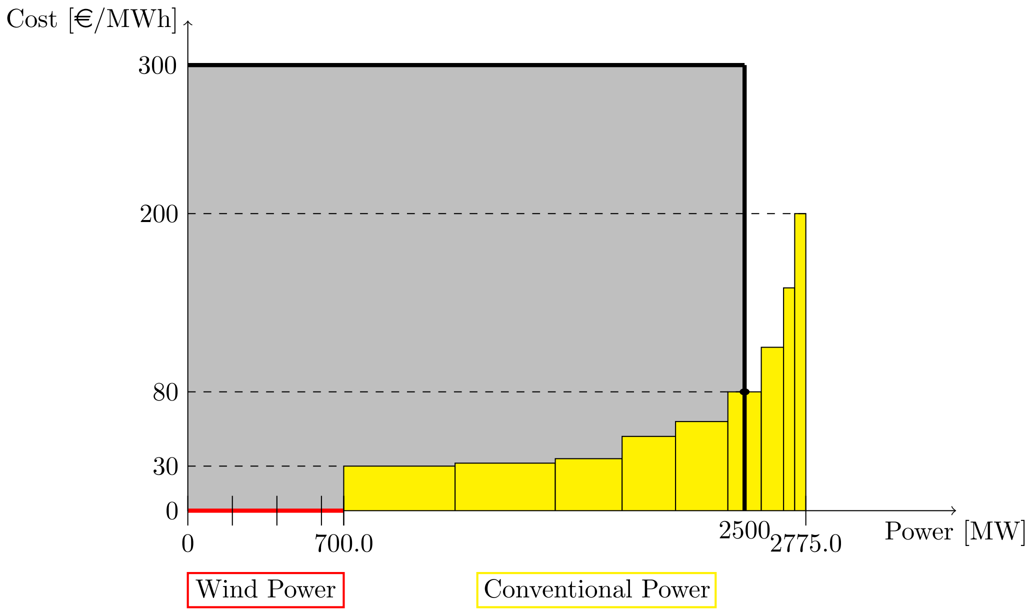

Figure 4.1: Supply and demand curves with the social welfare indicated as the grey area. The red part of the supply curves represents the bids of the WPP's, while the yellow part represents the bids of the GenCo's. The WPP's are represented as bidding their average wind power forecast.

determining a quantity bid. Secondly, the aggregate demand curve of the customers is shown as an inelastic demand of 2500 MW with a marginal utility of demand of 300 $\frac{€}{\text{MWh}}$.

The intersection of the supply and demand curves indicates the market clearing. For example, when the quantity bid of each WPP equals his average wind power forecast, an equilibrium price of 80 $\frac{€}{\text{MWh}}$ is reached as indicated on Figure 4.1. It follows that the quantity bids of all WPP's and GenCo 1 up to GenCo 5 are fully accepted, while the quantity bid of GenCo 6 is only partly accepted. The bids of GenCo 7 up to GenCo 9 are not accepted and do not trade their energy. Next to the intersection of the supply and demand curves, the market clearing is performed via the maximisation of social welfare. The grey area equals the value of the realised social welfare.

It should be noted that the discussed social welfare corresponds with the DA market only, disregarding the realised social welfare in other electricity markets. Contrary, the discussed profits for WPP's consist of the realised revenues in the DA market on the one hand, and the imbalance costs from the balancing market on the other hand.

The EPEC model allows for each decision-making market participant to incorporate the effect of information, available to the decision-making market participant. Therefore, the set-up of the supply curve and thus the market clearing problem can differ along the decision-making market participant, depending on the information

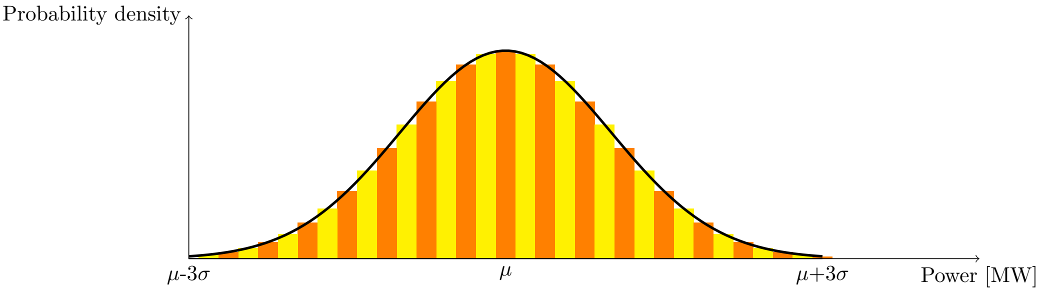

Figure 4.2: The wind power forecast of a WPP. These forecasts are assumed to be normally distributed, taking 33 samples with a relative fixed position around the average forecast.

that is available to him. The solution of the model leads to results on the bids and expected price from every market participant on the one hand, and the cleared profit[2] for every market participant, cleared price and social welfare on the other hand.

### 4.1.3 Stability analysis

In order to represent the normally distributed uncertainty on the wind power forecast in a discrete way, a scenario set needs to be developed out of the continuous probability density. This thesis consistently opts for 33 samples (and thus scenarios) with a fixed relative value with respect to the average: 33 equidistant samples ranging from $\mu - 3\sigma$ up to $\mu + 3\sigma$. It is essential to recognise the difference between the probability density as depicted on a gaussian curve and the discrete probabilities related to the samples. Consequently, a simplified rectangular integral is taken for each sample in order to obtain the approximated probability related to each sample. The surfaces of each colored box in Figure 4.2 equal the probrabilities related to their associated samples. Finally, all probabilities related to their samples are rescaled so that the sum of probabilities for an individual wind power forecast equals one.

The solution of the model should exhibit both in-sample and out-of-sample stability, defined by Bruninx [66] as an indication that the addition of more scenarios, in the considered scenario set to the optimisation problem, does not change the UL objective function of the model. On the one hand, in-sample stability can be claimed when the objective value does not change when different scenario trees are applied, representing the same underlying distribution. On the other hand, out-of-sample stability is claimed when the UL objective function does not change, when the same different scenario trees as in the case of in-sample stability are applied. Hereby, the UL decision variables, obtained in the case of in-sample stability, are fixed and the problem is solved with a relatively large scenario tree.

In-sample and out-of-sample stability is tested for the MPEC model, as the EPEC model is presented as a set of MPEC models. Hereby, the considered strategic

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[2] The cleared profit is defined as the profit that follows out of the ex-post market clearing.

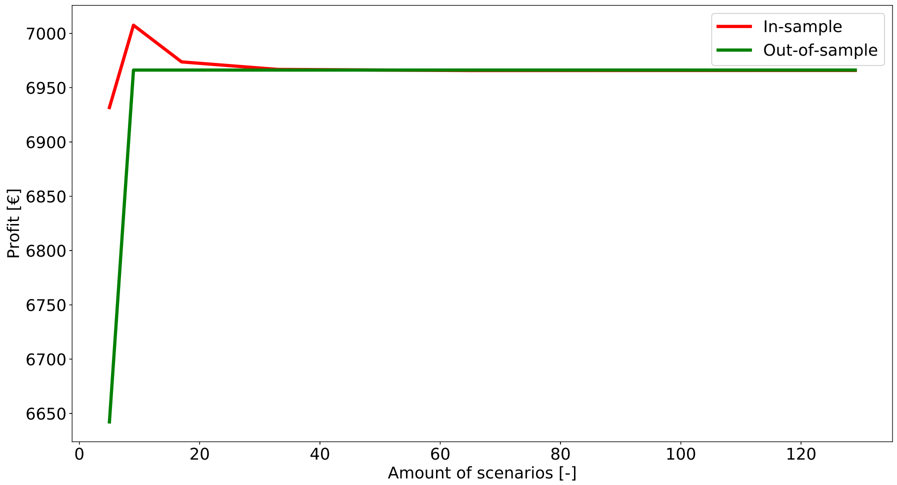

Figure 4.3: The in-sample and out-of-sample profit in function of the number of scenarios taken, in the in-sample profit calculation. The out-of-sample profit is calculated with the fixed decision variables of the in-sample profit, but with at least 500 scenarios. In-sample and out-of-sample stability is reached when using minimum 33 scenarios.

market participant is WPP 1. The input parameters, as defined in Section 4.1.1, are applied. WPP 2 up to WPP 4 are assumed to bid their average wind power forecast. In the out-of-sample analysis, at least 500 scenarios are used. Figure 4.3 shows the in-sample and out-of-sample UL objective function (the profit of WPP 1) in function of the different scenario trees, expressed in the amount of scenarios. Both the in-sample profit and the out-of-sample profit converge towards each other and do not change much from 33 scenarios on. In-sample and out-of-sample stability of the model in this setting can thus be claimed. The choice for 33 samples, taken in the individual wind power forecasts is hereby justified.

## 4.2 Applicability of the model

This section aims to motivate the applicability of the EPEC and MPEC model, making use of the aspect of IS as was introduced in Section 3.1. The solution procedure of the appropriate model is numerically illustrated, leading to useful insights. The section is split up, based on the level of IS. Section 4.2.1 discusses the 'perfect IS' case. Herein, it is demonstrated why the EPEC model is better suited than an MPEC for a realistic simulation of the strategic behavior of the WPP's on the DA market. Next, Section 4.2.2 demonstrates the 'no IS' case, whereby it argues why an MPEC model gives a more realistic representation of the strategic behavior of WPP's than an EPEC model. Finally, Section 4.2.3 argues why this thesis opts

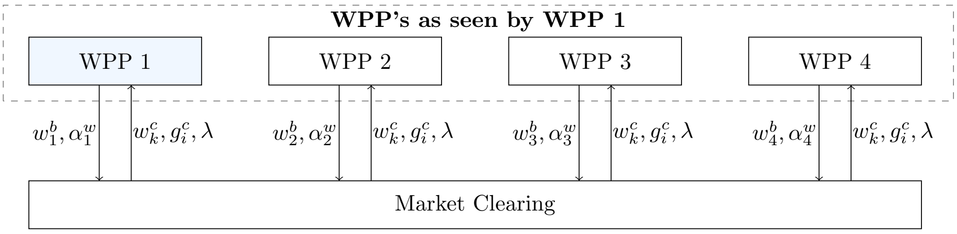

Figure 4.4: The EPEC model in the case of perfect IS. The decision making process of WPP 1 is illustrated. However, the market set-up is identically seen by all strategic market participants.

for an EPEC model to represent the intermediate 'partial IS' case.

### 4.2.1 Perfect IS

Table 4.3a shows the strategic decisions of the WPP's using an MPEC model. The quantity bid is a direct decision, while the strategic WPP expects a certain DA market price and a certain profit based on his quantity bid. While applying the MPEC model, each strategic WPP with perfect information on the forecasts of other WPP's includes these stochastic forecasts as uncertainty in the DA market clearing. The assumed market clearing by a WPP is thus a sum of scenarios weighted for their probabilities. Because of this uncertain expected price, only the expected range is given here.

Similarly, Table 4.3b shows the strategic decisions of the WPP's when an EPEC model is applied. In the 'perfect IS' case, each market participant possesses perfect information on all other market participants as all WPP's share their wind power forecasts. Therefore, the representation of the DA market participants by every decision-making player is the same. This implies that instead of solving an EPEC for each decision-making player, only one is sufficient. Figure 4.4 depicts the market set-up from the point of view of WPP 1, which is equal to the point of view of the other market participants because of the aforementioned reason. The iteration over all MPEC's, representing the strategic behavior of each WPP, reaches an equilibrium after iterating over all WPP's once.

It should be noted that the uncertainty of wind power production is thus treated differently in both approaches. In the MPEC approach, the uncertainty on the wind power production of the price-taking WPP's results in uncertainty on the market clearing, as seen by the strategic player. In the EPEC approach, the uncertainty on the wind power production of others does not result in uncertainty on the market clearing as the behavior of the other players is modeled as they were independent price-making players as well, creating only one bid. In other words, in the MPEC approach, the uncertainty is in the LL problem while in the EPEC approach, it is in each of the UL problems.

Table 4.4 represents the decision variables that follow from the ex-post market clearing when either the MPEC model or the EPEC model is applied. The cleared

| Player | Bid [MW] | Expected Profit [€] | Expected price [$\frac{€}{\text{MWh}}$] |
|---|---|---|---|
| WPP 1 | 191.40 | 15134.41 | 60...200 |
| WPP 2 | 213.00 | 13513.31 | 60...110 |
| WPP 3 | 199.21 | 16487.58 | 60...200 |
| WPP 4 | 105.27 | 6926.54 | 60...150 |

(a) MPEC

| Player | Bid [MW] | Expected Profit [€] | Expected price [$\frac{€}{\text{MWh}}$] |
|---|---|---|---|
| WPP 1 | 224.75 | 14966.8 | 80 |
| WPP 2 | 249.5 | 13933.6 | 80 |
| WPP 3 | 200.75 | 15812.5 | 80 |
| WPP 4 | 100.0 | 6643.5 | 80 |

(b) EPEC

Table 4.3: The strategic decision of the WPP's in the 'perfect IS' case, in the form of their quantity bid on the DA market. Each WPP expects a certain profit and price via its strategic participation.

quantity and the profit for every WPP is shown, next to the cleared DA market price.

A useful observation is that both models realise the same cleared DA market price of 80 $\frac{€}{\text{MWh}}$. However, the combination of taking the strategic price-making behavior of the other WPP's into account on the one hand, and the fact the every player has perfect information on the others, makes that every WPP can estimate the market outcome perfectly in the EPEC model. Therefore, the expected profit and expected price of every WPP equals the cleared profit and market price. Contrary, the MPEC model does not allow the strategic players to make perfect estimations on what the other players will bid on the DA market, so that the realised profit differs from the expected profit. Moreover, the MPEC model that every decision-making player applies, inherently considers only one strategic player while neglecting the price-making behavior of the other WPP's. It is intuitively clear that a strategic market participant should be able to estimate the market clearing perfectly in the 'perfect IS' case, therefore the EPEC model approaches the market situation more conveniently.

