Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Economics, Management and Humanities

Modelling of electricity markets using an agent-based simulator
North American flow-based market coupling analysis and simulation

Master thesis

Study program: Electrical engineering, power engineering and management

Field of study: Economy and management of power engineering

Scientific advisor: prof. Ing. Oldřich Starý, CSc.

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MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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II. Master's thesis details

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Guidelines:

Introduction to electricity markets and agent-based systems.
Describe Market coupling in North America.
Make agent-based simulation, analysis and results.
Development and Implementation of model to simulate electricity markets.

Bibliography / sources:

1. Weiss, Gerhard. Multiagent Systems, edited by Ronald C. Arkin, MIT Press, 2013. ProQuest Ebook Central, https://ebookcentral.proquest.com/lib/cvut/detail.action?docID=3339590.
2. SHAHIDEHPOUR , Mohammad., Hatim. YAMIN and Zuyi. LI . Market operations in power systems: forecasting, scheduling, and risk management . New York: Wiley, © 2002. xiv, 531 pp. ISBN 0-471-44337-9 .
3. OCHOA, Camila and VAN ACKERE, Ann, 2015. Winners and losers of market coupling. Energy [online]. 2015. Vol. 80, p. 522–534. DOI 10.1016/j.energy.2014.11.088.

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Topic registration form

Student: Arturo Montes de Oca Zapiain

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4. VAN DEN BERGH, Kenneth, Jonas BOURY a Erik DELARUE. The Flow-Based Market Coupling in Central Western Europe: Concepts and definitions. *Electricity Journal* [online]. 2016, **29**(1), 24–29. ISSN 10406190. Dostupné z: doi:10.1016/j.tej.2015.12.004

“I hereby declare that this master’s thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – “On maintaining ethical principles when working on a university final project, CTU in Prague“.

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Abstract

Electricity markets have suffered radical transformations in the last 30 years. However, this transmission has not arrived at the same pace to all places. The economical and ideological differences in the North American region have created barriers that stand in the way of electrical integration on the region. While close economic ties exist within the three countries that comprise the region, electricity markets have been left aside regarding Mexico and the rest of the countries.

Electricity market integration is characterized for being a complex economical and technical problem that till date has not been addressed fully. The increase in welfare brought by enhancing interconnector capacity, is blocked by a series of factors that will be addressed on this paper. However, due to information limitations and geographical factors, the scope of the paper will be limited to bordering regions of USA with Mexico and the National Interconnected System within Mexico.

Regarding the technical aspect of the market coupling on the region, a Flow-based market coupling approach is proposed to deal with the congestion, inherent to electricity markets, and with the differences between the transaction flow and the real flows.

Regarding the economical aspect of the electricity market complexity, a multi-agent base model is proposed to solve the generation bidding side of the equation. This type of models offers a bottom-up approach to electricity systems rather than the classical Top-down approaches that lack the ability to properly model the behaviors within the market. furthermore, these types of models are easily scalable and can be expanded to include different type of behaviors and agents. Q-learning will be the chosen reinforcement learning algorithms that will function as the decision-making tool for the agents.

The purpose and motivation of this paper is to explore an increased interconnection between these two countries and to model the behaviors that market players may choose if this interconnection is realized.

Abstrakt

Trhy s elektřinou prodělaly radikální transformaci v posledních 30 letech. Tato transformace ale nedorazila do všech míst stejným tempem. Ekonomické a ideologické rozdíly v regionu Severní Ameriky vytvořily bariéry, které zabránily plné integraci jednotného elektrického trhu. I když existují blízké ekonomické vazby všech tří zemí, které tvoří tento region, trhy s elektřinou mezi Mexikem a ostatními zeměmi byly z těchto vazeb vynechány.

Integrace trhu s elektřinou je charakterizována jako komplexní technický a ekonomický problém. Rostoucí blahobyt vycházející ze zvyšování přeshraničních kapacit je pozastaven díky řadě faktorů, které budou popsány v této práci. Kvůli omezeným informacím a geografickým faktorům bude tato práce zaměřena pouze na regiony hraničící mezi Spojenými státy americkými a Mexikem a regiony v rámci Mexika.

V rámci technických aspektů propojování trhů v regionu bude navrhnut přístup Flow-based market coupling, který by měl zabraňovat ucpávání přeshraničních kapacit a nekonzistentnosti mezi ekonomickým tokem a fyzickým tokem energie

V rámci ekonomických aspektů bude navrhnut “multi-agent” model, který by měl řešit nabídkovou stranu rovnice. Typy těchto modelů využívají k elektrickým sítím přístup bottom-up místo klasického top-down přístupu konvenčních metod, které nedokážou správně popsat chování v rámci trhu. Dále, tyto modely jsou snadno škálovatelné a mohou být rozšířeny o další chování nebo typy agentů. Jako nástroj algoritmů posilovaného učení bude vybráno Q-učení, které bude nástrojem pro agenty pro učinění rozhodnutí.

Cílem a motivací této práce je prozkoumání ekonomicko-technického chování zvýšených přeshraniční kapacit mezi USA a Mexikem, a modelování chování hráčů na trhu v případě realizace zvýšení kapacit.

