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Methods for the determination of flow-based capacity parameters: description, evaluation and improvements

Jonas Boury

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Thesis supervisor:
Prof. Dr. Ir. W. D'haeseleer

Assessors:
Prof. Dr. Ir. R. Belmans
Prof. Dr. Ir. J. Meyers

Mentors:
Ir. K Van den Bergh
Dr. Ir. E. Delarue

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Preface

First, I would like to thank prof. W. D'haeseleer for offering me this interesting thesis-topic and guiding me during this project. Furthermore, I thank my assessors, prof. R. Belmans and J. Meyers for accepting the invitation to participate in my master thesis committee. I am especially grateful to my mentor Kenneth Van de Bergh for his contribution and guidance. I would like to thank my co-mentor Erik Delarue for his interest in this topic and his helpful input. Additionally, I would like to thank Alain Marien and Patrick Luickx from the CREG. They supervised my progress and organized an internship at the CREG to give me the change to familiarize with the complex topic. With them, Kenneth and Erik I had very interesting discussions that gave direction to my research. I would like to thank all the other specialists from Elia and Belpex that were willing to sit together with me to discuss the topic. These discussions really helped me to broaden my understanding. Finally, I deeply thank my family for all their love, support and patience throughout the difficult moment that obviously arise during the making of a thesis.

Jonas Boury

Contents

Abstract

Since the liberalization of the electricity market the European Union has been looking for economically efficient and transparent market mechanisms. In order to couple the markets of different countries it is however important to take into account the network constraints. The implementation of the network constraints is not straightforward. A hybrid flow-based approach was developed that is known as the flow-based market coupling (FBMC). The FBMC is currently implemented in the Central-West-European market area on the day-ahead market coupling. For the implementation and operation, the power exchanges (PXs) and transmission system operators (TSOs) work together to determine the input parameters and subsequently run the market coupling optimization algorithm. For the determination of the input parameters of the FBMC, viz. the flow-based capacity parameters, a lot of assumptions and estimations are used. The parameters are not unambiguously defined and some unclarity still exists.

In this thesis an effort is made to describe the technical implementation of the flow-based market coupling and to investigate the impact of the flow-based capacity parameters on the solution. This way we hope to increase the understanding, give more insight and clarify ambiguities. From previous studies and the test run performed during the last year, it was already concluded that the proposed flow-based market coupling implementation performs significantly better than the old available transfer capacity (ATC)-based market coupling. In this study the FBMC is compared with the ideal nodal market coupling.

After an extensive description of the flow-based market coupling implementation, an evaluation is made using a simulation model. The focus is on the theoretical fundamentals of the FBMC. The evaluation is conceptual and thus not based on real-life data. From the insights that were gained propositions for improvements are made in the final part.

From the analysis it can be concluded that the current methods used in the FBMC result in significant lower social welfare than an ideal nodal market coupling in congested cases, mainly caused by the inaccurate assumptions and estimations used for the determination of the flow-based capacity parameters. There certainly is room for improvement. With respect to improvements two categories are distinguished: using better assumptions and estimations and using less assumptions and estimations. First, the estimations and assumptions can be improved by increased collaboration between the TSOs. This is proven with the simulation model in this research. Second, an alternative proposition is made for a flow-based market coupling that is less influenced by assumptions and estimations by using an iterative approach. A simulation of this concept proved significant improvements to the fairness, the flow-modeling accuracy and consequently the social welfare of the market solution. Further research with more realistic data should be done in order to quantify the improvements of this method and to investigate the stability of the iterative process.

Abstract

Sinds de liberalisering van de elektriciteitsmarkt is de Europese Unie op zoek naar economisch efficiënte en transparante marktmechanismen. Om de markten van de verschillende landen te koppelen is het echter noodzakelijk om rekening te houden met de netwerkbeperkingen. De implementatie van deze randvoorwaarden is echter niet eenvoudig. Een hybride flow-based aanpak werd ontwikkeld onder de naam flow-based marktkoppeling (FBMC). De FBMC wordt momenteel geïmplementeerd in het Centraal-West-Europese marktgebied op de day-ahead marktkoppeling. Voor de implementatie en het functioneren werken elektriciteitsbeurzen (PXs) en transmissienetbeheerders (TSOs) samen om de inputparameters te bepalen en vervolgens het optimalisatie algoritme uit te voeren. Voor de invoerparameters van deze implementatie, nl. de flow-based capaciteitparameters worden veel veronderstellingen en schattingen gebruikt. De parameters zijn niet eenduidig gedefinieerd en er is nog steeds onduidelijkheid omtrent hun impact op de oplossing.

In dit proefschrift wordt een poging gedaan om de technische uitvoering van de flow-based marktkoppeling te beschrijven en de impact van de flow-based capaciteit parameters op de oplossing te onderzoeken. Op deze manier hopen we meer inzicht te geven en onduidelijkheden weg te werken. Uit eerdere studies en tests, uitgevoerd tijdens het afgelopen jaar, werd reeds geconcludeerd dat de voorgestelde flow-based marktkoppelingimplementatie beduidend beter presteert dan de ATC-gebaseerde marktkoppeling.

In deze studie wordt de FBMC vergeleken met een ideale nodale marktkoppeling. Na een uitgebreide beschrijving van de flow-based marktkoppelingimplementatie, wordt een evaluatie gemaakt met behulp van een simulatiemodel. De focus ligt op de theoretische fundamenten van de FBMC. De evaluatie is conceptueel en dus niet gebaseerd op de werkelijke data. Vanuit de inzichten die werden verworven worden in het laatste deel voorstellen voor verbeteringen gemaakt.

Vanuit de analyse kan worden geconcludeerd dat de huidige methodes die in de FBMC worden gebruikt tot significant lager sociaal welzijn leiden dan een ideale nodale marktkoppeling in gecongesteerde situaties. Dit is hoofdzakelijk te wijten aan onjuiste veronderstellingen en schattingen die worden gebruikt voor de bepaling van de flow-based capaciteitparameters. Er is zeker ruimte voor verbetering. Met betrekking tot verbeteringen worden twee categorieën onderscheiden: het gebruik van betere veronderstellingen en het gebruik van minder veronderstellingen. Ten eerste kunnen de schattingen en veronderstellingen worden verbeterd door meer samenwerking tussen de TSOs. Dit wordt bewezen aan de hand van het simulatiemodel. Ten tweede wordt een alternatief voorstel gedaan voor een flow-based marktkoppeling die door middel van een iteratieve aanpak minder wordt beïnvloed door aannames en schattingen. Een simulatiemodel met deze aanpak toonde aanzienlijke verbeteringen aan de rechtvaardigheid en de accuraatheid van gemodelleerde stromen. Dit leidt bijgevolg tot een hoger sociaal welzijn van de marktoplossing. Verder onderzoek met meer realistische gegevens moet worden gedaan om de verbetering van deze methode te kwantificeren en om de stabiliteit van het iteratieve proces te onderzoeken.

List of Abbreviations, Definitions and Symbols

Abbreviations

ATC	Available transfer capacity
BRP	Balance responsible parties
CB	Critical branches
CM	Congestion management
CWE	Central West European Region
D-1	Day-1, refers to the day before the delivery day
D-2	Day-2, refers to two days before the delivery day
D-2CF	Two day-ahead congestion forecast
DACF	Day-ahead congestion forecast
DSK	Demand shift keys
FB	Flow-based
FBMC	Flow-based market coupling
FRM	Flow reliability margin
GSK	Generation shift keys
LTN	Long term nominations
MC	Market coupling
NEX	Net exchange position
PX	Power Exchange
PTDF	Power transfer distribution factor
RAM	Remaining available margin
TSO	Transmission system operator

Definitions

- **ATC:** Part of the net transfer capacity still available for trade at a certain moment. It equals the net transfer capacity minus the already notified transmissions flows at that moment.
- **Common grid model:** Model of the grid that represents the best forecast of the corresponding hour of the execution day.
- **Critical branches:** A line of the network which could probably limit the commercial exchanges between the areas because it often reaches its physical limits.
- **Demand shift keys:** Define how a change in net position of a zone is mapped into the demand nodes of that zone.
- **Explicit auction:** Auction where the product sold is a right to program an exchange on a given contractual path.
- **Flow reliability margin:** Reliability margin used to cope with the uncertainty within the market process.
- **Generation shift keys:** Define how a change in net position of a zone is mapped to the generating units of that zone.
- **Implicit auction:** Auction for which the allocation capacities are combined with the functioning of an organized electricity market.
- **Marginal clearing price:** The shadow-price of the market clearing condition.
- **Market coupling:** Consists in a coupling of N markets, according to a decentralized approach, resulting in a virtual market as long as the interconnection capacities are not saturated.
- **Net load:** The real load minus the local generation which mostly refers to renewable generation connected to the distribution grid.
- **Netting of flows:** Take into account that the flow exchanges in an opposite direction counterbalance each other.
- **Power transfer distribution factor:** Based on a state of the initial network, this is the influence on a critical branch flow of every additional MW injected at a participating node. Two types of PTDF can be distinguished:
  - node i on line I: with respect to a change in injection at node i and a corresponding withdrawal at the reference node.

  - zone Q on line I: defines the effect on line I with respect to a change of the net exchange position of zone Q and withdrawal at the reference node.

- **Spot price:** Price set by the intersection of the selling and the buying bids on the spot market.

Symbols

$F_{max,l}$	The maximum amount of electric power that can be exported through a transmission line in MW.
$F_{\max market,l}$	The maximum amount of electrical power than can be exported through a transmission line via the day-ahead power exchange in MW.
$F_{non-market,l}$	The flows resulting from intra-zonal transactions that are not traded via the day-ahead power exchange in MW.
$F_{ref,l}$	The reference flows in MW.
F_l	The day-ahead market coupling flows in MW.
$F_{LTN,l}$	The long term capacity nomination in MW.
$F_{z,l}$	Zonal modeled day-ahead market coupling flows in MW.
$F_{n,l}$	Nodal modeled day-ahead market coupling flows in MW.
Fo_l	The loop flows in MW.
$F_{bc,l}$	The flows in the base case situation in MW.
$z \in Z$	A bidding zone z among the bidding zones Z.
$b \in B$	A bidder b among the bidders B.
$n \in N$	A network node n within the topology consisting of N nodes.
$l \in L$	A critical branch l among the critical branches L.
d_n	Demand for one hour in node n in MW.
g_b	The accepted generation of bid b in MW.
c_b	The cost of the generation bids in €/MWh.
$NB(n, b)$	The bid-to-node matrix.
$BZ(z, b)$	The bid-to-zone matrix.
$NZ(z, n)$	The node-to-zone matrix.
p_n	The nodal market clearing prices in €/MWh.
p_z	The zonal market clearing prices in €/MWh.
P_n	The nodal power injection in MW.
NEX_z	The net exchange position of the bidding zone z in MW.
$PTDF_n(l, n)$	The PTDF of node n on the critical branch l.
$PTDF_z(l, z)$	The PTDF of zone z on the critical branch l.
RAM_l	The remaining available margin on the critical branch l in MW.

Chapter 1

Introduction

1.1 Background/Scope

Since the liberalization of the electricity market, the European Union has been aiming for a secure, competitive and sustainable supply of electric energy to the society and its economy [18]. This transposition of the European electricity and gas legislation in all Member States is still ongoing. Presently, Europe finds itself in the middle of the process of integrating the liberalized national electricity markets into a single European market for electricity. Europe considers a well interconnected electricity grid and market as a requirement to achieve a robust and economically viable electricity system [17]. To achieve an interconnected electricity system investments in interconnection capacity are being made and effort is done to operate the existing grid to its operational limits. Integrating the network limitations in the day-ahead market coupling can be seen as an effective way to unlock the full potential of the existing network. It can reduce the need for network extension, it can provide the flexibility to utilize the full potential of the network in an economic efficient way and it can offer a transparent price signal to transmission system operators (TSOs) and market participants about the location of needed investments. The legislation to initiate the efficient operation of the grid and to enhance the cross-border trade was incorporated in the Third Internal Energy Market Package in 2009. But until recently, this market integration process has only slowly developed.

To obtain a fully integrated European market the Third Internal Energy Market Package proposes the implementation of a flow-based market coupling [7]. The flow-based model is a methodology which describes the network in order to take into account the impacts of cross-border exchanges on network security constraints when optimizing the market flows and matching supply and demand [8]. The TSOs and power exchanges (PX) in Europe have put in place a project,"Price Coupling of Regions", that was tasked with the design and implementation of the European Market Coupling. In a first step, the project parties have decided to implement an available transfer capacity (ATC)-based market coupling which went live on

November 9th 2010 for the day-ahead market. Parallel to the daily operation of the ATC-based market coupling, the project parties have been working on the next step which is the implementation of a flow-based market coupling (FBMC) in a part of Europe, viz. the Central West European region (CWE) consisting of the Benelux, France and Germany. This system went live on 20 May 2015 [15]. Nevertheless, there are still ambiguities about the implementation, the working and the efficiency of the FBMC.

To start with, it is important to understand where this problem is fundamentally situated. Electricity is supplied by generator companies which have generation units at certain locations. Electricity is transported from the generation units to the users via a transportation network. To do these transactions in an economic efficient way electricity markets are organized where electricity can be traded between suppliers and buyers. These markets maximize the social welfare (i.e. consumer surplus + producer surplus + congestion rents) of all the market bids. The more trade, the more welfare but of course trade is limited by the available line capacities. Bringing these line constraints into account is not trivial as physical flows do not correspond with commercial transaction. For instance, a commercial electricity trade between a German generator and a French consumer also causes electric power flows through the parallel path Germany-Netherlands-Belgium-France. In the current ATC-market coupling heuristic methods are used to translate the physical constraints to commercial constraints on the cross border exchange capacity. A better and more accurate way would be to use a network model to translate all commercial bids into physical flows and subsequently implement the line constraints. The new FBMC tries to implement this second option for the day-ahead market coupling in the CWE by considering an accurate network model in the market coupling algorithm. The FBMC should contribute to a more effective and legitimate electricity market integration process, which is particularly relevant considering the economic and social significance of the electricity sector and the generally agreed objective of creating a single efficient European electricity market. The goal of the FBMC project is to achieve a transparent market mechanism adjusted to the future needs that maximizes the social welfare by maximizing the usage of cross-border capacity.

Yet it is important to keep in mind that the day-ahead market coupling is only a step in the process of electricity trading. Only a fraction of all the trade is done on the day-ahead market. On average only 20% of the eventual electricity is traded on the day-ahead market[1]. The other 80% is traded on long term future markets or via bilateral contracts[2]. The major function of the day-ahead market is the formation of a price point in each zone. This price-point will be a crucial factor in the portfolio decisions of BRPs [5]. Once the price point is known also the TSOs have a better idea of the state of the electricity grid in their zone. High prices for example will

[1] This number is not exact and difficult to accurately determine as a unit of eventually delivered electricity can be traded multiple times on different markets as a result of hedging.

[2] Direct trade contracts between retailers and generator, not through the power exchange.

indicate possible shortage. The day-ahead market thus has a crucial function in the electricity trading process although only a small part of trade is actually done via the day-ahead market platform.

1.2 Opportunities for research and the aim of this thesis

Within the FBMC the calculation of the flow-based capacity parameters is one of the most important steps. The flow-based capacity parameters are the input for the market coupling algorithm that will determine te most optimal market solution that falls within the flow-based domain determined by these capacity parameters. The domain has to represent the real line limitations as accurately as possible. A domain that is too restrictive will lead to an underutilization of the available transmission capacity. If the domain is too large the market outcome will result in an overloading of the grid. In both cases the market results are not optimal. Research to improve the capacity calculation methods in order to reach a flow-based domain that coincides more with reality line constraints therefore has an economic value. The effect is even doubled by the fact that a more realistic flow-based domain diminishes the need for high safety margins.

Concerning the determination of the current flow-based capacity parameters there is some haziness. As the go-live date is approaching it is important that all market participants understand the system and that regulators are able to verify the correctness of the FBMC calculation processes. Current literature discussing the flow-based capacity parameters and their implementation is very rare. The available sources are limited to the official approval package [10] and reports of the regulators [11]. This current literature is often complex and no clear distinction is made between the fundamental FBMC approach and very specific corrective measures. Additionally, the flow-based approach is still developing and evolving which makes the available literature outdated and inconsistent with the latest developments.

This thesis has three major motivations: explaining, evaluating and improving the FBMC proposal. The first goal is to provide more insight in the FBMC functioning and capacity calculations. A public consultation of market parties on FBMC [12] has indicated that few market participants are fully aware of the exact determination of the flow-based capacity parameters. Most parties stated that they want more information and transparency regarding the specific implementation of the FBMC. Over the past years the understanding and interpretation of flow-based market coupling has rapidly evolved resulting in lots of different interpretations, contradictory definitions and terminology. An example of this is the remaining available margin (RAM)[3] parameter that is defined in two different ways in the official approval package [10]. Moreover certain aspects of the methodology used in the flow-based market

[3] $RAM = F_{max} - F_{ref} - FRM - FAV$ and $RAM = F_{max} - F'_{ref} - FRM - FAV$ with $F'_{ref} = F_{ref} + (LTN - RefProg) \cdot PTDF$

coupling are still not completely clear or have not yet clearly been defined. The determination of the base case and generation shift keys (GSKs) are two frequently mentioned problem areas. Making this document easily understandable and restricted to the flow-based fundamentals would therefore be enlightening for people lacking the full background to understand the current literature. Giving a simple and well-defined overview of the current understanding and implementation of the FBMC will thus be the focus of the first part of the thesis. Current documents describing the flow-based method strongly lack mathematical representation. This has resulted in different interpretations and understandings. In this thesis all parameters will be clearly defined mathematically in order to unambiguously define the approach and clarify concepts that have been indistinct until now.

As already indicated the main problem areas in the current FBMC implementation are the base case and the generation shift keys (GSK). Together they form the foundation for the determination of the flow-based capacity parameters. The second aim of the thesis is to discuss these flow-based input parameters critically and evaluate their impact on the solution's accuracy and fairness by simulating the flow-based market coupling in a simplified setup. The evaluation of the FBMC will bring insight and will indicate room for improvements. In the latest stage of the research possible improvements are discussed and examined in the simulation model.

Hence the three goals of the thesis thus are accomplished through different approaches. The first goal of explaining the FBMC is based on a review of the existing literature and interviews with employees from the Belgian CREG, TSO and power exchange. Towards goal two and three (evaluation and improvements), a dedicated simulation model is developed.

1.3 Thesis outline

Chapter two The report starts with an introduction of the basic concepts needed to understand the working of the electricity market and the flow-based market coupling. In this chapter a lot of information, coming from different parties, has been gathered to feature the background and basis of the problem.

Chapter three In this chapter the flow-based implementation proposal is explained. Starting from the flow-based principles the need for the different flow-based parameters is derived. For all parameters the practical implementation proposals are handled. Throughout the chapter a three node example is used to illustrate the flow-based concepts.

Chapter four The fourth chapter describes the simulation model that was made to evaluate the flow-based capacity calculation methods that are proposed in the current FBMC approval package.

Chapter five The evaluation of the FBMC is discussed with the help of the simulation model. From the simulations a few important conclusions can be made.

Chapter six In the sixth chapter an overview of improvements is given. A differentiation is made between improvements within the current FBMC framework and improvements by adapting the FBMC framework. For the proposed improvements the impact is validated and discussed on the basis of model simulations.

Chapter seven In conclusion the overall results of the research are given and further research opportunities are discussed.

Chapter 2

Flow-based market coupling in the electricity market

This chapter will describe how the electricity market works in general and how different parties are involved. The cross-border capacity allocation mechanism included in this market will be discussed more in detail. The current available transfer capacity (ATC) system will be explained and compared with the flow-based market coupling.

2.1 The electricity markets in Europe

Originally electricity markets were implemented within each country, referred to as market zones, separately to organize the trade of electricity. At these wholesale[1] markets producers and consumers come together to trade energy in the form of electricity. Producers offer their generation output for a certain time interval on the market. By aggregating these offers the supply curve is formed. This supply curve usually shows the merit order of the different technologies of electricity generation as is shown in figure 2.1 for two zones. The wholesale demand bids are aggregated to form the demand curve[2]. The clearing of the market for every time interval is found at the intersection of supply and demand and determines the electricity price in that zone (see figure 2.1). All demand and supply bids left from the market clearing are accepted. Suppliers will receive the market price for their accepted bids and buyers will pay that price. To achieve an economically efficient system, different

[1] Wholesale markets comprise the sale of goods to retailers; to industrial, commercial, institutional, or other professional business users; or to other wholesalers. The standard consumer will buy the good on retail markets where it is offered by retailers.

[2] In reality demand bids and supply offers are done by balance responsible parties (BRPs) who are responsible for a balanced portfolio. The BRP trade on the markets in order to get their portfolio balanced in the most cost efficient way. Appointing the commercial players as BRP is a measure to give them more responsibility in safeguarding the balance in the electricity system. This nuance is not very relevant in the context of this thesis and therefor not explained any further. From the market perspective electricity suppliers and buyers can be seen as two separate entities [22].

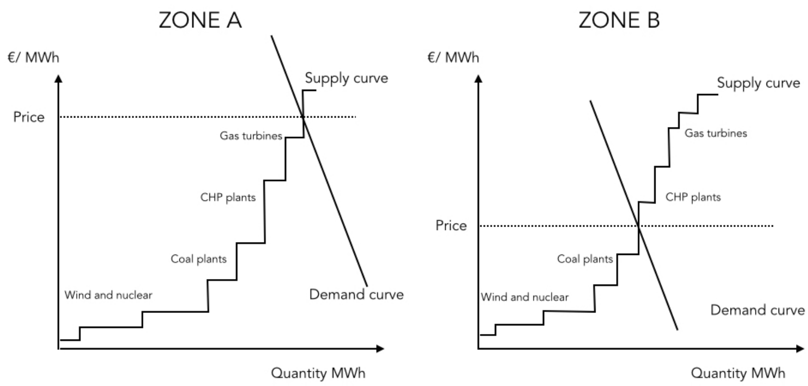


Figure 2.1: Supply and demand curves for two zones resulting in two different equilibrium prices.

markets are organized on different timings with respect to the delivery moment of the electricity. These are shown in figure 2.2. The electricity trading process start years before the delivery moment when electricity is traded for long periods via long term bilateral contracts and on forward and future electricity markets. On the delivery day minus 1 (D-1) the day-ahead power exchange market is organized at which the market is cleared for hourly intervals. At the end of D-1 all the balance responsible parties have to hand in their balanced portfolios to the TSO. This portfolio gives an overview of the generation and demand of each BRP. This program will consist of day-ahead power exchange transactions and non-day-ahead market transactions, viz. transactions done on long term power exchanges, transactions done within the own portfolio assets of the BRP and exchanges between different BRPs that are not done via organized power exchanges[3] but via bilateral contracts.

At the delivery day itself electricity can finally be traded on the intraday market and the balancing markets for 15 minutes intervals. In this thesis the day-ahead market is considered. To determine the transmission capacity that is still available for the market on each line all previous market trades and non-market portfolio exchanges needs to be considered. In this research we focus on the day-ahead market-coupling of Central-West Europe (CWE). This is the market zone shown in figure 2.3 consisting of Germany, Belgium, The Netherlands and France. These countries are interconnected as shown in the figure. The CWE-market zone plays an innovative role in creating interconnected markets. Currently, this market coupling is still ATC-based but it will be the first European market area converted to the flow-based coupling. Some elementary characteristics of this market zone should be highlighted. First of all there is a very large difference in scale. The market zone consists of two big market zones (France and Germany) and two smaller zones (Belgium and The Netherlands) consisting of a significant lower order of nodes. German and French

[3]In this thesis all transaction done outside of the day-ahead power exchange are consider as non-market transactions.

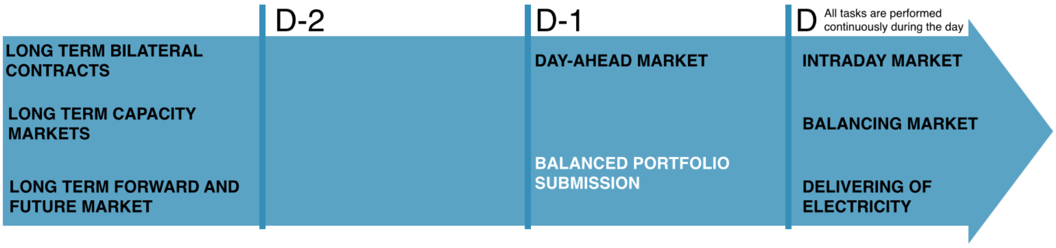


Figure 2.2: Different markets and their timing before the delivery of electricity.

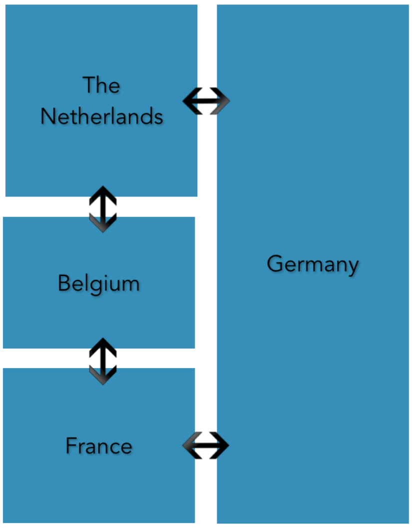


Figure 2.3: The CWE market zone and its coupling

TSOs and generators can easily influence the smaller market zones if it is in the best interest of these countries. To avoid the abuse of market power a well designed market mechanism will be necessary. This is one of the reasons why the switch to the flow-based market coupling is being thoroughly investigated. A second remark is that there has been no direct connection between Belgium and Germany up to the present. Such interconnection is planned to be commissioned in 2018.

In the electricity markets different parties are involved. Four types of actors can be distinguished.