Another insightful observation is that the equilibrium in the EPEC is already reached after iterating once over all WPP's. The order of the WPP's in which the EPEC is solved, plays an important role there. As an illustration, Figure 4.5 shows the supply and demand curves related to this setting, applying the EPEC model. A market equilibrium is reached at a price of 80 $\frac{€}{\text{MWh}}$ and an aggregate quantity of 2500 MW. On top of that, the equilibrium lays exactly on the border between the price level of 80 $\frac{€}{\text{MWh}}$ and 60 $\frac{€}{\text{MWh}}$. Using the EPEC model, this is intentionally

| Player | Quantity [MW] | Price [$\frac{€}{\text{MWh}}$] | Profit [€] |
|---|---|---|---|
| WPP 1 | 191.40 | 80 | 14351.0 |
| WPP 2 | 213.00 | | 13595.6 |
| WPP 3 | 199.21 | | 15769.6 |
| WPP 4 | 105.27 | | 6770.67 |

(a) MPEC

| Player | Quantity [MW] | Price [$\frac{€}{\text{MWh}}$] | Profit [€] |
|---|---|---|---|
| WPP 1 | 224.75 | 80 | 14966.8 |
| WPP 2 | 249.5 | | 13933.6 |
| WPP 3 | 200.75 | | 15812.5 |
| WPP 4 | 100.0 | | 6643.5 |

(b) EPEC

Table 4.4: Determined decision variables that follow out of the market clearing in the ‘perfect IS’ case: cleared quantity and profit for each WPP on the one hand, and the cleared market price on the other hand. A comparison is made between the MPEC model and the EPEC model.

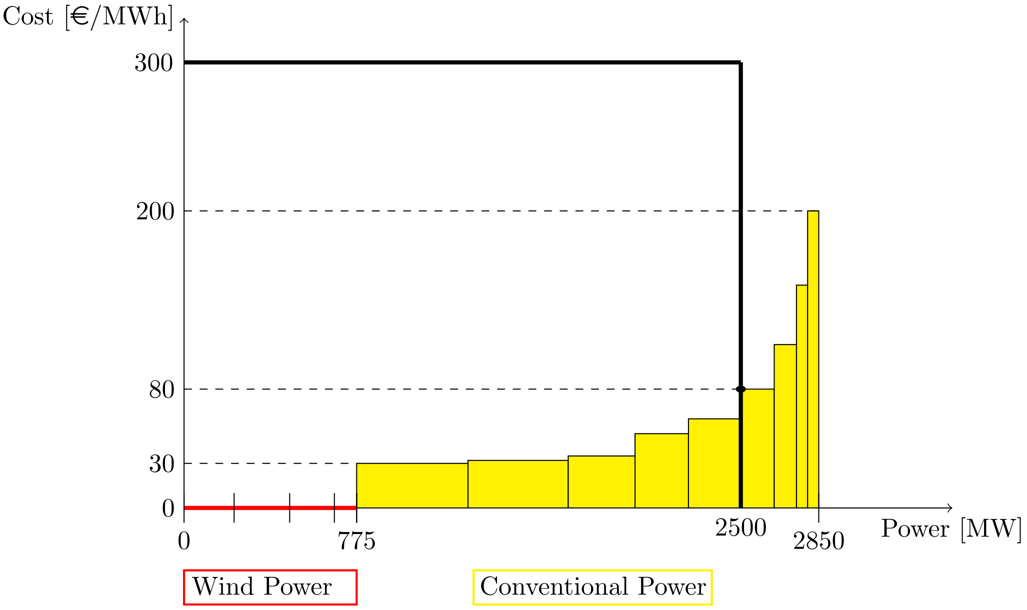

Figure 4.5: Supply and demand curves, applying the EPEC model. An equilibrium price of 80 $\frac{€}{MWh}$ is reached, which is the result of commonly realised trade-off by the strategic price-making WPP’s between a higher price on the one hand, and a higher volume on the other hand.

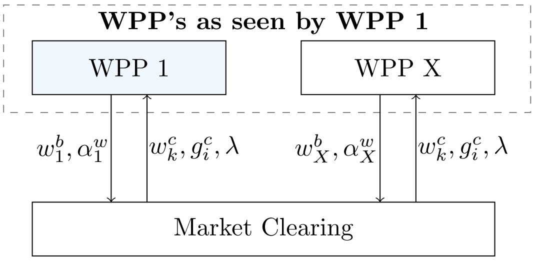

Figure 4.6: Visualisation of the EPEC model in the 'no IS' case for the decision-making process of WPP 1. WPP 1 has no information on WPP 2 up to WPP 4, so it represents them as a single individual WPP X with a deterministic forecast, equalling the aggregate wind power forecast minus the average wind power forecast of WPP 1 itself.

pursued by the strategic behavior of the WPP's. When WPP 1 and WPP 2 made a bid of 224.75 MW and 249.5 MW respectively in the EPEC, it is up to WPP 3 to make a decision. Because WPP 3 is aware of the bids of WPP 1 and WPP 2, it is taken into account that when he bids more than 200.75 MW, the price would drop to 60 $\frac{\text{€}}{MWh}$ as he assumes that WPP 4 will bid his average forecast later. When it is WPP 4's turn to make a bid, there is no other possible output decision than bidding 100 MW in order to optimise his profits. When WPP 4 places a bid, higher than 100 MW, the price would drop to 60 $\frac{\text{€}}{MWh}$ which does not outweight the advantage for WPP 4 of bidding a higher quantity. Therefore, WPP 4 is bounded by the actions of WPP 1, WPP2 and WPP 3 as these latter WPP's are arbitrarly chosen to be first in the order of the iterations over the set of MPEC's in the EPEC model. It can be concluded that the EPEC model results in indirect collaboration between WPP's in the 'perfect IS' case: a trade-off is commonly realised between a higher price and a higher schedule quantity on the market.

### 4.2.2 No IS

The 'no IS' case is solved with an MPEC model. However, the case is first solved when using the EPEC model, followed by a reasoning on why an MPEC is better suited.

The high-level framework of the EPEC model is visualised in Figure 3.5. As each strategic decision-making WPP does not possess information on the other WPP's, the 'other' WPP's are represented by the decision-making WPP as one single individual WPP X. The decision-making WPP hereby assumes that WPP X maintains an individual deterministic forecast, equalling the aggregate wind power forecast minus the average forecast of the decision-making WPP itself. The EPEC model, to be solved in order for WPP 1 to make his strategic decision, is visualised in Figure 4.6. Only two price-making strategic market participants can be recognised: the decision-making strategic WPP 1 on the one hand, and the strategic WPP X on the other hand. WPP X represents WPP 2 up to WPP 4.

| Decision-making player | EPEC player | Bid [MW] | Expected Profit [€] | Expected price [$\frac{€}{MWh}$] |
|---|---|---:|---:|---:|
| WPP 1 (*EPEC 1*) | **WPP 1** | **224.75** | **14966.8** | **300** |
| | WPP X | 200.25 | 60075 | 300 |
| WPP 2 (*EPEC 2*) | **WPP 2** | **249.5** | **13933** | **300** |
| | WPP X | 175.5 | 52650 | 300 |
| WPP 3 (*EPEC 3*) | **WPP 3** | **203.75** | **15843** | **300** |
| | WPP X | 221.25 | 66375 | 300 |
| WPP 4 (*EPEC 4*) | **WPP 4** | **124.75** | **6966** | **300** |
| | WPP X | 300.25 | 90075 | 300 |

(a) EPEC model

| Player | Bid [MW] | Expected Profit [€] | Expected price [$\frac{€}{MWh}$] |
|---|---:|---:|---:|
| WPP 1 | 224.75 | 14966.8 | 80 |
| WPP 2 | 249.5 | 13933.6 | 80 |
| WPP 3 | 203.75 | 15843.5 | 80 |
| WPP 4 | 124.75 | 6966.79 | 80 |

(b) MPEC

Table 4.5: The strategic decision of the WPP's in the 'no IS' case, in the form of their quantity bid on the DA market. Each WPP expects certain profit and price via its strategic participation. The results show the unrealistic market power of WPP X in the EPEC model. The deterministic forecasts of WPP X amount 500 MW, 500 MW, 500 MW and 600 MW in the four cases respectively.

Table 4.5a covers the numerical solution procedure by which the EPEC is solved. In the decision-making process of each WPP, an equilibrium is reached after two iterations over the two considered strategic market players of which only the final iteration is depicted in Table 4.5a, for each of the four decision-making WPP's. The results show an expected price of 300 $\frac{€}{\text{MWh}}$ in the equilibria of each decision-making process, which equals the marginal utility of demand. Consider for example the decision-making process of WPP 1. Herein, WPP X is modeled as applying a deterministic forecast of 500 MW[3]. Nevertheless, the strategic WPP X determines his bid to be 200.25 MW. His bid of only 40.05% of its deterministic wind power forecast[4] illustrates the market power of WPP X as to increase the expected price. WPP X opts to withhold a relatively large part of its deterministic forecast in order the raise its expected profit via the expected price. This market power behavior is

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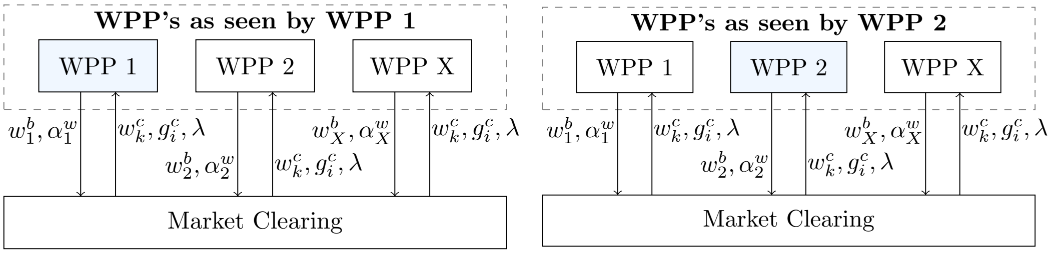
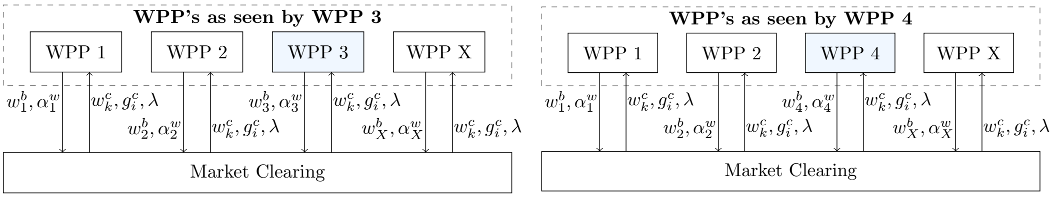
[3] The difference between the aggregate wind power forecast of 700 MW and the average of the individual wind power forecast of WPP 1 of 200 MW.

[4] WPP X is, by definition of a deterministic forecast, certain that he will be able to deliver 500 MW.



(a) WPP 1 (b) WPP 2



(c) WPP 3 (d) WPP 4

Figure 4.7: Visualisation of the EPEC model in the 'partial IS' case for the decision-making process of all four WPP's. The wind power forecasts of WPP 1 and WPP 2 are known by every market participant. WPP X represents the WPP's of which the individual forecasts are not known by the considered decision-making player, but for which the aggregate deterministic forecast is used.

considered to be unrealistic as WPP X is only a modeling of WPP 2 up to WPP 4 together. In the 'no IS' case, it is impossible for WPP 2 up to WPP 4 to collaborate in order to raise the expected price.

Generally, this underbidding behavior becomes unrealistical in case of a large deterministic forecast of WPP X compared to the individual WPP's that it is representing. This is obviously a flaw in the EPEC model. Therefore, WPP X should be considered as a non-strategic price-taking WPP. As the decision-making process of each WPP consisted already of only two strategic market participants, the applied EPEC model is thus reduced to an MPEC model.

Table 4.5b shows the strategic decisions of the WPP's in case the MPEC model is applied. The reduction of the EPEC model to the MPEC model only influences the expected profit and expected price of each WPP, while the actual bid of the decision-making WPP on the DA market stays the same.

### 4.2.3 Partial IS

This thesis opts for the EPEC model in order to represent the 'partial IS' case. There exist a lot of intermediate cases between the 'perfect IS' case and the 'no IS' case. The case in which only WPP 1 and WPP 2 make their individual wind power forecasts available to every other market participant is discussed in this section in order to argue on the applicability of the EPEC models. Figure 4.7 visualises the EPEC model for the decision-making process of WPP 1 up to WPP 4. The EPEC's, in which WPP 1 and WPP 2 make their decision, consist of 3 strategic players:

| Decision-making player | EPEC player | Bid [MW] | Expected Profit [€] | Expected price $[\frac{€}{\text{MWh}}]$ |
|---|---|---|---|---|
| WPP 1 (*EPEC 1*) | **WPP 1** | **224.75** | **14966.8** | **80** |
| | WPP 2 | 249.5 | 13933 | 80 |
| | WPP X | 300.0 | 24000 | 80 |
| WPP 2 (*EPEC 2*) | WPP 1 | 224.75 | 14966.8 | 80 |
| | **WPP 2** | **249.5** | **13933** | **80** |
| | WPP X | 300.0 | 24000 | 80 |
| WPP 3 (*EPEC 3*) | WPP 1 | 224.75 | 14966.8 | 80 |
| | WPP 2 | 249.5 | 13933 | 80 |
| | **WPP 3** | **200.75** | **15812** | **80** |
| | WPP X | 100.0 | 8000 | 80 |
| WPP 4 (*EPEC 4*) | WPP 1 | 224.75 | 14966.8 | 80 |
| | WPP 2 | 249.5 | 13933 | 80 |
| | **WPP 4** | **100.75** | **6661.5** | **80** |
| | WPP X | 200.0 | 16000 | 80 |

Table 4.6: The strategic decision of the WPP's in the 'partial IS' case, in the form of their quantity bid on the DA market. WPP 1 and WPP 2 are considered to share their individual wind power forecast with all other market participants. Each WPP expects a certain profit and price via its strategic participation. The deterministic wind power forecasts of WPP X amounts 300 MW, 300 MW, 100 MW and 200 MW respectively.