Contents

Glossary

List of abbreviations

Abbreviation	Signification
ABS	Agent based system(s)
ACE	Agent based computational economics
ATC	Available transfer capacity
BA	Balancing autority
BDI	Beliefs, desires and intention
CEL	Clean energy certificate
CFE	Comisión Federal de Electricidad (Federal commission of electricity) [Mexico]
CWE	Central Western Europe
FERC	Federal Energy Regulatory commission
EU	European Union
FB	Flow Based
FBMC	Flow based market coupling
GHG	Green House Gases
GSK	Generation Shift Key
HVDC	High voltage direct current
ISO	Independent System Operator
LMP	Locational Marginal Price
NAFTA	North American Free Trade Agreement
NAPEX	North American Power Exchange
NERC	North American Electric Reliability Corporation
NP	Net position (supply-demand)
NN	Neural network
MAS	Multi-agent System(s)
MASCEM	Multi-agent simulation of competitive electricity markets
PPA	Power Purchase Agreement
PTDF	Power Transfer Distribution Factors
RES	Renewable energy source(s)
RAM	Remaining Available Margin
RTO	Regional Transmission Organization
SEN	National electricity system [Mexico]
SIN	Interconnected national system [Mexico]
SO	System Operator
TSO	Transmission System Operator
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

USMCA	Unites States Mexico Canada Agreement (North American Free Trade Agreement renegotiation agreement)

- 2013 Mexico's energetic reform: Change from a vertically-integrated state monopolistic system to a liberalized generator market [1].
- North America: Understood as Mexico, United States of America and Canada.
- Export: The act of sending goods or services to another country for sale.
- Import: The act of bringing goods or services from another country for sale.
- Energy vector: A mean that allows to transfer a quantity of energy though space and time [2].
- Complementarity: Relationship or situation in which two or more different things improve or emphasize each other's qualities.
- Electrical interconnector: The fiscal link permitting the international transfer of electricity. Thus, allowing international trade of electricity.
- Generation capacity: Maximum electrical output an electrical generator or country can produce under specific conditions.
- Merit order: Ordering method where the cheapest generation bids and the highest demand bids are dispatched first and ordered in an ascending and descending order respectively.
- Interconnector: Cross-border transmission line.
- Phase shifting transformer: power transformer which is able to control the flow of active power by varying the phase angle between two buses.
- Virtual Power Plant: is a technological platform which enables distributed energy resources to have access to markets and services they could not access on their own.
- Bidding zone: economical region, that might coincide with a fiscal region delimited by sovereign nations or states, with the same clearing point. Interconnection capacity between bidding zones is treated as a scarce resource.

- Congestion management: Situation when at least one-line transmission capacity is binding, hence limiting the interzonal transmission capacity.

- Copper plate: Assumption that the intrazonal transmission capacity is not binding for interzonal trade.

- Parallel flow: Non-economic path followed by a physical flow. Path that deviates from the economic path due to Kirchhoff's laws and grid topology.

Preface

The energy has been, in modern ages, an invisible hand that influence the world's economy. It works as a silent integrator of nations making regional economic blocs as the countries under the USMCA and EU a reality in today's world. Mexico is experiencing a unique moment of opportunities thanks to the energy liberation and the integration of energy markets.

Even though North America is made up of only 3 different countries, the land extension that comprises the subcontinent is considerable, and the region has been in tight economic relations since the application of NAFTA. Nonetheless, regarding the electrical sector, international trade, has been a point left unspoken specially between Mexico and the rest of North America.

While Canada and USA enjoy relatively good relations regarding this topic, and all of the bordering Canadian Provinces (including Quebec), are part of NERC, Mexico, due to its late electrical market liberalization and technological deficiencies, has been left out of this corporation. Thus, limiting Mexico's ability to export and import electrical energy with its northern neighbors.

Knowing this and in a spirit of international integration, this paper will focus on the integration of the North American region including Mexico under the latest trends of market coupling by the means of an agent-based simulation. Altogether North America has a population of ~572 million people, so the proposed welfare increases will be enjoyed by a large population and could have positive impacts in emission reduction as USA is one of the biggest emitters of GHG in the world according to the UNFCCC [3]. This paper is also done to see if the benefits of a coupled market are sustainable given the current regulations and the big differences in capacities between the countries.

1 Introduction

North America is a land of continuous change, a place where new opportunities rise with the verge of every new day. Even today, considerable steps towards further international integration in the region are being taken, despite the current political situation and relative tensions that exist between the countries due to the difference in political reasoning and sprouts of nationalistic movements throughout some of the Parties Signatories of the USMCA. Nevertheless, I am confident that these trends won´t prevail and that the ideas of strong regional blocks and globalization will be restored.

One increasingly important topic that is still undervalued in the regional integration initiatives taken in North America, is that of an electrical market integration or market coupling. This lack of adaptation is something that goes against the inherent ability of the electrical energy to flow, which make electricity one of the best vectors of energy for final use in today's world.

Talking about market liberalization both, opportunities and risks, emerge and specifically in the case of a market coupling of the electrical markets. Extra sensitiveness to reforms and subsidies exists, tilting the balance one way or another. These subsidies and regulations may vary from one market participant to another bringing different conditions for investments and general growth of the electrical system. Some of the factors proven to be driving the social welfare are: Complementarity, interconnector size, generation capacity, regulation authorities (referred here as subsidies and regulations) [4, 5].