Electricity generators and retail companies. Electricity generators and retailers are the market players that offer and bid electricity on the market. By trading on the market they hope to improve their economical situation given their available assets. An example of a Belgian electricity supplier and retail company is Electrabel.

Regulators. The regulators are not directly involved in the daily functioning of the electricity markets but they behold the market-events to make sure no regulations are broken and all market parties are treated equally. Five regulators are responsible for the well-functioning of the CWE market coupling: the CREG (federal regulator for electricity and gas) for Belgium, CRE (regulatory commission of energy) in France, Bundesnetzagentur-BNetzA for Germany, ILR (institut Luxembourgeois de regulation) in Luxembourg and nMA (Dutch office of energy regulation) in the Netherlands.

Power exchanges. The power exchanges or market operators organize and clear the market for a certain market-area. They collect all the bids to make the aggregated supply and demand curves. Additionally they collect the parameters determining how much trade between zones is possible from the TSOs. The FBMC project counts three electricity exchanges (the British/Dutch APX ENDEX, the Belgian Belpex, and the German/French EPEX Spot)

TSOs. The transmission system operators are responsible for the safe exploitation of the grid. This entails the balancing of the grid and making sure the network is not overloaded. For the market they are responsible of making sure that the outcome of the market falls within the possibilities of the grid. Elia is the Belgium TSO, RTE (reseau de transport d' électricité) is tasked with the job in France. In Germany four TSOs are responsible for a part of Germany, viz. 50Hertz Transmission, Amprion, Tennet TSO and EnBW Transportnetze. TenneT is the Dutch TSO and finally Creos is the Luxembourg TSO. In total the FBMC counts seven independent grid operators among its participants.

2.2 Coupling the electricity markets taking into account network limitations

For the two zones shown in figure 2.1 a big difference between the electricity prices can be noticed. By coupling the markets trade between the two zones is made possible. Zone A would then import electricity from zone B. If there were no limitations on the allowable trade this would result in price convergence as shown on figure 2.4. Eventually this leads to an increase of total welfare [28]. Coupling the markets denotes an efficient trading mechanism between regional markets by using a power exchange that first collects bids on each sub-market and then couples and clears the markets. This way one tries to maximize the interregional market efficiency in a decentralized market system. To couple the markets of two zones it is important to consider the network constraints.

2.2.1 Bringing into account the network limitations

To organize a coupled market without overloading the network, congestion management is required. This system has to prevent a situation where the electricity supply exceeds the capacity of the grid (congestion). An efficient congestion management

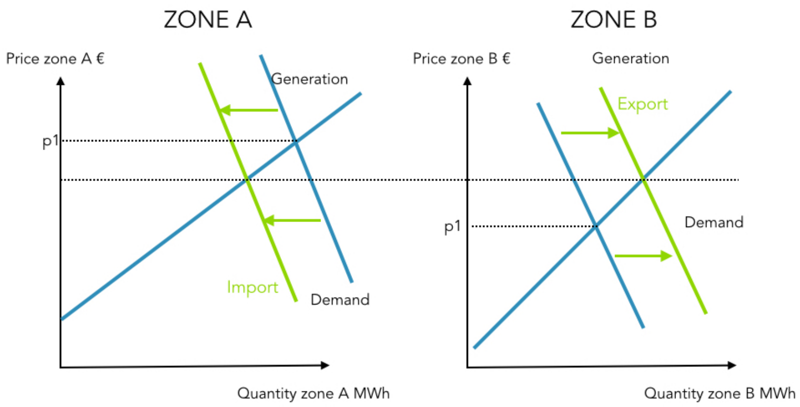


Figure 2.4: Effect of trade on the price of two zones. The prices of the two zones converge due to trade.

makes use of price mechanisms and market forces in the energy sector to manage supply and demand without overloading the regional and international interconnections. For regular trade inside a zone network constraints are less binding and therefore often not considered in the zonal electricity market. Within a zone the network is often considered as a copper plate, meaning that intraregional electricity connections are assumed to have sufficient capacity in order to clear the market without imposing constraints. In the situation where line overload would occur, the TSO can prevent the congestion by re-dispatching some generation. This is called passive congestion management.

When regional markets are coupled the assumption of infinite trade capacity no longer stands. Cross-border capacities are often very limited and thus far more binding. In the market clearing the limitations of the grid have to be taken into account. Bringing the network constraints into account in the market algorithm is not trivial. Since the introduction of electricity markets, the economic and technical system have grown apart. Liberalization broke up the economic electricity subsystem and created a new economic layer on top of the technical subsystem [1]. This economic layer covers the trading of electric energy.

On the technical layer the laws of Kirchhoff determine physical electricity flows. The physical flow laws combined with the thermal capacity of the transmission line determine the level of line congestion in the network. This level of congestion needs to be known on the economic level to determine the constraints on the trade. This implies that the economic and technical systems cannot be fully decoupled. Electric energy always flows from a source (generation of power plants) to a sink (consumer). The flow patterns in the grid result from the in-feed of all sources, the consumption at all sinks and the grid topology at any moment in time. Electricity transmission flows fan out across all available parallel paths in accordance with the laws of Kirchhoff.

This means that there will be parallel flows if there are two or more ways between points of exchange. Economic transactions on the other hand are described by one

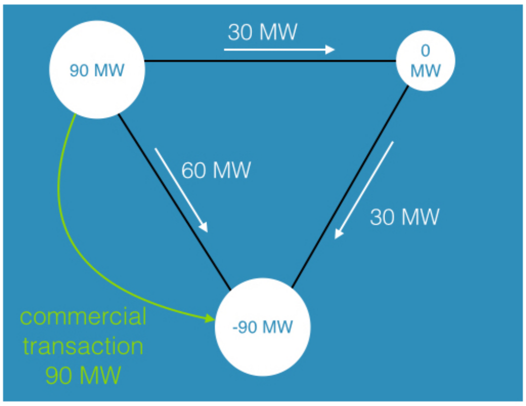


Figure 2.5: Physical flows resulting from a commercial exchange for a three node network assuming equal line impedances.

single path. The difference between economic transactions and physical flows is illustrated in figure 2.5. For the three node network, connected by three similar interconnections, the commercial transaction of 90 MW results in parallel flows of 30 MW through the zone which is not involved in the commercial trade. Every physical flow can be decomposed in an economic and a non-economic part. The non-economic path will be referred to as parallel flows[4]. Considering market coupling of three zones each consisting of multiple nodes (see figure 2.6) the problem is clearly illustrated. The trade possibilities between zone A and B do not only depend on the nodes in A and B but also on the trade between other zones.

2.2.2 Defining congestion management

Congestion represents the situation when the transmission capacity of at least one transmission line is binding and thus restricting the power transmission between regions. Congestion management denotes all the systems that aim at obtaining a cost-optimal power dispatch while accounting for these constraints. The problem sketched in the previous paragraph is part of the complete congestion management. More specifically this type of congestion management is called cross-border capacity allocation. An adequate congestion management method needs to account for the capacity allocation in complex networks by integrating the impact of cross-border trades on the physical power flow.

[4]In other literature often referred to as loop flows. In a later stage we will define loop flows in another way. To avoid confusion the term parallel flow is used here.

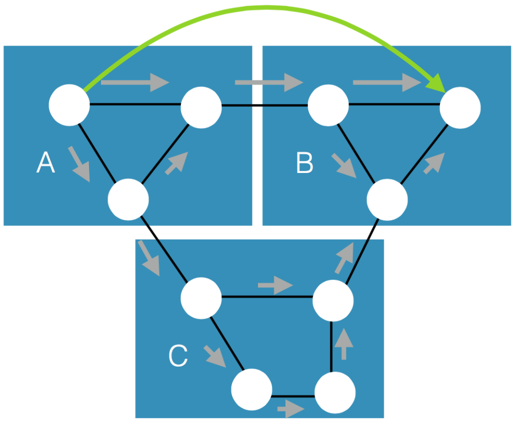


Figure 2.6: Commercial transaction (green) between two nodes in zone A and B and the corresponding physical flow representation (gray).

2.3 Cross-border capacity allocation

The cross-border capacity allocation is an important part of congestion management. As already mentioned this congestion management could be done passively by re-dispatching power generation if congestion would occur from the market outcome results. A more efficient way is to actively incorporate the network constraint in the market coupling process. The most simple concept to allocate the cross-border capacity uses explicit auctions. In this method the market players first have to acquire transmission rights on capacity markets to use transmission capacity for energy trade in the second step. Generators and consumers have to trade on capacity as on energy markets. This cross-border capacity allocation method is therefore very complex for the market participants.

A better alternative is to couple the separate regional power markets by means of an implicit auction where energy and the use of line capacities are traded simultaneously. Now transmission rights do not have to be acquired explicitly. For implicit market couplings two approaches can be distinguished. In a first approach one can try to translate the physical constraint to commercial constraints. An alternative approach is to map every commercial transaction to a physical flow and subsequently impose the physical constraint. These approaches are respectively called the available transfer capacity (ATC)-based market coupling and the nodal flow-based market coupling [3].

2.3.1 ATC-based market coupling

With the ATC method, TSOs calculate the "for the market available capacity ex-ante" for each border separately. The available transfer capacity (ATC) is the maximum directional exchange program between two zones compatible with operational security standards assuming that the future network conditions, generation, and load patterns were perfectly known in advance [26]. The ATC value is a measure for the commercial exchange potential between two zones and therefore no longer depending on the real physical flows. The ATC trade constraint is a constraint on net exchange position (NEX) of a zone z represented as

$$NEX_z \leq NEX_{\max,z} \quad \forall z \in Z \tag{2.1}$$

To determine a value for this commercial potential it is necessary to attribute a certain amount of the total capacity to parallel flows and thus to make assumptions about the trade that will be done between zones. The computation of ATC starts with establishing a prediction of the market outcome, based on the best available information on the network conditions, generation and load patterns, and planned cross-border transactions [25]. The calculated ATC is attributed to the market through the market coupling allocation process. For a three-zone network, the

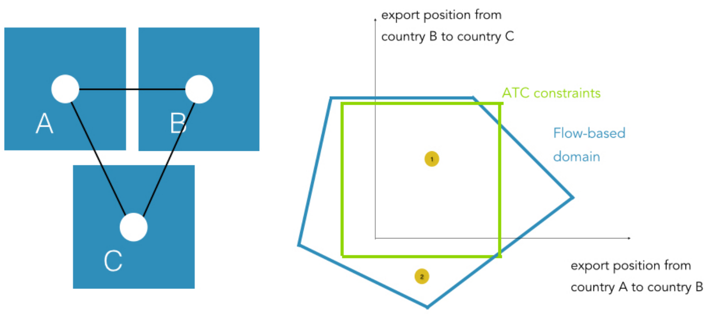


Figure 2.7: The NEX domain limits for ATC and FBMC. Where ATC has fixed values for the NEX assuming a certain situation to bring into account physical flows the FBMC determines the limits taking into account the physical flows in all situations.

domain in which trade is allowed, can be visualized in a two-dimensional graph (see figure 2.7) showing the net export position of zone A and B (NEX of C is also determined as the total balance has to be zero). A market outcome, shown as a dot on this graph, will be located within the domain. The ATC constraint can be represented by straight lines (shown in green) that demarcate the ATC domain. The ATC values of cross-border links are assumed to be independent from exchange of other zone. The ATC domain is strongly dependent on the quality of the best estimate of the solution as it only considers the parallel flows of this best estimate situation to determine the available transfer capacity. The limits for the cross-border trade are fixed values (green rectangle in figure 2.7) and therefore only exact if the outcome of the market is perfectly equal to the prediction.

The currently used ATC capacity calculations are really simple but the heuristic approach to determine the ATC values based on predictions of the parallel flows are not transparent, they are complex and have a large influence on the trade possibilities of the market. Because this dependency on predictions large safety margins are needed to cope with the uncertainty. The network capacity is not used in an optimal way in the ATC domain as feasible market solutions will not be allowed (see dot two in figure 2.7). A better method should consider the exact flows of each transaction.

2.3.2 Nodal flow-based market coupling

The nodal flow-based market coupling, referred to as nodal market coupling, is a second capacity allocation market mechanism. It tries to maximize the use of interregional transmission capacity. The flow-based term refers to the fact that not just the "contract path" but all modeled electrical flow paths are taken into account in the market coupling itself [20]. Commercial bids are translated to their physical flows to simultaneously determine the energy trade and cross border capacity in the market clearing. The network constraint is now brought into account by a flow constraint:

$$F_l \leq F_{\max,l} \quad \forall l \in L \tag{2.2}$$

The flow constraints entail accurate modeling with only technical input parameters. The constraints will result in a flow-based domain as shown in figure 2.7. The market coupling exactly incorporates the network constraints without the need for assumptions and estimations [23]. The flow constraint on each line will however result in nodal prices as will be explained in chapter 3. Nodes within the same zone can subsequently have different market clearing prices.

The nodal market coupling has many benefits compared to the ATC approach. It is therefore used in certain well developed US electricity markets. On the other hand it also has some disadvantages. An overview of pros and cons is given from a European viewpoint [16].

Pros

- ✓ More price convergence between zones as the trade potential between zones increases.
- ✓ A more efficient allocation of the day-ahead interconnection capacity with respect to the economic value of commercial transactions (economic advantage).
- ✓ A better understanding of network behavior, which contributes to the safe operation of the interconnected network (technical advantage).
- ✓ Lower capacity safety margins on the defined technical constraints and, consequently, a higher amount of interconnection capacity that can be offered to the market. This would enforce the welfare increase effect (economic advantage).

- ✓ Easily expandable approach that would facilitate the integration of the complete European electricity market.
- ✓ Better performance than ATC in situations where the solution deviates from prediction. This is an important advantage as the increasing market penetration of renewable generation will make forecasts of the market outcome more difficult and less reliable.
- ✓ A better cooperation between TSOs since FB forces TSOs and power exchanges to work together.
- ✓ More transparency regarding critical transmission lines which could lead to better decisions about investments in new infrastructure.
- ✓ Security of supply could also benefit, since FB is closer to the physical reality of the grid. This means the risk for possible overloading of network elements is reduced.
- ✓ Clear locational market and investment incentives. This could sufficiently decrease network investments that are currently needed to compensate the lack of locational incentives.

Cons

- ✗ Price differences between different nodes within a zone raise political resistance.
- ✗ Nodal location information required in the bids.
- ✗ Increased risk for strategic behavior. The market coupling now is composed of nodal sub-markets. On nodal level the distribution of market shares is often not equalized as is the case on zonal level. Market participants could exploit their nodal high market power to influence the market outcome.

The nodal market coupling is built on a very fundamental network theory. A nodal flow-based market coupling seems a very righteous way to find the optimal solution for all transactions that are requested. It seems logical that implementing a nodal flow-based market coupling would be a step forward compared with the ATC approach. The main problem with the nodal market coupling is the nodal pricing. This would be an interesting measure on the long term because of locational investment incentives. The social inequality of different electricity prices for different nodes within the same zone, makes political acceptance within Europe very difficult. The European requirements of a zonal pricing mechanism consequently doesn't match with the nodal flow-based approach.

Within the CWE market coupling one wants to combine the benefits of the flow-based approach with zonal electricity prices as in the case of ATC. The result is the zonal flow-based market coupling, referred to as FBMC that is currently implemented. In a zonal FBMC, the commercial transactions are translated in physical flows (as in nodal flow-based coupling), but every country is considered as one uniform "node" with one zonal electricity price (as in the zonal ATC market coupling).

2.3.3 Zonal flow-based market coupling

The FBMC proposal tries to combine the benefits of the nodal flow-based approach with the European zonal market setting. However, the implementation of such an FBMC is , unfortunately, not straightforward.

First of all the transformation of the nodal flow-modeling to a zonal approach is not intuitive and will require assumptions as will be explained in chapter 3. Second, the day-ahead market remains only one step in the process of electricity trading. In practice, the FBMC is used to determine some short term transactions, to determine at short notice what is still possible with the network given the forward/future capacity bookings and energy exchanges that have already taken place. Integrating the FB approach in the complete trading process makes the practical implementation of the FBMC very difficult. A third aspect that endangers the FBMC has to be searched with the involved parties. For the CWE FBMC 15 corporate entities have to work together on the implementation. The market coupling implementation has strong consequences for electricity generators and retailers so also these firms have to agree with the proposed implementation. All these parties have their own expectations, needs and interest in the market coupling and its capacity allocation methodology.

- **The regulators** are tasked with the responsibility to guide the transition from ATC to FBMC. They control and approve implementation proposals of the TSOs. Their aim is to achieve a transparent, efficient and safe market coupling mechanism that treats all market participants equally. The regulators will encourage improvements to the market as long as these two aspects are fulfilled.

- **The power exchanges** organize and clear the market. The more trade is done using the market coupling the more revenues they gain. The power exchanges are responsible for the implementation of the FBMC optimization algorithm but have to work closely together with TSOs who determine the input parameters of the network constraints in the market clearing algorithm.

- **The transmission system operators** are tasked with the exploitation of the high voltage electricity grid. The first and most important concern to the TSO is safeguarding a feasible and stable grid operation. Together with the power exchanges they are tasked with the job of designing the flow-based implementation. The FBMC benefits them to make a save operation of the grid possible by increasing the market awareness of the exact flows it causes. On the other hand the aim of the FBMC is to make more extreme operation of the physical high-voltage grid possible as the safety margins can decrease due to a more accurate market representation. Making this system work is a major challenge for the TSOs but they have no benefits from the "better system". The TSOs make money when congestion occurs as the price difference between two zones multiplied with the transported volume is an income for the TSO, known as congestion rent. By law this income has to be used for grid investment or a decrease in their tariffs. The congestion rent is consequently no real profit for the TSO. It is however clear that there are some conflicting interests resulting from a cost-income paradox of the TSOs. By investing in additional transmission capacity they reduce their congestion rent income. The TSOs have no direct incentive to try and maximize the available capacity as this endangers safe operation of the system. With regard to the other market parties the TSOs have no known incentives to favor certain parties. Thus it can be assumed that they will treat all parties equal.

- **Electricity generators and retailers.** The retailers aim to fulfill their clients' demand at a minimal cost. In the context of this thesis generators and retailers determine the bids on the day-ahead market and all other transactions that are done. Moreover they want to avoid risk in order to be sure of returns on investment. They hedge the risks by using the long term market mechanisms that are currently in place. Most of these market participants are opponents of the implementation of FBMC [12]. For these parties, improving the trade possibilities will result in winners and losers. Some will profit from more trade, others will lose profits. As in this stage it is still unclear who will be the winner or the loser, the majority of the market participants have a negative bias towards the FBMC. This negative bias could be explained by an economic theory that blames the uncertainty of winners and losers for the negative bias of all [27].

- **Retail customers** The customers are the persons that should eventually gain from the flow-based market coupling. The improved market coupling should result in more price convergence and in general lower prices because of more ideal competition. So because of the FBMC the eventual end consumer should have to pay less. Studies have already shown that the FBMC is a beneficence for the consumers because of a small increase in overall consumer surplus [11]. Similar as for the generators and retailers there will be winners and losers. As price convergence increases some will pay more, some less. The effect for the customers will, however, be very small. Retail customers are therefore not very relevant in the validation of the flow-based market coupling.

It can be concluded that the problem is tormented by two major conflicting interests. On the one hand the prior concern is security of supply. The electricity system should be operated safely to guarantee that electricity is always available to the customers. To achieve an efficient electricity trade mechanism on the other hand, a more extreme exploitation of the grid is desirable.

Transparency in a flow-based market coupling

One of the most discussed subjects in the context of a flow-based market coupling is transparency. Transparency is a very vague concept that can be interpreted in different ways. By making an attempt to define the transparency that is meant in this case it should be possible to evaluate whether the flow-based market coupling contributes to the transparency.

Defining transparency

Within the context of this study, transparency refers to the extent and way in which information related to the functioning of electricity wholesale markets is exchanged or disclosed between the involved market parties. This section focuses on transparency for the benefit of market participants, hereafter referred to as market transparency. In economics a market is transparent if much is known by all market players about:

- what products, services or capital assets are available;
- at what price;
- where [9].

Despite of the very vague definition transparency is very important since it is one of the theoretical conditions required for a free market to be efficient.

Since Regulations (CE) No. 714/2009 and (CE) No. 543/2013 the TSOs are obliged to publish information about the electricity market [14]. The purpose of the regulations is to provide the basis for a harmonized, transparent environment on the European electricity market. The publication of data should create a level playing field between all market players, which fosters the development of the electricity market. The transparency should increase the informational efficiency of the market [9].

All involved parties agree that the publication of data about the market contributes to transparency. But whether the flow-based market coupling also contributes to transparency is less clear. Until now no conclusive evidence of an increase in transparency is given. A higher level of market transparency contributes to effective competition. Market participants need information about the electricity wholesale market, the transmission network, the balancing market, and the regulatory framework in order to make well- considered business decisions. Moreover, discrepancies between the (legally required) transparency levels in different countries may cause unreasonable damage to certain market participants in relation to others so it is also important that the level of transparency is equal for all member states of a market coupled area. Building on the definition of transparency it could be argued that the market coupling should be simple in order to be "known by many". In that way the ATC system could be seen as very transparent. In the ATC market coupling the NEX limits are published before the market clearing. These NEX values are expressive and straight forward to interpret as limits for the cross-border trade. The only "untransparent" problem is that is remains a little unclear for all participants on what the ATC values are based on and how they were calculated. Regulators also interpret transparency as being able to verify the calculations and methods. For ATC this is not the case as the NEX constraints are based on heuristic methods that are not clearly defined.

On the other hand a nodal flow-based market coupling cannot be considered transparent when using simplicity as a criteria for transparency. The published information in this case are the limitations on each line but these give no clear indication of how much trade actually is possible. In a zonal market coupling like the current flow-based proposal this matter becomes even worse. The complex flow-based capacity parameters do not to any extent give a clear indication of the trade possibilities for an outsider. Moreover, a lot of these data can be questioned when published as the flow-based parameters are based on strong assumptions (see chapter 3).

One may distinguish two categories of transparency: a category related to open and adequate communication (perspicuity) and a category related to the easiness to understand (clarity). Defining the optimal level of market transparency is a challenging task that is not the primarily focus of this thesis. It is however important to keep in mind the requirements of market transparency during the evaluation of the FBMC approach.

Chapter 3

Flow-based parameter calculations and current method

The aim of this chapter is to give a clear understanding of the flow-based market coupling principle and its parameters. The theoretical principle of a nodal flow-based market coupling is simple and intuitive. However, a nodal flow-based market coupling is not possible in the European socio-political context (see section 2.3.2), therefore a zonal implementation is used. The current European zonal implementation, referred to as the flow-based market coupling (FBMC), is quite complex and less intuitive. In this chapter the theoretical principle of a nodal market coupling is first explained. From this theory the zonal flow-based approach is derived. The problems arising in practice are discussed to arrive at the real and current implementation method.

To explain the flow-based methodology a three-node, two zone example is elaborated as illustration. The example is simple but clearly demonstrates the principles and problems of the zonal flow-based implementation. The network topology is shown in figure 3.1. The network is characterized by three interconnected nodes. The maximum transport capacity of the lines is 100 MW. The three nodes are divided over two zones. Zone A contains node 1, zone B consists of node 2 and 3. Demand and generation bids provide the input for the market coupling. In the example, there is an inelastic load of 150 MW at node 2 and zero load at the other nodes. Generation bids are elastic. They are characterized by a marginal generation cost and a maximum generation capacity. A generator bid of 100 MW at 10 €/MWh is considered in node 1, no generator is implied at node 2 and a generator bid of 100 MW at 20 €/MWh is considered in node 3.

3.1 Market coupling optimization algorithm

The market coupling aims at finding the economic equilibrium of the aggregated bids. Finding the equilibrium is equivalent to an optimization problem. In the specific case of our electricity market the equilibrium problem translates into a maximization of

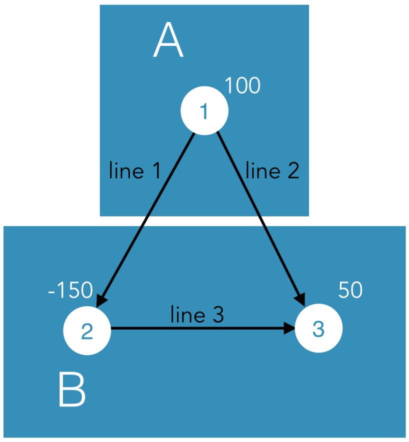


Figure 3.1: Topology of the three nodes, two zones example. In the figure the nodal injections (MW) of the optimal solution are shown in white.

the social welfare. The market coupling aims at finding the highest welfare solution given the generation and load bids and the network constraints. Consider $z \in Z$ a bidding zone z among the bidding zones Z and $b \in B$ a bidder b among the bidders B. In this research the demand, d_n (MW), is assumed inelastic and fixed for each node. This simplifies the objective function to a minimization of the accepted generation costs.

$$\min_{g_b} \sum_{b \in B} c_b \cdot g_b \tag{3.1}$$

g_b (MW) represents the accepted generation bids, c_b (€/MWh) the corresponding cost of the generation bids. The optimization problem is constrained by two inequality constraints. Every generator bid is limited by a minimum and a maximum output.

$$g_b \leq g_{\max,b} \quad \forall b \in B \tag{3.2}$$

$$g_b \geq 0 \quad \forall b \in B \tag{3.3}$$

Next to this inequalities three additional types of constraints are considered in the market coupling algorithm: two equality conditions, viz. market clearing conditions and balancing conditions and finally inequality network constraints are considered. The exact implementation of these constraints depend on the market coupling algorithm that is used (see discussion below). It can already be put that the last, imposed by the physical capacity of the network components, will be the most difficult to implement. The flow on each line,F_l, cannot exceed the maximum line capacity available for the market, $F_{\max\, market,l}$.

$$-F_{\max\, market,l} \leq F_l \leq F_{\max\, market,l} \quad \forall l \in L \tag{3.4}$$

This equation entails two problems. The line flows will need to be expressed in terms of the optimization variables, g_b. The second subproblem entails the determination of the $F_{\max\, market,l}$. How these problems will be seized upon will be explained in the following sections.