WPP 1, WPP 2 and WPP X of which the latter represent WPP 3 and WPP 4. On the one hand, WPP X is modeled as being a strategic WPP with a deterministic forecast, based on the aggregate wind power forecast. On the other hand, WPP 1 and WPP 2 are modeled a strategic players with a stochastic forecast as their wind power forecasts are known. Similarly, the EPEC's in which WPP 3 and WPP 4 make their decision, consider 4 strategic players as the forecasts of both WPP 1 and WPP 2 are known by WPP 3 and WPP 4 respectively.

Table 4.6 shows the numerical solution procedure of the EPEC model in the decision-making process of all WPP's. Two insightful effects, also appearing in Section 4.2.1 and Section 4.2.2, become visible. Firstly, the EPEC model allows for the decision-making players to estimate the price-making behavior of the other market participants, on which he has their forecasts at his disposal. This induces an intention to collaborate between the market participants, of which their forecasts are available, in order to raise the market clearing price. For example, in the decision-making process of WPP 1, market participants WPP 1 and WPP 2 determine the same strategic bid as in the 'perfect IS' case, expecting the same profit and price.

However, when WPP X determines his strategic quantity bid, a second effect appears. Contrary to the MPEC model in the 'no IS' case, WPP X is modeled as a strategic price-making WPP. WPP X applies a deterministic forecast[5]. Therefore, WPP X is unable to determine its bid in a perfectly informed way. However, this thesis opts for an MPEC model in the 'no IS' case in order to avoid the unrealistic market power of the price-making WPP X in situations where the deterministic forecast of WPP X is large compared to the forecasts of the individual WPP's that it represents. Hereby, it is rather arbitrary to determine a condition whether WPP X can be assumed to be a price-taker. Therefore, the 'partial IS' case is considered to contain a WPP X that behaves strategically. This will potentially cause a bias in the cases where WPP X has a significantly large deterministic forecast in comparison with the forecasts of the individual WPP's that it represents. The presented example does not show excessive market power of WPP X in the EPEC models.

## 4.3 Perfect IS

This section aims to discuss the implications of 'perfect IS' compared to 'no IS', where the latter is taken as a reference case. Section 4.3.1 provides the results, while Section 4.3.2 discusses them.

### 4.3.1 Results

The provision of the results is two-fold. Firstly, the decision variables of each strategic price-making WPP are presented. Specifically, the strategic bid and the considered expected price of each WPP is depicted. Secondly, the determined ex-post decision variables of the market clearing problem are presented in which the profits for each WPP, the cleared DA market price and the realised social welfare is depicted. The cleared quantities are not shown explicitly as they equal the related quantity bids of WPP's. The presented quantities are compared between the 'perfect IS' case and the 'no IS' case, both in an absolute and in a relative way.

The results are displayed three times, each for a different level of aggregate demand. For a demand of 1500 MW, Table 4.9 is constructed; for a demand of 2000 MW, there is Table 4.8 while Table 4.7 shows the results for an aggregate demand level of 2500 MW.

### 4.3.2 Results' analysis

The results show that the cleared profits for the WPP's increase when applying 'perfect IS' at a demand level of 2500 MW and 2000 MW in Table 4.7 and Table 4.8 respectively. Furthermore, it shows an increase of the cleared DA market price and a decrease of the social welfare. However, at a demand level of 1500 MW, no single difference between both cases can be noted in Table 4.9. The results allow to describe the ability of market participants to manipulate the cleared DA market price, the impact on the profitability of WPP's and GenCo's and the valorisation of the act of

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[5] The deterministic forecast equals 300 MW as the aggregate wind power forecast amounts 700 MW and the averages in the individual forecasts of WPP 1 and WPP 2 each amount 200 MW.

| | WPP 1 | | WPP 2 | | WPP 3 | | WPP 4 | |
|---|---|---|---|---|---|---|---|---|
| Situation | Bid | Ex. price | Bid | Ex. price | Bid | Ex. price | Bid | Ex. price |
| | [MW] | $[\frac{€}{\text{MWh}}]$ | [MW] | $[\frac{€}{\text{MWh}}]$ | [MW] | $[\frac{€}{\text{MWh}}]$ | [MW] | $[\frac{€}{\text{MWh}}]$ |
| Perfect I.S. | 224.75 | 80 | 249.5 | 80 | 200.75 | 80 | 100.0 | 80 |
| No I.S. | 224.75 | 80 | 249.5 | 80 | 203.75 | 80 | 124.75 | 80 |
| Difference | 0.0 | 0.0 | 0.0 | 0.0 | -3.0 | 0.0 | -24.75 | 0.0 |
| | 0.0% | 0.0% | 0.0% | 0.0% | -1.47% | 0.0% | -19.84% | 0.0% |

(a) Bids and expected prices of the strategic WPP's

| | WPP 1 | WPP 2 | WPP 3 | WPP 4 | | |
|---|---|---|---|---|---|---|
| Situation | Profit | Profit | Profit | Profit | Price | Social Welfare |
| | [€] | [€] | [€] | [€] | $[\frac{€}{\text{MWh}}]$ | [€] |
| Perfect I.S. | 14966.8 | 13933.6 | 15812.5 | 6643.5 | 80.0 | 684000.0 |
| No I.S. | 11225.1 | 10450.2 | 11882.6 | 5225.1 | 60.0 | 685665.0 |
| Difference | 3741.7 | 3483.4 | 3929.9 | 1418.4 | 20.0 | -1665.0 |
| | +33.3% | +33.3% | +33.1% | +27.2% | +33.3% | -0.24% |

(b) Determined decision variables of the ex-post market clearing

Table 4.7: Comparison between 'perfect IS' and 'no IS' at an aggregate demand level of 2500 MW.

'perfect IS' towards society through the social welfare. The key findings, discussed in this section, are listed:

- 'Perfect IS' allows for each strategic price-making market participant to **estimate the market outcome perfectly**. The strategic participant solves an EPEC model, in which the price-making strategic behavior of the other market participants can be perfectly modeled.

- A WPP **strategically withholds his quantity bid** in order to cause a higher price, settled at the boundary between two generation units in the merit order, in the case of 'perfect IS'. Hereby, he considers the higher cleared price, outweighting the lower cleared quantity.

- The **order by which the EPEC model is solved** as a set of MPEC's determines which WPP's are mostly profiting of sharing wind power forecasts. Hereby, the relative increase of the cleared DA market price indicates an upper limit for the relative profit increase of the WPP's.

- **GenCo's** do not necessarily face a decreased profit when 'perfect IS' is in place, compared to the 'no IS' case. Moreover, the upper limit for the relative profit increase of WPP's does not hold for GenCo's. This is a direct consequence of the strategic withholding behavior of WPP's.

| | WPP 1 | | WPP 2 | | WPP 3 | | WPP 4 | |
|---|---|---|---|---|---|---|---|---|
| Situation | Bid | Ex. price | Bid | Ex. price | Bid | Ex. price | Bid | Ex. price |
| | [MW] | $[\frac{\text{€}}{\text{MWh}}]$ | [MW] | $[\frac{\text{€}}{\text{MWh}}]$ | [MW] | $[\frac{\text{€}}{\text{MWh}}]$ | [MW] | $[\frac{\text{€}}{\text{MWh}}]$ |
| Perfect I.S. | 224.75 | 50 | 225.25 | 50 | 200.0 | 50 | 100.0 | 50 |
| No I.S. | 224.75 | 50 | 249.5 | 50 | 203.75 | 50 | 124.75 | 50 |
| Difference | 0.0 | 0.0 | -24.25 | 0.0 | -3.75 | 0.0 | -24.75 | 0.0 |
| | 0.0% | 0.0% | -9.72% | 0.0% | -1.84% | 0.0% | -19.84% | 0.0% |

(a) Bids and expected prices of the strategic WPP's

| | WPP 1 | WPP 2 | WPP 3 | WPP 4 | | |
|---|---|---|---|---|---|---|
| Situation | Profit | Profit | Profit | Profit | Price | Social Welfare |
| | [€] | [€] | [€] | [€] | $[\frac{\text{€}}{\text{MWh}}]$ | [€] |
| Perfect I.S. | 9354.25 | 8620.84 | 9871.54 | 4152.19 | 50.0 | 560100.0 |
| No I.S. | 6547.97 | 6095.94 | 6931.51 | 3047.97 | 35.0 | 561946.25 |
| Difference | 2806.28 | 2524.9 | 2940.03 | 1104.22 | 15.0 | -1846.3 |
| | +42.86% | +41.42% | +42.42% | +36.23% | +42.86% | -0.33% |

(b) Determined decision variables of the ex-post market clearing

Table 4.8: Comparison between 'perfect IS' and 'no IS' at an aggregate demand level of 2000 MW.

- **Social welfare cannot increase** when all WPP's share their wind power forecasts with all other market participants. This is a direct consequence of the strategic withholding behavior of WPP's.

### Estimation of the market outcome

As it is intuitively expected, market participants with perfect information on the price-making behavior of the competitors can perfectly estimate the market outcome. Therefore, the expected price equals the cleared price for the case of 'perfect IS'. Contrary, in the 'no IS' case, the strategic behavior of the WPP's leads to a strategic decision where the decision-making WPP's make an assumption on the price-taking behavior of the other WPP's. Figure 4.8 visualises the expected market clearings of each WPP in the case of 'no IS' at the demand level of 2500 MW. It can be seen that each WPP has a different expectation on the market clearing, of which none of them corresponds with the actual ex-post market clearing. A fundamental reason for this is the construction of the deterministic forecast of WPP X, representing the WPP's of which the decision-making WPP has no individual information on. The aggregate wind power forecast is by definition a deterministic forecast, leading to a deterministic forecast for WPP X. The deterministic forecast equals the sum of the averages of the individual WPP's that WPP X represents. A decision-making strategic WPP can therefore underestimate the bids of his price-taking competitors.

| Situation | WPP 1<br>Bid<br>[MW] | WPP 1<br>Ex. price<br>[$\frac{€}{\text{MWh}}$] | WPP 2<br>Bid<br>[MW] | WPP 2<br>Ex. price<br>[$\frac{€}{\text{MWh}}$] | WPP 3<br>Bid<br>[MW] | WPP 3<br>Ex. price<br>[$\frac{€}{\text{MWh}}$] | WPP 4<br>Bid<br>[MW] | WPP 4<br>Ex. price<br>[$\frac{€}{\text{MWh}}$] |
|---|---|---|---|---|---|---|---|---|
| Perfect I.S. | 224.75 | 32 | 249.5 | 32 | 203.75 | 32 | 124.75 | 32 |
| No I.S. | 224.75 | 32 | 249.5 | 32 | 203.75 | 32 | 124.75 | 32 |
| Difference | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% |

(a) Bids and expected price of the strategic WPP's

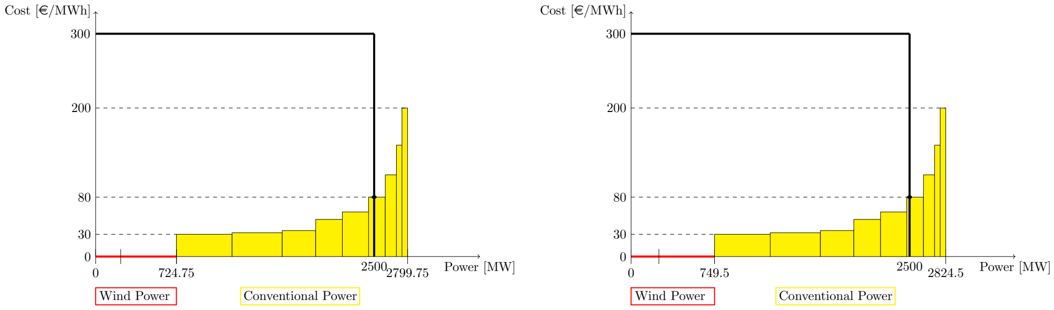
| Situation | WPP 1 Profit [€] | WPP 2 Profit [€] | WPP 3 Profit [€] | WPP 4 Profit [€] | Price [$\frac{€}{\text{MWh}}$] | Social Welfare [€] |
|---|---|---|---|---|---|---|
| Perfect I.S. | 5986.72 | 5573.43 | 6337.38 | 2786.72 | 32.0 | 428688.0 |
| No I.S. | 5986.72 | 5573.43 | 6337.38 | 2786.72 | 32.0 | 428688.0 |
| Difference | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% | 0.0<br>0.0% |

(b) Determined decision variables of the ex-post market clearing

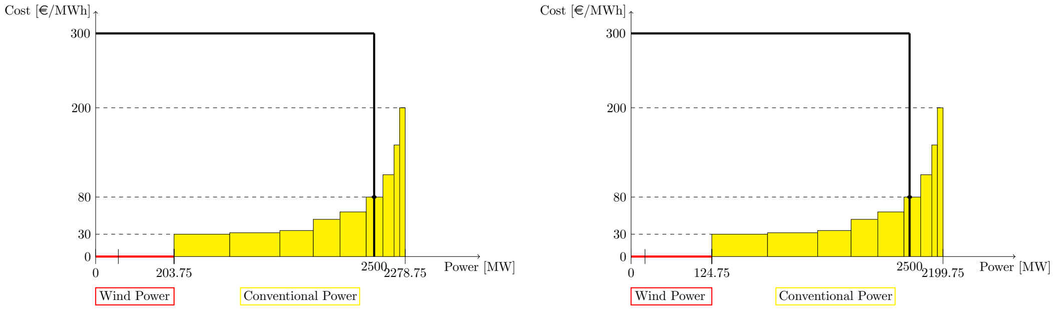
Table 4.9: Comparison between 'perfect IS' and 'no IS' at an aggregate demand level of 1500 MW.