As proposed by Camila Ochoa and Ann van Ackere in their analysis done to a market coupling of Colombia and Ecuador [4], the market coupling benefits depend heavily on the policies, subsidies and generation capacities of each of the interconnected countries. They suggest that the current disparities on the region can provide benefits to some members at expense of the others. Hence, the need of simulations to justify every step towards a North American market coupling which maximizes the social welfare without bringing energetical dependencies and unequal conditions.

Liberalized wholesale markets are considered complex systems because the main commodity traded within them (electricity) has specific characteristics that make the trading somewhat difficult. These characteristics include, among others, the need of instantaneous balancing of supply and demand, the storability of this vector is limited, and it can only be transported by a transmission grid with limited capacities [6].

Taking all of the above in count, this paper will be divided into 3 different sections with the objective of providing the reader with a general vision of the current situation of North American energy (specifically electrical) sector panorama and most importantly; how this conditions and future projections will affect a hypothetical market coupling Day-Ahead prices by means of an agent-based simulation. The first section of the paper is devoted to introducing the specifics of the electrical markets and a description of what is market coupling and agent-based systems. Following this, is the main body of the paper referred to the modeling which includes detailed information of the decisions taken and the scenarios modelled. Finally, a sensitivity analysis, together with conclusions, of the market coupling parameters and scenarios will be provided to see the different degrees of impact this proposed market coupling can have taken in count the current situation.

In short, one of the main objectives of this paper (model) is to revise the behavior of day ahead electricity market prices due to the current generation capacities and existing transmission capacities.

1.1 Electricity Markets

Liberalization has come at different paces throughout the world and most, if not all, the countries come from vertically integrated monopolistic power market structure which was usually conformed by state owned entities. Under this regime, all of the components, which include, generation, transmission, distribution, retail and consumption, where under the control of only one state owned company. As an example, Figure 1 shows the structure of the vertically integrated market of Mexico before the reform where all the market was controlled by CFE. Each participant of the electricity market is going to be explained more in detail in the next section.

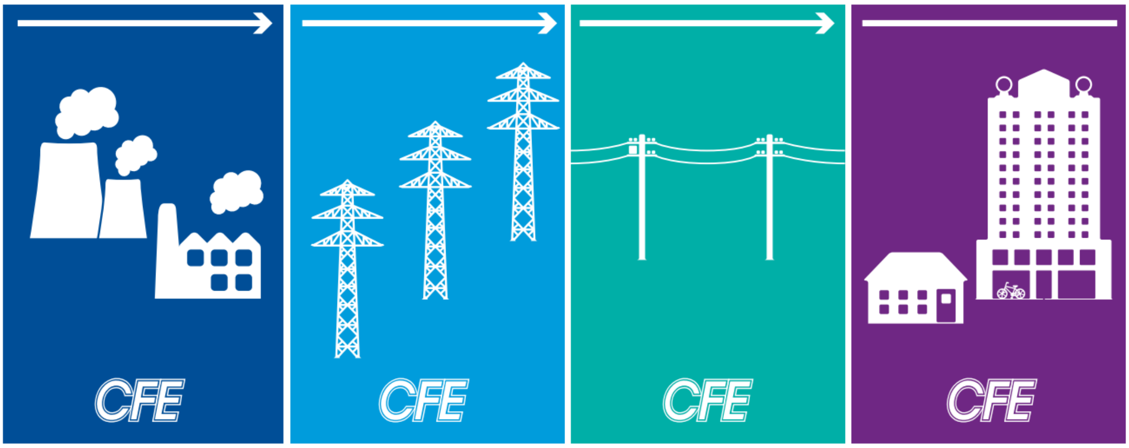

Figure 1: Mexican vertically integrated electrical market, before the energy reform. Source: [7]

The structure described by the image above is less and less a reality in today's world, and the panorama is shifting towards a liberalized electricity market where the focus of this paper resides. Liberalizing the market does not mean that the state-owned company disappears. In fact, one of the main difficulties to overcome when liberalizing an electrical market is to lessen the market power of the incumbent company. Even though, big steps have been done towards liberalization and this comes at different degrees regarding the institutional framework. In this section a general overview of a liberalized electricity market is explained.

The liberalization of an electrical market is defined as the opening for private investment of one or more of the components conforming the market. The degree of private investment penetration can vary significantly from one country to another. Some institutional frameworks allow private funds to operate throughout the entire market structure with state entities regulating and overseeing their actions. Such is the case of USA. However, more regularly the transmission and distribution segments remain in the hands of the state, hence, it remains the state's responsibility to maintain, operate, and upgrade the electrical grid [8]. Figure 2 shows the electricity market structure of USA, which is a good example of a fully liberalized electricity market with all its complexities.