3.1.1 Ideal nodal market coupling

The minimization problem is constrained by the market clearing condition. A few new variables need to be defined. The nodal injection P_n equals the net injection into to grid of a node n. It is determined as the sum of all accepted generation bids in that node minus the demand in the node. To determine the nodal sum of accepted generation bids the bid-to-node matrix, $NB(n, b)$ is defined. This matrix maps each generation bid to a node. The market clearing condition is then given by:

$$P_n = \sum_{b=1}^{B} NB(n, b) \cdot g_b - d_n \quad \forall n \in N \tag{3.5}$$

The overall balancing constraint can be expressed as follows:

$$\sum_{n \in N} P_n = 0 \tag{3.6}$$

This constraint represents the generation and demand equilibrium that has to be respected at all times in an electricity system. The only constraint left to consider is the network flow constraint. The optimization problem needs to bring into account the flows in the network. Doing an exact optimization considering the complete electricity grid and accurately modeling the flows would be impossible. To translate the issue to a susceptible problem simplifications have to be made.

- The AC network equations, describing the flows and voltages as a function of the injections, are simplified by a DC flow model.
- In the optimization only transmission lines that are reckoned to be restricting are considered. The first step of the market coupling thus entails the determination of the components that are expected to be congested. This step is not handled in the thesis as it not relevant for the fundamental principle of cross-border capacity calculations of the market coupling. This step is simply done to reduce the computational complexity of the optimization problem by reducing the number of line constraints.

DC power flow

The DC load flow is a linear approximation of the AC power flow. By assuming a flat voltage profile and small voltage angles, the AC load flow equations are reduced as such that the active power flow on a given line linearly depends on the transmission line reactances and the difference of the voltage angles at each end of that line. Additionally, transmission line losses are omitted. These assumptions result in a linearization for which superposition is valid. The DC load flow approximation therefore allows some very useful simplifications regarding the process of calculation [13].

The problem can be described as follows. The network is constrained by the physical line capacities, $F_{\max,l}$. Not all of this capacity is available for the market, as we will discuss further in section 3.2.3. The maximum capacity for the market will be noted by $F_{\max\,market,l}$. This maximum capacity is assumed to be known for now. To bring the flow constraint (equation 3.4) into account a relation between the nodal injections and the corresponding flows needs to be made. As already described in the previous chapter real network flows do not correspond to a commercial transaction (matching generation bid and demand bid). Physical flows run in parallel paths according to Kirchhoff laws. The exact relation between a flow in a line, F_l, and nodal power injection, P_n, is complex as each line is characterized by a resistance and a reactance. In a DC power flow analysis the resistance is assumed to be zero. This simplifies the relation between a power injection in the grid and a line flow to a linear relation.

The linear relation can be expressed in a matrix, called the power transfer distribution factor matrix, $PTDF_n$ with dimensions LxN. Each element $PTDF_n(l,n)$ contains the influence on the flow through a line l of an injection of 1 MW in node n and a withdrawal in the reference node. This parameter is strictly a function of the network elements and the topology. The flow equations become:

$$F_l = \sum_{n=1}^{N} PTDF_n(l,n) \cdot P_n \leq F_{\max\,market,l} \quad \forall l \in L \tag{3.7}$$

or in matrix notation it can be written as:

$$\begin{bmatrix} F_1 \\ \vdots \\ F_L \end{bmatrix} = \begin{bmatrix} PTDF_n(1,1) & \cdots & PTDF_n(1,N) \\ \vdots & \ddots & \vdots \\ PTDF_n(L,1) & \cdots & PTDF_n(L,N) \end{bmatrix} \times \begin{bmatrix} P_1 \\ \vdots \\ P_N \end{bmatrix} \leq \begin{bmatrix} F_{\max\,market,1} \\ \vdots \\ F_{\max\,market,L} \end{bmatrix} \tag{3.8}$$

Remark that during this derivation the flow constraint is, for reasons of simplicity, only written for the positive flow direction. In reality the flow has to be smaller than the positive flow limit and larger that the negative flow limit. With this flow constraint the flow-based problem formulation is complete. The described optimization problem is a Linear Programming as the objective function and all constraints are linear. It can be solved with a numerical optimization algorithm.

The solution of the algorithm will give all the accepted bids g_b and the market prices, p_n. The electricity prices are determined as the dual values of the market clearing condition (see Equation 3.5). These shadow prices for each node are found by determining the cost and demand increase with one in the considered node.

Example For our three node example this optimal welfare solution seems straight forward. A demand of 150 MW needs to be fulfilled in the cheapest way possible. Two generator units of 100 MW are available at a different price. It is logic that the cheapest generator is operated at its full capacity. The remaining 50 MW is delivered by the other generator. The resulting solution is stated in figure 3.1. So far the optimization seems logical but whether this solution is technically feasible still needs to be verified . The optimization procedure should consider the network constraint. Written out the flow constraint equation for our three node example results in the following equation.

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} PTDF_n(1,1) & PTDF_n(1,2) & PTDF_n(1,3) \\ PTDF_n(2,1) & PTDF_n(2,2) & PTDF_n(2,3) \\ PTDF_n(3,1) & PTDF_n(3,2) & PTDF_n(3,3) \end{bmatrix} \times \begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} < \begin{bmatrix} F_{\max\, market,1} \\ F_{\max\, market,2} \\ F_{\max\, market,3} \end{bmatrix} \tag{3.9}$$

The $PTDF_n$ for our example assuming line impedances of one is given by

$$PTDF_n = \begin{bmatrix} 0.667 & 0 & 0.333 \\ 0.333 & 0 & -0.333 \\ -0.333 & 0 & -0.667 \end{bmatrix} \tag{3.10}$$

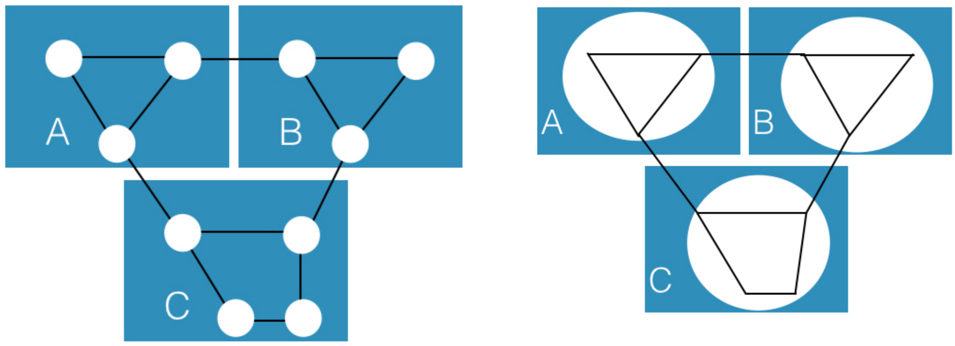
For the intuitively expected solution the flow constraint can be verified to conclude that g_b equal to $100, 0$ and 50 indeed is the optimal solution without exceeding line limits.

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} 0.667 & 0 & 0.333 \\ 0.333 & 0 & -0.333 \\ -0.333 & 0 & -0.667 \end{bmatrix} \times \begin{bmatrix} 100 \\ -150 \\ 50 \end{bmatrix} = \begin{bmatrix} 83.3 \\ 16.6 \\ -66.6 \end{bmatrix} < \begin{bmatrix} 100 \\ 100 \\ 100 \end{bmatrix} \tag{3.11}$$

The respective prices p_n of the nodes are 20, 20 and 20.

Unfortunately this implementation cannot be used in reality. The results of the ideal nodal market would give the accepted bids and an electricity price in each node. As the flow constraints impose limits on each nodal injection the shadow prices and consequently the nodal prices can vary for different nodes if congestion occurs.

If congestion occurs on a line within a zone, the different nodes of that zone will have different prices caused by the definition of shadow prices. In the European CWE market area price differences between nodes within a zone are not allowed. As was explained in section 2.3.2 of the previous chapter. Current social and political setting wants electricity prices to be uniform within a country/zone. A second additional argument against the nodal pricing system is the lack of nodal information in the bids. In an ideal system all biddings are known in each node so the nodal injection can be determined. However, in reality the bids that are done on the market are not assigned to a node but only linked to a zone. Each trader has to present his bids to the market organizer of his zone without indication to which node these bids are linked. The determination of nodal injections P_n cannot be done without assumptions. This second argument is not really fundamental and should be seen as a result of the zonal pricing requirement. Because market coupling algorithms used in Europe (like the ATC market coupling) have zonal pricing and are not flow-based, the addition of the nodal information to the bids seemed irrelevant. The market traders now value the flexibility and freedom given to them but fundamentally there are strong arguments to remove this flexibility.



(a) Nodal representation

(b) Zonal representation

Figure 3.2: Representation of a three zone network each consisting of multiple nodes.

Summarizing it can be stated that because of political and social requirements a zonal pricing market coupling is desired. Combined with the current lack of nodal bidding information the ideal nodal flow-based market coupling is not implementable. An alternative flow-based methodology had to be determined. It should deliver zonal pricing and can cope with the lack of nodal information by making assumptions and estimations. The nodal approach has to be transferred to a zonal approach in which no distinction is made between the nodes in the zone. Instead of considering the bids in a node (see figure 3.2a) the bids need to be considered in a zonal context (see figure 3.2b). At the same time the implementation should accurately take into account the network limitations while remaining simple and transparent. The current zonal FBMC proposal is an attempt to fulfill these requirements.

3.1.2 From a nodal to a zonal market coupling

In the zonal flow-based market coupling the bids are considered per zone instead of per node. Instead of the nodal net injection, P_n, the zonal net exchange position, NEX_z now defines the market clearing condition. NEX_z represents the difference between the zonal injections and the zonal load.

$$NEX_z = \sum_{b=1}^{B} ZB(z,b) \cdot g_b - \sum_{n=1}^{N} ZN(z,n) \cdot d_n \quad \forall z \in Z \tag{3.12}$$

Two new matrices are introduced. The node-to-zone matrix, $NZ(z,n)$ maps each node to a zone. The bid-to-zone matrix, $ZB(z,b)$ maps each generation bid to a zone. The NEX definition is in theory equivalent to the sum of all nodal injections of a zone.

$$NEX_z = \sum_{n=1}^{N} NZ(n,z) \cdot P_n \quad \forall z \in Z \tag{3.13}$$

In reality the nodal injections P_n simply no longer exist in the zonal FBMC context. The balancing equality constraint then states that the exchanges of all the zones have to sum up to zero to achieve a closed system.

$$\sum_{z \in Z} NEX_z = 0 \tag{3.14}$$

The original line flow constraint can be viewed as a translation of the line flow limits to limitations on the nodal injections. Each node has its corresponding limits implicating that shadow prices can be different for each node. To obtain zonal pricing and therefore zonal shadow prices the constraint translation should result in limitations per zone. Instead of constraints for each node there should only be a constraint for each zone. The line flow constraint equation should be a relation between the line flows and the zonal net exchange position (NEX_z).

The matrix describing the relation between the flow through a line and the NEX_z is the zonal power transfer distribution factor ($PTDF_z(l,z)$) with dimensions LxZ. This $PTDF_z$ maps the influence of a change in the NEX_z of a zone z to a flow in line l. In contrast to the original nodal $PTDF_n$, this zonal $PTDF_z$ is no longer strictly a technical network characteristic. Assumptions, represented by generation shift keys ($GSK(n,z)$), are required to determine the $PTDF_z$ matrix. The GSK are discussed in section 3.2.1. The $PTDF_z$ is determined by

$$PTDF_z(l,z) = \sum_{n=1}^{N} PTDF_n(l,n) \cdot GSK(n,z) \quad \forall l \in L, \forall z \in Z \tag{3.15}$$

In matrix notation the expression is written as:

$$\begin{bmatrix} PTDF_z(1,1) & \cdots & PTDF_z(1,Z) \\ \vdots & \ddots & \vdots \\ PTDF_z(L,1) & \cdots & PTDF_z(L,Z) \end{bmatrix} = \begin{bmatrix} PTDF_n(1,1) & \cdots & PTDF_n(1,N) \\ \vdots & \ddots & \vdots \\ PTDF_n(L,1) & \cdots & PTDF_n(L,N) \end{bmatrix} \times \begin{bmatrix} GSK(1,1) & \cdots & GSK(1,Z) \\ \vdots & \ddots & \vdots \\ GSK(N,1) & \cdots & GSK(N,Z) \end{bmatrix} \tag{3.16}$$

Because of the assumption made in the GSK matrix the calculated flows will no longer be exact. This error can be compensated by an extra term in the equation, Fo_l. The loop flows are defined as the difference between the contracted exchanges (flows assumed by the market) and the actual physical flows. They represent the error that is made by the GSK assumptions. Adding the loop flow term to the equation results in the flow-based constraint as defined in the current flow-based market coupling proposal.

$$F_l = Fo_l + \sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z \leq F_{\max market,l} \quad \forall l \in L \tag{3.17}$$

$$\begin{bmatrix} F_1 \\ \vdots \\ F_L \end{bmatrix} = \begin{bmatrix} Fo_1 \\ \vdots \\ Fo_L \end{bmatrix} + \begin{bmatrix} PTDF_z(1,1) & \cdots & PTDF_z(1,Z) \\ \vdots & \ddots & \vdots \\ PTDF_z(L,1) & \cdots & PTDF_z(L,Z) \end{bmatrix} \times \begin{bmatrix} NEX_1 \\ \vdots \\ NEX_Z \end{bmatrix} \tag{3.18}$$

To fully understand this equation more information is required. Three main parameters can be distinguished which require special attention. They are often referred to as the flow-based parameters:

- Fo_l
- GSK and the corresponding $PTDF_z$
- $F_{\max\, market,l}$

These will be discussed and illustrated with the three node example in the following section. With the given constraint equation the FBMC optimization problem is completely defined. As the nodal market coupling, the FBMC optimization problem consists of linear equations resulting in a linear programming optimization.

3.2 Flow-based parameter calculations

In the previous section it became clear that two parts need to be determined to define the flow constraint equation. First there is the network model, represented by the zonal PTDF, containing the GSK assumptions accompanied by loop flows to take GSK simplification deviations into account. Second, the $F_{\max\, market,l}$ needs to be determined. Starting from the physical line limit $F_{\max,l}$ the part that is available for the market needs to be determined for each in transmission line. In this section these three parameters that have not been clearly defined yet are further discussed.

3.2.1 Generation shift keys

In the flow-based market coupling implementation the function of GSKs is to transform the $PTDF_n$ to $PTDF_z$ by providing a relation between the nodal injections and the net export position of a zone. GSK values determine how a change in net exchange position of a zone is mapped to the generating units/nodes of that zone. In the optimization algorithm the $PTDF_z$ is used as input parameter. Thus, GSK values need to be determined ex ante without the exact knowledge of how the market outcome generation will be divided over the nodes. They need to be determined upfront to achieve a zonal pricing solution and a convex optimization problem. The GSK values can vary for every hour and are given in dimensionless units. Additionally the bids are even not known per node, so the bids can't be used to determine the GSK matrix. We will need to rely on an estimation that will most probably not represent the exact distribution of the eventual accepted bids/ generation in reality.

Current GSK definition

GSKs are theoretically defined as the increase in a power plant's output if the net exchange position of the zone is increased with one. Mathematically this corresponds to the derivative of the nodal power injection in the grid on the market with respect to the zonal net export position.

$$GSK(n, z) = \frac{dP_n}{dNEX_z} \quad \forall n \in N, \forall z \in Z \tag{3.19}$$

Unfortunately, the contribution of generation unit to the NEX is unknown at the time of calculation. In theory to determine the GSKs the solution already needs to be known. The determination of GSKs is a circular problem.

GSK definition

Generation shift keys defines how a change in net position is mapped to the generating units in a bidding area. It contains the relation between the change in net position of a zone and the change in output of every generating unit within the same market zone [10].

The current definition is not really complete. The derivative of a non-linear function depends on the point of derivation. Which generation units will contribute to a changing NEX depend on the NEX position for which the change is considered and thus the point in which the network is considered to operate. That point is unknown before the market coupling and more importantly that point is not specified in the current definition. When doing a linearization one should know the reference point from which we need to linearize. The lack of a reference point in the definition leaves unintended room for interpretation to the different TSOs.

Example For the simple three node example a GSK matrix can be determined. Applying the direct GSK definition and using the expected market solution as the reference point the following GSK is given.

$$GSK = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \tag{3.20}$$

To determine this GSK a forecast for the eventual solution was used, which for this example was assumed to be exact. In each zone there is only one generation node so a change in NEX is fully appointed to this node.

Next to the unclear theoretic definition we note that the GSK calculations done by TSOs in reality are not accurately based on the definition. In practice, every TSO assesses GSKs for its control area taking into account the characteristics of its network and generation units. The TSOs distinguish two classes of generation units. The non-market oriented generation units refer to units that are not flexible and whose output is already known before the market coupling is applied, for instance a nuclear unit[1]. Only sudden outage or re-dispatching will change the output. For the non-market generation units the GSK according to the given definition is zero as these plants will normally not offer their capacity on the day-ahead market coupling. The second class are market oriented generation units. The output of these plants will depend on the market. For each of these plant a factor is assigned that tells

[1] In France, nuclear units are flexible units and also taken into account in the GSK method.

how a change in net position in the zone is linked to the plant's output. For the determination of the GSKs multiple methods are currently in place. These methods can vary from a simple uniform distribution over the different nodes of a zone to complex methods based on best forecast of the contribution of generation units to a power transfer.

Generation shift key methods applied in practice

For the GSK determination three methods are currently used by different TSOs. A uniform distribution between all the market oriented plants is done by Amprion, the West German TSO. Another possibility is to distribute the GSK's values proportional to their contribution to the base case[2] generation. This method is applied by RTE, the French TSO. A last option is the linear interpolation method that is implemented by Elia. The GSK for each generator now equals the gradient of the line between the MWs produced at a max import and MWs produced at a max export position [10]. These arbitrary methods strongly deviate from the mathematical GSK definition that was given.

Due to the unclear definition, the reliance on assumptions and arbitrary methods in the determination process, it can be concluded that the GSK determination is a weak point of the capacity calculation methods. The impact of the GSK assumptions will be addressed in this research.

Determination of the zonal power transfer distribution factors

The calculation of nodal PTDF is extensively covered in literature [13] and is a strict characteristic of the network once the network topology is known. Combined with the GSK matrix the zonal PTDF can be determined [24]:

$$PTDF_z(l,z) = \sum_{n=1}^{N} PTDF_n(l,n) \cdot GSK(n,z) \quad \forall l \in L, \forall z \in Z \tag{3.21}$$

Example The $PTDF_z$ in the example is found to be

$$PTDF_z = \begin{bmatrix} 0.667 & 0 & 0.333 \\ 0.333 & 0 & -0.333 \\ -0.333 & 0 & -0.667 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} 0.667 & 0.333 \\ 0.333 & -0.333 \\ -0.333 & -0.667 \end{bmatrix} \tag{3.22}$$

Note on demand shift keys

Similar to GSK also demand shift keys (DSK) can be defined. In theory the definition is the same, viz. the change of the nodal injection with respect to the zonal net exchange position.

$$DSK(n,z) = \frac{dP_n}{dNEX_z} \quad \forall n \in N, \forall z \in Z \tag{3.23}$$

[2] The base case will be explained in detail in section 3.3.

For the practical determination of dP_n the change of demand is now considered instead of a change in generation output. DSKs are therefore not necessarily the same as the GSKs. Increasing the NEX of a zone with one by increasing the output of generators will have a different nodal distribution than increasing NEX by decreasing the demand. While this nuance in interpretation can have an influence on the solution, demand shift keys are not considered or defined in the flow-based implementation proposal.

3.2.2 Loop flows

Explaining the importance of loop flows

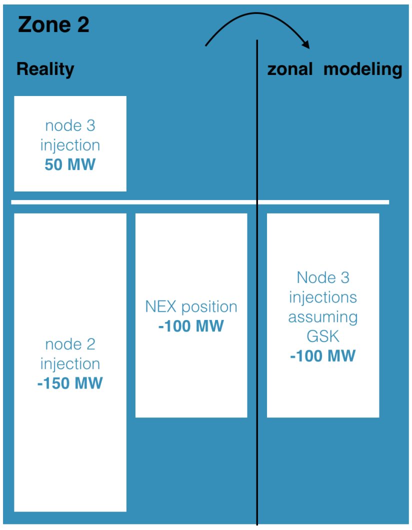


Figure 3.3: Graphical representation of the netting effect of GSK

Because of GSKs and their current definitions the fundamental zonal flow-calculation formula:

$$F_z, l = \sum_{z=1}^{Z} PTDF_z(l, z) \cdot NEX_z \quad \forall l \in L \tag{3.24}$$

is far from exact in the flow constraint equation 3.17. The faults are caused by two reasons. First, information about the nodal injections is lost. The GSKs are all positive values that sum up to one. In the flow equation GSK will divide the NEX over the nodes. All the nodal injections will have the same sign as the NEX position. Information of nodal injections with the opposite sign is lost as can be seen in figure 3.3. Second, errors are simply introduced because the generation distribution assumptions in the GSK will not correspond with the real distribution of the market outcome. Therefore the zonal flow calculation in the flow equation will not correspond with the reality flows.

Example In the example a perfect prediction of the market outcome is assumed and the GSKs are calculated with their exact definition so the second type faults will not occur. In figure 3.3 effect of the strictly positive GSKs is clearly shown. The nodal injections assumed in the zonal model do not correspond with the real injections. Consequently the resulting zonal flow calculations are strongly deviating from the real flows.

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} 0.667 & 0.333 \\ 0.333 & -0.333 \\ -0.333 & -0.667 \end{bmatrix} \times \begin{bmatrix} 100 \\ -100 \end{bmatrix} = \begin{bmatrix} 33.3 \\ 66.6 \\ -33.3 \end{bmatrix} \tag{3.25}$$

Loop flow determination

Loop flows should try to represent the error on the flows that is made in the zonal flow calculation by the GSK assumptions made in the market algorithm. These flows are then considered as given before the market coupling, as fixed flows that are already in place before the market coupling, while in reality these flows are a result of market trade but only not considered in the market's zonal flow calculations.

Loop flow definition

Loop flows are defined as the difference between the real market flows and the flows assumed in the market coupling algorithm. Note that loop flows are often referred to as flows through a market zone resulting from intra-zonal exchanges in another zone. This definition doesn't stand in the current context [10].

The determination of the loop flow is graphically illustrated in figure 3.4. An estimation of the market outcome is required on which a nodal model can be applied to determine the forecast market coupling flow in each line noted by $F_{fmc_n,l}$. Applying the zonal model to the same market outcome forecast will result in different flows, $F_{fmc_z,l}$. The difference between $F_{fmc_n,l}$ and $F_{fmc_z,l}$ is an estimation for the loop flows.

Example This procedure can be illustrated with the example. Assume an exact forecast of the market coupling (fmc), with the corresponding flows:

$$\begin{bmatrix} NEX_{fmc,1} \\ NEX_{fmc,2} \end{bmatrix} = \begin{bmatrix} 100 \\ -100 \end{bmatrix}, \begin{bmatrix} F_{fmc_n,1} \\ F_{fmc_n,2} \\ F_{fmc_n,3} \end{bmatrix} = \begin{bmatrix} 83.3 \\ 16.6 \\ -66.6 \end{bmatrix} \tag{3.26}$$

The loop flows are then determined by $Fo = F_{fmc_n} - F_{fmc_z}$

$$\begin{bmatrix} Fo_1 \\ Fo_2 \\ Fo_3 \end{bmatrix} = \begin{bmatrix} F_{fmc_n,1} \\ F_{fmc_n,2} \\ F_{fmc_n,3} \end{bmatrix} - \begin{bmatrix} PTDF_z(1,1) & PTDF_z(1,2) \\ PTDF_z(2,1) & PTDF_z(2,2) \\ PTDF_z(3,1) & PTDF_z(3,2) \end{bmatrix} \times \begin{bmatrix} NEX_{fmc,1} \\ NEX_{fmc,2} \end{bmatrix} = \begin{bmatrix} 50 \\ -50 \\ -100 \end{bmatrix} \tag{3.27}$$

The loop flow components represent large fractions of the eventual flows. The illustration demonstrates that the loss of information by netting the nodal injections

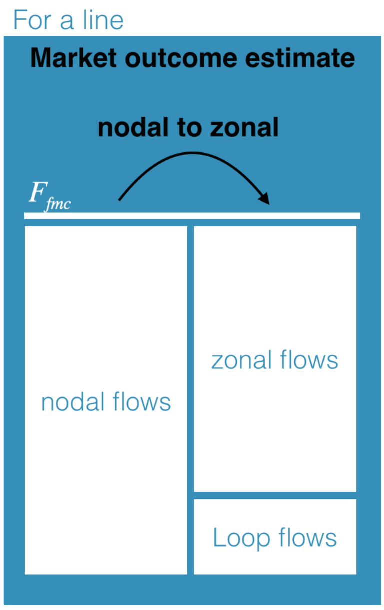


Figure 3.4: Visualization of the loop flow determination starting from a market outcome estimate for a line. The nodal flows are defined as the flows on the transmission lines according to the expected market outcome and a grid model. The zonal flows on the other hand represent flows on the lines according to the expected market outcome and a zonal grid model.

of a zone has a big influence on the cross border flows. The loop flows are not considered inside the flow-based market coupling optimization. Their effect is not taken into account in the market. Determining the error that will be made by the market and subsequently correcting the market for it seems a questionable method but in practice TSOs do this because it reduces the impact of wrongly chosen GSK assumptions.