This effect can result in overbidding, so that a lower cleared DA market price than expected is reached as the aggregate supply curve in the merit order shifts to the right.

However, there is no difference in cleared DA market price at a demand level of 1500 MW between the 'perfect IS' case and the 'no IS' case. In this level of demand, the strategic WPP's did estimate the cleared price correctly, despite that no price-making behavior of the competitors is assumed. It can be generalised that at lower demand levels, there is a trend that the overall probability of a wrong market price estimastion is lower than at higher demand levels because of the typical shape of the supply curve in the merit order. Generally, the GenCo's with the largest generating capacity face the lowest marginal operational costs and are positioned in the merit order in the front. Contrary, the GenCo's with the smallest generating capacity generally face the highest marginal operational costs and are positioned in the back of the merit order. In general, the gradient of the supply curve strongly increases with the power generation. Therefore, overbidding or underbidding, compared to the bid that is needed to realise the expected price also in the ex-post market clearing, influences the cleared DA market price to a lesser extend in the beginning of the merit order. There is thus more margin to fail in estimating the market clearing by a strategic WPP. Specifically, at a demand level of 1500 MW, the price is determined by GenCo 2, which has a marginal cost of 32 $\frac{€}{\text{MWh}}$. The bid of GenCo 2 is 450 MW, which is its capacity. On the other hand, at a demand level of 2500 MW, the price is



(a) WPP 1 (b) WPP 2



(c) WPP 3 (d) WPP 4

Figure 4.8: Visualisation of the expected market clearing by each of the strategic WPP's, considering the 'no IS' case at a demand level of 2500 MW.

determined by GenCo 5 which bids 235 MW to the DA market. As the quantity bid of the price-setting GenCo is lower at higher demand levels, there is thus a higher probability that the expected market price is not realised.

Furthermore, the strategic WPP's ability to withhold power capacity allows him to force a higher price. Moreover, the price will always be set at a border between two generation blocks in the merit order. Hereby, it makes a trade-off between a higher quantity and a potentially higher cleared market price, as discussed in Section 4.2.1. When the price lays at a border between two generation blocks in the merit order, the strategic WPP assumes that the market clearing happens at the highest possible price at the border. This is an optimistic assumption of the strategic WPP, which is inherent to a BL model. This is a situation in the limit, as the WPP's actually aim to set the price infinitesimal beyond the boundary between the two generating blocks[6]. The strategic WPP realises a higher market price while not taking any additional risks of being obliged to pay imbalance costs in case the WPP cannot deliver his cleared quantity. A strong condition in order to realise such a market price, is that the strategic market participants collaborate through sharing of wind power forecasts. Through 'perfect IS', this collaboration is realised as strategic market participants are able to perfectly simulate the price-making behavior of their

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[6] Because in reality, the market clearing generally occurs at a price that is the average of the two generating blocks in case of a market clearing at the boundary.

competitors.

### Profitability

A potentially higher cleared DA market price - in the case of ‘perfect IS’ compared to ‘no IS’ - has some implications. At demand levels of 2500 MW and 2000 MW, the higher market price leads to higher profits for the WPP’s. This is illustrated when observing the relative profit increases at a demand level of 2500 MW. The cleared DA market price increases by 33.3%, which leads to a profit increase of 33.3% for WPP 1 and WPP 2. However, for WPP 3, the profit increase is only 33.1% as the effect of a lower cleared bid limits the profit increase. The same holds for WPP 4, which faces a profit increase of 27.2%. In that sense, the relative increase of the cleared DA market price sets an upper limit for the relative profit increase that every strategic market participant can realise when having perfect information on the other market participants. However, it is necessary that at least one WPP does not face the maximum profit increase as the price increase is otherwise not realised. In other words, there needs to be at least one WPP that enforces the price increase by withholding quantity. The fact that WPP 3 and WPP 4 are relatively profiting less from the act of ‘perfect IS’ than WPP 1 and WPP 2, is caused by the order in which the MPEC’s as part of the EPEC model are solved as explained in Section 4.2.1.

As argued in Section 4.1.1, GenCo’s are considered as price-takers in this thesis’ case study as it was observed that GenCo’s consistently bid their generation capacity on the DA market. It can be noted that the profit of GenCo’s does not necessarily decrease when applying ‘perfect IS’. A lower wind power penetration into the DA market implies a higher GenCo penetration into the DA market. On top of that, a higher cleared DA market price can eventually be realised as a consequence. These two implications of the strategic behaviour of WPP’s imply a potential profit increase for GenCo’s as well. The upper limit for the relative increase of the profit of WPP’s, defined as the relative increase of the realised cleared market price, is not valid for GenCo’s as GenCo’s can potentially face both a higher cleared quantity and a higher price.

### Social welfare

Social welfare decreases when applying ‘perfect IS’. As visualised in Section 4.1.2, a higher wind power penetration into the DA market leads to a higher realised social welfare because of the low operational costs of WPP’s. In the ‘perfect IS’ case, the wind power penetration in the DA market decreases or at least stays constant (instead of increasing) so that a decrease of social welfare is inevitable. However, the relative decrease in social welfare is small compared to the relative increase of profits for the WPP’s[7].

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[7] In the presented results, an order of magnitude smaller.

Applying 'perfect IS' will never lead to a higher wind power penetration, using this thesis' model. Therefore, it can be stated that 'perfect IS' will never induce an increased social welfare.

## 4.4 Partial IS

This section discusses the implications of 'partial IS' as intermediate cases between the 'perfect IS' and the 'no IS' case, where the latter is once again taken as a reference case.

### 4.4.1 Results

Similarly as in Section 4.3.1, the provision of the results is two-fold. On the one hand, the decision variables of each strategic price-making WPP are presented. On the other hand, the determined ex-post decision variables of the market clearing problem are presented in which the profits for each WPP, the cleared DA market price and the realised social welfare are depicted. The cleared quantities are not shown explicitly as they equal the related quantity bids. The results for the 'perfect IS' case and 'no IS' case are repeated by means of comparison. The results are shown for a demand level of 2500 MW as the difference between the 'perfect IS' case and the 'no IS' case is the largest at this demand level.

Table 4.10 shows the results for each combination of one or more WPP's that share their individual wind power forecasts with every other DA market participant.

### 4.4.2 Results' analysis

The results in Table 4.10 show that the cleared profits for the WPP's only increase in one specific case when applying 'partial IS' at a demand level of 2500 MW: when WPP 1 up to WPP 3 share their wind power forecasts. Furthermore, it shows a deviating strategic bidding behavior five cases out of fourteen, compared to 'no IS'. The key findings, discussed in this section, are listed:

- 'Partial IS' shows a clear **intention of collaboration** between WPP's. More specifically, the cleared DA price in the 'perfect IS' and 'no information sharing' case indicate an upper and lower limit respectively for the increase in cleared price.
- It is essential that a **sufficient number of WPP's** share their wind power forecasts in order to be able to raise the cleared DA market price. When the price-making behavior of certain WPP's is modeled incorrectly due to a lack of information, the market outcome is estimated incorrectly.
- If insufficient WPP's share their wind power forecasts, it might result in **lower cleared profits for the WPP's** that did share their wind power forecasts, compared to the 'no IS' case. Specifically, strategically withholding quantity

| WPP's sharing their forecasts | WPP 1 | | WPP 2 | | WPP 3 | | WPP 4 | |
|---|---|---|---|---|---|---|---|---|
| | Bid [MW] | Ex. price [$\frac{€}{\text{MWh}}$] | Bid [MW] | Ex. price [$\frac{€}{\text{MWh}}$] | Bid [MW] | Ex. price [$\frac{€}{\text{MWh}}$] | Bid [MW] | Ex. price [$\frac{€}{\text{MWh}}$] |
| None | 224.75 | 80 | 249.5 | 80 | 203.75 | 80 | 124.75 | 80 |
| WPP 1 | 224.75 | 80 | 249.5 | 80 | 203.75 | 80 | 124.75 | 80 |
| WPP 2 | 224.75 | 80 | 249.5 | 80 | 203.75 | 80 | 124.75 | 80 |
| WPP 3 | 224.75 | 80 | 249.5 | 80 | 203.75 | 110 | 124.75 | 110 |
| WPP 4 | 224.75 | 200 | 249.5 | 200 | 203.75 | 200 | 124.75 | 300 |
| WPP 1 and 2 | 224.75 | 80 | 249.5 | 80 | 200.75 | 60 | 100.75 | 80 |
| WPP 1 and 3 | 224.75 | 80 | 249.5 | 80 | 203.75 | 80 | 124.75 | 80 |
| WPP 1 and 4 | 224.75 | 80 | 249.5 | 80 | 203.75 | 80 | 124.75 | 80 |
| WPP 2 and 3 | 224.75 | 60 | 249.5 | 80 | 203.75 | 80 | 121.75 | 80 |
| WPP 2 and 4 | 224.75 | 80 | 249.5 | 80 | 203.75 | 80 | 124.75 | 80 |
| WPP 3 and 4 | 224.75 | 80 | 249.5 | 80 | 203.75 | 110 | 124.75 | 110 |
| WPP 1, 2 and 3 | 224.75 | 80 | 249.5 | 80 | 200.75 | 80 | 100.0 | 80 |
| WPP 1, 2 and 4 | 224.75 | 80 | 249.5 | 80 | 200.75 | 60 | 100.75 | 80 |
| WPP 1, 3 and 4 | 224.75 | 80 | 249.5 | 80 | 203.75 | 80 | 124.75 | 80 |
| WPP 2, 3 and 4 | 224.75 | 60 | 249.5 | 80 | 203.75 | 80 | 121.75 | 80 |
| All | 224.75 | 80 | 249.5 | 80 | 200.75 | 80 | 100.0 | 80 |

(a) Bids and expected prices of the strategic WPP's

| WPP's sharing their forecast | WPP 1 Profit [€] | WPP 2 Profit [€] | WPP 3 Profit [€] | WPP 4 Profit [€] | Price [$\frac{€}{\text{MWh}}$] | Social Welfare [€] |
|---|---|---|---|---|---|---|
| None | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 1 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 2 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 3 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 4 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 1 and 2 | 11225.1 | 10450.2 | 11859.4 | 4996.18 | 60 | 684045.0 |
| WPP 1 and 3 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 1 and 4 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 2 and 3 | 11225.1 | 10450.2 | 11882.6 | 5219.41 | 60 | 685485.0 |
| WPP 2 and 4 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 3 and 4 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 1, 2 and 3 | 14966.8 | 13933.6 | 15812.5 | 6643.5 | 80 | 684000.0 |
| WPP 1, 2 and 4 | 11225.1 | 10450.2 | 11859.4 | 4996.18 | 60 | 684045.0 |
| WPP 1, 3 and 4 | 11225.1 | 10450.2 | 11882.6 | 5225.09 | 60 | 685665.0 |
| WPP 2, 3 and 4 | 11225.1 | 10450.2 | 11882.6 | 5219.41 | 60 | 685485.0 |
| All | 14966.8 | 13933.6 | 15812.5 | 6643.5 | 80 | 684000.0 |

(b) Determined decision variables of the ex-post market clearing

Table 4.10: All possible cases of 'partial IS' at a demand level of 2500 MW. The colored cases indicate that one or more bids from the WPP's are deviating from the 'no IS' case.

without succesfully raising the cleared DA price due to a lack of infomation, leads to lower profits.

- The act of sharing wind power forecasts by WPP's never leads to decreased profits for **GenCo's** when an inelastic demand is applied. This is a direct consequence of WPP's that will always withhold quantity strategically instead of increasing their quantity bid.
- There exists no case of 'partial IS' in which **social welfare** increases, compared to the 'no IS' case. Similarly, this is a direct consequence of WPP's that will always withhold quantity strategically instead of increasing their quantity bid.

### Estimation of the market outcome

As argued in Section 4.2.3, the effect of IS becomes visible, compared to the 'no IS' case as the decision-making WPP's start considering (a part of) the other WPP's as price-makers when their wind power forecasts are known. This results in a deviating bidding behavior for five combinations of WPP's that share their forecasts. The act of sharing information leads to a behavior in which strategic price-making WPP's intend to withhold generation capacity in order to cause a higher cleared DA market price. Despite the five cases in which a deviating bidding behavior is noted, only one case effectively results in a higher cleared DA market price, equalling 80 $\frac{€}{\text{MWh}}$.

Figure 4.9 shows the four market equilibria that are realised in all cases of 'partial IS'. The red dot indicates the market equilibrium that is also realised in the 'no IS' case. The green dot shows the market equilbrium when WPP 2 and WPP 3 or WPP 2, WPP 3 and WPP 4 share their wind power forecast. Furtermore, the orange dot depicts the market equilibrium when WPP 1 and WPP 2 or WPP 1, WPP 2 and WPP 4 share their forecast. Finally, when WPP 1, WPP 2 and WPP 3 share their forecast, the same market equilibrium is reached as in the 'perfect IS' case. Therefore, in this case study, the prices in the market equilibria in the 'perfect IS' case and the 'no IS' case define an upper bound and a lower bound respectively for the prices that can be realised through 'partial IS'.