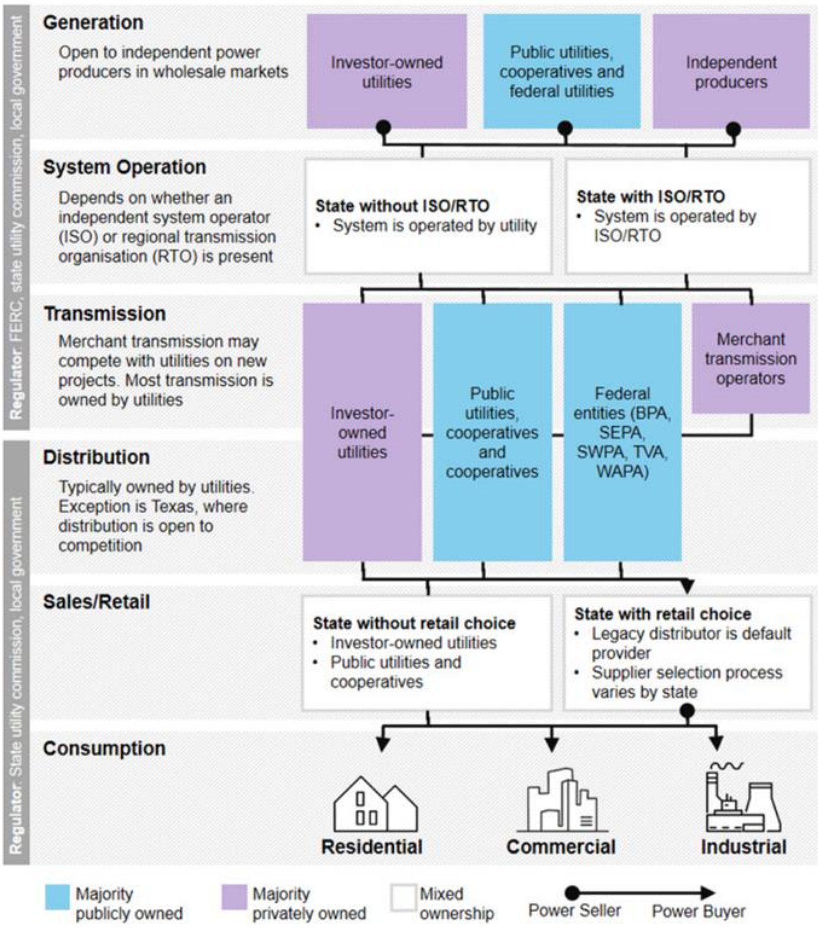

Figure 2: USA electricity market structure. Source: [18]

Electricity market liberalization opened the door to new competing players in the market. With this competition over a first need commodity, an impartial entity had to ensure the competitiveness an efficiency of the market. System operators (SO) emerged as the operational controllers of the networks and the wholesale electricity market. These SO are usually organized into ISOs or RTOs and there can be more than one for each country and in some cases, can expand even international borders as is the case of NERC. SOs responsibilities are mainly related to transmission access which include, among others: reliability, non-discrimination, independence, efficiency, economic dispatch and efficient pricing [9].

1.1.1 Characteristics of electrical markets

Till now, I have only described the structure of a liberalized electricity market, but, there is much more to that. Englobed in the term electrical wholesale market, exists all the commodities and related services linked to the electricity trade and flow. At the same time, the electricity wholesale market had to adapt to the special characteristics of the electricity and all the complexity involved in trading it. I am going to start describing the main entities that conform the electrical wholesale market:

- Electricity generators and retail companies: these are the market players that offer and bid electricity with the goal of economic benefit. Their offers are limited by their available assets and they are in charge of the supply of electrical energy and generation capacity for the consumers [10].

- Regulators: even though they do not play a direct function in the everyday functioning of the electricity markets, they make sure no regulations are broken and that all the players are treated equally [10].

- Power exchanges: they are in charge of organizing and clearing the market for the area under their jurisdiction. They collect all the bids of supply and demand and the parameters determining the trans-zonal trade [10] .

- TSO: Their main objective is the safe exploitation of the grid. They try to accomplish this throughout grid balancing and avoiding congestion. Market wise, they must ensure that the clearing results are within the capabilities of the grid [10].

- Consumers: their participation in the market has been somewhat overseen and are most of the time considered a passive actor in the electrical wholesale market. With the introduction of the spot markets (will be discussed later on this section) and by means of strategic bidding, they can affect the prices by modifying the demand curve. Recently, technological platforms such as virtual power plants, give access to consumers to markets and services that otherwise they would not be able to access. Load management has also become an important aspect of the wholesale electricity market.

As there are different players on the electrical wholesale market. Different timeframes for the electricity delivery create different markets within the wholesale market. Products and services can be traded all the way from 15 minutes before delivery, on the so-called Real-time market, to years before the delivery date in the form of futures or Power purchase agreements (PPA) [8].