3.2.3 The capacity available for the day-ahead market

The last important parameter that still needs to be quantified is the maximum flow capacity of each line that is available on the market $F_{\max\, market,l}$. The total line capacity that can be used for transport of electricity is the physical line capacity $F_{\max,l}$. Unfortunately, electricity is not only traded on the day-ahead market that is considered here. The total real-time[3] flows can be seen as a substitution of three types of transactions.

- **Day-ahead market transactions** These are the transactions resulting from

[3] The Intraday and balancing markets are not considered and not relevant for this research as the available capacity for these markets is derived from the scheduled programs on the evening of the day-ahead. In this research the real-time flows are the result of the day-ahead scheduled programs.

the day-ahead market coupling. The day-ahead market transactions result in the market flows, F_l.

- **Long term cross-border transactions with capacity nominations** Long term cross-border transactions can be done via future markets or bilateral contracts. The market participants is however is obliged to buy cross-border capacity rights that are required for this energy transaction. Long term nominations thus are capacity rights that are bought by market participants on long term capacity markets to cover their long term cross-border transactions. These capacity rights need to be nominated/published before 8h00 on the day-ahead to make use of them. The nominated capacities are then known by the TSOs which can bring this into account for the determination of the capacity available for the day-ahead market. If the capacity right is not nominated the capacity is available for the day-ahead market but potential congestion revenues go to the owner of the capacity rights instead of the TSO (owning all the capacity that was not bought on capacity markets). The long term nominations of each line will be denoted with $F_{LTN,l}$.

- **Intra-zonal non-market transactions (referred to as non-market transactions)** This last category of transactions bundles all transactions that are not part of the two previous categories. These transactions are intra-zonal exchanges that are not done via the day-ahead power exchange. Three groups can be distinguished. First, this category includes intra-zonal long term trades done via bilateral energy contracts or long term energy markets. As these transactions are intra-zonal, they don't require capacity bookings. Second, transactions between market players of the same zone are still possible once the day-ahead market coupling is executed. Balance responsible parties can make bilateral agreements with each other. Trade agreements between different zones are no longer possible. Third, this category also includes flow transactions between nodes that simply follow from exchanges in the portfolio of a BRP. These three types of transactions have two common features. First of all, the information of these transactions is only available for the TSOs when the BRPs hand in their balanced portfolios in the afternoon of the day-ahead and thus after the day-ahead market clearing. Second, the transactions of this category are all intra-zonal but this doesn't imply that the transactions don't cause cross-border flows. The flows corresponding with these transactions will be referred to as $F_{non-market,l}$.

To determine the maximum capacity that is available on the market we have to subtract the capacity that will be used by non-day ahead market transactions from that physical capacity. These non-market transactions are a combination of nominated long term transactions and the other transactions, referred to as non-market trades. This results in the following formula:

$$F_{\max market,l} = F_{\max} - F_{non-market,l} - F_{LTN,l} \quad \forall l \in L \tag{3.28}$$

The formula is represented in figure 3.5.

Chronology of transaction information on the day-ahead

The trading process on the day-ahead starts at 8h00 with a submission of all the LTN. At 11h00 all the flow-based capacity parameters are calculated. the maximum market capacity is one of the parameters that needs to be determined in order to solve the flow-based market algorithm. At 12h00 the day-ahead market is cleared. All the bids are collected and the market algorithm determines the optimal solution. The outcome is made public to all players. At 14h00, a day ahead of the delivery day, the BRPs hand in their eventual nominations containing the information of all scheduled transactions. At that moment the exact state of the grid, a result of long term market and non-market transactions is known.

The chronology clearly shows that at the moment of determining $F_{\max market,l}$ not all information is already available to calculate the capacity available for the market. The LTNs are known but all non-market transactions are not known until the submission of the balanced portfolio at 14h00. The determination of $F_{\max market,l}$ will consequently be based on assumptions and estimations.

Determination of the capacity available for the market

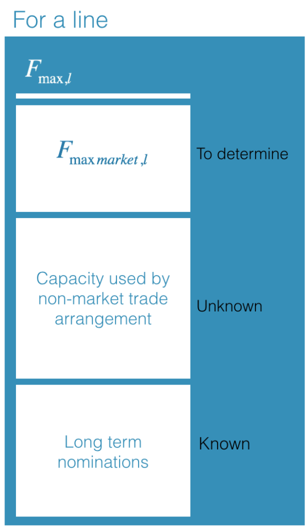


Figure 3.5: Division of the line capacity over the transaction types in order to determine $F_{\max market,l}$.

To determine the $F_{\max market,l}$ an estimate of the non-market trades will need to be made determined. The ex-ante estimation of the non-market transactions is a questionable point in the flow-based methodology. The market coupling will determine the prices and this price will have a significant influence in portfolio choices and thus the transactions of the BRP. Non-market flows will depend on the market flows and vice versa. In a trading system in which legitimate non-market transactions after the market are allowed this circularity is unavoidable.

Addition of a flow reliability margin

Because of all the assumptions that have been made, it is clear that the real flows will deviate from the calculated flows and that the FBMC will not be completely accurate. The deviation is introduced by mainly five uncertainties and assumptions:

- the uncertainty introduced by the non-market flow estimation, thus differences between forecasts and realized programs of the BRP will occur;
- the inherent error introduced by the GSK and loop flow approach, thus approximations within the flow-based methodology will occur;
- the error introduced by inaccurate predictions that are used in the GSK and loop flow determination;
- the faults caused by simplifying the grid components and flow analysis;
- the uncertainty of external exchanges with zones outside the CWE market coupling.

This uncertainty must be quantified and discounted in the allocation process, in order to prevent that on day D TSOs will be confronted with flows that exceed the maximum flows of their grid components. To compensate for the deviations a flow reliability margin (FRM_l) is introduced to guarantee safe operation of the grid. The FRM_l is a fixed fraction of the physical line characteristic that is subtracted from the $F_{\max\, market,l}$. The flow constraint relation is now given by:

$$F_l = \sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z + Fo_l < F_{\max\, market,l} - FRM_l \quad \forall l \in L \qquad (3.29)$$

The FRMs are determined by comparing the flow-based flows and the real physical flows of the day before the delivery day. The specific determination of the FRMs is not handled in this thesis. More information on this topic can be found in the flow-based approval package [10].

Note on conservative grid operation The FRMs are, however, not the only safety mechanisms. Additional safety measures are taken with the N-1 rules. These are extra measures to guarantee safe operation in case of an outage or an other fault. The N-1 rules are applied in a totally different stage of the grid operation process. But eventually the FRM and N-1 safety measures (both very conservative) are added up. This certainly results in a safe operation of the grid which is maybe a little too conservative. Integrating the error calculation of the FRM and N-1 rules in one step could decrease the safety margins.

Once all the flow-based capacity parameters are determined the problem is theoretically completely defined. The flow constraints demarcate a domain in which trade is allowed. For a three zone network this domain can be represented graphically in a two dimensional plot as shown in figure 3.6. In the practical implementation some

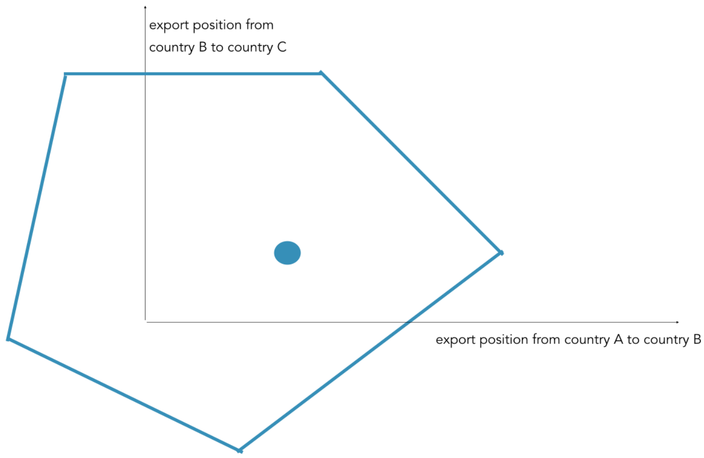


Figure 3.6: The flow-based domain for a three zone network configuration.

additional aspects have to be brought into account and some theoretical steps will be combined as we will discussed in the following sections.

3.3 The base case

In this section the base case formulation and the data merging process are discussed. Throughout the theoretical description often estimations of certain parts of the electricity transactions were used. In the practical approach these estimations are gathered in one estimation of the eventual state of the grid, called the base case. Over the years the meaning and interpretation of the base case has changed a lot. In all interpretations the base case estimation is fundamentally used to cope with the uncertainty in the market coupling. In each interpretation however the base case is defined and used in a different way. In previous interpretations for example the base case refers to the (hypothetical) case in which the countries are not coupled at all (no coupling) [21]. In the current interpretation the base case refers to an estimate of the expected state of the grid at the moment of delivery, made two days in advance. In the old ATC market coupling the base case is used to determine the $NEX_{\max,z}$. In the current flow-based proposal the base case is used for both the determination of the $F_{\max\ market,l}$ and the Fo_l. The base case thus determines two crucial flow-based capacity parameters and consequently has an very important influence on the result. The base case is referred to as the two-day ahead congestion forecast files (D-2CF).

3.3.1 The intuitive and mathematical function of the base case

The intuitive aim of the base case is to provide a starting point from which the flow-based domain can be derived using the GSK assumptions. This is visualized in figure 3.6 for three countries. In this graph the blue dot represents the reference point determined from the base case (net export/ import position). The determination of the flow-based domain thus is done with a linearization (using GSKs) starting from the base case. The starting point for this linearization should be as close as possible to the solution of the market to limit the impact of bad GSK assumptions. The base case thus should approximates the final solution as well as possible.

Mathematically the base case is characterized by its flows, nodal injections and net exchange positions, respectively $F_{bc,l}$, $P_{bc,n}$ and $NEX_{bc,z}$[4]. This is an estimation for the eventual outcome of the trading process (considering the submission of the nominated portfolios as the trading result). This base case can now be used to determine a value for the available capacity on the market and the loop flows. From the base case situation the day-ahead market flows are subtracted making use of the GSK assumptions to get the reference flows.

$$F_{ref,l} = F_{bc,l} - \sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_{bc,z} \quad \forall l \in L \tag{3.30}$$

This is equivalent to

$$F_{ref,l} = F_{bc,l} - \sum_{n=1}^{N} PTDF_n(l,n) \cdot P_{bc,n} + Fo_l \quad \forall l \in L \tag{3.31}$$

So $F_{ref,l}$ represents the reference situation which includes all flows resulting from the non-market transactions and a measure for the flows that are not taken into account by the GSK assumption in the zonal market calculation. $F_{ref,l}$ is the estimation of $F_{non-market,l} + Fo_l$. With this definition the flow constraint equation becomes:

$$\sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z < F_{max,l} - F_{ref,l} - F_{LTN,l} - FRM_l \quad \forall l \in L \tag{3.32}$$

A new parameter, the remaining available margin is introduced and defined as $RAM_l = F_{max,l} - F_{ref,l} - F_{LTN,l} - FRM_l$. The eventual flow constraint equation is given by:

$$\sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z < RAM_l \quad \forall l \in L \tag{3.33}$$

The calculation process of the RAM is graphically demonstrated in figure 3.7.

[4] Note that the symbols used here will not correspond with assignment used in other literature like the flow-based approval package [10] as these designations were confusing and unclear.

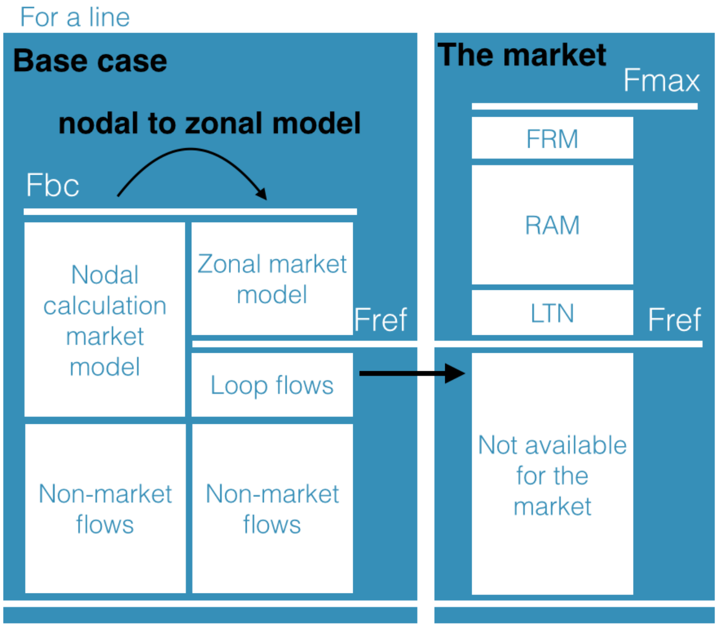


Figure 3.7: The determination of the RAM using the base case.

3.3.2 Determination of the base case

To determine the base case two difficulties need to be taken into account. The base case estimates the realized programs of the BRP and thus the state of the electricity grid at the delivery moment. At the moment of making the base case, two days before the delivery day, only little exact information is given. Second, this base case is made for the complete market coupled zone. Theoretically it would be optimal if one overarching organization would make this estimation for the complete market area using all information of the different zones. In reality however this forecasting by one overarching organization is very difficult to implement because the information is dispersed over the TSOs. Each TSO understands and exploits its zonal grid and only the TSO has all the required information to make an estimation for his zone. Each TSO subsequently uses its own methods and assumptions to make a base case estimation. In the real world the process of making a base case of a complete market area implies two steps. First each TSO makes the forecast for its own zone. Virtual nodes called x-nodes, are added at the boundaries of its control area to bring the interconnections into account. In a second step all these forecasts are collected in 1 aggregated model. This process is called merging. The result of the merging process is called the two day-ahead congestion forecast (D-2CF) and it is the **base case** as we will refer to for the rest of this thesis [2].

Two day-ahead congestion forecast files (D-2CF) definition

The D-2CF is a prediction of the injections and extractions in every node after all transactions have been done. With the nodal flow equation the base case flows in every line can be calculated and thus the state of the grid is known for the base case.

Note on terminology

As already mentioned the base case has had multiple interpretations and functions over time. Even in the current setting the base case is confusingly used for two different forecasts, viz. the already mentioned D-2CF and the day ahead congestion forecast (DACF). The second forecast is also an estimation of the eventual state of the grid but made at a different moment and with a different function. It is made at the evening of the day-ahead and is used to evaluate the safe operation of the grid given the results of the day-ahead market coupling and nominations of the balance responsible parties. For the DACF a lot of knowledge of the system is available to make an accurate prediction of the real state of the system. The result of this base case is a deterministic point that represents as accurately as possible the state of the physical grid for the next day. From this network state one can determine the operational safety of the system and the available exchange capacity for the intraday market can be derived. This type of base case will not be discussed further in this research.

3.3.3 Practical determination of the base case (D-2CF)

In the base case all the available information is used to make an estimation of the system for every hour on the delivery day. Two days ahead of the delivery day there is however very little accurate information available. The real topology in which the system will operate has not yet been fixed and can be changed during the following days, for instance as a result of unforeseen maintenance. The market outcome of the day-ahead market is unknown. Thirdly the TSOs still have no good information on which plants will operate and what the exchange between the countries will be as these variables are all determined by the market outcome. So almost non of the available information is exact. Luckily some reliable information is available for which the amount of uncertainty is limited. The load forecasts are quite accurate as loads are not very price dependent. Renewable generation forecasts are disposable. These are of course less accurate than load forecasts as they depend strongly on local weather conditions. Remark that the impact of the renewable generation on other generation units is not known. If for instance a lot of renewable generation is expected for the delivery day it is not know at D-2 which generation units will be replaced by this renewable generation. It is the market that will determine this outcome. In figure 3.8 an overview is given for the different actions performed in the

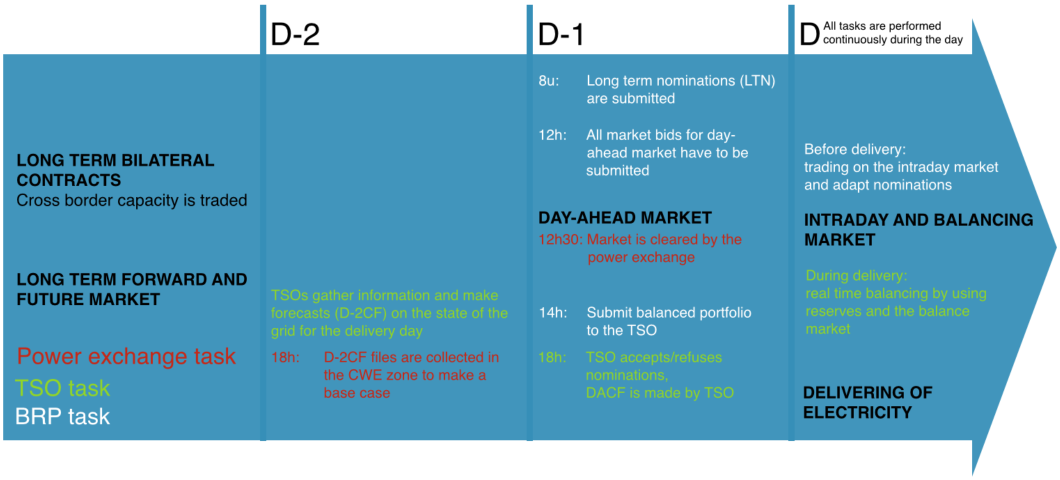


Figure 3.8: Chronological overview of the market process.

process of the wholesale electricity market. The TSO and balance responsible parties are two major actors that can be distinguished. At the moment of the D-2CF files in fact nothing is known with certainty. It is only on the morning of D-1 that some accurate information comes available when the LTNs are announced. The D-2CF files thus are based purely on estimations of nodal demand and nodal generation made by the TSO.

The making of the D-2CF files contains several steps. The first step consists of determining the net exchange position of the zones. Subsequently information about zonal generation and demand is supplemented. In a third step the generation and demand has to determined in each node. For each of these steps several methods have been mentioned in the FBMC proposal package. The different steps and their methods are shown in figure 3.9. In the following paragraph each step and its corresponding possible methods is handled in detail.

Steps of the D-2CF done by the TSO

1. **Net exchange position of a zone** First one needs to estimate what will be the net exchange position of the zone for every hour. For this at the moment 3 different approaches are considered. Logically the total exchanges between all zones have to sum up to zero. For this step the TSOs need to agree on a certain methodology in order to achieve a balanced base case situation.

    a) **Zero exchange:** A first option is to assume the net exchange position of each zone will be zero. This is a simple method that strongly deviates from the real solution with considerable exchanges between zones.

    b) **Reference exchange:** In a second method the net exchange between zones can be fixed at a certain value determined by a reference case that

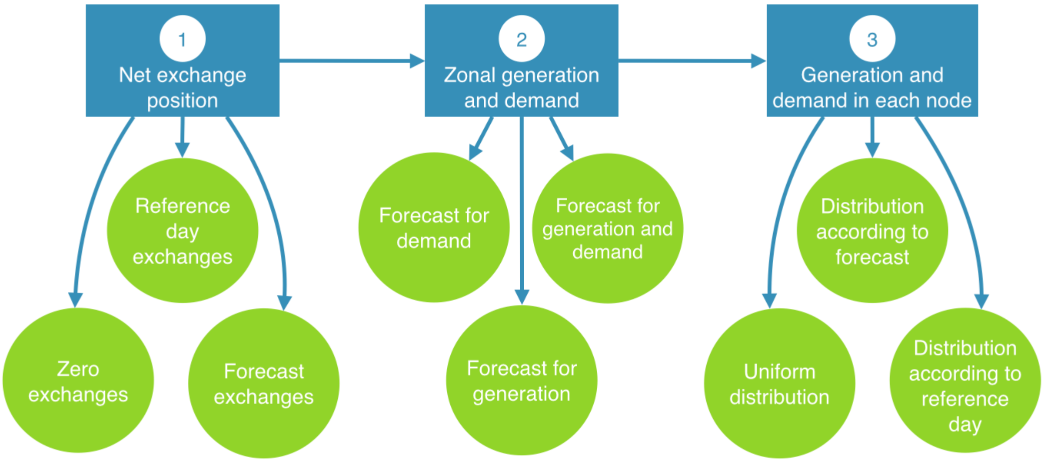


Figure 3.9: Base case steps and their possible methods.

D-2 (day of making)	Reference day	Delivery Day
Monday	Tuesday	Wednesday
Tuesday	Wednesday	Thursday
Wednesday	Thursday	Friday
Thursday	Saturday week before	Saturday
Friday	Sunday week before	Sunday
Saturday	Friday	Monday
Sunday	Monday	Tuesday

Table 3.1: Overview of the reference days used by Elia

has already taken place. This is the currently agreed method between TSOs. From the reference day (see table 3.1) the DACF files are used to determine the exchange position.

c) **Forecast exchange:** The last possible option is the usage of forecasting models to determine the expected exchange between countries. This would require strong collaboration between TSOs in order to achieve a balanced base case.

2. **Generation and demand forecasting information** The second step consists of adding information about supply and demand to the base case model. The result of this step is a prediction of generation and demand in each zone. Three options are possible to supplement the demand and/or generation information to the previous step. Total zonal generation (G_z), total demand (D_z) and the net exchange position can be seen as three variables for which the following holds:

$$G_z - D_z = NEX_z \tag{3.34}$$

The net exchange position was already fixed to a certain value in the previous step. This suggests that actually only one other variable can be chosen.

a) **Forecast for demand:** A first option is to use the demand forecast information and consequently determine the generation with equation 3.34. This follows the logical concept that generation follows demand.

b) **Forecast for generation:** The generation forecast is used. The demand follows from equation 3.34.

c) **Forecast for generation and demand:** This last option uses both the forecasts for generation and demand and can therefore only be combined with the third method for the determination of the net exchange position. It is easily seen that the exchange position forecast is actually built with information of generation and demand forecasts. This option fixes the generation and demand according to forecasts and determines the NEX.

This step can be expanded by adding forecast of renewable generation and power plant availabilities. The net exchange position stays fixed even if for instance the wind forecast would result in a different net exchange position than at the reference day. Such situations are solved by adapting the demand until for the given forecasts the net exchange position stays the same.

3. **Division of generation and demand over the nodes** From the previous steps the total generation and demand data for each zone are known. This generation and demand has to be divided over the different grid nodes. The division is done with different methods.

   a) **Uniform distribution:** The total demand or generation is equally divided over all nodes.

   b) **Distribution according to the reference day:** The demand or generation is divided over the nodes proportionally to the reference day distribution.

   c) **Distribution according to forecasts for generation or demand:** The forecast generation or demand of every node is scaled to meet the total demand or generation.

Merging process Once all TSOs have made their D-2CF the files are collected in the evening of D-2 and merged into 1 model that represents the best estimate for every hour of the execution day. The result of this merging is the complete base case for the market area.

3.4 Conclusion

To summarize a schematic overview is given of the steps in the process of the flow-based market coupling in figure 3.10. The different parameters and their dependence are shown on a high level. The flow-based input parameters are determined by each TSO separately. The determination of the flow-based capacity parameters is subsequently done by 1 entity that assembles the parameters of the TSOs. Finally the flow-based market coupling algorithm is executed by the power exchanges. The

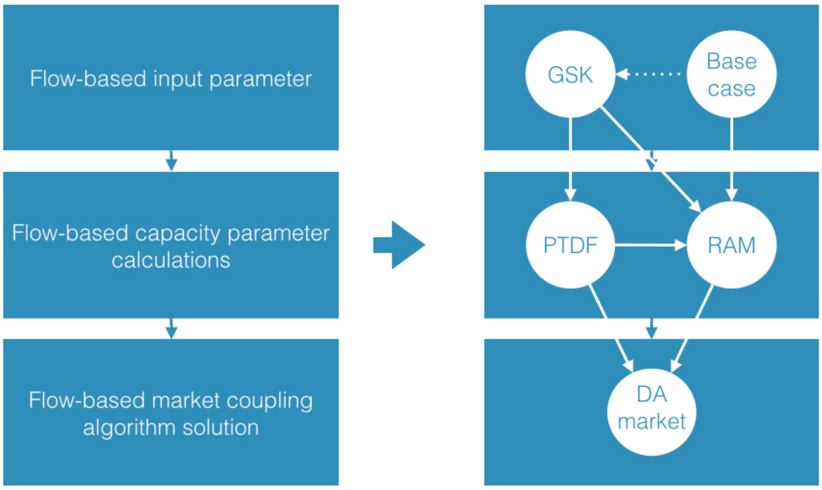


Figure 3.10: Visualization of the flow-based parameters and their dependence.

eventual flow constraint implementation is given in the blue box.

Summary of the flow constraint implementation and parameters

The eventual flow constraints that have to be respected in the optimization algorithm of the FBMC is:

$$RAM_{2,l} < \sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z < RAM_{1,l} \quad \forall l \in L \tag{3.35}$$

with

$$RAM_{1,l} = F_{max,l} - F_{ref,l} - F_{LTN,l} - FRM_l \quad \forall l \in L \tag{3.36}$$

$$RAM_{2,l} = -F_{max,l} - F_{ref,l} - F_{LTN,l} - FRM_l \quad \forall l \in L \tag{3.37}$$

$F_{ref,l}$ is an estimation of $F_{non-market,l} + Fo_l$ derived from the base case.

In this chapter a clear elaboration of the flow-based approach was given. The focus was on understanding the need and function of each step. The resulting flow-based approach is mathematically simple but entails a lot of assumptions and estimations. Additionally the practical determination of the base case and GSKs strongly deviate from what they should mathematically represent as they can simply not be calculated. In practice the determination of these parameters is thus based on heuristic methods. A fundamental study about the impact of these parameters could increase the understanding and potentially reveal possible improvements.