Moreover, a trend is noted that when more WPP's share their forecasts, it affects the bidding behavior of the strategic WPP's more, indicating the intention for collaborative behavior. In these results, no different bidding behavior is noted when only one WPP shares his forecast; in two out of six cases, a different bidding behavior is noted when only two WPP's share their forecasts; in three out of four cases, the bidding behavior differs when three WPP's share their forecasts. It should be noted that the collaborative behavior is a result of the ability for market participants to take the price-making participation of their competitors into account when the extent to which information is shared, is sufficiently high.

### Profitability

As already argued in Section 4.3.2, the strategic withholding of generation capacity is a common strategy for WPP's in order to raise their expected price. However, it

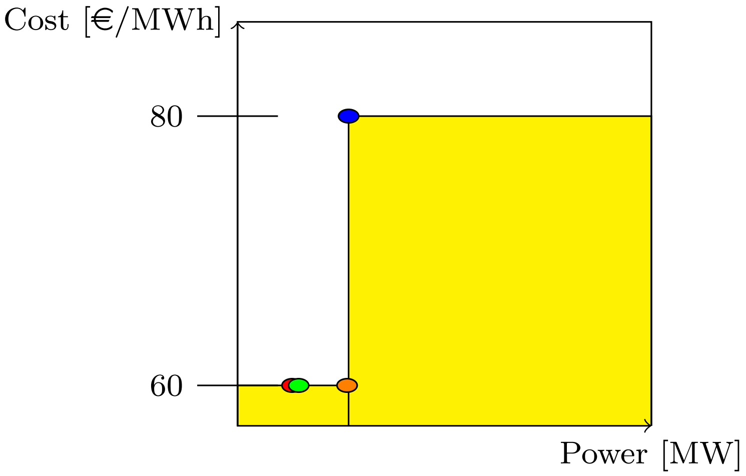

Figure 4.9: Supply curve with four different market equilibria, resulting from all possible cases of 'partial IS' for an aggregate demand of 2500 MW: three equilibrium prices of 60 $\frac{€}{\text{MWh}}$ and one of 80 $\frac{€}{\text{MWh}}$. The market equilibria in the 'perfect IS' case and the 'no IS' case indicate an upper bound and a lower bound respectively.

is seen that in multiple 'partial IS' cases, WPP's do not succeed in their intention to raise the price despite their act of strategic withholding. The combination of a lower cleared quantity and a constant cleared DA market price leads to decreased profits, assuming that the imbalance costs are limited. Decreased profits can indeed be noticed for five cases of 'partial IS' in which the deviating quantity bids do not lead to a higher cleared market price.

Moreover, WPP 1 and WPP 2 do not face a decreased profit in any of the cases. Similar to the reasoning in Section 4.3.2, in which WPP 1 and WPP 2 are profiting the most from 'perfect IS', the order in which the MPEC's are solved (as part of the EPEC) plays an important role. As WPP 4 is consistently the last strategic WPP in the iteration over MPEC's, it takes the strategic price-making decision of the other WPP's into account, leading to a withholded strategic quantity bid. Besides, the case where WPP 1 up to WPP 3 share their forecasts, leads to a situation where WPP 4 has perfect information on the market clearing. The situation in which the only strategic WPP with perfect information is positioned lastly in the sequence, leads to the succesful realisation of a cleared price increase. Again, WPP 4 is profiting relatively less than the other WPP's for the aforementioned reason, which has its foundation in the order of the MPEC's that are solved in the EPEC.

In that regard, a type of market power can be recognised for WPP 1 and WPP 2. For example, when WPP 1 up to WPP 3 share their forecast, an increased cleared price and profits for the WPP's is noticed. However, when WPP 1 decides to stop sharing his wind power forecast, it will still lead to an attempt of strategic withholding of generation capacity by WPP 4 that appears to be unsuccessful. In that situation, WPP 4 is directly affected by the choice of WPP 1 whether to share his wind power forecast while the profits of WPP 1 will not get affected.

Finally, an increase in profits of GenCo's is realised as their aggregate cleared quantity increases. Combining this conclusion with the findings in Section 4.3.2, the act of sharing wind power forecasts by WPP's never[8] leads to a decrease in profits for GenCo's as their aggregate cleared quantity will never decrease, applying an inelastic demand.

#### Social welfare

As already mentioned in Section 4.3.2, a lower wind power penetration into the DA market leads to a decreased social welfare. Five cases of 'partial IS' lead to an (un)successful strategic bidding behavior, deviating from the 'no IS' case in order to raise the cleared DA market price. These five cases thus cause a decrease in social welfare. It should be noted that of these five cases, the four cases in which the attempt to raise the cleared DA market price failed, thus lead to both decreased profits for the WPP's and a decrease in social welfare.

## 4.5 Impact of uncertainty in wind power forecasts

### 4.5.1 Key findings

The key findings are listed:

- Profits increase and social welfare decrease when the uncertainty in the wind power forecasts are decreased, independently of the level of IS. This is intuitively expected as the imbalance costs for WPP's decrease.
- A tipping point can be reached when lowering the overall uncertainty in the wind power forecasts sufficiently after which no difference between the 'perfect IS' case and the 'no IS' case can be noted.
- A trade-off for strategic WPP's could exist. In order to raise his profit, a WPP could invest in obtaining information on other wind power forecasts or he could invest in its own wind power forecast so that the uncertainty in his own forecast decreases.

### 4.5.2 Results and discussion

This section discusses the impact of the extent to which WPP's face uncertainty in their individual wind power forecasts. The uncertainty is modeled as a gaussian distribution through a standard deviation. The profits for the WPP's and social welfare are shown for both the 'perfect IS' case and the 'no IS' case, in function of the relative uncertainty in the wind power forecasts of the considered WPP's. The relative uncertainty can be interpreted as a correction factor on the standard deviations in the individual wind power forecasts of the WPP's of which the uncertainty is varied.

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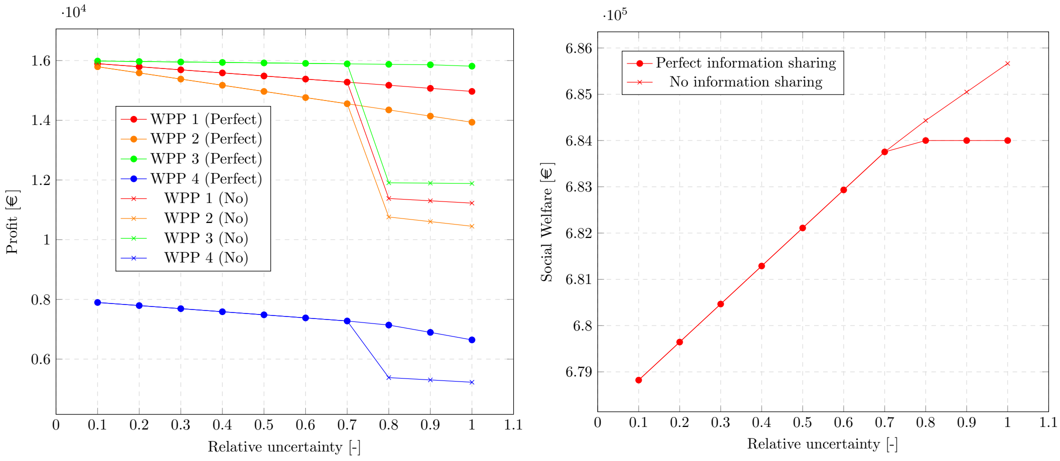
[8] On the one hand, both in the 'perfect IS' case and the 'partial IS case', and on the other hand both when the attempt to raise the cleared DA price is successful and unsuccesful.



(a) Profits

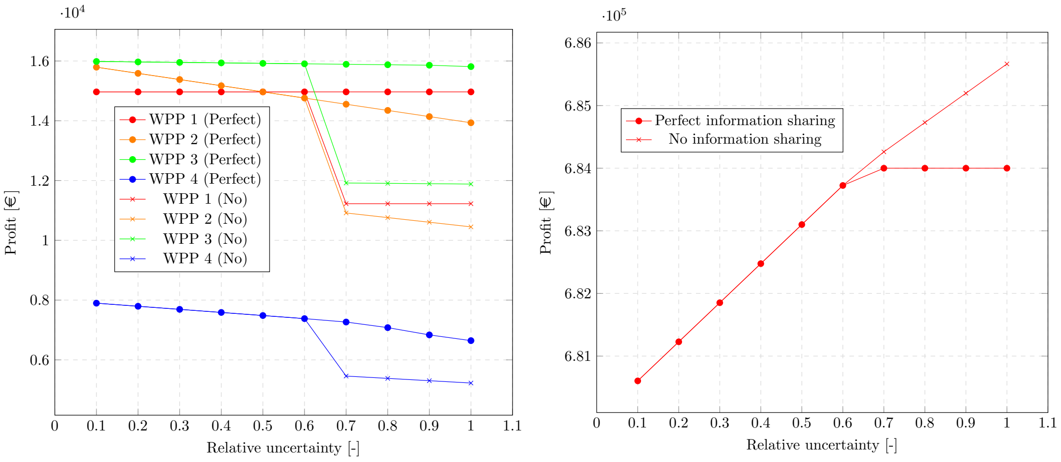
(b) Social welfare

Figure 4.10: The impact of a changing uncertainty in the forecast of all WPP's on the profits of every WPP and on social welfare at an aggregate demand of 2500 MW. The horizontal axis depicts the relative uncertainty, which can be interpreted as a correction factor on the standard deviations in the individual wind power forecasts of all WPP's.

Moreover, a distinction is made in the standard variations that vary. Specifically, Figure 4.10 shows the results for a changing uncertainty in the forecasts of all WPP's. A relative uncertainty of 1 means that the standard deviations in the respective forecasts equal 33 MW, 66 MW, 5 MW and 33 MW, as was introduced in Section 4.1.1. A relative uncertainty of 0.1 corresponds with standard deviations of 3.3 MW, 6.6 MW, 0.5 MW and 3.3 MW in the WPP's forecasts respectively. Figure 4.11 depicts the results when the uncertainty in the forecasts of only WPP 2 up to WPP 4 is varied. Finally, Figure 4.12 shows the profits and social welfare in case that uncertainty in the forecasts of only WPP 3 and WPP 4 is varied. It can be noted that the results at a relative uncertainty of 1 equals the results that were discussed in Section 4.3.

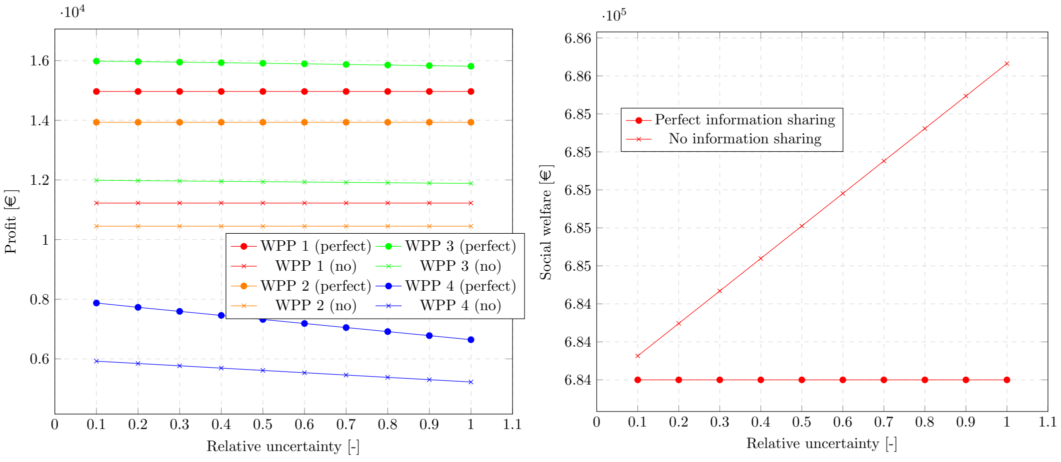
Firstly, Figure 4.10 shows a trend of increasing profits for the WPP's when the standard deviations in all forecasts decrease in both the 'perfect IS' case and the 'no IS' case. This is intuitively expected, as the imbalance costs are thereby reduced. Besides, social welfare shows a decreasing trend when the standard variations decrease. This is a direct consequence of the strategic bidding behavior of all WPP's that determine a quantity bid, higher than their average wind power forecast. Consequently, when the standard deviations decrease, their quantity bids will be closer to their average wind power forecasts. As it decreases the wind power penetration into the DA market, this results in a decrease of social welfare.

Furthermore, when decreasing the relative uncertainty in Figure 4.10, a discrepancy in both the profit and social welfare can be noted until a relative uncertainty



(a) Profits (b) Social welfare

Figure 4.11: The impact of a changing uncertainty in the forecasts of WPP 2 up to WPP 4 on the profits of every WPP and on social welfare at an aggregate demand of 2500 MW. The horizontal axis depicts the relative uncertainty, which can be interpreted as a correction factor on the standard deviations in the individual wind power forecasts of WPP 2 up to WPP 4.



(a) Profits (b) Social welfare

Figure 4.12: The impact of a changing uncertainty in the forecasts of WPP 3 and WPP 4 on the profits of every WPP and on social welfare at an aggregate demand of 2500 MW. The horizontal axis depicts the relative uncertainty, which can be interpreted as a correction factor on the standard deviations in the individual wind power forecasts of WPP 3 and WPP 4.

of 0.7[9] is reached. For smaller standard deviations, there is no difference between the ‘perfect IS’ case and the ‘no IS’ case. The reason is that when the standard deviations in the wind power forecasts are smaller, it follows that that the uncertainty on the wind power output is smaller and thus a wind power output equal to the average wind power forecast is more probable. The strategic bids of the WPP’s will consequently also lay closer to the average forecast. In the ‘no IS’ case, each decision-making WPP represents the other WPP’s as a single WPP X with a deterministic forecast that equals the sum of the average wind power forecasts of the WPP’s that WPP X represents. Therefore, when the actual strategic bid of each decision-making WPP approximates the average of its individual forecast, the assumption of each decision-making strategic WPP on the bids of the other WPP’s[10] is more correct. Consequently, the relative uncertainty of 0.7 represents a tipping point below which the price-making behavior[11] of the competiting WPP’s is estimated accurately enough by the decision-making strategic WPP’s in order to cause the same cleared DA market price in the ‘no IS’ case as in the ‘perfect IS’ case.