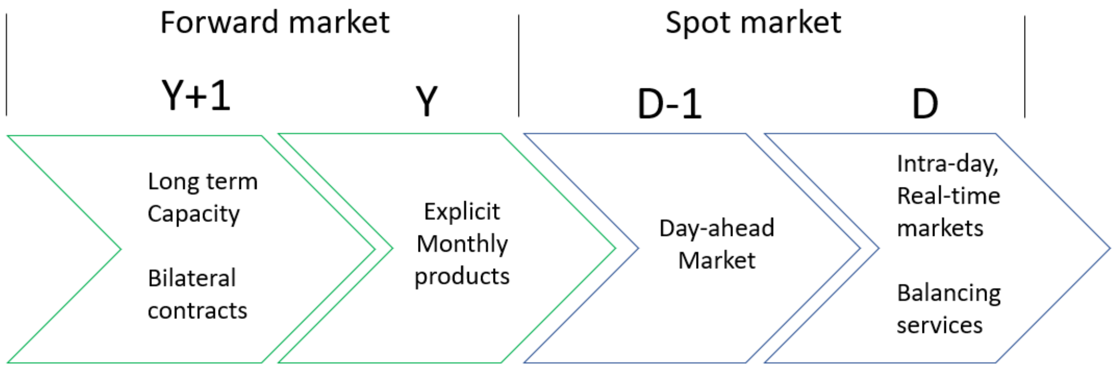

Figure 3: Markets available in the wholesale electricity markets and their timeframe before the delivery of electricity. Based on: [11–13]

Forward and future market[14]

Future and future markets go from years before to the day before delivery. Forward and futures are contracts to deliver or consume a certain amount of electricity at a certain time in the future for a price agreed today. The futures are standardized contracts that can be negotiated in power exchanges. Forwards are mainly bilaterally traded over the counter and are not standardized, giving greater flexibility to the parties involved; usually they do not negotiate anymore.

Electricity generators sell electricity in the forward and futures markets to ensure future sales and reduce their vulnerability to possible decrease of electricity price. Analogously, big electricity (industrial) consumers could buy electricity in the futures and futures markets to ensure their electricity consumption in the future knowing in advance costs and reduce their vulnerability to possible electricity prices increases. Big consumers use this market to hedge their positions.

In forward and futures markets, electricity can be exchanged between different market zones or within a market area. The allocation of the transmission capacity between two market zones in the forward and futures markets happens explicitly. In such explicit cross-border allocation, the transmission capacity is negotiated separately of electric energy. This implies that market players first buy the right to use the transmission capacity between two market zones before buying or selling electricity in another area.

With respect to trade within a market area, it is assumed that trade between areas is never limited by the transmission capabilities; the transmission capabilities are not taken into account when negotiating within a market area.

Day-ahead market [14]

In the daily market, electricity is sold the day before real delivery. The daily market is of great importance since the market area must be balanced at the end of the daily market (that is, the programmed generation in the market area equals the expected demand in the market area plus the net export to other markets. market areas).

Electricity can be traded daily bilaterally (over-the-counter operations) or in the energy exchange of the previous day. This type of exchange can be done implicitly. In the implicit cross-border allocation, a buyer or seller of electricity automatically has access to the transmission capacity when sending orders to the power exchange. Energy and transmission capacity are marketed together.

All the net positions are sent to the TSO to create an estimation on the supply and demand. These bids should be delivered usually before 2 p.m. local time so the respective parties have time to organize and clear the market. The power exchange is in charge for the market clearing and give the results to the participants and the TSO´s

Intra-day market [14]

In the intra-day market, electricity is sold on the day of delivery itself. The intra-day market allows market participants to correct changes in their daily nominations due to better wind forecasts, unexpected interruptions of the power plant, etc.

After the intraday market compensation, each BRP can send intraday nominations to the corresponding TSO each quarter hour, from 3.30 p.m. day-ahead until 2 p.m. the day after delivery. Intraday nominations are added to the anticipated nominations for the day-ahead market from the balance responsible parties (BRP). The BRP portfolio may be in imbalance after the intraday market, in contrast to the daily market, where a balanced portfolio is required. These portfolios of imbalances are solved in the balancing market.

Balancing market [14]

The individual BRPs might face a real-time imbalance. The BRP's imbalance is the net quarter-hourly difference between the BRP's total injections and offtakes. The total imbalance in the control area is the net sum of all BRP imbalances.10 The TSO will maintain the system balance by activating reserves.

Balancing markets can be split into a procurement side (i.e., procurement and activation of reserves by the TSO) and a settlement side (i.e., financial settlement of the BRP imbalances by the TSO).

Implicit and explicit auctions

The explicit auction is when the transmission capacity in an interconnector is auctioned to the market separately and independently from the markets where electric power is auctioned. The explicit auction is considered as a simple method to manage the capacity of international interconnections in Europe. The capacity is normally auctioned in portions through annual, monthly and daily auctions. Since the two products, transmission capacity and electric power are sold in two separate auctions, there is a lack of information on the prices of the other product. This lack of information can result in an inefficient use of interconnectors, that is, less social welfare, less convergence of prices and more frequent adverse flows [15].

With the implicit auction, the daily transmission capacity is used to integrate spot markets in the different bidding areas in order to maximize overall social welfare in both (or more) markets. The flow in an interconnector is based on the market data of the market in the connected markets. Thus, the auction of transmission capacity is included (implicitly) in auctions of electric power in the market. In implicit auctions, the transmission capacity between bidding areas (price areas / control areas) is made available to the spot price mechanism in addition to offers / offers per area, so the resulting prices per area reflect both the cost of energy in each internal offer Area (price area) and the cost of congestion. The implicit auctions ensure that electric power flows from surplus areas (low price areas) to deficit areas (high price areas), which also leads to price convergence [15].