Chapter 4

Flow-based market coupling simulation model

By building an accurate model of the current flow-based implementation, this research will try to uncover problems and possible improvements in the current FBMC proposal. The model represents a simplified version of the flow-based market coupling proposal. All the crucial steps that characterize the real FBMC approach are implemented. With this model a case study, based on the topology of the CWE region, is analyzed. As the focus of this thesis is on understanding the FBMC concept the studied case is simple. The simulation model itself is compatible with larger datasets so it can in the future be used to evaluate the FBMC on realistic data. The studied case data are virtual and thus not representative for reality situations. Yet, the data have been chosen to be feasible for the CWE. The aim of the model is not to imitate the flow-based market coupling algorithm but rather to give insight in the used concepts.

In this chapter a description of the developed simulation model is given. Starting from the studied data the implementation of the market coupling is discussed. In the model a nodal market coupling is compared with the zonal flow-based market coupling proposal.

From the previous chapter it can be concluded that the determination of flow-based parameters is based on assumption and artificial parameters, like the GSKs. Investigating the impact of the current FBMC methodology in a simple model could enlighten our understanding and provide new insights for possible improvements. In the current FBMC proposal mainly the base case and GSKs have not unambiguously been defined and different methods are still applied. This model aims at evaluating the impact of these flow-based capacity parameter calculation methods. The evaluation of the model will be discussed in the next chapter.

4.1 Design of the simulation environment

The basis of the model is made in Matlab. All the methods for the flow-based capacity calculation have been implemented in this environment. To solve the flow-based optimization problem a specialized optimization package called GAMS [19] was used. The General Algebraic Modeling System is a high-level modeling system for mathematical optimization. The package itself uses the C-plex solver to perform the optimization. The flow-based market coupling algorithm is thus implemented in GAMS. Between GAMS and Matlab exchange of information is needed. The modeling environments are coupled as shown in figure 4.1. In figure

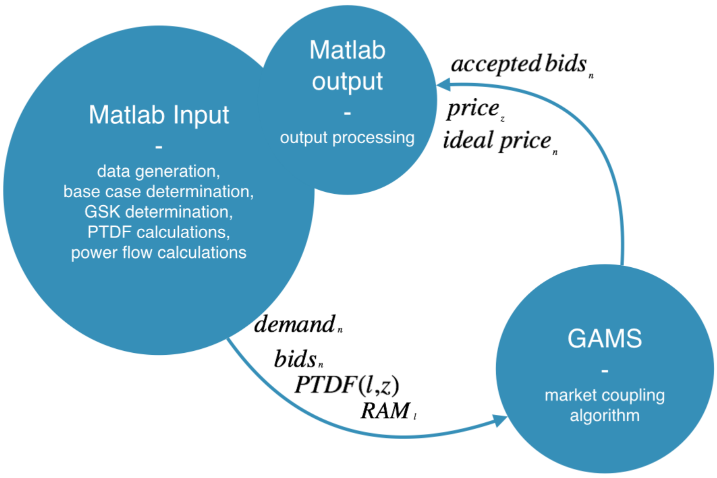


Figure 4.1: Overview of the simulation environment coupling.

4.2 the high level structure of the model is shown. Green blocks stand for high level variables. The inputs of the model are shown in the left. They entail data of topology, generation, demand and LTN for the upcoming week. The hourly market simulator is shown in the middle. These model components will clear the market for every hour by using the nodal or zonal flow-based market coupling. For the zonal FBMC simulator forecasts, derived from the data, are used for the calculation of the flow-based capacity parameters. The zonal flow-based market coupling can run with different methods and assumptions. The final output for every hour can be found on the right. Every blue building-block represents a function of the program. The scheme doesn't clearly show the working of the program but it can serve as a guideline to understand the links between sub-functions when these are handled in detail later.

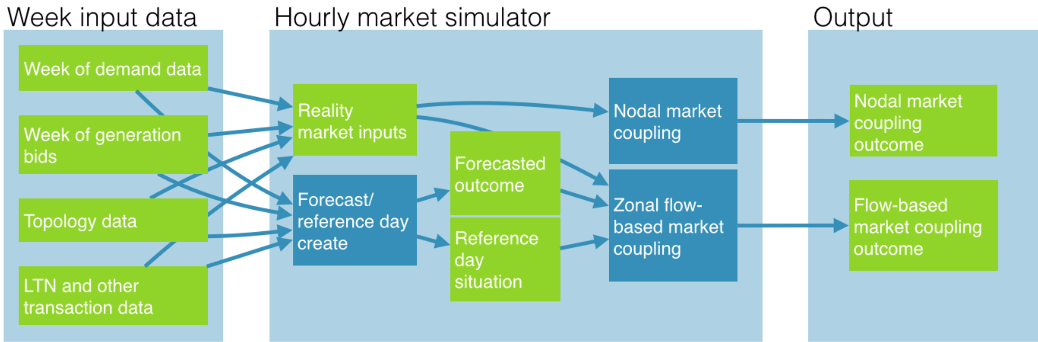


Figure 4.2: Overview of the model building blocks.

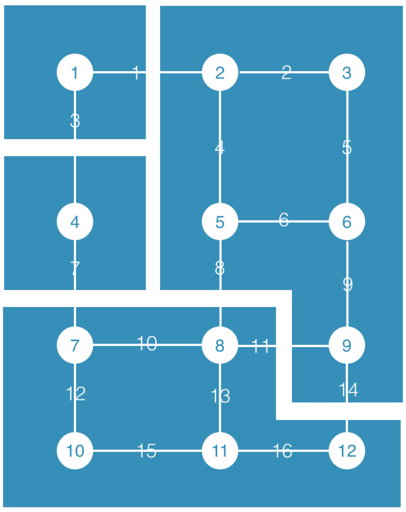


Figure 4.3: Topology of the studied case representing the CWE market zone.

4.2 Study case data

4.2.1 Topology

The eventual aim of the model is to draw conclusions about the capacity calculation methodology in the FBMC. The model should therefore give clear and easily understandable results about the FBMC outcome. The case discussed in this thesis is simple but the simulation model is perfectly capable of handling bigger and more realistic data sets. The case that is considered here is a strongly simplified representation of the CWE. The topology consists of twelve nodes in four zones and 16 interconnection lines as is shown in figure 4.3. The zones and lines are chosen to represent the reality CWE situation on a high level in order to have some meaningful results. The physical interconnection limits used are shown in table 4.1. The intra-zonal lines are clearly less limiting than cross-border lines as is also the case in reality. All lines have a relative impedance equal to 0.04 p.u.

Line	$F_{max,l}$(MW)
1: Dutch German interconnection	3000
2: German internal line	4000
3: Dutch Belgian interconnection	2400
4: German internal line	4000
5: German internal line	4000
6: German internal line	4000
7: Belgian French interconnection	3400
8: German French interconnection	1000
9: German internal line	4000
10: French internal line	4000
11: German French interconnection	1000
12: French internal line	4000
13: French internal line	4000
14: German French interconnection	700
15: French internal line	4000
16: French internal line	4000

Table 4.1: The maximum line capacities of the given topology.

4.2.2 Demand and generation

For the given topology the day-ahead market outcome is modeled for one week. The demand and generation data for this week are virtually generated starting from an hourly mean data case shown in table 4.2. The hourly demand in each node is determined by multiplying the mean demand situation with a relative load profile (see figure 4.4) and subsequently adding some deviations according to a normal distribution. The hourly generation bids are determined by adding a normal deviation to both the capacity and the marginal cost of the mean generation bids. In generation and demand data the impact of renewables is taken into account by adding a stronger capacity deviation to renewable demand and generation bids. During the evaluations variations of this mean case will be used to illustrate different situations. Demand, generation or line capacity data are then multiplied by a certain factor.

The generation bids of each node have been chosen to resemble the different generation technologies and their realistic distribution within the CWE zone. In table **??** an overview is given of the technologies assigned to each zone. Renewables, nuclear, coal and combined cycle gas turbines are the considered technologies with respective marginal costs of 10, 15, 40 and 60 €/MWh. Each node only has 1 generation bid. In the current simulation with only 12 nodes this implies that the number of generation bids is really not realistic. This assumption is supported by the fact that the relative ratio of 1 bid per node is representative for the reality trading situation on the day-ahead market. Only a fraction of total generation units, viz. the power price setting power plants are offered. The current implementation doesn't allow multiple

	Demand	Generation	
Node	D_n(MW)	Generation bid (MW)	Bid price (€/MWh)
1	1000	500	60
2	100	1000	10
3	100	1000	10
4	1500	1000	40
5	1500	500	40
6	100	1000	40
7	100	1000	60
8	500	1000	15
9	1500	1000	40
10	500	1000	15
11	500	1000	60
12	500	1000	15

Table 4.2: The mean demand and generation studied case.

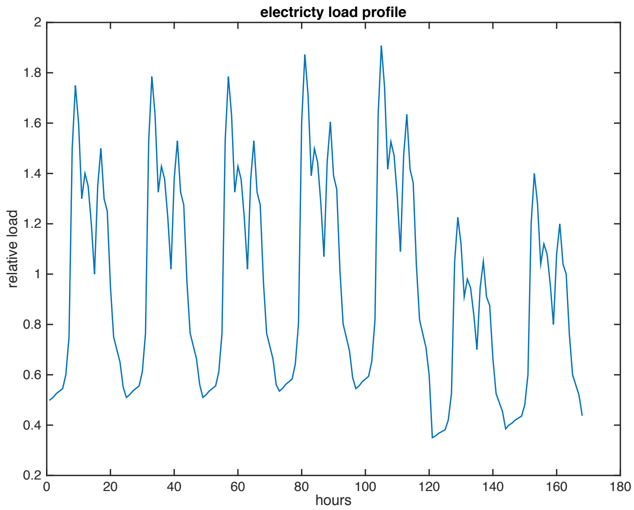


Figure 4.4: The relative demand profile for the simulated week.

generators per node because of the calculation approach of GSKs. If an extended topology were loaded into the model, still only one generation bid per node would be possible. It should be kept in mind that the data in the simulation are by no means a measure for reality. Simulating a reality situation is currently not the focus of the thesis. The input data have been fabricated to represent theoretic feasible situations as the aim is to discover how the flow-based market coupling principles perform theoretically.

4.2.3 Long term nominations

LTNs for every hour are generated as random bookings of cross-border line capacities. These will be subtracted from the maximum line capacity. In practice not the line bookings but the net exchange bookings between two zones are known. This introduces an extra uncertainty component which will need to be compensated by higher safety margins. In the simulation model this additional uncertainty is not considered.

4.2.4 Forecast and reference data

Next to the topology, demand and generation data additional information is needed for the determination of the flow-based capacity parameter, viz. a forecast of the market outcome and a reference day situation. In the model both these forecasts can be seen as an approximation of the reality with a certain accuracy. The forecast can consequently be represented by the reality generation and demand information plus a random forecasting error. Running the ideal nodal market coupling with the forecast input data completely features the forecast situation. Both forecasts are assumed to deviate from the hourly reality situation according to an at-random Gaussian deviation. Using Gaussian deviations for the forecast is an ideal way to determine the impact of poorer forecasts on the eventual outcome. By varying the Gaussian standard-deviation the effect of increasing forecast errors can be considered and a clear distinction can be made between forecast errors and inherent methodological errors.

4.3 Market simulation optimization algorithm

Two optimization algorithms are distinguished: the nodal market coupling, representing an ideal market coupling and the zonal FBMC which is representing a simplified version of the FBMC Euphemia algorithm that has been used for the day-ahead market clearing since 20 May. Most of the model equations have already been discussed and explained during the derivation of the flow-based methodology. They are repeated here to give a clear description of the exact implementation in the simulation model.

For every time step of the simulated week the market simulation optimization algorithm is run independently from the previous and later time steps. Both the nodal and flow-based market coupling optimization have the same objective function, viz. a minimization of the hourly generation costs needed to fulfill the hourly demand in each node. With g_b (MW) the hourly accepted generation capacity and c_b(€/MWh), the corresponding cost of the generation bids, the cost minimization can be written as

$$\min_{g_b} \sum_{b \in B} c_b \cdot g_b \tag{4.1}$$

Both optimization problems are constrained by the limit of the generation bids.

$$g_b \leq g_{\max,b} \quad \forall b \in B \tag{4.2}$$
$$g_b \geq 0 \quad \forall b \in B \tag{4.3}$$

Further constraints of the optimization subsequently depend on the optimization method that is used. The eventual result of both the nodal and flow-based market algorithm will be a linear programming optimization problem.

4.3.1 Nodal flow-based market algorithm

In case of the nodal flow-based market coupling algorithm the optimization variables for every hour are the accepted hourly generation capacity outputs, g_b(MW). In a nodal market coupling the generation bids are made on a node. This link between nodes and bids is represented in the bid-to-node matrix, $NB(n, b)$. The balancing constraint is implemented by

$$\sum_{b \in B} g_b - \sum_{n \in N} d_n = 0 \tag{4.4}$$

The second constraint represents the market clearing condition, with P_n the net nodal injection.

$$P_n = \sum_{b=1}^{B} NB(n, b) \cdot g_b - d_n \quad \forall n \in N \tag{4.5}$$

Lastly the flow constraint equations are implemented as

$$\sum_{n=1}^{N} PTDF_n(l, n) \cdot P_n \leq NRAM_{1,l} \quad \forall l \in L \tag{4.6}$$
$$\sum_{n=1}^{N} PTDF_n(l, n) \cdot P_n \geq NRAM_{2,l} \quad \forall l \in L \tag{4.7}$$

The $NRAM_{1,l}$ and $NRAM_{2,l}$ respectively represent the remaining available capacity in the positive and negative direction, with the NRAM in the negative direction non-positive. The calculation of these parameters is explained in section 4.4. The optimization model is solved in Gams with the linear programming solver Cplex. The nodal prices are equal to the marginal values of the market clearing equation.

4.3.2 Zonal flow-based market algorithm

In the zonal flow-based market coupling the bids are considered per zone instead of per node. Instead of the nodal net injection, P_n the zonal net exchange position, NEX_z now defines the market clearing condition. NEX_z represents the difference between the zonal generation and demand.

$$NEX_z = \sum_{b=1}^{B} ZB(z, b) \cdot g_b - \sum_{n=1}^{N} ZN(z, n) \cdot d_n \quad \forall z \in Z \tag{4.8}$$

Two new matrices are introduced. The node-to-zone matrix , $NZ(z,n)$ maps each node to a zone. The bid-to-zone matrix ,$ZB(z,b)$ maps each generation bid to a zone. The balancing constraint states that the exchanges of all the zones have to sum up to zero to achieve a closed system on order to achieve a balanced market.

$$\sum_{b \in B} g_b - \sum_{n \in N} d_n = 0 \tag{4.9}$$

The final flow constraint imposes the capacity limits of the transmission lines. In the zonal FBMC the zonal flow-modeling is used to estimate the flow on each line, F_l. This flow cannot exceed the directional remaining available margin for the market.

$$\sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z \leq RAM_{1,l} \quad \forall l \in L \tag{4.10}$$

$$\sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z \geq RAM_{2,l} \quad \forall l \in L \tag{4.11}$$

The determinations of the parameters used in these equations are elaborated in the next section. In the FBMC the price in each zone is equal to the marginal value of the market clearing condition.

4.4 Market coupling capacity parameters

To solve the optimization problems described in the previous section the capacity parameters need to be determined. First of all the $F_{\max,l}$ is a crucial parameter for both the nodal and flow-based market coupling. Subsequently a differentiation can be made between the nodal and flow-based capacity parameter. In the context of the nodal market coupling the determination of $PTDF_n(l,n)$ and $NRAM_l$ is discussed. For the FBMC the $PTDF_n(l,n)$ and directional RAM_l needs to be calculated.

4.4.1 Determination of $F_{\max,l}$

In the model the given F_{max} is assumed to be the $F_{\max,l} - F_{non-market,l}$. This implies that the capacity of intra-zonal non day-ahead market transactions is already subtracted from the physical line capacity. In reality the estimation of the non-market exchanges is entailed in the base case. But without realistic data the addition of the non-market transactions in the base case has no value. It is thus important to keep in mind that the value of $F_{\max,l}$ that is here assumed to be known, is in fact an estimate of $F_{\max,l} - F_{non-market,l}$ after making assumptions about the non-market transactions. As long as non-market transactions resulting from portfolio nominations are allowed, these unknown transactions will induce uncertainty in the determination of the $F_{\max market}$. The non-market transactions additionally are very difficult to predict so large safety margins are needed to cope with the uncertainty. Assessing whether a decrease of the fraction of non-market transactions with respect to the total transactions would result in less uncertainty is impossible without accurate data about the size and variability of the non-market transactions. It can only be stated that the uncertainty would completely disappear if all transactions would be done on the market or registered before the day-ahead market.

4.4.2 Nodal parameter calculations

In the nodal algorithm the $PTDF_n(l,n)$ and $NRAM$ parameters need to be calculated. Schematically the calculation of the nodal parameters is represented in figure 4.5.

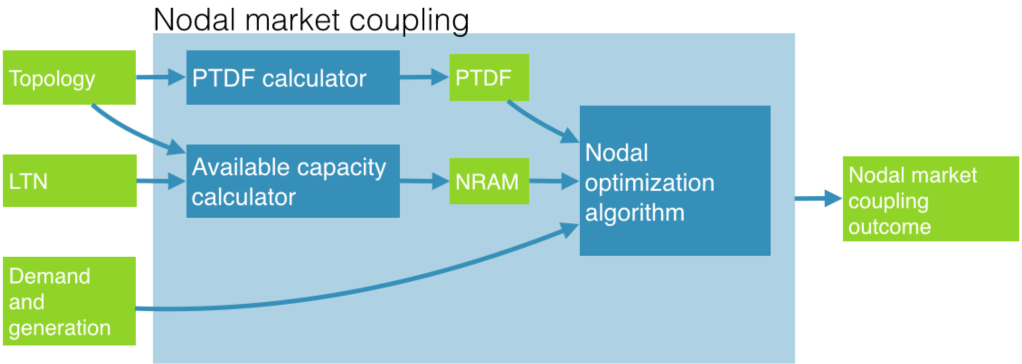


Figure 4.5: Structure of the nodal market coupling building block.

Determination of nodal PTDF

The PTDF is a technical network characteristic that is calculated according to the principles explained in the TME working paper about DC power flows in unit commitment models [13]. Given the topology and line impedances the PTDF can be determined using the theoretical methodology described in the working paper. The network is described by its incidence matrix A and its line admittance matrix B_d. The incidence matrix is an LxN-matrix describing the topology of the network (i.e. which lines are connected to which nodes). Admittance matrix is an LxL-diagonal matrix with the DC line admittances on the diagonal. Given these matrices the PTDF-matrix can be calculated with the following formula.

$$PTDF_n(l,n) = (B_d \cdot A) \cdot (A^T \cdot B_d \cdot A)^{-1} \quad \forall l \in L, \forall n \in N \tag{4.12}$$

This method is valid and exact. In practice the TSOs determine the components of the PTDF matrix by executing multiple load flow analyses with small variations to the nodal injections. By determining the impact of the injection variations on the line flows the PTDF components can be derived.

Determination of NRAM

The directional remaining available margins for the market, $NRAM_{1,l}$ and $NRAM_{2,l}$ are determined by respectively subtracting and adding the LTN line capacity from the $F_{\max market,l}$. Given these parameters the nodal market coupling problem is completely defined and implemented.

4.4.3 Flow-based parameter calculations

To solve the flow-based optimization problem other capacity parameters need to be determined upfront. Schematically the calculation of the flow-based parameters is represented in figure 4.6. The zonal PTDF needs to be determined to model the flows. The RAM represents the remaining available margin for the market in the zonal market coupling implementation. To determine the zonal PTDF and the RAM respectively the GSKs and the base case need to be determined primarily.

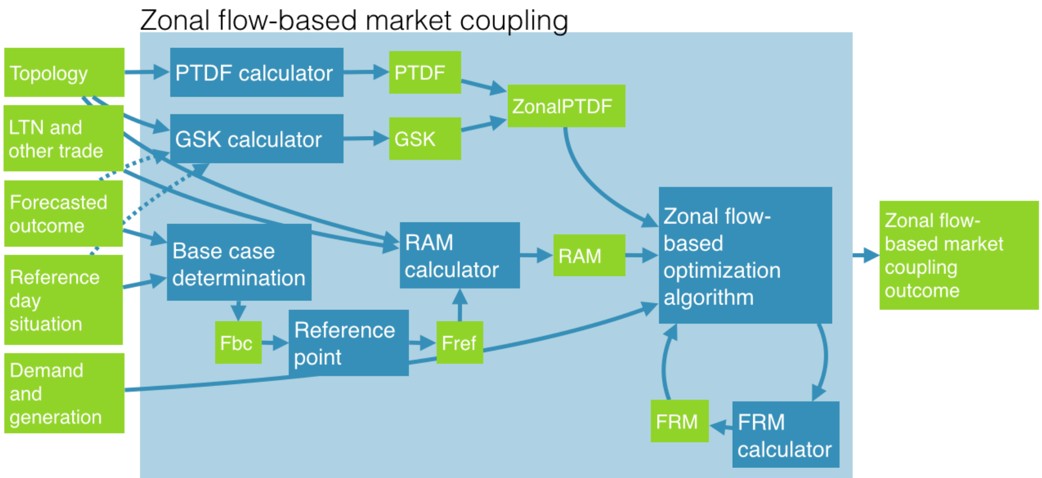


Figure 4.6: Structure of the zonal market coupling building block.

Base case determination

While in reality the base case is a prediction of the eventual state of the electricity grid the simulation model only considers a prediction of the day-ahead market outcome in the base case. As the non-market flows are assumed to be excluded from the input F_{max}, there is no need to estimate the non-market transaction by means of the base case. The base case determination is a combination of three steps as explained in Chapter 3.3. The last two steps can be aggregated in one function that determines the nodal generation and demand of the base case. The two steps now become: the determination of the net exchange position and the addition of the information of demand and generation forecasts. The structure of the base case simulator is shown in figure 4.7. From the methods that were explained in section 3.3 for each step 9 different base case implementations could be composed in total. We will only consider the three options that were proposed in the latest FBMC approval package [10].

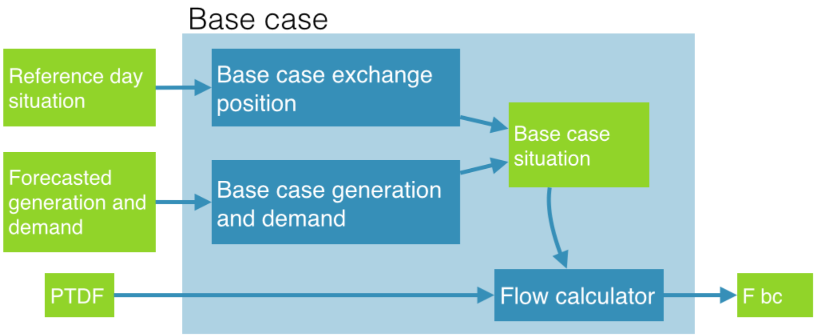


Figure 4.7: Structure of the base case calculation function.

1. **Zero exchange and forecast of generation and demand:** The exchange between zones is assumed to be zero, meaning the zonal net exchange positions are zero. From the demand and generation forecasts the total zonal demand and generation are determined. The smallest variable is fixed. The other variable is proportionally scaled in every node.

2. **Exchange based on reference day and forecast for generation:** For every zone the net exchange position is fixed to the reference day value. The expectations of generation are used as the generation data in every node. The total zonal demand is calculated by respecting the $G_z - D_z = NEX_z$ equation for each zone. The total zonal demand is divided uniformly over all nodes.

3. **Exchange based on reference day and forecast for demand:** Similar to the second implementation. Only now the expectations of the demand are used and the total generation is calculated respecting the $G_z - D_z = NEX_z$ equation for each zone. The total generation is divided over the nodes according to the generation forecast distribution.

The result of this function is a base case that contains an estimate of the generation and demand for every node. The base case situation is thus a completely defined network state of the market outcome.

GSK determination

For the determination of the GSK the three options currently used by TSOs (see section 3.2.1) can be implemented. The three options can be summarized as follows:

1. a uniform distribution between all plants of a zone;

2. a distribution proportional to the contribution to the base case;

3. a linear interpolation method determining the GSK for each generator equals the gradient of the line between the MWs produced at a max import and MWs produced at a max export position [10].

Once the GSK matrix is determined the zonal PTDF matrix is calculated by multiplying the GSK with the nodal PTDF as shown in equation 3.21.

RAM determination

Given the base case situation (bc) and the capacity available for the market, $F_{\max market,l}$ the directional RAMs are determined by respectively subtracting and adding $F_{ref,l}$ from $F_{\max market,l}$. $F_{ref,l}$ represents the base case flows that are not considered by a zonal flow modeling of the base case situation. This is expressed by the following equation:

$$F_{ref,l} = F_{bc,l} - \sum_{z=1}^{Z} PTDF_n(l,z) \cdot NEX_{bc,z} \quad \forall l \in L \tag{4.13}$$

With this $F_{ref,l}$ and the LTN the remaining available margin is determined by

$$RAM_{1,l} = F_{\max market,l} - F_{ref,l} - LTN_l - FRM_l \quad \forall l \in L \tag{4.14}$$

$$RAM_{2,l} = -F_{\max market,l} - F_{ref,l} - LTN_l - FRM_l \quad \forall l \in L \tag{4.15}$$

Allocation of the FRM

Lastly the flow reliability margin is introduced to compensate for the uncertainty. As was explained in section 3.2.3 this uncertainty is caused by 4 components. In the simplified simulation model only the second and third cause of uncertainty are relevant, viz. the inherent error due to approximations within the zonal flow-based methodology and the estimations that are used in these methods. Other uncertainty components disappear as a perfect prediction of the realized programs and thus the non-market trades are assumed. The FRM in this simulation only compensates for the fault caused by GSK assumptions. This research did not focus on FRM calculations. The FRM is assumed to be chosen perfectly meaning that the FRM is equal to the biggest line overload in case of running the FBMC with FRM equal to zero.