Thirdly, Figure 4.11 depicts an identical situation, where the tipping point is shifted from a relative uncertainty of 0.7 towards 0.6, meaning that the standard deviations equal 33 MW, 39.6 MW, 3 MW and 19.8 MW respectively in this case. The reason is that, when decreasing the relative uncertainty of only WPP 2 up to WPP 4, it has to be decreased more[12] to achieve the same degree of overall uncertainty, aggregated over all WPP’s. Besides, it can be noted that the profit of WPP 1 in the case of ‘perfect IS’ stays constant. This confirms the previous finding whereby the trend of increasing profits with decreasing uncertainties for WPP’s is caused by the reduced imbalance costs.

Finally, Figure 4.12 shows results in which there is consistently a difference in profits and social welfare between the ‘perfect IS’ case and the ‘no IS’ case. There is thus no tipping point reached when decreasing the relative uncertainties in the forecasts of only WPP 3 and WPP 4. The uncertainty of WPP 1 and WPP 2 (which equals 33 MW and 66 MW respectively) is kept constant after all. The strategic quantity bids of WPP 1 and WPP 2 deviate too much from their average wind power forecast so that WPP 3 and WPP 4’s assumption on the quantity bid of WPP 1 and WPP 2 deviates too much from their actual bid. Consequently, a cleared DA market price as in the ‘perfect IS’ case cannot be reached in case of ‘no IS’.

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[9] A relative uncertainty of 0.7 means that the standard deviations in the wind power forecasts of WPP 1 up to WPP 4 amount 23.1 MW, 46.2 MW, 3.5 MW and 23.1 MW respectively.

[10] The other WPP’s are modeled as being non-strategic price-takers in the MPEC model.

[11] Despite that the price-making behavior of the ‘other’ WPP’s is modeled as price-taking behavior in the MPEC model of ‘no IS’ by the decision-making player.

[12] When comparing it to the case where the standard deviations of all WPP’s are varied.

## 4.6 Impact of risk-averse behavior

### 4.6.1 Key findings

The key findings are listed:

- The 'perfect IS' case still leads to a perfect estimation of the market outcome by the strategic participants in case of risk-aversness. The strategic price-making behavior of other market participants is perfectly modeled, due to having perfect information. An important assumption hereby is that all decision-making WPP's consider the same risk-aversness settings, both for theirselves as for the other participants.

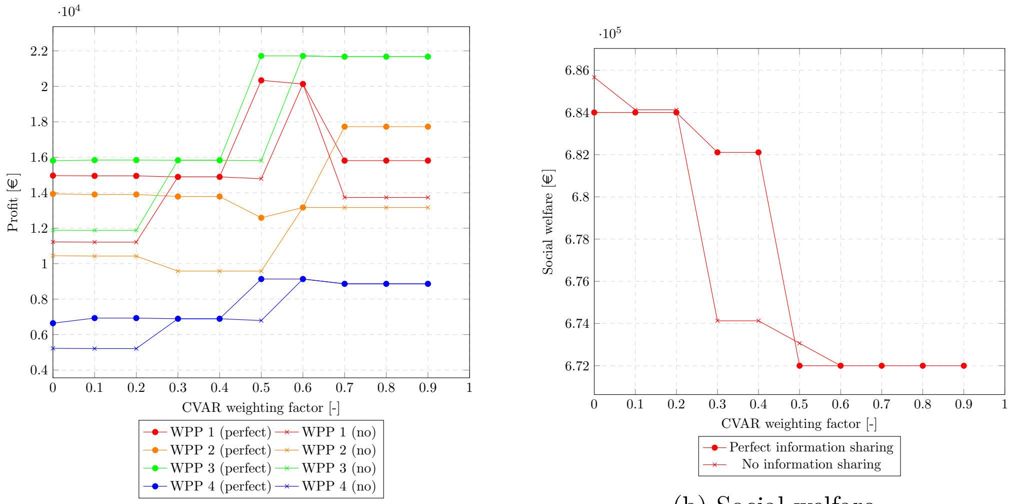
- Risk-aversness stimulates withholding quantity by a strategic WPP, leading towards higher cleared DA market prices more easily. However, this holds for both the 'perfect IS' case and the 'no IS' case. This can lead to smaller differences between both cases.

### 4.6.2 Results and discussion

This section aims to discuss the effect of risk-averse behavior of strategic market participants while making use of the Conditional Value at Risk. Two parameters characterise the risk-aversness: the CVaR parameter $\beta$ and the CVaR weighting factor $\gamma$. On the one hand, the CVaR parameter defines which percentage of the worst-case scenarios should be taken into account, while on the other hand, the CVaR weighting factor represents the weight that should be given in the UL objective function to the worst-case scenarios instead of on a risk-neutral expected profit. Therefore, Figure 4.13 depicts the WPP's profit, social welfare, the WPP's quantity bids and WPP's (expected) price in function of the CVar weighting factor $\gamma$ at a CVaR parameter $\beta$ of 0.5. In each plot, the CVaR weighting factor is varied from 0 to 0.9, where a CVaR weighting factor of zero corresponds with the results that are discussed in Section 4.3, i.e. risk-neutral behavior. Similarly, Figure 4.13 shows the WPP's profits and the social welfare for a CVaR parameter of 0.2 and 0.8. A distrinction is again made between the 'perfect IS' case and the 'no IS' case, where the latter serves as a reference case. It should be noted that the same risk-averse behavior is modeled for all strategic market participants in both the EPEC and MPEC model.

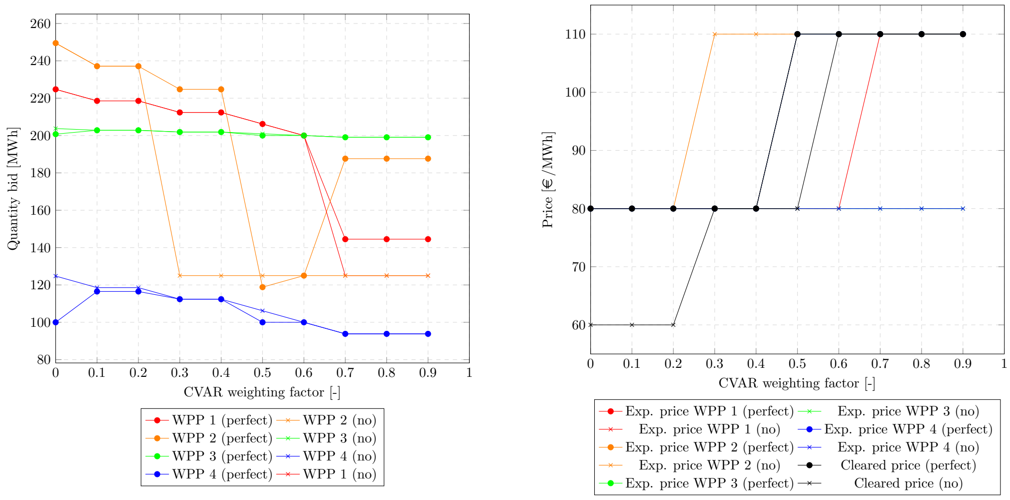
#### Perfect IS

In the 'perfect IS' case, the risk-averse strategic behavior leads to a strongly varying bidding pattern, depending on the CVaR settings. Consider for example the profits and realised social welfare at a CVaR parameter of 0.5. The WPP's face a total profits increase when the CVaR weighting factor evolves from 0.4 towards 0.5. Similarly, a decrease in social welfare can be noticed within this domain. This indicates that the cleared DA market price increases because of the stimulated withholding of generation capacity by the strategic WPP, subject to risk-aversness.



(a) Profit

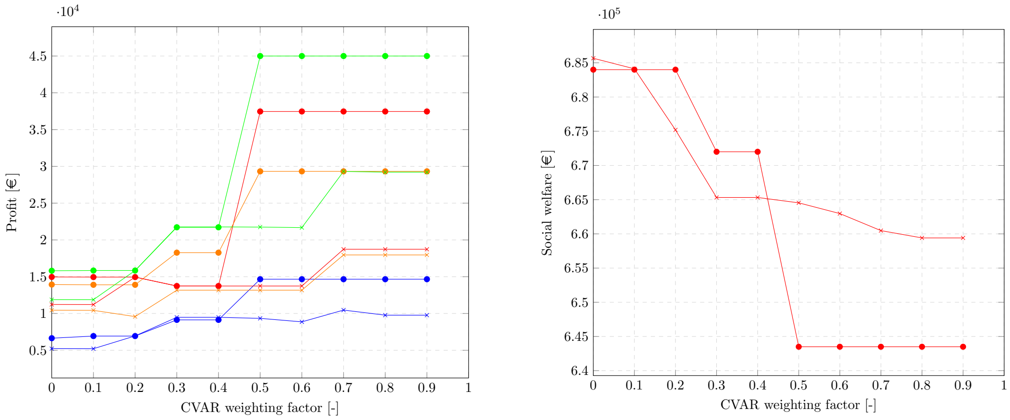
(b) Social welfare



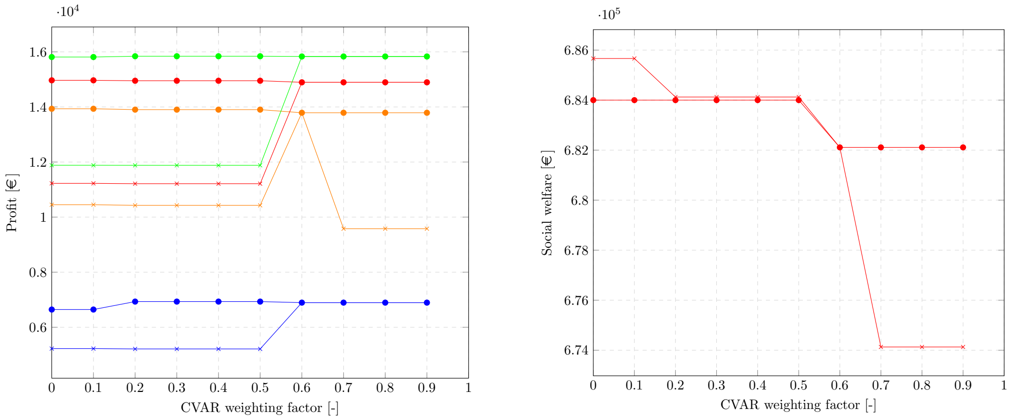
(c) Quantity bid

(d) (Expected) price

Figure 4.13: The impact of risk-aversness of all strategic market participants through the CVaR. The WPP's profit, social welfare, the WPP's quantity bids and WPP's (expected) price are plotted in function of the CVar weighting factor $\gamma$ at a CVaR parameter $\beta$ of 0.5.



(a) Profit (CVaR parameter = 0.2) (b) Social welfare (CVaR parameter = 0.2)



(c) Profit (CVaR parameter = 0.8) (d) Social welfare (CVaR parameter = 0.8)

Figure 4.14: The impact of risk-aversness of all strategic market participants through the CVaR. Both the WPP's profits and social welfare are plotted in function of the CVaR weighting factor, while two CVaR parameters are considered: 0.2 and 0.8.

Besides, when the CVaR weighting factor evolves from 0.2 towards 0.3, a decrease in social welfare is noticed again in the 'perfect IS' case, but with a small decrease of the WPP's profits. This illustrates the stimulated withholding of the WPP's bids, without successfully causing a higher cleared DA price. The WPP's hereby face a decreased total revenue, but also a (slightly less) decreased imbalance cost.

A third insightful case is the range where the CVaR weighting factor evolves from 0.6 towards 0.7 in the 'perfect IS' case. Hereby, social welfare stays constant, but the profits of WPP 1 and WPP 4 decrease, while the profits of WPP 2 increases. Less obviously, this is the results of a decreasing quantity bid of WPP 1 and WPP 4 and an increased quantity bid of WPP 2, which declares the evolution in their related profits. However, social welfare stays constant because the sum of the decrease in the quantity bids of WPP 1 and WPP 4 equals the increase in the quantity bids of WPP 2.

A general trend when the CVaR parameter is increased, is that the WPP's total profits decrease, just as their variation across a changing CVaR weighting factor. Figure 4.14 confirms this. When a rather soft[13] CVaR parameter of 0.8 is set, the difference of the realised profits and social welfare with the case of risk-neutral behavior (i.e. at a CVaR weighting factor of zero) is relatively limited, no matter the CVaR weighting factor. The opposite is true for a strong[14] CVaR parameter of 0.2.

### Comparison between ‘perfect IS’ case and ‘no IS’ case

In the ‘no IS’ case, a similar reasoning as in the three aforementioned cases in the previous paragraph is valid. Each strategic WPP still aims to estimate the market outcome and eventually withhold generation capacity in order to raise the cleared DA market price without succeeding. However, the risk-aversness stimulates the act of withholding generation capacity. Therefore, it is possible in some case of risk-aversness that there is no diference between the ‘perfect IS’ case and the ‘no IS’ case, the strategic price-making WPP’s may succeed in raising the cleared DA market price by withholding a sufficient amount of generation quantity on the DA market.