The implicit auction means the concept used for "market coupling" and "market division". There is not necessarily any difference in the calculation algorithms, or the principles used for market coupling and market division. What differentiates the coupling of the market from the market division is how the algorithm is operated and possessed, and what results are obtained from the central calculation of the use of the local markets subsequently.

1.2 North American Electrical panorama

In this subsection the electricity markets of Mexico and USA will be described in detail. Some historical background will be given in the case of the Mexican electricity market as it is one of the motivations of this paper and also due to the fact that it has been liberalized in recent years, and it still is undergoing serious changes as the political panorama in Mexico is changing radically.

1.2.1 Mexico

Under the current market structure, the different entities that now participate, where either updated (given new responsibilities) or created. This, with the objective of having the legal work on. Here CEL refers to Certificado de energias limpias (Clean energy certificate) which is an incentive scheme for renewable energies and will be explained further in this paper. The description is as follows:

- Secretariat of Energy (SENER): The lead energy policy ministry in charge of designing Mexico's national electricity policy, with a mandate to guarantee competitive and sufficient supply of high-quality, affordable, and sustainable energy to the public. Is responsible for a number of specific areas, including the publication of the PRODESEN, oversight of the wholesale electricity market, oversight of other CFE activities, such as transmission development. SENER will also be responsible for establishing CEL criteria.
- Regulatory bodies: Both regulatory institutions have technical, operational, and management autonomy in their specific areas of expertise, and are responsible for a number of regulatory functions, including: the publication of acts, resolutions, directives, and regulations; conducting audits; issuing permits and authorizations, documenting inspections; and providing accreditation to third parties that conduct regulatory activities.
    - Energy Regulatory Commission (CRE): Responsible for oversight of the technical, operational, and management of the energy sector, including the midstream oil and gas sector, and the electricity sector. Includes regulation and development of transportation, storage, distribution, compression, gas liquefaction and regasification, retailing of fossil fuels and petrochemicals, electrical generation, transmission, and distribution.
- The National Center for Energy Control (CENACE): Formerly a part of CFE, CENACE was made an independent system operator of the national electric system. It has a mandate to guarantee impartial access to the national transmission and distribution grid and manage the wholesale electricity markets under conditions that "promote competition, efficiency, and impartiality, through optimal dispatch." It is also responsible for establishing expansion and modernization programs for national transmission and distribution infrastructure, when authorized by SENER.
- The CFE remains the stablished TSO and DSO which is in charge of ensuring the reliability and security of the system.

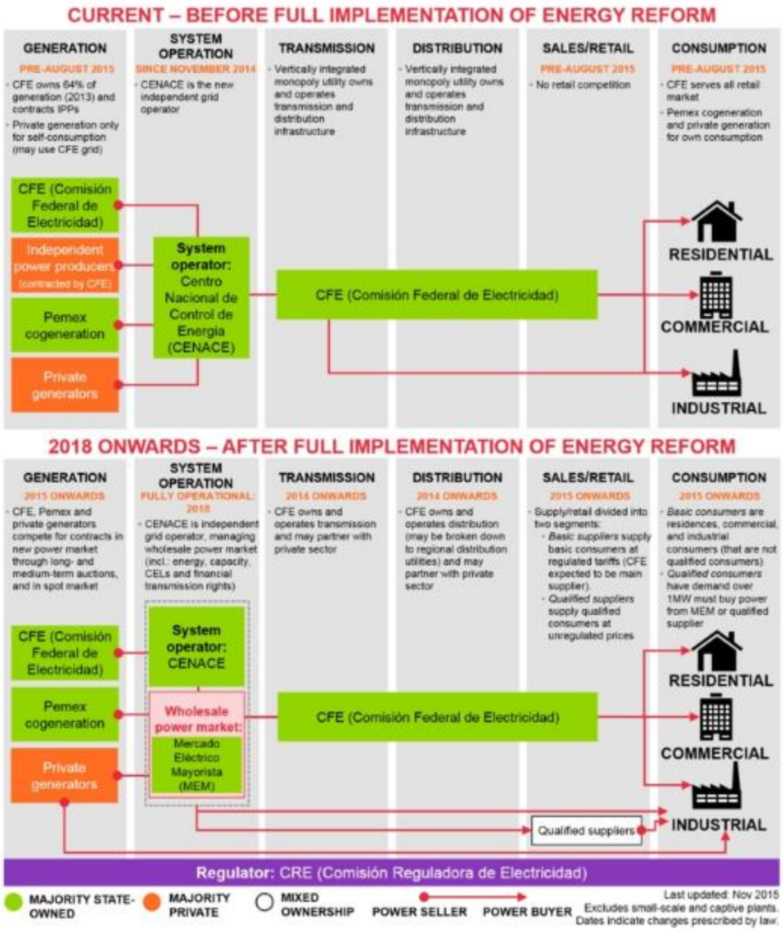

Figure 4: old and Current Mexican Market structure. Source: [50]

Mexico currently counts with 4 independent transmission systems, all operated by CFE. All four systems combined conform the Sistema Eléctrico Nacional (SEN).

This transmission systems are at the same time divided into 10 different control regions.