4.5 Conclusion

In this chapter a brief overview of the simulation model implementation is given. Following this overview the simulation model can be imitated in order to check the evaluation results that will be handled in the following chapter. As a way of reflection an overview can be made of all the modeling assumptions.

4.5.1 Model assumptions

In this simulation model a few important assumptions were made. Consequently these have to be taken into account when interpreting results of the simulation. In this section the most important assumptions will be discussed. To start the simulation model uses the same assumptions as made in the actual flow-based market coupling proposal. This implies that the flow-based calculations are based on DC power flow analyses; a linearization of the AC power flow that combines computational simplicity with an acceptable level of accuracy [13]. Second, the flow-based implementation considers only critical lines on which congestions are expected. In this simulation model some additional assumptions are made in order to have easily understandable results. These assumptions don't affect the fundamental approach of the flow-based market coupling.

Topology simplifications

- The grid topology is assumed to be fixed for all simulation moments and N-1 situations are not considered. This also implies that the position of tap changers is fixed.
- The topology used in the model is a strong simplification of the real grid. Components other than lines, active power generators and active power consumers are not considered. In reality the grid exists of hundreds of high voltage transmission lines. The simulated grid only exists of 16. This will be discussed further in the case study section.
- Only critical branches are considered. All branches of the study case are automatically considered as critical branches. In reality this is not the case as it would result in too many constraints for the optimization problem. Instead the TSO of each zone makes an estimate of which branches will be critical for each day. From the nodal PTDF matrix all rows corresponding with non-critical lines are simply deleted and subsequently not considered in the flow-based market coupling optimization.
- A final simplification with respect to the topology is that the CWE market zone is considered to be isolated from other market zones. Exchanges with other market zones are not considered in the model.

Market simplifications

- The final state of the grid at the delivery day is considered to be a combination of the LTN and the day-ahead market. Transactions on other markets, like forward markets and non-market transactions resulting from the portfolio program are not considered. This assumption was explained while discussing the $F_{\max\ market,l}$ parameter.

- The demand curve is completely inelastic. Consequently, considering bids for the demand is irrelevant. The implementation of the market coupling only has to consider the generation bids to fulfill the hourly demand in each node. This assumption simplifies the interpretation of the market outcome.

- The generation bids are characterized by a certain capacity and marginal cost for each hour. In reality these bids can be done for multiple periods at once, called block bids. These type of bids are not considered in the model. For each hour the generation bids are considered independent from the previous or following periods.

Forecasting

- This research does not have the aim to make accurate forecasting models nor does it have the data to do so. The used forecasting data are therefore always derived from reality by adding a random Gaussian deviation.

- The practical determination of the base case consists of a large number of corrective measures to improve the accuracy of the forecasts [10]. In this model the base case determination is limited to the basic principles that are proposed in order to focus on the validation of the fundamental approach.

Chapter 5

Evaluation of the flow-based parameter calculations

In this section we hope to find the answers to the following questions: what are the best methods for the determination of the flow-based capacity parameters? What is the influence of the GSK assumptions? What is the influence of uncertainty on all this and is it possible to reduce the safety margins of the flow-based calculations?

To find answers to these questions, the evaluation starts with the analyses of four specific hourly cases that will provide insight in the calculation process. A second part will cover the weekly simulation results. These are more comprehensive but they uncover some expressive results for the flow-based market coupling methodology. A comparison is made between the different methods for the base case and the GSK calculation in order to find the optimal methodologies. Both for the base case and the GSK calculations currently 3 different methods are used by different TSOs. To determine the optimal approach these methods will be applied to the complete market area. In total 9 different scenarios, that will be evaluated over a weekly simulation, can be distinguished. These scenarios are shown in table 5.1. To compare the different methods, parameters which indicate the 'goodness' and 'correctness' of the capacity calculations have to be defined. The eventual total generation cost that is minimized in the flow-based market coupling can be considered a good quantitative indicator. The total generation cost of the exact nodal flow-based market coupling is the most ideal cost situation. The difference between the nodal and flow-based total cost can be considered as a 'goodness' indicator. A lower total cost after the market coupling for the same market input situation indicates better capacity parameters. However this is only valid if the market solution results in real flows that are technically feasible and don't exceed the system limits. The feasibility of the solution thus has to be checked and line overloads can be seen as a second evaluation criteria. A last evaluation indicator is the converge rate. This represents the ratio of time steps with complete price convergence to the total number of time steps for a simulated week. Again the nodal solution can be seen as the reference/maximal

Scenario	GSK method	Base case method
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

Table 5.1: The different scenarios with their respective GSK and base case methods.

converge rate. In a final stage of the evaluations the impact of imperfect predictions is considered. A sensitivity analysis is made to determine the impact of predictions.

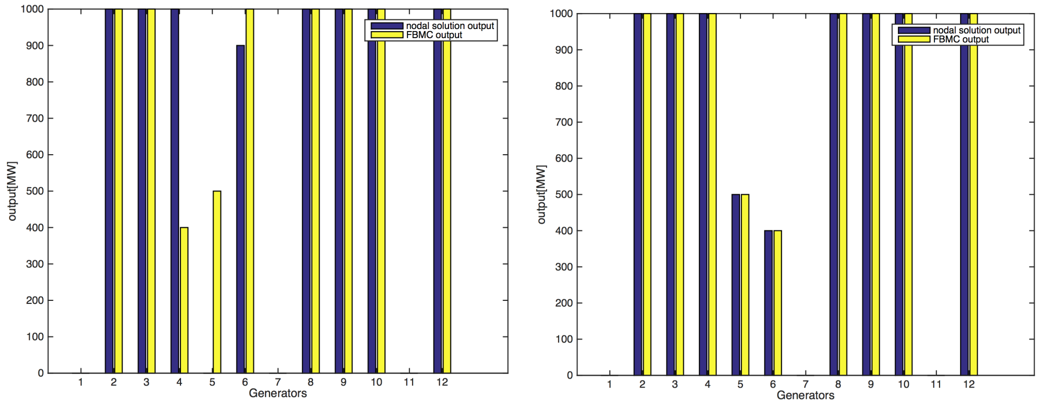
5.1 Hourly analysis

In a first step a differentiation of 4 cases is made. For each case the FBMC algorithm uses the first GSK and base case method (scenario 1) for the determination of the capacity parameters.

5.1.1 Case differentiation

Non-congested case

A first case that can be considered is the solution of the mean study case data as given in section 4.2. Given these input data the nodal and flow-based market coupling both find a non-congested solution for which the electricity prices in all zones will be equal. For the studied case the prices in all zones are equal to 40 €/MWh. Subsequently the total cost is equal for the nodal and FBMC outcome. When multiple solutions with the same total generation costs are feasible, the nodal and flow-based market coupling will not necessarily result in the same solution. This is for example the case when two price-setting generation units have equal marginal generation costs as shown in figure 5.1. Figure 5.1a represents the outcome of the mean study case data. In figure 5.1b the generation bid costs are varied a little, by adding small variations of 0.1 €/MWh to the mean study case data, in order to have different costs for each generator bid. In the second situation the nodal and FBMC solution are exactly the same while the first situation results in two different generator outputs. Even in non-congested cases the FBMC outcome is not unambiguously defined and different parameter calculation methods can result in different solutions. Only when all accepted generator units have different costs the non-congestion outcome of FBMC is equal to the ideal nodal market coupling outcome.



(a) For generation bids with equal costs. (b) For generation bids with different costs.

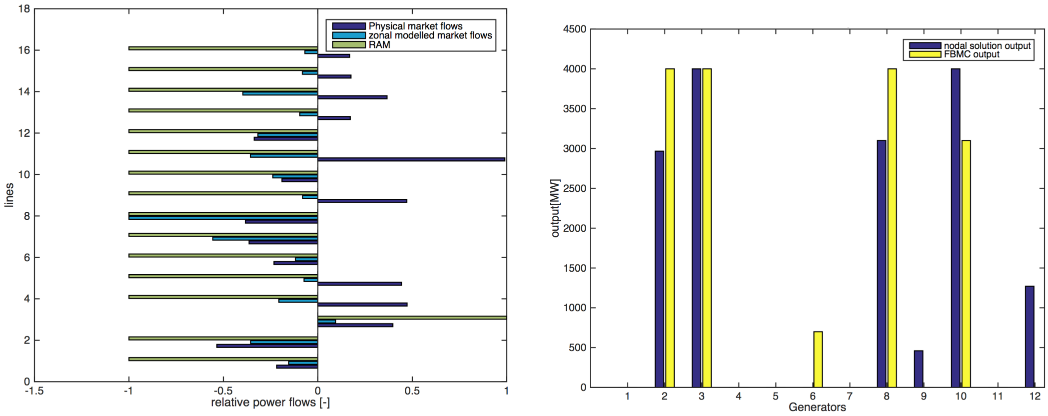
Figure 5.1: Generation output for an non-congested case using the nodal and FBMC solver.

Nodal non-congested, FBMC congested case

The nodal non-congested, FBMC congested case is a second situation that can be distinguished. This situation is obtained by multiplying the demand and generation capacities by two. The nodal solution algorithm finds an optimal solution without congestion. In the FBMC on the other hand the optimal solution assumes congestion. As can be seen in figure 5.2a the flow constraint is active for line 8 as the market modeled flows are equal to the RAM. In this figure relative flows with respect to the RAM of the modeled flow direction are represented. The real physical market flows, calculated by plugging the zonal flow-based market outcome into a nodal network model, are nowhere near to the RAM limit. The flow-based methodology is blocking a feasible solution caused by wrong flow modeling. The flow-based market coupling solution is less optimal than the nodal market algorithm as the total generation cost for the FBMC solution is higher and the rate of price converging is lower.

Congested nodal, non-congested FBMC case

A third characteristic outcome situation can be created by multiplying the demand and generation capacity with 1.5. For this input the nodal market coupling solution reckons congestion resulting in different nodal prices.The flow-based market coupling algorithm does not notice this congestion because of inaccurate flow-modeling. The zonal modeled flows deviate from the physical market flows and the loop-flow component doesn't compensate for the error. The optimal solution according to the flow-based market coupling approach is in reality infeasible due to a physical overload of 346 MW on line 11 (see figure 5.3) The resulting solution of the FBMC has a lower total generation cost relative to the nodal solution. The FBMC considers an infeasible solution when optimistic (FRM equal to the line overload if FRM would be zero) flow reliability margins are considered. This clearly indicates that



(a) Comparison of relative flows with respect to the restricting component of the directional RAM.

(b) Generation output of the market algorithms.

Figure 5.2: The flow and generation outcome of the nodal non-congested, FBMC congested case.

in reality high FRM have to be used to cope with the methodological error of the flow-based approach as a result of inaccurate flow-modeling. Without high FRM the TSO would have to take expensive re-dispatch measures to prevent the overload. The cause of this problem will be explained in detail in section 5.1.3 when the loop flows will be analyzed. The FBMC using the current capacity parameter calculation methods can result in infeasible market solutions. A total cost lower than the nodal market coupling solution is a sufficient condition for infeasibility. It is not a necessary condition as also FBMC solutions with costs higher than the nodal solution can be infeasible.

Congested case

In a final possibility both the nodal as the FBMC solution have congested lines in their market solution. The nodal and FBMC will have different total costs and generation outcome. Similar to the previous case the FBMC can result in infeasible situations when the flow modeling of the congested line is not accurate enough.

5.1.2 Theoretical flaw in the flow-based market coupling

The fundamental function of generation shift keys is to transform the nodal constraint to zonal constraints. The current GSKs are defined as the change in the node injection compared to a change in the net export position of the zone to which the node belongs. Mathematically this is written as follows:

$$GSK(n,z) = \frac{dP_n}{dNEX_n} \quad \forall n \in N, \forall z \in Z \tag{5.1}$$

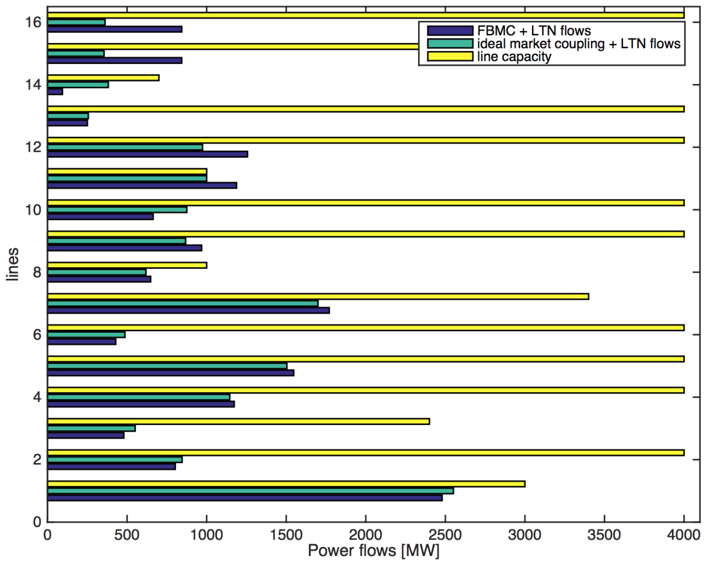


Figure 5.3: Comparison of absolute value of the physical flows of the solution resulting from the market with the maximum line capacity for the nodal congested, flow-based non-congested case.

On the market the aggregated generation bidding curves of zones are stepwise non-linear functions. This has two major consequence. The non-linearity of the biddings curves implies that the determination of the GSK strongly depends on the reference point for which the derivative is taken. The stepwise form of the function implies that a local derivative would always be zero or one. When the export position of a zone changes this is intrinsically always done with just one generator. For an increase of the NEX the cheapest available generator will deliver the additional power, for a decrease the most expensive generator in operation will decrease its output. The currently used definition of GSKs should result in ones or zeros divided over the nodes depending on the reference point of the derivative (see figure 5.4). The current FBMC optimization is done using GSKs between 0 and 1 that are independent from the reference point [6]. The current definition of GSKs is fundamentally wrong.

5.1.3 Wrong prioritization caused by inaccurate GSKs compensated by loop flows

In this simulation the $F_{ref,l}$ is equal to Fo_l as the non-market flows are considered to be already subtracted in the input $F_{\max,l}$. The need for this loop flow correction is clearly illustrated with the simulation. The zonal flow-based modeled flows and

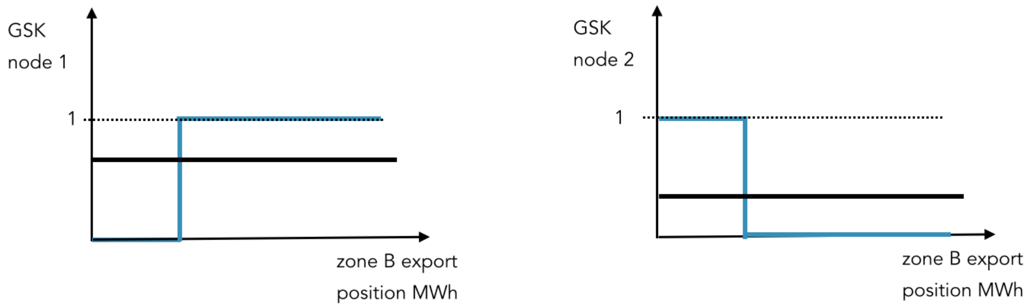


Figure 5.4: Graphical representation of the GSK assumption.

physical flows can be determined respectively with

$$F_{z,l} = \sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z \tag{5.2}$$

$$F_{n,l} = \sum_{n=1}^{N} PTDF_n(l,n) \cdot P_n \tag{5.3}$$

For the mean data case market outcome, these flow calculations are shown in figure 5.5. There is a clear difference between the flows (assumed by the market when using

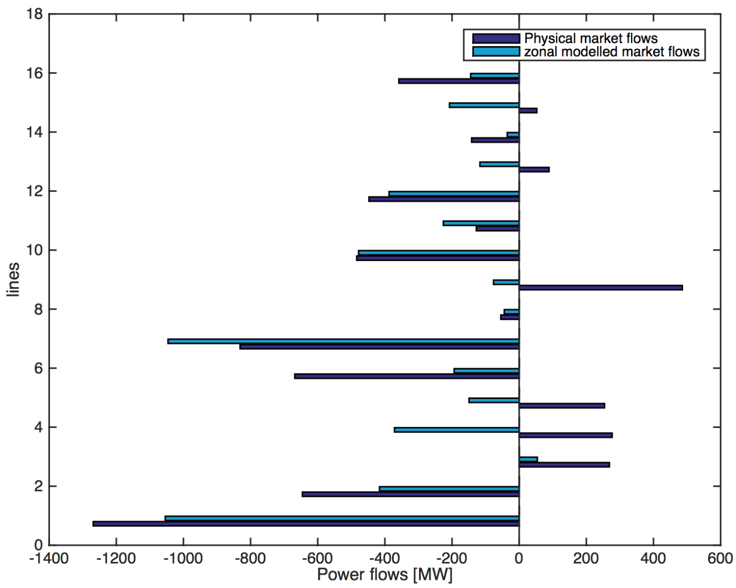


Figure 5.5: Comparison of nodal and zonal flow determination for the first scenario.

zonal calculations) and the physical market coupling flows. The difference between these two flow calculations, $F_{error,l}$ is a good measure for the accuracy of the GSK methods.

$$F_{error,l} = \sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z - \sum_{n=1}^{N} PTDF_n(l,n) \cdot P_n \tag{5.4}$$

The difference should be taken into account by loop flows that are derived from the base case. For the determination of Fo_l all "market flows" are subtracted from the total base case flows using formula 3.30.

When the base case contains an accurate prediction of the market outcome the loop flows will be equal to the error flows. This is shown in figure 5.6 for the mean input data. In this case the loop flows completely compensate the zonal modeling error

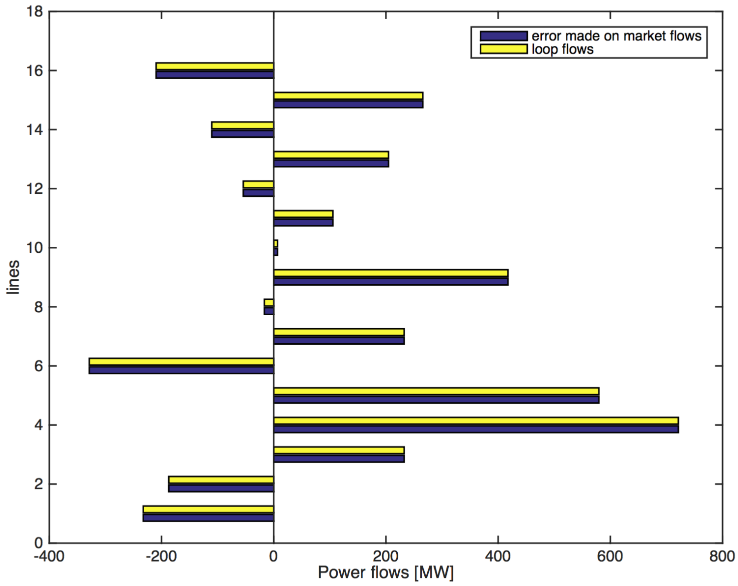
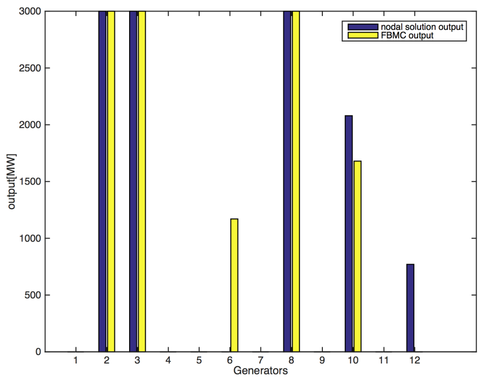


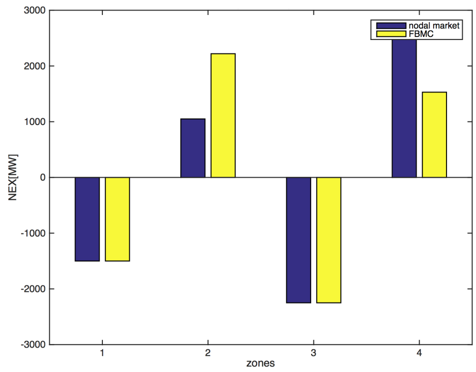
Figure 5.6: Comparison of loop flows and error flows in case of perfect prediction in the base case.

caused by the GSK assumptions. Even though the modeling error is compensated by loop flows as a component in the RAM, the real physical flows are not completely considered within the optimization algorithm. This has important consequences for the "correctness" of the FBMC methodology. In case of congestion the algorithm could give priority to an exchange that in reality has an even worse impact on the congested line. So even when in the best possible case a perfect base case prediction is used and the physical flows are taken into account by the superposition of loop flows and zonal modeled flows, the optimization process itself (considering only zonal modeled flows) does not take into account the physical flow effect of a transaction.

This effect is shown in figure 5.7 for scenario 9 (third GSK and base case method) in case of 1.5 times the mean data case. The nodal solution clearly shows that the



(a) Generation output of the nodal and FBMC.



(b) The resulting net exchange position of the zones.

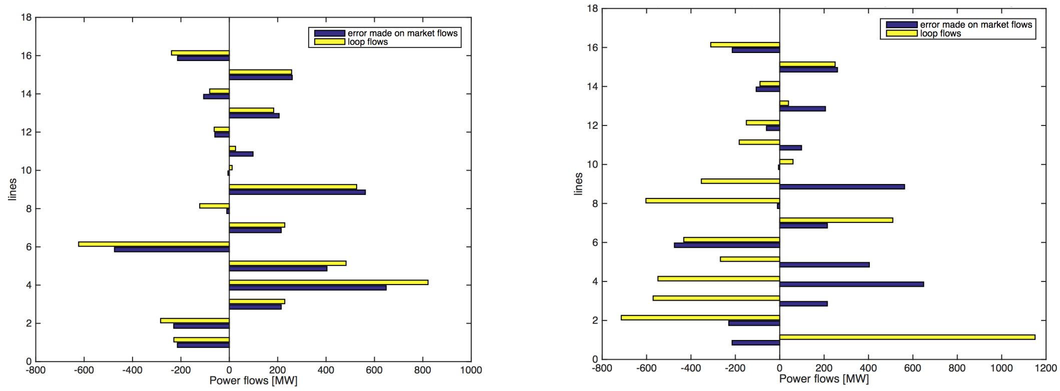
Figure 5.7: Results for a congested case using the scenario 9 methodology on the mean data case multiplied with 1.5. This solution is a clear example of wrong prioritization caused be GSK.

generator in node 12 is economically interesting to fulfill the South German demand despite of the limited transmission capacity of line 14. In the zonal flow-based modeling however, the GSK of node 12 is estimated to be 0.2. Consequently, the model will determine that more generation in node 12 has a high impact on the flow of line 14 from France to Germany. The FBMC will conclude that it is more efficient to use the more expensive generator in node 6. However, in the nodal solution the net injection in node 12 will still be lower than zero. The GSK of node 12 should be -0.3. Flows in line 14 will flow from Germany to France so increasing the generation in node 12 would only diminish the congestion of line 14. The FBMC assumed that it would increase the congestion on line 14. Unjustified priority is given to generation in node 6.

This faulty prioritization is theoretically explained by the netting effect (see section 3.2.2) that is incorporated in the current GSK implementation. The netting effect, resulting from the sheer positive GSKs, implies a loss of information that is compensated by loop flows. The transactions covered with these loop flows are subsequently not correctly considered in the optimization algorithm.

5.1.4 Base case estimation

In the simulation model the base case ideally should be a perfect estimation of the market coupling outcome. In most cases the base case prediction will not enclose a perfect market outcome estimation because of two reasons. First of all the data used for the predictions will not be perfect. Second, the specific methodology used to make an outcome prediction from this data (the base case method) will additionally introduce an error. Consequently, the loop flows derived from the base case will not accurately compensate for the zonal modeling error. This is shown for two base



(a) Base case with accurate market information assuming a nodal market solution.

(b) Base case according to the second base case methodology.

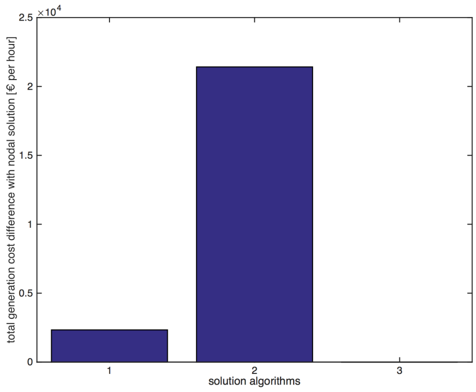
Figure 5.8: Comparison of loop flows and error flows for an hourly calculation for two base case estimations.

case estimations in figure 5.8. The right graph represents a base case with accurate market information that assumes a nodal market solution. In this case the base case is determined by running a nodal market coupling on exact market input bids. Because of the assumption of a nodal market coupling the base case will not perfectly correspond with the FBMC outcome. There is a difference between the error and loop flows. So even when the generation bids and demand are accurately predicted, the methodology used for the base case prediction has an influence on the accuracy of the loop flow. Figure 5.8b demonstrates the results of base case estimation using the second base case methodology as described in chapter 3. A reference day is used for the determination of the net exchange position between zones instead of an accurate prediction. The resemblances between loop flows and error flows are almost non-existing. The wrong loop flow assumptions will result in underutilized or overloaded lines. As a conclusion it can be stated that two interesting measures have been distinguished to evaluate the goodness of the flow-based capacity parameter calculations. The accuracy of the GSK can be measured by the sum of all modeled flow-errors.