For example, in a risk-aversness setting with a CVaR parameter of 0.5 and a CVaR weighting factor of 0.6, the same profits and social welfare are realised in the ‘perfect IS’ case and the ‘no IS’ case. It indicates that also the quantity bids in both cases of IS correspond. This is due to coincidence, as each decision-making strategic WPP still has a different view on the market outcome than the other WPP’s in the ‘no IS’ case.

Furthermore, the perfect market estimation by each decision-making WPP in the ‘perfect IS’ case implies that the realised profits of the WPP’s will never be lower in the case of ‘perfect IS’ than in the case of ‘no IS’, regardless of the risk-aversness parameters. An equivalent statement on the realised social welfare is not valid as the act of withholding generation capacity by the WPP’s can still lead to different strategic bids, depending on the IS case.

An interesting observation is that some settings of risk-aversness can be found in which both the WPP’s profits and the realised social welfare increase in the ‘perfect IS’ case compared to the ‘no IS’ case. For example, this is the case at a CVaR parameter of 0.5 and a CVaR weighting factor of 0.3. Herein, the cleared DA market price is identical for both levels of IS, just as the bids of WPP 1, WPP 3 and WPP 4. However, a higher quantity bid of WPP 2 in the ‘perfect IS’ case is noted, leading to a higher profit.

Finally, it should be noted that the above reasoning is only valid in case the same risk-aversness parameters are assumed for alle strategic players in both the EPEC and MPEC model. When it is assumed that the decision-making WPP considers a different set of risk-aversness parameters than the other strategic price-making WPP’s in the market, he is unable to estimate the price-making behavior of the other strategic WPP’s perfectly. Therefore, a bias in the model appears so that it is

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[13] A soft CVaR parameter considers limited pessimistic risk-aversness.

[14] A strong CVaR parameter considers heavily pessimistic risk-aversness.

not impossible anymore that the 'perfect information sharen' case leads to higher profits for the WPP's than in the 'no IS' case.

## 4.7 Impact of an incorrect aggregate forecast

### 4.7.1 Key findings

The key findings are listed:

- An overestimation of the aggregate wind power forecast leads to smaller differences between the 'no IS' case and the 'perfect IS' case in this case study. In the 'no IS' case, the estimation of the price-making WPP's on the quantity bids of the other WPP's is more accurate. This is because the quantity bids of the WPP's are generally higher than their average wind power forecast.

- An underestimation of the aggregate wind power forecast also leads to smaller differences between the 'no IS' case and the 'perfect IS' case in this case study because each WPP sees greater opportunities in increasing the cleared DA market price. Each WPP incorrectly assumes that a higher price could be reached, which makes him also withholding quantity in order to cause a higher cleared price.

### 4.7.2 Results and discussion

In all presented concepts and results so far, it is consistently assumed that the aggregate deterministic wind power forecast, provided by the TSO, is a correct representation of the sum of the averages of the individual wind power forecasts of all WPP's. This section aims to discuss the influence of an underestimation and an overestimation of the aggregate wind power forecast. Table 4.11 and Table 4.12 show the results for an overestimation and an underestimation of the aggregate wind power forecast respectively. Herein, the contribution of the results is two-fold. On the one hand, the strategic participation of the WPP's is shown through their strategic bids and expected prices. On the other hand, the decision variables of the ex-post market clearing are depicted through the WPP's profits, the cleared DA market price and the realised social welfare. It should be noted that the results for the 'perfect IS' case do not differ from the results presented in Section 4.3 as it does not make use of the aggregate wind power forecast. However, these results are repeated here to facilitate an explicite comparison between the 'perfect IS' case and the 'no IS' case.

#### Overestimation by 10%

In case of an overestimation, the assumption of the decision-making strategic participant on the bids of the other WPP's in the MPEC model is higher than without the overestimation. This incorrect assumption triggers withholding behavior of the strategic participant in the 'no IS' case. Similarly as without the overestimation, each strategic player aims to determine its quantity bid in order to expect a price

| Situation | WPP 1 Bid [MW] | WPP 1 Ex. price [$\frac{€}{\text{MWh}}$] | WPP 2 Bid [MW] | WPP 2 Ex. price [$\frac{€}{\text{MWh}}$] | WPP 3 Bid [MW] | WPP 3 Ex. price [$\frac{€}{\text{MWh}}$] | WPP 4 Bid [MW] | WPP 4 Ex. price [$\frac{€}{\text{MWh}}$] |
|---|---|---|---|---|---|---|---|---|
| Perfect I.S. | 224.75 | 80 | 249.5 | 80 | 200.75 | 80 | 100.0 | 80 |
| No I.S. | 205.0 | 80 | 205.0 | 80 | 203.75 | 80 | 105.0 | 80 |
| Difference | 19.75 | 0 | 44.5 | 0 | -3.0 | 0 | -5.0 | 0 |
| | 9.63% | 0.0% | 21.71% | 0.0% | -1.47% | 0.0% | -4.76% | 0.0% |

(a) Bids and expected prices of the strategic WPP's

| Situation | WPP 1 Profit [€] | WPP 2 Profit [€] | WPP 3 Profit [€] | WPP 4 Profit [€] | Price [$\frac{€}{\text{MWh}}$] | Social Welfare [€] |
|---|---|---|---|---|---|---|
| Perfect I.S. | 14966.8 | 13933.6 | 15812.5 | 6643.5 | 80 | 684000 |
| No I.S. | 14764.0 | 13407.0 | 15843.5 | 6764.01 | 80 | 679500 |
| Difference | 202.8 | 526.6 | -31.0 | -120.51 | 0 | 4500 |
| | +1.37% | +3.93% | -0.20% | -1.78% | 0.0% | +0.66% |

(b) Determined decision variables of the ex-post market clearing

Table 4.11: Comparison between 'perfect IS' and 'no IS' at an aggregate demand level of 2500 MW when the aggregate wind power forecast is overestimated by 10%.

of 80 $\frac{€}{\text{MWh}}$. Without the overestimation, the strategic WPP's failed to realise a cleared DA market price of 80 $\frac{€}{\text{MWh}}$ as they underestimated the actual bid of the price-making competing WPP's when modeling them as price-takers in the MPEC model. By increasing - and thus overestimating - the aggregate wind power forecast, the estimation of each WPP on the bids of other WPP's approaches the actual bids of these WPP's. Therefore, the strategic WPP's do succeed in causing a cleared DA market price of 80 $\frac{€}{\text{MWh}}$ when overestimating the aggregate wind power forecast by 10%, in contrast to when a correct aggregate forecast is applied.

Consequently, an identical cleared DA market price in both the 'perfect IS' case and the 'no IS' case leads to only little differences in the WPP's profits. It can be noted that both WPP 1 and WPP 2 are the drivers behind the realisation of the cleared DA market price of 80 $\frac{€}{\text{MWh}}$ as their bid significantly reduced[15]. Therefore, a clear difference in profits for these WPP's still exists between the 'perfect IS' case and the 'no IS' case. Contrary, the bids of WPP 3 and WPP 4 are higher in the latter case leading to a reduced profit for WPP 3 and WPP 4 when switching from the 'no IS' case towards the 'perfect IS' case. Furthermore, the total wind power penetration into the DA market is higher in the 'perfect IS' case when overestimating the aggregate forecast. This leads to an increased social welfare in this case, in contrast to the results in Section 4.3.

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[15] When a comparison is made with the case in which no overestimation occurs.

| | WPP 1 | | WPP 2 | | WPP 3 | | WPP 4 | |
|---|---|---|---|---|---|---|---|---|
| Situation | Bid [MW] | Ex. price $[\frac{€}{\text{MWh}}]$ | Bid [MW] | Ex. price $[\frac{€}{\text{MWh}}]$ | Bid [MW] | Ex. price $[\frac{€}{\text{MWh}}]$ | Bid [MW] | Ex. price $[\frac{€}{\text{MWh}}]$ |
| Perfect I.S. | 224.75 | 80 | 249.5 | 80 | 200.75 | 80 | 100.0 | 80 |
| No I.S. | 195.0 | 110. | 195.0 | 110 | 195.0 | 110 | 95.0 | 110 |
| Difference | 29.75 | -30 | 54.5 | -30 | 5.75 | -30 | 5.0 | -30 |
| | 15.26% | -27.27% | 27.95% | -27.27% | 2.95% | -27.27% | 5.26% | -27.27% |

(a) Bids and expected prices of the strategic WPP's

| Situation | WPP 1 Profit [€] | WPP 2 Profit [€] | WPP 3 Profit [€] | WPP 4 Profit [€] | Price $[\frac{€}{\text{MWh}}]$ | Social Welfare [€] |
|---|---|---|---|---|---|---|
| Perfect I.S. | 14966.8 | 13933.6 | 15812.5 | 6643.5 | 80 | 684000 |
| No I.S. | 14484.0 | 13127.5 | 15557.7 | 6484.01 | 80 | 676400 |
| Difference | 482.8 | 806.1 | 254.8 | 159.49 | 0 | 7600 |
| | +3.33% | +6.14% | +1.64% | +2.46% | +0.0% | +1.12% |

(b) Determined decision variables of the ex-post market clearing

Table 4.12: Comparison between 'perfect IS' and 'no IS' at an aggregate demand level of 2500 MW when the aggregate wind power forecast is underestimated by 10%.

### Underestimation by 10%

In case of an underestimation of the aggregate wind power forecast, the results are - less obviously - not the reverse for the 'no IS' case. Where in case of an overestimation, the estimation of the bids of the price-takers better suits their actual price-making bids, the strategic WPP now sees an opportunity to raise the cleared DA market price even higher in case of an underestimation. Each decision-making strategic WPP considers the other WPP's as bidding a smaller quantity on the market, leading to a potentially higher cleared DA market price. The strategic WPP consequently determines his bid, in which it withholds quantity in order the raise the expected price towards 110 $\frac{€}{\text{MWh}}$.

Contrary to the results in Section 4.3, this leads to a quantity bid lower than the average wind power forecast for each decision-making WPP. Therefore, one could expect that the combination of a strategic quantity bid, lower than the average forecast on the one hand, and the underestimation of the aggregate forecast on the other hand, could lead to a succesful realisation of the cleared DA market price of 110 $\frac{€}{\text{MWh}}$. However, this is not the case: the quantity bids of the price-making competing WPP's are not sufficiently accurately estimated by the decision-making WPP when modeling them as price-taking WPP's.

For example, in case of an underestimation of 10%, the aggregate forecast amount 630 MW. When WPP 1 is considered as decision-maker, its assumption on the quantity bid of WPP X - representing WPP 2 up to WPP 4 - amounts 430 MW. However, the actual price-making behavior of WPP 2 up to WPP 4 results in a total quantity bid of these WPP's of 485 MW. This uderestimation of 55 MW on the quantity bids of the competing WPP's results in a incorrect estimation of the market outcome, leading to a cleared DA market price of 80 $\frac{€}{\mathrm{MWh}}$ instead of the expected price of 110 $\frac{€}{\mathrm{MWh}}$.

Again, an identical cleared DA market price in both the 'perfect IS' case and the 'no IS' case is realised, in contrast to the results in Section 4.3. Therefore, the difference in the WPP's profits are relatively limited. It should be noted that the underestimation of the aggregate forecast leads to both increased WPP's profits and social welfare in the 'perfect IS' case compared to the 'no IS' case.

### Synthesis

Finally, it can be stated that an overestimation of the aggregate forecast leads to a better estimation of quantity bids of the price-making WPP's by the decision-making WPP. This is due to coincidence, as the actual strategic bids of the price-making WPP's are higher than their average individual forecast. Besides, an underestimation of the aggregate forecast leads to greater opportunities for each decision-making WPP to increase the cleared DA market price. However, they only succeed to a limited extend by increasing the cleared price only partially.

In [3], Exizidis et al. research the impact of an incorrect aggregate wind power forecast by using it similarly as in this thesis. However, this thesis obtains opposite results in case of an overestimation of the aggregate wind power forecast which is due to different assumptions in the applied modeling approach. Specifically, [3] finds that an overestimation leads to a decreased social welfare and increased WPP's profits in the 'no IS' case. The model in [3] only considers price bids of producers on the DA market endogenously, while the model in this thesis also considers quantity bids. Consequently, the stochastic wind power output of the strategic WPP is again only considered to a limited extent as it only affects an imbalance penalty because the quantity bid is exogenously imposed. Contrary, this thesis directly applies the uncertain wind power output in the determination of the strategic quantity bid, leading to a more realistic strategic behavior of market players.

## 4.8 Conclusion

This chapter discussed both the developed model and the introduced framework of forecast sharing. Results were generated for a fictitious power system. Hereby, two simplifications with respect to the developed model were performed: the price bids of market participants are exogenously imposed as equalling the associated marginal operational costs and the GenCo's are considered to behave as price-takers, bidding their generation capacity. A stability analysis showed the robustness of the model in this setting, using 33 samples in the distribution function representing the uncertainty in the wind power forecasts.

The applicability of the model in the introduced case study is illustrated for the three levels of IS. For the 'perfect IS' case, an EPEC model is better suited than an MPEC model as it considers the behavior of competitors as being price-makers instead of price-takers. Contrary, the MPEC model is better suited for the 'no IS' case in order to avoid the modeling of an unrealistic market power given to WPP X. In the 'partial IS' case, this thesis aplied the EPEC model, which can cause a small bias in the expected price of decision-making market participants when WPP X represents a relatively large amount of WPP's.

A comparison of the results with a varying level of IS with the 'no IS' case, delivered insightful results. The results are qualitatively summarised in Table 4.13. Different settings are depicted. When the setting is not specified, the results correspond to the setting that was introduced in Section 4.1. The total profits for the WPP's, the realised social welfare, the total WPP's bids (the wind power penetration) and the cleared DA market price are shown. First, the cases of Section 4.3 and 4.4 are shown for the basic risk-neutral setting in which the aggregate wind power forecast is correct. Next, samples from the graphs of Sections 4.5 and 4.6 are shown, of which the considered sample is specified under 'Setting'. A reduced uncertainty of 50% in the forecasts of the specified WPP's is considered. Besides, risk-aversness is set at CVaR parameter $\beta = 0.5$, with CVaR weighting factors of $\gamma = 0.3$, 0.5 and 0.7. Finally, the results of Section 4.7 are shown, in which the aggregate wind power forecast is incorrect.