Figure 5: Mexican transmission control regions. Source: [51]

On figure 5 we can see a representation of the SEN where each color represents a transmission region. The blue area represents the Baja California System, number 10 represent the Mugelé system, and the remaining yellow area represent the Baja California Sur system.

The generation capacities and net yearly generations are summarized in figure 6 and 7.

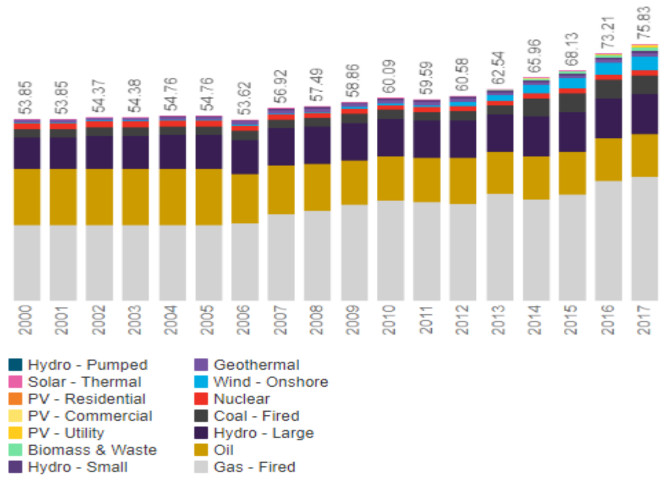

Figure 6: Installed capacity in Mexico [GW].

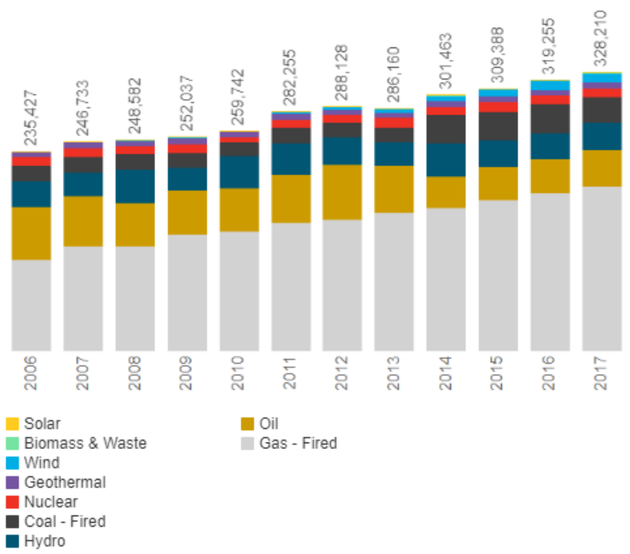

Figure 7: electricity generation in Mexico [GWh].

The main take away from these figures are the increases share of renewables in later years, as well as the high share of gas electricity generation.

Participants

In the Mexican Wholesale Market (MEM Mercado eléctrico mayorista) different participants are established within the Diario Oficial de la Federación (DOF). And are the following [7]:

- Certified Users: A certified user is the cone that has a demand equal or higher to 5 GW and as an annual consumption of 20 GWh. The requirements will be decreasing over time to ensure more consumers participate directly on the MEM. This type of consumer can participate in the MEM under two modalities.
    - Certified Users that represent their load centers themselves and buy electricity and ancillary services directly at the MEM.
    - Certified Users which load centers are represented by a retailer of certified services or a last resource supplier.

- Retailers: The retailers are able to sell the electricity under 3 modes.
    - Basic supply retailer: sells electricity to the consumes with demand under 5 GW. In other words, they supply all the consumers not able to participate directly on the MEM. They cell their electricity at regulated prices, and they have the obligation to supply the area they control.
    - Certified services retailer: This retailer buys the electricity directly on the MEM with the objective to supply citified users. They can hedge their positions through long term auctions.
    - Last resource retailer: they supply the certified users when their contracted retailer fails to comply with the CRE or CENACE requirements. Used to meet the demand at all time and ensure the security of the system.

- Generators: they sell their electricity and ancillary services on the MEM. They can also celebrate long term contracts with retailers and certified users to ensure the electricity supply
    - Exempt Generators: Small generators (>.5MW) which not requires permission to generate electricity. They can sell their energy to Basic supply retailers.

Markets and products

- Short term Markets: in the Mexican market structure, they are 2 operating markets and 1 that yet has to ho live. The Day ahead market and the hour ahead market is already live in the SIN and the Baja system. The remaining market, 15-minut ahead market, has yet to go live.

In the Mexican market scheme, they are ancillary services that can be traded on the MEM and those that are acquired yearly by the CFE and CENACE to ensure the reliability of the system.

- Services that can be acquired at the MEM:
    - Secondary reserves
    - Spinning reserves

    - Operative reserves
    - Supplementary reserves
- Services that cannot be acquired at the MEM are:
    - Reactive power reserves
    - Reactive Power
    - Emergency start
    - Island operation

Also, imports and exports are treated independently and have to be presented to the CENACE in due time.

- Bilateral or legacy contracts: All the participants hat have celebrated a bilateral contract before the signing of the reforms are given the choice to stay with the contract for the length established on it, or to go to the MEM.