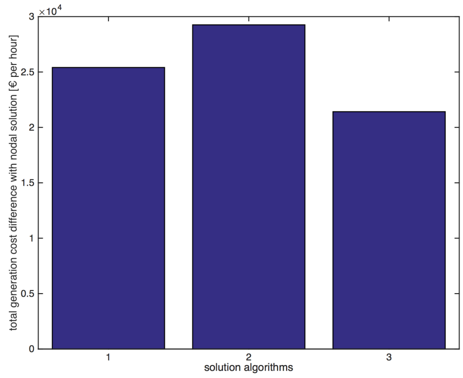
$$GSK\ accuracy = \sum_{l=1}^{L} \left| \frac{\sum_{z=1}^{Z} PTDF_z(l,z) \cdot NEX_z - \sum_{n=1}^{N} PTDF_n(l,n) \cdot P_n}{\sum_{n=1}^{N} PTDF_n(l,n) \cdot P_n} \right| \tag{5.5}$$

Subsequently, the difference between the error flow and the loop flows is a good measure for the "goodness" of the base case.

$$BC\ accuracy = \sum_{l=1}^{L} \left| \frac{F_{error,l} - Fo_l}{Fo_l} \right| \tag{5.6}$$



(a) The total cost difference of the solution in comparison with the nodal solution for the respective base case methods assuming the third GSK method.



(b) The total cost difference of the solution in comparison with the nodal solution for the respective GSK methods assuming the first base case method.

Figure 5.9: Comparison of the total hourly cost difference with the ideal nodal solution for different methods in a specific time slot.

These measures will be used for the evaluation of the simulated week. It can be stated that the currently used methods for the GSK determination and base case determination have an impact on the flow-modeling of the FBMC algorithm.

5.1.5 Hourly evaluation of the GSK and base case calculation methods

In case of congestion the different GSK and base case methods will lead to different results. In figure 5.9 a comparison of the cost difference with the nodal solution of different GSK and base case methods is given for a nodal and FBMC congested time slot. The considered demand and generation data are a factor 1.5 of the mean hourly data case. The different GSK methods clearly lead to different total costs of the solution. For this specific time slot the last GSK method and last base case have the best performance. In the weekly simulation we will verify if this result can be generalized.

5.2 Weekly simulation results

To determine the optimal methodology for the base case and GSKs the FBMC is simulated for a week for the 9 scenarios. In a first step the total hourly generation cost for the different scenarios can be examined. In figure 5.10 the relative hourly generation cost with respect to the nodal solution is shown for the first 24 time slots. The different approaches clearly result in different cost solutions in case of congestion (from time slot 8 to time slot 19 on the graph). Hourly cost of generation is up to 1.8 times higher than for the nodal solution. The impact of the FBMC implementation methodology is significant. In the figure a few scenarios with generation costs lower than 1 can be distinguished. In these respective scenarios and time slots the FBMC is unfortunately infeasible as overload is occurring. For these cases the TSO will have to re-dispatch generation to correct the market solution, leading in the end to a much higher cost. Such situations are undesired as they come with high costs. The price

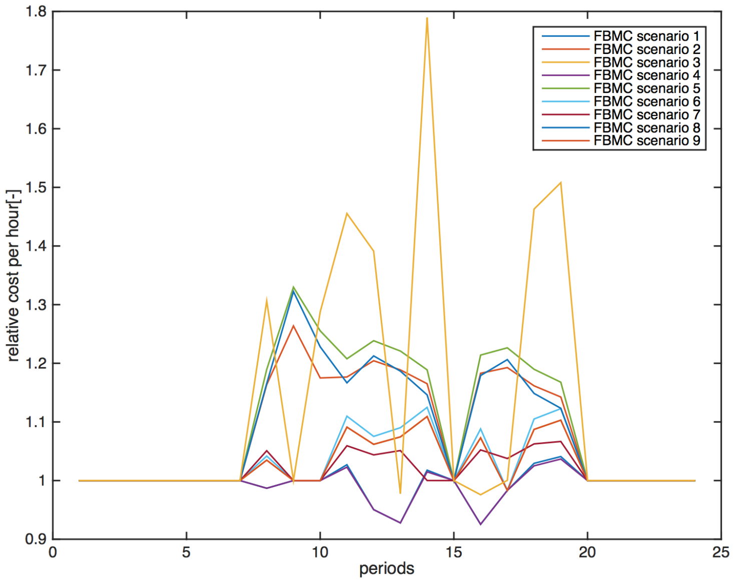


Figure 5.10: The relative cost with respect to the nodal simulation result for the first day of simulated week for the 9 scenarios.

convergence rate, shown in figure 5.11, is a second measure for the goodness of the methods. For the nodal market algorithm the price convergence ratio amounts 83%, as indicated by the red line. A normal week has a high number of non-critical time slots (nights and non-peak hours) resulting in this high number of price convergence. The FBMC scenarios have different price convergence ratios oscillating around the ideal nodal ratio. The higher convergence scenarios indicate high number of infeasible hourly solutions. In these cases congestion is not observed by the flow-based methodology. The seventh scenario has the highest price convergence that still is lower than the nodal convergence ratio. Table 5.2 gives an overview of "goodness" measures. First of all the total relative generation cost with respect to the nodal solution generation costs for the week is given. A few scenarios have costs lower than the nodal market solution. In these cases the low costs are caused by infeasible solutions with overload situations. The third column shows the percentage of time slots with overloads within the week. As this doesn't yet demonstrate the severity of the overload the sum of overloaded capacity is given in the fourth column. In the last two columns the base case and GSK correctness measures discussed in section 5.1.4 are given for the different scenarios. From the table and the previously discussed figures it can be stated that scenarios 7 and 8 are the best performing methodologies. Scenario 8 has a higher cost but a lower total overload capacity compared to scenario

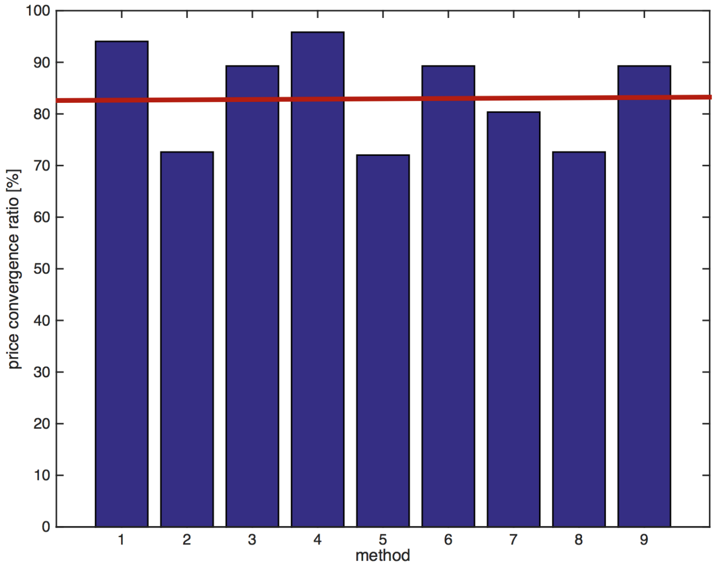


Figure 5.11: The convergence rate for the 9 different scenarios for the simulated week. The nodal price convergence is represented by the red line.

Scenario	relative cost	percentage of overload (%)	total overload capacity (MW)	GSK error (10^6 MW)	base case error (10^6 MW)
1	0.9949	14	4865.95	1.6597	0.5708
2	1.0633	2.19	97.938	1.6645	1.2624
3	1.0061	11.3	2976.84	1.6611	1.3983
4	0.9925	16.6	5667.37	1.5326	0.4817
5	1.0781	0.59	64.86	1.5263	1.2603
6	1.0080	11.3	2976.84	1.5328	1.3923
7	1.0149	1.19	221.55	1.2445	0.3040
8	1.0643	1.19	97.93	1.2318	1.2286
9	1.0061	11.3	2976.84	1.6611	1.3983

Table 5.2: Comparison of the results of the different scenarios for a week.

7. For further analyses scenario 8 will therefore be considered as most optimal. In this scenario the GSKs are calculated according to the base case distribution and the base case is determined using a reference day and generation predictions. However, even the optimal approach has a fundamental inaccuracy incorporated in its methodology resulting in a need for high safety margins, significant higher costs than the nodal solution, less price convergence and eventually still a few situations for which re-dispatching will be necessary due to overloading. Finally, it is important to realize that uncertainty yet has to enter the story.

Demand forecast standard-deviation (MW)	Relative total generation cost (-)	Percentage of overload (%)
100	1.1079	0
200	1.0412	12.50
300	1.0189	20.83
400	1.0522	4.17
500	1.0708	4.17
600	1.0839	4.17
700	1.0884	0
800	1.0926	4.17

Table 5.3: Comparison of the results for different demand uncertainties for a week.

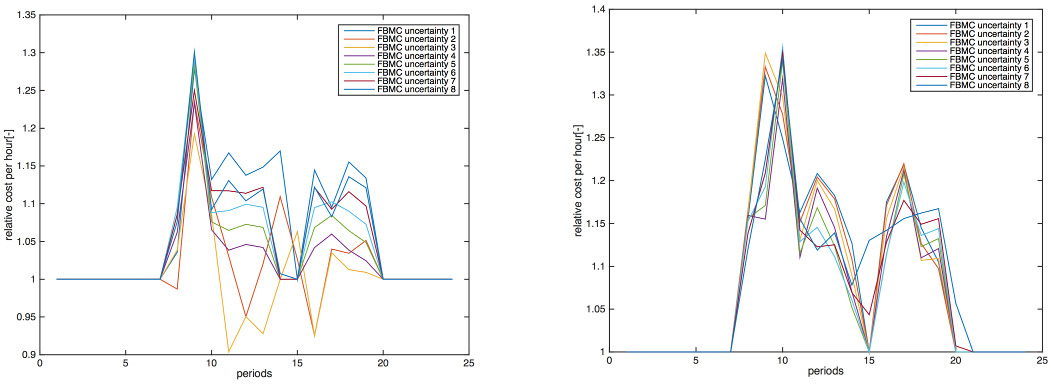
5.3 Sensitivity analysis with respect to uncertainty

Until now the predictions used in the simulation model have been considered to be perfect. This means that the demand and generation bid data of the prediction is equal to the actual data. The errors in the FBMC outcome are thus strictly caused by the methodology that is used. In a next step uncertainty can be added to the problem. A limited sensitivity analysis is done for two crucial sources of uncertainty. "Errors" in the outcome are now a substitution of the flow-based methodology and forecasting errors. For the analysis scenario 8 is considered. A first important component of uncertainty is the nodal demand forecasting error. The predictions of demand used for the determination of the flow-based capacity parameters will not be perfect. In figure 5.12a the effect on the relative generation cost of random Gaussian forecasting errors for the demand in each node is given. The standard deviation of the forecasting error is increased with 100 MW in each scenario. The total relative generation cost for the complete week and the overload ratio is given in table 5.3. It is clear that the performance of the FBMC decreases with increasing uncertainty. A combined effect of increased cost and increasing overloads can be noticed. Quantification of the impact of demand uncertainty is, however, not possible without quantifying the cost of overload.

A second major term of uncertainty is introduced in the prediction of renewable generation offered on the market. Accurately predicting the renewable generation capacity is much more difficult than predicting the conventional generation units because of its dependency on local weather conditions. With the outlook of increasing renewable market penetration the impact of these prediction faults is very relevant. In figure 5.12b the effect on the relative generation cost of Gaussian forecasting errors for the renewable generator capacities is given. The standard deviation of the forecasting error is increased with 200 MW in each scenario. The total relative generation cost for the complete week and the overload ratio is given in table 5.4. The increased uncertainty of renewables has no significant effect on the outcome. This is explained by the fact that renewable generation is only considered in Germany.

Renewable uncertainty per node (MW)	relative total generation cost (-)	percentage of overload (%)
0	1.1448	0
200	1.1455	0
400	1.1441	0
600	1.1209	0
800	1.1205	0
1000	1.1234	0
1200	1.1263	0
1400	1.1329	0

Table 5.4: Comparison of the results for renewable generation uncertainties for a day.



(a) 8 demand uncertainty scenarios. For each scenario the standard deviation of the demand forecast is increased with 100 MW.

(b) 8 renewable uncertainty scenarios. For each scenario the standard deviation of the renewable generation forecast is increased with 200 MW.

Figure 5.12: Comparison of the relative hourly cost for 24 time slots with respect to the nodal solution for different uncertainty scenarios assuming the third GSK and second base case method.

The uncertainty introduced on these generators apparently has no significant impact on the accuracy of the FBMC.

5.3.1 Stress scenarios

During the uncertainty analysis the flow-based market coupling algorithm concluded the non-existence of a feasible solution in three time slots while a nodal market coupling solution existed. Flow-based market coupling algorithm will in stress situations often conclude that a feasible solution is non-existing while the nodal market coupling will find a feasible solution. The liquidity of the market thus depends on the solution algorithm and the respective capacity parameters that are used. The flow-based market coupling has a significant lower liquidity than the nodal alternative.

5.4 Conclusion

It is clear that the current FBMC outcome strongly depends on the methods and the accuracy predictions that are used. From our evaluation it can be concluded that the second base case combined with the third GSK method results in the optimal performance. Yet the overall performance of the FBMC using the capacity parameters as currently defined, is substandard. The zonal flow calculation approach used in the FBMC is only accurate if the following two conditions are fulfilled:

- the market outcome prediction has to be exact. If this is not the case the loop flow component will not compensate for the flows not considered in the zonal flow-modeling;
- no congestion occurs. In case of congestion the GSK assumptions will result in wrong prioritization. When congestion arises the market coupling should value the impact of different injections on the lines to determine which injections are prioritized. With the current implementation the impact of an injection is only partly considered within the market coupling (GSK), a second part is considered as fixed outside of the coupling (Fo). The prioritization will therefore not be accurate.

The GSKs determine the prioritization of the bids in case of congestion and should accurately represent the distribution of the NEX position of a zone over its nodes. As long as GSKs don't entail the real distribution of the market outcome the flow modeling will always be wrong. As a consequence the market solution will not be the best possible optimal solution in case of congestion. Wrong GSK assumptions result in wrong prioritization of the bids. Additionally, it is unfair and non-transparent that part of the flows are considered in loop flows outside of the optimization process. An accurate flow-based market coupling should consider all physical flow effects inside the market coupling. For this the GSKs should accurately represent the distribution of injections within a zone.

In practice the results of the flow-based market coupling are rather positive. The results of the parallel run presented in the design decisions document of the CREG [11] clearly show an increase in price convergence and social welfare compared with the current ATC market coupling. These results are not really in line with the conclusions that can be drawn from the current simulation model, which can be explained by two reasons. First of all in this research the FBMC is compared with an ideal nodal market coupling instead of the ATC market coupling which is highly under-performing in congested situations. A second explanation is found in the parameter tweaking done by the TSOs to achieve a performant system given the behavior of the market parties. During the long period of parallel runs TSOs have perfected the capacity parameters with corrective and complex measures, given the expected behavior of the market parties [4].

Chapter 6

Improvements in the flow-based parameter calculations

This chapter will discuss possible improvements to the flow-based market coupling. In a first section an overview is given of the errors made by the current flow-based market coupling. These errors indicate the problem areas in which to look for improvements. In a next step the improvements will be categorized in two groups. The first group covers improvements with the current FBMC proposal framework. The second group of improvements entails fundamental changes in the flow-based methodology. This classification is equivalent to making better assumptions and estimations on the one side and using less assumptions and estimations on the other hand.

6.1 Error made by flow-based market coupling

When using a flow-based market coupling the solution contains errors because of two major reasons. A methodological error caused by the methodology and assumptions used in the FBMC. Second, an error caused by inaccurate estimations and data used in the FBMC approach.

Both errors discussed in the previous paragraph will directly lead to incorrect flow modeling. This will in its turn result in a non-optimal market coupling solution. By decreasing the error that is made by the FBMC algorithm a more optimal welfare solution can be obtained. It should be noticed that not all errors have equal impact and importance. From the TSO's perspective, an underestimation of the flows is more dangerous than an overestimation. An underestimation could result in a line overload in reality. Such overloads are undesired so underestimation error could be penalized with a greater weight-factor.

6.2 Possibilities for improvements within the current FBMC framework

Given the current FBMC framework one can work on two fronts to increase the total welfare from a theoretical perspective:

- decreasing the flow reliability margins by decreasing the level of uncertainty. This would result in a higher available capacity $RAM_l = F_{max,l} - F_{ref,l} - FRM_l$;
- more accurate flow modeling.

These different options are interlinked. More accurate modeling of the flows could directly decrease the need for safety margins. In both options the eventual aim is to better match the flow-based domain with reality constraints. Within the current FBMC proposal there are two opportunities:

- improve the base-case determination in order to more accurately predict the eventual outcome;
- improve the GSKs estimation.

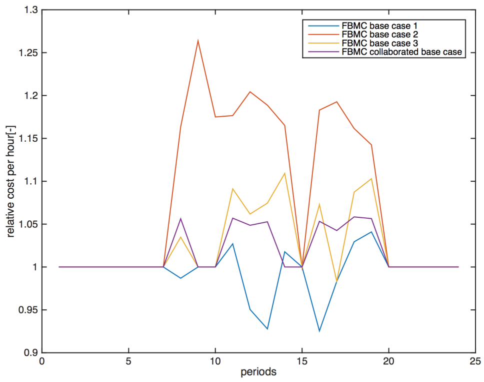
Improving both estimations means the usage of more accurate regression models that take into account more data to predict the future, given the expected weather and network configuration. In theory a very sophisticated prediction model is not very difficult. The practical realization of these estimation models is complicated by the need for collaboration between TSOs. Sophisticated prediction models should be made by 1 entity for the whole market zone and thus require all TSOs to work together.

6.2.1 The need for European collaboration

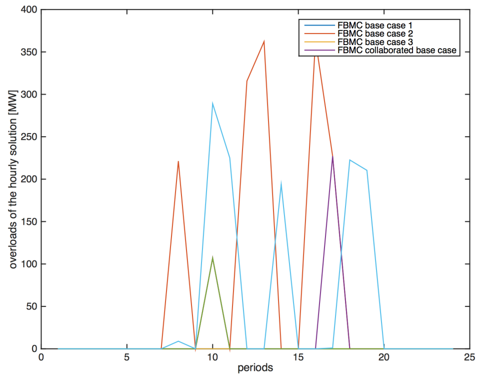
The need for collaboration can be demonstrated for both the base case and the GSK determination.

Effect of improved base case

In the current flow-based proposal the lack of collaboration between TSOs results in very basic estimation models. The NEX positions for all zones have to balance each other out so TSOs have simply agreed to use the NEX position of a reference day. The NEX estimation thus is very basic. It even doesn't entail information about the expected weather conditions of the delivery day. If TSOs aggregated all their information and knowledge to determine the expected NEX positions with a



(a) The relative hourly generation cost with respect to nodal solution for the three base case methods and a base case approach assuming perfect collaboration between the parties.



(b) The hourly capacity overloads for the different base case scenarios.

Figure 6.1: Comparison of different base case scenarios assuming the third GSK methodology.

prediction model, the NEX estimation would be much more accurate. The original expression for the net exchange position,

$$NEX_{bc,z} = NEX_{reference\,day,z} \quad \forall z \in Z \tag{6.1}$$

could for example become

$$NEX_{bc,z} = f(NEX_{hist,z}, weather, network) \quad \forall z \in Z \tag{6.2}$$

The effect of a collaboration to make the base case based on expected generation and demand bids for the whole market zone is illustrated in figure 6.1. The relative cost and overload capacity for the three base case methods and a collaboration method is mapped for 24 time slots. The GSKs in this simulation are determined using the third methodology. The collaboration method clearly results in lower relative costs without allowing infeasible situations. This improvement requires no extra information or data. Only a collaboration between the TSOs is necessary in order to determine the NEX positions of the base case using forecast for demand and generation for the complete market area. A better base case results in a more accurate flow-based outcome and subsequently less overload as shown in figure 6.1b. At this moment the TSOs have figured out the importance of collaboration with respect to the prediction of the zonal exchange position. They are making efforts to accommodate a more sophisticated and accurate NEX prediction model [11].

Uniformly defined generation shift keys

The better the base case the less impact the GSK assumptions will have on the modeled flow solution. The loop flows derived from the base case then compensate for the errors of GSKs. Still the GSKs have a major impact on the prioritization of the bids in case of congestion. The current GSK calculation methods themselves are currently very basic guesses. The reason for the basic approach is in this case not only the lack of international collaboration. The GSK calculation method has a very important influence in the prioritization of the different generation bids in case of congestion. In theory the most accurate determination of GSKs could be done by deriving the GSK from an accurate estimation of the market outcome. Solving the market algorithm with GSK assumptions derived from an estimation of the market outcome brings the TSOs in an awkward position. The TSOs' market outcome predictions directly influence the eventual market outcome. For some market parties this would be a stumbling block for the objectivity of the FBMC. To avoid being blamed for market manipulation TSOs therefore opt for simple and transparent approaches like uniform distributions despite the fact that GSKs based on market outcome predictions would lead to more accurate flow-based modeling results. This was proven in the previous chapter as the optimal GSK choice is a distribution according to the base case prediction. Further improving the GSKs by using more accurate prediction seems difficult without compromising the objectivity of the market solution.

Yet, there is room for improvement. In the current FBMC proposal the determination of the GSKs is not harmonized. Each TSO applies a method of its own choice for the determination of the GSKs within its zone. In the simulations so far, 1 GSK method is applied to the complete market area. To determine the impact of the unharmonized approach a fourth GSK method is defined with different GSK methods for different zones. In each zone, the GSK method is used that is applied by its TSO according to the official approval package [10]. The results of this unharmonized method is shown in figure 6.2 assuming the second base case method. The relative cost of the unharmonized GSK approach that is currently operational is in all congested time slots higher than for the uniform methods. Determining the GSKs in the same way in all market coupling zones, even with very basic methods, still has potential to improve the overall flow-based market coupling outcome.

6.3 Improvements to the flow-based approach

In a second step we investigate the possibilities for fundamental changes with respect to the flow-based approach in order to decrease the need for estimations and assumptions. As concluded in the previous chapter the current FBMC still doesn't model the flows exactly. Implementing an alternative that models the flows more accurately without using assumptions and estimations, will lead to better market solutions and potentially a decrease in the necessary safety margins.

6.3.1 An iterative flow-based market coupling algorithm

To demonstrate and explain an improved implementation of the flow-based market coupling we come back to the three nodes, two zones illustration example used

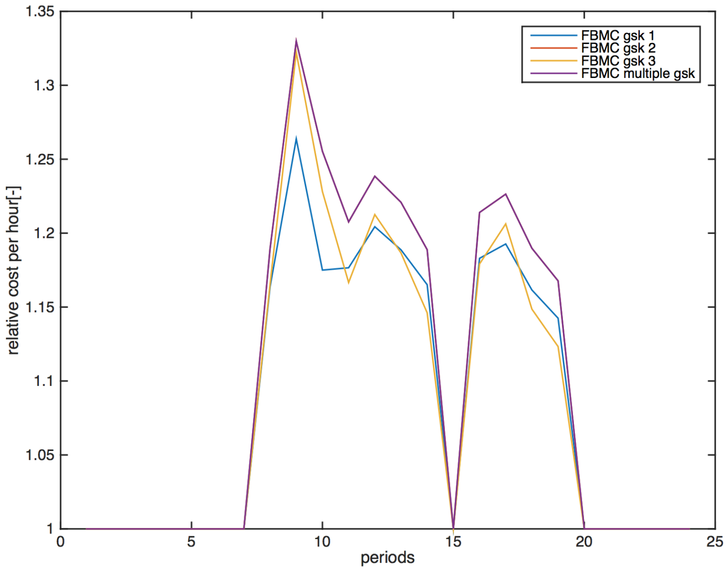


Figure 6.2: Comparison of the hourly relative costs of the different GSK and an unharmonized GSK approach for 24 time slots. In the unharmonized scenario each zone uses one of the GSK methods. In all cases the base case is determined using the second base case method.

in chapter 3 and shown in figure 6.3. Again the network description approach is considered first, before discussing the optimization procedure.

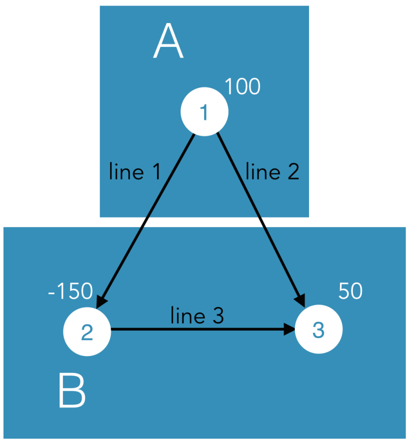


Figure 6.3: Three nodes, two zones example

Proposition 1: an alternative GSK definition

In the market coupling the GSKs are used to capture the distribution of all the generation on the market within one zone. If the bidding-curves were be linear the current GSK linearization would be an acceptable way to bring into account the generation distribution. With non-linear and stepwise functions this linearization by using the derivative is, from a theoretical perspective, very doubtful. The current GSK definition (linearization) is wrongly used in a non-linear context and additionally leads to loss of information because nodal injections not contributing to the NEX are not taken into account correctly (netting effect explained in section 3.2.2). An alternative definition of GSKs seems therefore appropriate.

The GSK could be defined as the proportion of the nodal market injection to the zonal net exchange position of the market result:

$$GSK(n,z) = \frac{P_n}{NEX_z} \quad \forall n \in N, \forall z \in Z \tag{6.3}$$

With this definition less information is lost. There is no netting effect as both demand and generation is considered in the nodal injections. A more appropriate name for this new parameter would be the node shift keys (NSK) but for now the terminology of GSKs is kept.