When all strategic market participants possess perfect information on each player, the market outcome can be estimated perfectly so that it can be manipulated by withholding quantity in order to raise the cleared DA market price. Therefore, profits are generally higher in the 'perfect IS' case, while social welfare decreases. Furthermore, the two extreme cases of IS define an upper and lower bound on the cleared DA market price in case of 'partial IS'. It is useful to remark that GenCo's never face decreased profits in case of 'partial or perfect IS', due to their higher aggregate penetration into the DA market as a consequence of WPP's that withhold quantity from the DA market.

Finally, this chapter discussed the sensitivity of the results to three parameters. Firstly, the results show that decreasing the uncertainty in the individual wind power forecasts can cause a disappearance of the differences between the 'perfect IS' case and the 'no IS' case because of the stimulated withholding of quantity. Secondly, risk-averse behavior shows cases in which both the WPP's profits and the realised social welfare increase in parallel when applying 'perfect IS'. Finally, an overestimation or underestimation of the aggregate wind power forecasts can turn out to benefit WPP's profits and/or social welfare without applying 'perfect IS'.

| Sharing WPP's | Demand [MW] | Setting | WPP's profits | Social welfare | WPP's bids | Price |
|---|---|---|---|---|---|---|
| All | 1500 | - | = | = | = | = |
| All | 2000 | - | ↑ | ↓ | ↓ | ↑ |
| All | 2500 | - | ↑ | ↓ | ↓ | ↑ |
| WPP 1 | 2500 | - | = | = | = | = |
| WPP 2 | 2500 | - | = | = | = | = |
| WPP 3 | 2500 | - | = | = | = | = |
| WPP 4 | 2500 | - | = | = | = | = |
| WPP 1,2 | 2500 | - | ↓ | ↓ | ↓ | = |
| WPP 1,3 | 2500 | - | = | = | = | = |
| WPP 1,4 | 2500 | - | = | = | = | = |
| WPP 2,3 | 2500 | - | ↓ | ↓ | ↓ | = |
| WPP 2,4 | 2500 | - | = | = | = | = |
| WPP 3,4 | 2500 | - | = | = | = | = |
| WPP 1,2,3 | 2500 | - | ↑ | ↓ | ↓ | ↑ |
| WPP 1,2,4 | 2500 | - | ↓ | ↓ | ↓ | = |
| WPP 1,3,4 | 2500 | - | = | = | = | = |
| WPP 2,3,4 | 2500 | - | ↓ | ↓ | ↓ | = |
| All | 2500 | 50% st. dev. WPP 1,2,3,4 | = | = | = | = |
| All | 2500 | 50% st. dev. WPP 2,3,4 | = | = | = | = |
| All | 2500 | 50% st. dev. WPP 3,4 | ↑ | ↓ | ↓ | ↑ |
| All | 2500 | CVaR: $\gamma = 0.3$, $\beta = 0.5$ | ↑ | ↑ | ↑ | = |
| All | 2500 | CVaR: $\gamma = 0.5$, $\beta = 0.5$ | ↑ | ↓ | ↓ | ↑ |
| All | 2500 | CVaR: $\gamma = 0.7$, $\beta = 0.5$ | ↑ | = | = | ↑ |
| All | 2500 | Underestimation 10% | ↑ | ↑ | ↑ | = |
| All | 2500 | Overestimation 10% | ↑ | ↑ | ↑ | = |

Table 4.13: Qualitative overview of the results, compared with the 'no IS' case. Different settings are depicted. The total profits for the WPP's, the realised social welfare, the total WPP's bids (the wind power penetration) and the cleared DA market price are shown. First, the cases of Section 4.3 and 4.4 are shown. Next, sample of the graphs of Sections 4.5 and 4.6 are shown, of which the considered sample is specified under 'Setting'. Finally, the results of Section 4.7 are shown.

# Chapter 5

# Conclusion

## 5.1 Summary and conclusions

In order to reach the goals, set by the Euopean Union, concerning the penetration of RES into the electricity market, an analysis on the optimal facilitation of wind power into the market is useful. This thesis researched the impact of a framework in which WPP's can make their individual wind power forecasts available to other DA market participants. Specifically, it offered a model that is intended as a tool for WPP's to optimise their strategic behavior on the one hand, and for policy makers to validate the possible allowance of such a framework on the other hand.

### Chapter 2

Chapter 2 gave an overview on the background information that is relevant to this thesis. It discussed the broad range of methods to determine wind power forecasts. Besides, it showed that the uncertainty on wind power forecasts can be distributed differently, depending on the considered time frame and magnitudes. The beta distribution is a better fit to represent short-term uncertainty than the gaussian distribution, despite the application of the gaussian distribution in this thesis. Furthermore, it noted that up until now, no initiative has been taken by policy makers in order to set up a framework in which individual wind power forecasts can be shared and/or traded.

In that regard, Chapter 2 introduced the fundamental theory and applications of BL models after having classified this thesis' model in a broad electricity market modeling framework. BL models are widely used in electricity market modeling to represent a Stackelberg game between a price-making strategic player and price-taking non-strategic players on the market, by modeling it as an MPEC problem. In order to represent a Nash equilibrium between multiple price-making strategic players, an EPEC model should be used, which is also adopted in this thesis.

Finally, Chapter 2 discussed the state-of-the-art in scientific literature concerning the act of sharing forecasts. Only little scientific studies are performed on this topic. However, the obligatory provision by TSO's of an aggregated wind power forecast covering their area, has been studied. This aggregate forecast is also used in this thesis' model. Besides, the influence of IS between the MO and a WPP has been studied. Nevertheless, this thesis focused on the aspect of sharing information between market participants themselves.

### Chapter 3

Chapter 3 developed the model. Therefore, the methods of sharing wind power forecasts are structured. Hereby, two extreme case have been defined: 'perfect IS' and 'no IS', in which all market participants have access to the individual wind power forecasts of all WPP's and no WPP's respectively. Moreover, 'partial IS' is defined as an intermediate case in which at least one and maximum all but one WPP share their forecasts. In that regard, an EPEC model is developed that fits the 'perfect IS' and 'partial IS' cases and an MPEC model for the 'no IS' case. In such an MPEC model, the strategic player determines a quantity and price bid on the DA market in the UL problem as to maximise its expected profit, while the MO clears the DA market in the LL problem as to maximise social welfare.

Furthermore, Chapter 3 introduced a high-level framework in which there is elaborated on the usage of the EPEC and MPEC models. On the one hand, a WPP of which the individual wind power forecast is known, is modeled as a single WPP with corresponding stochastic forecast. On the other hand, a WPP of which the individual wind power forecast is not known, is included in a fictive WPP X that represents all WPP's on which no forecasts are available. WPP X is modeled by the decision-making WPP as applying a deterministic forecast, equal to the difference between the aggregate wind power forecast and the sum of the averages of the wind power forecasts that are known by the decision-making player. After having set up the market according to the available information for a decision-making WPP, an EPEC or MPEC model is solved that mathematically considers uncertain wind power production. A conversion of the EPEC and MPEC model towards a MILP problem is performed so that it can be solved by a solver as Gurobi.

### Chapter 4

Chapter 4 discussed both the developed model and the introduced framework of forecast sharing. Results were generated for a fictitious power system. Hereby, two simplifications with respect to the developed model were performed: the price bids of market participants are exogenously imposed as equalling the associated marginal operational costs; and the GenCo's are considered to behave as price-takers, bidding their generation capacity. A stability analysis showed the robustness of the model in this setting, using 33 samples in the distribution function representing the uncertainty in the wind power forecasts.

The applicability of the model in the introduced case study is illustrated for the three levels of IS. For the 'perfect IS' case, an EPEC model is better suited than an MPEC model as it considers the behavior of competitors as being price-makers instead of price-takers. Contrary, the MPEC model is better suited for the 'no IS' case in order to avoid the modeling of an unrealistic market power given to WPP

X. In the ‘partial IS’ case, this thesis aplied the EPEC model, which can cause a small bias in the expected price of decision-making market participants when WPP X represents a relatively large amount of WPP’s.

A comparison of the results with a varying level of IS with the ‘no IS’ case, delivered insightful results. When all strategic market participants possess perfect information on each player, the market outcome can be estimated perfectly so that it can be manipulated by withholding quantity in order to raise the cleared DA market price. Therefore, profits are generally higher in the ‘perfect IS case’, while social welfare decreases. The decrease in the social welfare is due to the lower wind power penetration into the DA market. However, the order by which the EPEC model is solved is of importance. The WPP’s whose MPEC model is solved in the end of the EPEC iteration, are generally profiting less from ‘perfect IS’ than the WPP’s whose MPEC model is solved in the beginning of the EPEC iteration. The reason is that WPP’s, in the end of the EPEC iteration, are enforcing the higher cleared DA price by withholding quantity. The relative increase of the cleared DA price indicates the upper limit by which the WPP’s profits can increase when applying ‘perfect IS’.

Furthermore, the two extreme cases of IS define an upper and lower bound on the cleared DA market price in case of ‘partial IS’ in the presented case study. Specifically, it is essential that a sufficient number of WPP’s share their wind power forecasts in order to raise the cleared DA market price and thus their profits. Moreover, when only a limited number of WPP’s share their wind power forecasts so that the attempt to increase the cleared DA market price fails, it can potentially even lead to decreased profits for the WPP’s. It is useful to remark that GenCo’s never face decreased profits in case of ‘partial or perfect IS’, due to their higher aggregate penetration into the DA market as a consequence of WPP’s that withhold quantity from the DA market.

Finally, Chapter 4 discussed the sensitivity of the results to three parameters. Firstly, the results show that decreasing the uncertainty in the individual wind power forecasts can cause a disappearance of the differences between the ‘perfect IS’ case and the ‘no IS’ case. Secondly, risk-averse behavior shows cases in which both the WPP’s profits and the realised social welfare increase in parallel when applying ‘perfect IS’. Finally, an overestimation or underestimation of the aggregate wind power forecasts can turn out to benefit WPP’s profits and/or social welfare without applying ‘perfect IS’.

### Conclusion

As a final conclusion, incentives have been discussed for the installation of a framework in which WPP’s can share their wind power forecasts in order to increase WPP’s profits alongside a limited decrease in social welfare. Such an installation would provide incentives to invest in WPP’s as their profitability increases. In that sense, it could play a role in the facilitation of wind power into electricity markets. However, well-founded agreements should be made in terms of risk-aversness and a minimal number of WPP’s that is willing to share his wind power foecast in order to not let the WPP’s profits decrease, which is difficult from a practical point of view. Besides, the model relies on some assumptions that should be treated carefully. Furthermore, a trade-off could exist for WPP's. One could either invest in a better individual wind power forecast so that its uncertainty decreases or in a framework where one possibly buys wind power forecasts from other WPP's, both possibly resulting in higher profits for the WPP's.

## 5.2 Application to reality

The model correctly represents the strategic behavior of market participants in the DA market in order to maximise their profits. The EPEC models a Nash equilibrium between multiple price-making market participants. Hereby, some assumptions have been made that lead to a difference with reality.

First of all, demand is considered to be inelastic. However, realistic demand curves show elasticity to a limited extent. In this thesis, the 'perfect IS' case led to a situation in which the market clearing occured exactly at the border between two generation blocks in the supply curve, caused by strategic bidding behavior. When the demand curve shows elasticity, strategic market participants will need to withhold more quantity in order to raise the cleared price. It can possibly happen to an extent that the higher realised DA price does not outweight the lower cleared quantities for WPP's. This could possibly lead to smaller differences between the 'perfect IS' case and the 'no IS' case.

Secondly, certain technical constraints are not considered in the model. The incorporation of transmission constraints would lead to locational marginal prices. Therefore, both the UL and the LL problem in the model formulation should be adapted.

Thirdly, an EPEC model inherently considers the price-making behavior of the other market participants. However, in reality, a strategic player may not always perfectly anticipate the market clearing outcome. In the 'perfect IS' case, strategic players aim to set the cleared DA price exactly at the border between two generation blocks in the supply curves. A small deviation from perfect strategic behavior can result in a lower cleared price than expected.

## 5.3 Future research

The proposed future research is threefold. First, the developed model could be applied to a more extensive case study, in which a realistic power system is considered. Therein, the effects of the extent to which wind power forecasts are shared among market participants, could be tested. However, the results should account for the assumptions that are considered in the model, which are presented in Chapter 3.

A second contribution in future research could be in the application of the aspect of IS. Firstly, this thesis assumes the 'no IS' case as a reference case. However, a WPP can possess information on historical data on the cleared quantities for his competing WPP's. Using these historical data, it could a priori make an assumption on the bidding behavior of his competing WPP's which is potentially more useful than applying the aggregate wind power forecast only. Secondly, this thesis disregarded spatial correlations between wind power forecasts of WPP's that are located close to eachother. A WPP could a priore make an assumption on the bids of its neighboring WPP's, based on its own wind power forecast.

Finally, in order to let the model correspond more with reality, the model could be extended through some adaptations. Firstly, an introduction of an endogenous balancing and/or intraday market would allow market participants to make adjustments on their bids on the DA market as the wind power forecasts of WPP's become more accurate with the time closer to delivery. Moreover, this would deliver a more realistic formulation of the imbalance penalty for WPP's, which is in this thesis modeled as simply 30% higher than the cleared DA market price. Secondly, spatial constraints could be introduced in order to allow for a case study that considers a realistic power system.

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