Proposition 2.1: GSK as an endogenous parameter instead of exogenous input parameter

Ideally this new GSK definition could be directly included in the optimization algorithm. Then the GSK is no longer an input parameter but is directly linked to the variables in the optimization process. The flow limit equations of the algorithm become:

$$F_l = \sum_{z=1}^{Z}(\sum_{n=1}^{N}(PTDF_n(l,n) \cdot \frac{P_n}{NEX_z}) \cdot NEX_z) < F_{max,market} \quad \forall l \in L \tag{6.4}$$

This approach implies problems. First of all the nodal location of the bids needs to be known. In the old approach only the zonal exchange position was required as variable in the optimization process. The new approach also uses the nodal injections P_n as a variable. This information is currently not provided by the market bidders. Providing this information to the market is in practice not that difficult and doesn't require much change. Until now it has just not been done because the information seemed reluctant in a zonal pricing implementation.

A second, more serious problem is that the flow limit constraint equation is no longer linear. Solving a non-linear problem is very hard, unstable and often has multiple solutions. These characteristics are undesired in the context of an electricity market. The importance of a reliable and stable solution is preferred over an unreliable but theoretical correct solution. The non-linear approach of solving the market with the GSKs as an internal parameter in the optimization however sheds a new light for an alternative linear approach.

Proposition 2.2: iterative GSK input parameter

To convert the non-linear problem to a linear issue an iterative method could be used. In every iteration the market coupling is solved using GSKs that are derived from the market solution of the previous iteration. The GSK of iteration i+1 is defined as:

$$GSK^{i+1}(n,z) = \frac{P_n^i}{NEX_z^i} \quad \forall n \in N, \forall z \in Z \tag{6.5}$$

with P_n^i and NEX_z^i defined as respectively the nodal injection and the zonal exchange position of the i-th iteration. In each iteration i+1 the market coupling algorithm is solved using the GSK^{i+1} as an input parameter to calculate the zonal PTDF.

$$PTDF_z^{i+1}(l,z) = \sum_{n=1}^{N} PTDF_n(l,n) \cdot GSK^{i+1}(n,z) \quad \forall l \in L, \forall z \in Z \tag{6.6}$$

The line flow constraint now becomes

$$F_l^{i+1} = \sum_{z=1}^{Z} PTDF_z^{i+1}(l,z) \cdot NEX_z^{i+1} < F_{max,market} \quad \forall l \in L \tag{6.7}$$

To initiate the iterative process a first estimate of the GSKs is required. After a few iterations convergence should be reached. Then, the flows are calculated exactly within the market coupling optimization algorithm. This has two important benefits. First, there is no need for a corrective measure using loop flows. Consequently the base case no longer needs to be determined to estimate the loop flows. Second, the optimization process now considers the complete flow effect of an injection. The prioritization of the bids will subsequently be more optimal.

Example The methodology of proposition 1 en 2.2 can be demonstrated on the three nodes example. Assuming a perfect prediction of the market outcome, we have the following initial estimate to start the iterative process.

$$\begin{bmatrix} P_1^0 \\ P_2^0 \\ P_3^0 \end{bmatrix} = \begin{bmatrix} 100 \\ -150 \\ 50 \end{bmatrix}, \begin{bmatrix} NEX_1^0 \\ NEX_2^0 \end{bmatrix} = \begin{bmatrix} 100 \\ -100 \end{bmatrix} \tag{6.8}$$

The GSK-matrix for the first iteration, using the new GSK definition, is given by:

$$GSK^1 = \begin{bmatrix} 1 & 0 \\ 0 & \frac{3}{2} \\ 0 & -\frac{1}{2} \end{bmatrix} \tag{6.9}$$

The flow-based optimization algorithm will optimize the market, taken into account the flow constraint equation. The flows are calculated exactly within the market coupling optimization algorithm.

$$\begin{bmatrix} F_1^1 \\ F_2^1 \\ F_3^1 \end{bmatrix} = \begin{bmatrix} 0.667 & 0 & 0.333 \\ 0.333 & 0 & -0.333 \\ -0.333 & 0 & -0.667 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ 0 & \frac{3}{2} \\ 0 & -\frac{1}{2} \end{bmatrix} \times \begin{bmatrix} 100 \\ -100 \end{bmatrix} = \begin{bmatrix} 83.3 \\ 16.6 \\ -66.6 \end{bmatrix} \tag{6.10}$$

The solution is found feasible as the flows don't exceed the market capacity limitations. The market solution of the first iteration equals

$$\begin{bmatrix} P_1^1 \\ P_2^1 \\ P_3^1 \end{bmatrix} = \begin{bmatrix} 100 \\ -150 \\ 50 \end{bmatrix}, \begin{bmatrix} NEX_1^1 \\ NEX_2^1 \end{bmatrix} = \begin{bmatrix} 100 \\ -100 \end{bmatrix} \tag{6.11}$$

GSK^2 will be equal to GSK^1, indicating that convergence is reached and no further iterations are needed.

In reality the initial guess of the market outcome will never equal the eventual market coupling solution. To reach convergence at a sufficient speed it will be important that the initial guess is "good enough". To determine how good this initial guess has to be, research will have to be done using the exact topology data of the flow-based market coupling. A second consideration is the stability of the iterative process. In this context an important problem is detected in the GSK definition in the iterates. When the NEX_z^i of the i-th iteration solution equals zero, the GSK^{i+1} is undefined. Even when not zero but just small the GSK components will be very high and the stability of the iterative process will be affected. A possible remedy for the problem is to replace the NEX with bigger values for the GSK calculation process if the NEX solution values are too small. This stability issue will have to be considered and addressed in a real implementation proposal.

The conceptual improvement proposals can be summarized as follows. The new GSK definition solves the problem of information loss incorporated in the present GSK definition. The iterative approach solves the problem of GSK prediction faults by iterating until the GSK estimations correspond with the market solution. Loop flow compensation measures are no longer needed. Subsequently the prioritization of the market bids should be more correctly. A base case prediction is merely needed for an initial guess of the GSKs. This initial estimation will not have an impact on the market solution if the iterative process converges.

6.3.2 Modeling an iterative flow-based market coupling approach

Model description

To verify if the new flow-based implementation proposal entails significant improvements in comparison with the current methodology, the described iterative method is implemented in Matlab and GAMS and used to model the 12 node market coupling. The structure of the implementation is shown in figure 6.4. To solve the instability problem the NEX is assumed to be one for the determination of the GSKs for the next iteration if the absolute value of the market outcome NEX were smaller than one. The same FBMC optimization market solver is used as in chapter 5, only now the solver is used for multiple iterations. It was noticed that the quadratic programming solver performed better in the iteration process as it has less issues with the numerical instability due to the GSK iteration.

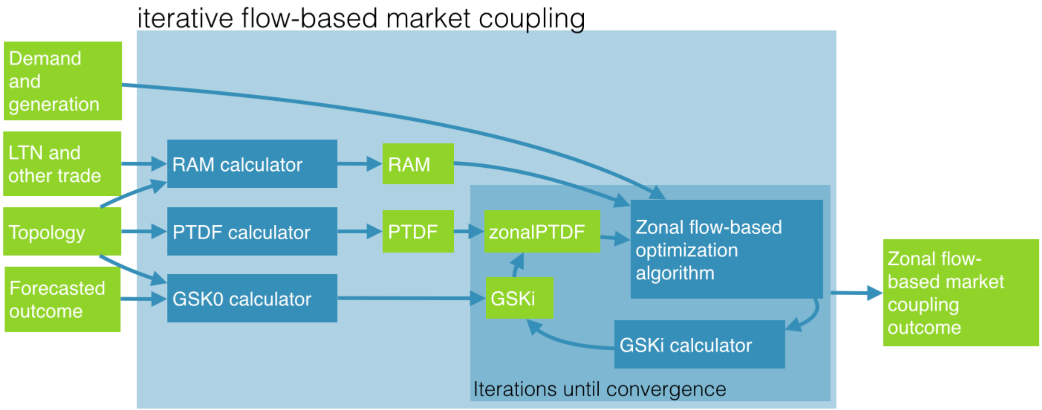


Figure 6.4: Structure of the iterative flow-based market coupling building block.

Convergence conditions

To stop the iteration a convergence criteria need to be implemented. The simulation model assumes that convergence is reached if the difference of consecutive GSK values in the iteration is smaller than 0.01. Additionally a mechanism is implemented to stop the iteration if convergence is not reached after 50 iterations.

Modeling results

To start an analysis is made of one time step. In figure 6.5 the modeled flows of the last iteration and physical flows are shown of the mean study case market solution using the iterative market coupling. Because of the new GSK definition the modeled flows are equal to the physical flows. There is no need for a corrective loop flow component. To verify if the iterative approach improves the performance of the FBMC the generation costs are analyzed for a simulated day. In figure 6.6 the hourly generation cost difference with the nodal market coupling is shown for 24 time slots. The iterative market coupling results (green curve) are significantly lower than the four FBMC methods using the different generation shift key methods combined with the second base case implementation. Additionally, the iterative market coupling approach does not need the high safety margins that were required in the original FBMC approaches to cope with the methodological error of the approach. In figure 6.6b the generation cost difference is shown without FRM. The costs of the flow-based market coupling are always lower than the nodal solution cost in case of congestion. This indicates overloading situations and consequently really poor performance of the FBMC. The iterative market coupling solution does not result in infeasible solutions. These findings are confirmed by the values for the flow modeling error. The sum of the difference between the modeled flows and the physical flows is much smaller for the iterative market coupling implementation than for the FBMC of scenario 8. Finally, the price convergence rate of a day can be compared for the different methods. The iterative market coupling, indicated with method 6, approaches the convergence

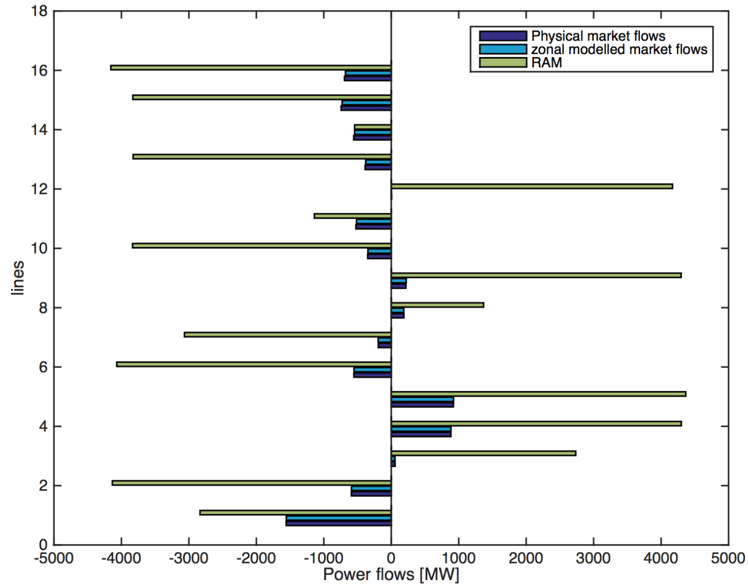
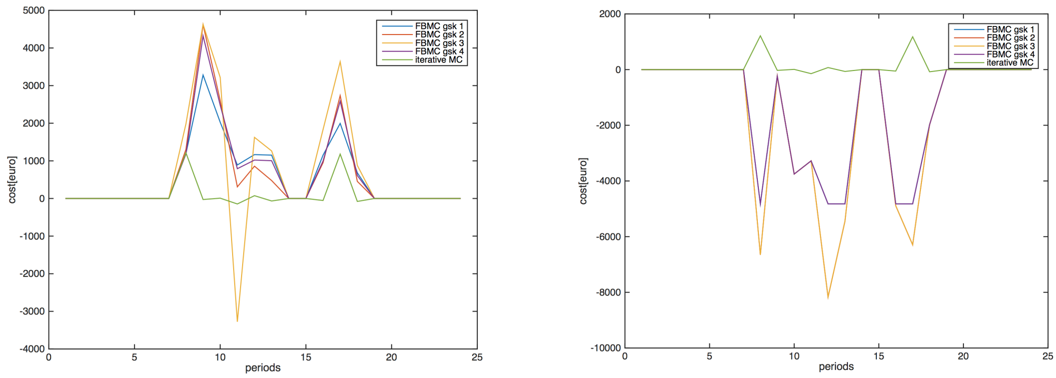


Figure 6.5: The last iteration modeled flows and the physical flows of the mean study case market solution using the iterative market coupling implementation.



(a) In case of the optimal FRM choose for the FBMC approaches.

(b) Case of no FRM for the FBMC approaches.

Figure 6.6: Cost difference with the nodal market coupling solution for four FBMC methods and the iterative market coupling method.

rate of the nodal solution. The flow-based market coupling has significantly lower price convergence.

Improved prioritization During the evaluation of the FBMC implementation in section 5.1.2 a situation of wrong prioritization was studied. Running the iterative market coupling algorithm on the same case does not result in the wrong prioritization in which the expensive generator of node 6 is used to fulfill the demand in node 10.

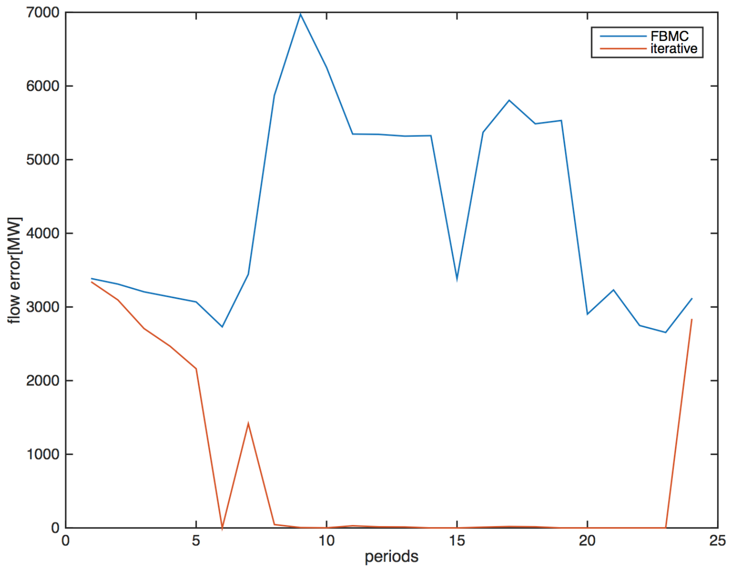


Figure 6.7: Total flow-modeling error for the FBMC implementation of scenario 8 and the iterative market coupling proposal.

Convergence rate of the iterative proposal and instability issues In figure 6.10 the convergence of the GSK values in the iterative process is given for two hourly cases. In the first case convergence is reached after 6 iterations. In this case the zonal flow-modeling is exact. In some cases however alternating convergence is reached. The GSK assumption of the final iteration does not correspond with the zonal distribution of the solution. The modeled flows subsequently deviate from the physical flows and the solution of the iterative market coupling can be non-optimal or may even contain overloads. For these cases FRM margins will be needed to cope with this modeling error. For more extended topologies, however, we suspect that these alternating convergent cases will be less frequently occurring. For the iterative process a starting GSK is required as input. This initial GSK should be derived from a market outcome estimation using the GSK definition in formula 6.3. In this simulation an nodal market coupling prediction was assumed. With this initial GSK estimation convergence or alternating convergence was always reached. Whether less accurate starting GSKs would or would not result in stability problems, should be studied more detailed with realistic simulations.

6.4 Conclusion

From this chapter it can be concluded that improvements to the flow-based market coupling implementation are possible. Significant performance gain can be accomplished in the short term through more collaboration between TSOs with respect to the base case and GSK determination.

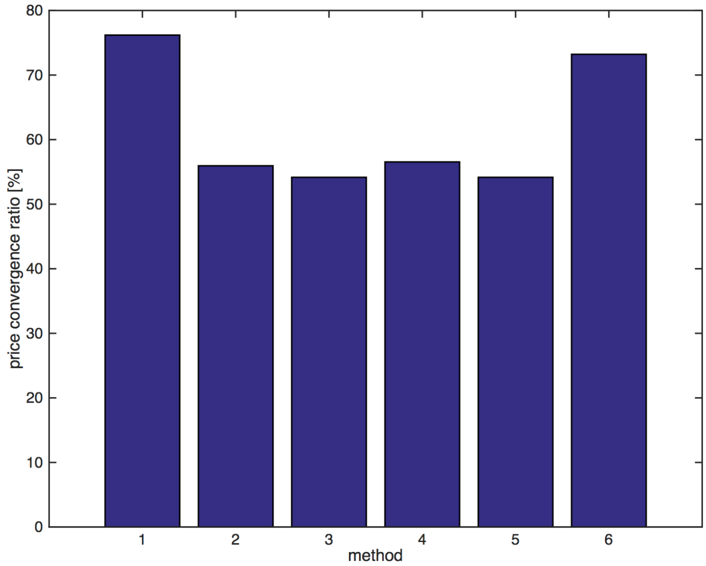
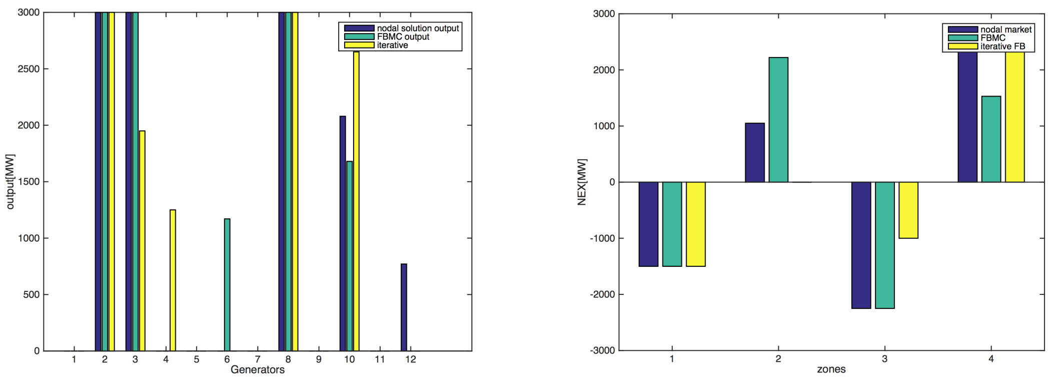


Figure 6.8: The relative number of periods with full price convergence in all zones for multiple methods. 1: Nodal market coupling, 2-4: FBMC with respectively 3 GSK methods, 5: FBMC with different GSK methods in each zone, 6: iterative flow-based market coupling.

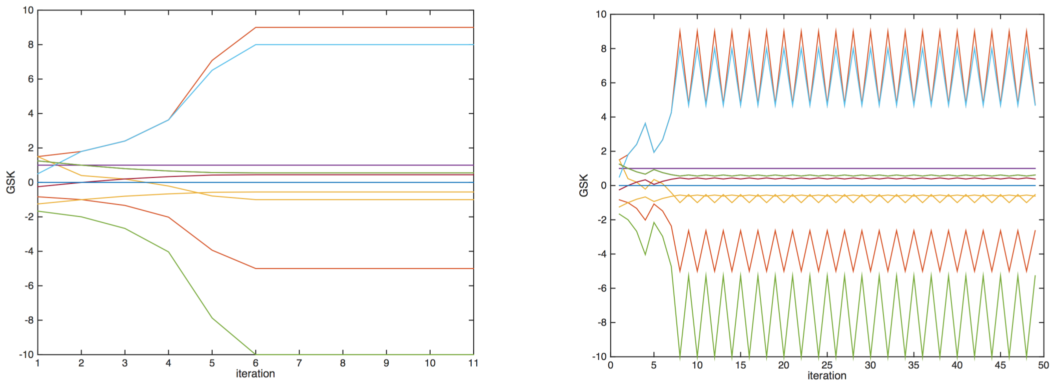


(a) The generation outputs.

(b) The NEX values.

Figure 6.9: Results of one time step for the nodal, FBMC (scenario 8) and iterative market coupling solution in case of 1.5 times the mean data case.

In the long term it would be interesting to transform the flow-based market coupling towards an iterative flow-based market coupling approach. The iterative implementation approach described in this chapter has considerable benefits compared to the current flow-based market coupling algorithm; a decreased dependency on estimations and assumptions (the base case is no longer needed and the initial GSK assumptions are not determinative for the outcome), a righteous prioritization of the market bids



(a) For this case convergence is reached after 6 iterations.

(b) Case of alternating convergence after 6 iterations.

Figure 6.10: The GSKs for each node for each iteration.

and a significantly higher welfare solution. To make such an implementation possible an important change has to be carried out. To enable an iterative market coupling the nodal information of the market bids for the day-ahead market will have to be published by the market bidders. This information is needed to recalculate the GSKs in the iterative process. Next to the need for political approval for the publishing of the nodal bidding data further research will be necessary to evaluate the stability of the iterative approach with realistic data.

Chapter 7

Conclusion

7.1 Description

The fundamental problem of bringing into account the network constraints in the electricity market clearing algorithm, can be represented by the following equation

$$F_l \leq F_{\max\, market,l} \quad \forall l \in L \tag{7.1}$$

and is divided in two subproblems:

- a calculation of the flows given the available information of the market bids on the one side (F_l);
- and a determination of the transmission capacity available for the market on the other hand ($F_{\max\, market,l}$).

The current flow-based market coupling proposal offers a solution for both these subproblems by mixing a zonal modeling approach with estimations to determine the transmission capacity for the market. The approach for the determination of the flow-based capacity parameters was described in chapter 3. This description clearly explains the current flow-based market coupling principles and it parameters. The description should result in better understanding and new insights in the used methodology. From this description of the FBMC proposal it can be concluded that the approach is not intuitive, often confusing and based on a lot of assumptions. Subsequently the methodology and the transparency of the approach can be questioned. An advantage of the flow-based market coupling implementation would be the increase in transparency towards the regulators. If the flow-based parameters are clearly defined, regulators can fully verify how the cross-border constraints are brought into account. In the ATC market coupling regulators absolutely have no insight in determination of the cross-border transmission limits. This was, however, not the primary concern for this research. The aim of this research was to evaluate the impact and accuracy of the flow-based parameter calculation methods.

This thesis can give conclusions about the two fundamental subproblems. however, in the simulation model only the first subproblem was investigated as the model assumed that the capacity available for the market was known.

7.2 Evaluation

In the flow-based market coupling proposal different methodologies for the base case and GSK determination are described. It was found that the combination of a base case made with a reference day and a prediction of the generation (method 2) and GSKs determined from that base case prediction (method 3), is the most optimal. In general, it can be concluded that the current flow-modeling approach is not accurate. The methodological flow modeling errors are big and require the introduction of high safety margins. Additionally, the FBMC fundamentally results in incorrect prioritization of bids as parts of the flows resulting from market transactions are considered as fixed loop flows parameters instead of optimization variables. A critical view on the FBMC proposal revealed high welfare losses in comparison with a nodal market coupling. Despite of these flaws in the FBMC methodology the current implementation proposal performs significantly better than the old ATC market coupling in terms of welfare. The comparison with ATC was not implicitly made in this research but the parallel run of the FBMC during the last year clearly proves that the FBMC performs better than the ATC market coupling in terms of welfare [11].

7.3 Improvements

There clearly is room for improvement in the flow-based market coupling implementation. In the short term, significant performance gain can be accomplished through more collaboration between TSOs with respect to the base case and GSK determination. Collaboration for the determination of the net exchange position of the base case would significantly improve the accuracy of the base case prediction. A harmonization of the methods used for the determination of the GSKs would increase the consistency of the loop flows. Both collaboration efforts would consequently lead to more accurate flow modeling, less overload situation and higher welfare for the complete market area.

In the long term it would be interesting to transform the flow-based market coupling towards an iterative flow-based market coupling approach. The iterative implementation approach described in chapter 6 has considerable benefits compared to the current flow-based market coupling algorithm: a decreased dependency on estimations and assumptions (the base case is no longer needed and the initial GSK assumptions are not determinative for the outcome), a righteous prioritization of the market bids, a significantly higher welfare for the solution. An implementation of this iterative method would however require the publication of the nodal location of the market bids. A crucial factor in unlocking the full potential of flow-based theory will be accurate input data. Gathering and using the information of the nodal location of the bids combined with an iterative approach for the determination of the GSK would significantly improve the market coupling results.

Although the second subproblem, viz. the determination of the capacity available for the market, was not the primary focus of this thesis a few important aspects should be mentioned. The proposal for the determination of the capacity for the market in the FBMC seems valid. Validating the accuracy of the proposed method is not meaningful without accurate data. Yet it is clear that there is a lot of uncertainty regarding the process because of the way the electricity markets are organized. 80% of trade is done via other platforms than the day-ahead power exchange. Assuming that also 80% of the tradable capacity is consumed via these other platforms, an optimistic uncertainty of 5% for the estimations of the trade done via these other platforms, implies an uncertainty of 25% on the 20% tradable capacity that is offered on the day-ahead market.

Implementing an accurate flow modeling on the day-ahead market coupling has no significant advantageous effects as long as it is combined with other electricity trading steps that don't have the same accuracy. Reorganizing the trade mechanisms to make a system for which the already used capacity before the day-ahead market coupling is accurately known, would unlock more trade possibilities as the uncertainty margins on the tradable capacity could be significantly decreased. As long as safety margins are not fundamentally changed, the full potential of the flow-based theory is not unlocked. Implementation of an FBMC would really be beneficial if there were a radical change in the way the market system is organized.

The current implementation is that far elaborated and complex that it is very difficult to unveil and discover the fundamental problems that come with a flow-based implementation. In this thesis special effort was made to describe the underlaying problems that have led to the current complex implementation. By taking a high level approach and focusing on the fundamental problems we were able to propose a new methodology that would perform better than the current flow-based proposal. In this thesis it was proven that an iterative market coupling algorithm could improve the market coupling results and reduce its dependency on predictions and assumptions. Yet, this approach yields some stability problems and can lead to high computation times. The elaboration of an efficient and stable solution algorithm would be necessary. More research to test the iterative market coupling approach on more realistic datasets would be interesting to validate the possibilities of this approach.

Chapter 8

List of Figures and Tables

List of Figures

List of Tables

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