- Power market: The Power market has the following elements
    - Facilitate transactions between the Load Responsible Entities and Contracts of electricity coverage was insufficient to meet the requirements to obtain power established by the CRE, and Market Participants that have power not committed in those contracts.
    - Establish a power demand curve in excess of the minimum requirements established by the CRE and purchase the portion of the available Power on behalf of the entities responsible for loading and ending the efficient operation of the Wholesale Electric market.
    - The Power refers to a commercial product that Generators can offer to their sale, through which they acquire the obligation to ensure the availability of physical Production and offer the corresponding energy to the Short-term market.

- Clean Energy Certificates (CEL) market: this Market is implemented as a incentive scheme to clean energy producers to make investments more attractive. CEL´s are products traded separately from the MEM that are given to each green generator for unit of energy produced (1 MWh). The CEL´s have value because the certified users and retailers are obligated to buy a defined percentage of their consumption from green producers. This obligation can be proved by the cancelation of CEL´s at the corresponding time (usually at the end of the natural rear). If they fail to comply, they will be sanctioned for a higher amount than the spot price of the CEL´s. CE´s can also be sold on bilateral contracts.

- Medium term auctions: The Medium-Term Auctions will be held annually. The contracts assigned through the Medium-Term Auctions will have a validity of three years counted from the date of start of operation, which will be 1 of January of the year following that in which the corresponding contract has been assigned or the one indicated in the corresponding Market Practices Manual.

Power and electricity can be offered at these auctions. The electricity is to cover certain percentage of the demand.

- Long-term auctions: The Long-Term Auctions will be carried out annually or, in the cases determined by the Market Practice Manuals, with another periodicity. The regular periodicity of the Long-Term Auctions will be established in order to coordinate the reception of offers with the issuance of requirements to acquire Clean Energy Certificates and with the planning of the expansion and modernization of the National Transmission Network. Contracts awarded through Long Term Auctions will establish obligations with the following validity from the date of commercial operation that has been agreed in the contract: 1) Any obligation of Power or Cumulative Electric Power will last 15 years. 2) Any obligation of CEL will last for 20 years.

1.2.2 United States of America

As it can be seen from figure 2 the USA electrical market structure is much more complex, and it is quite fragmented and privatized. Moreover, it varies form region to region. The biggest and federal entity that controls the electricity systems in USA is the Ministry of energy and functions in similar way than the Mexican Secretariat of energy but sees its power to enforce regulations by the ERO Enterprise Program Alignment that divides the country in RTOs. These RTOs are overseen by the federal NERC and FERC.

The FERC is an independent regulator that oversees the interstate transmission of electricity, natural gas, and oil. The responsibilities of the FERC are stated on the strategic plan of the ministry of energy and include but not limited by[16]:

- Licensing hydropower projects
- Reviews proposals to build LNG terminals and interstate natural gas pipelines.
- Regulates the transmission and wholesale sales of electricity in interstate commerce.
- Reviews certain merges and transactions between companies.
- Reviews the siting applications of electric transmission projects.
- Ensures the safe operations and reliability of the grid.
- Monitors and researches electricity markets.

Regarding NERC, it is a non-profit international organization whose sole mission is to ensure the effectiveness and reliability of the grid by reducing risks. It is international because it includes regions of Canada and Mexico within its oversight. The RTOs of members of NERC are shown in figure 8.

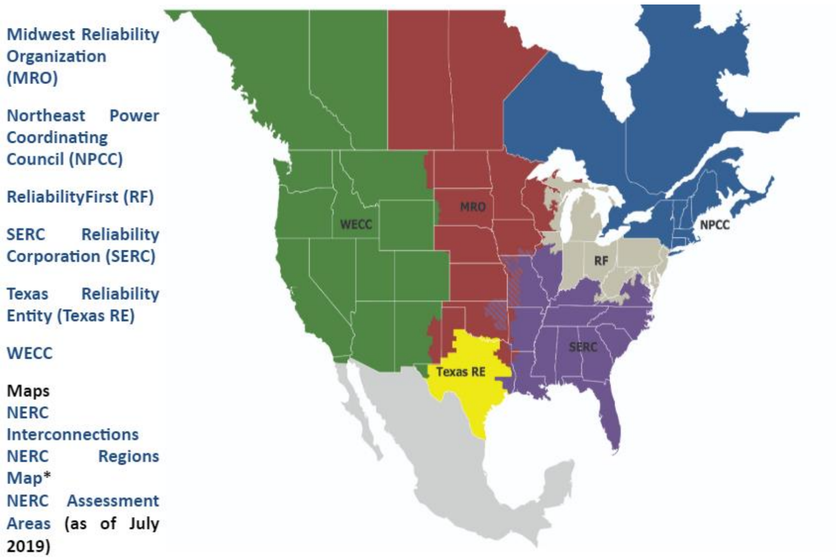

Figure 8: RTOs member of NERC, this are, in almost all cases, subdivided in smaller regions and further in Balancing authorities in charge of the reliability of their hubs. Source: [17]

In 2017, FERC gave the authority to NERC to delegate its authority and responsibilities of monitoring and enforcing compliance to the six regional entities in figure 8. This RTOs come in a wide range of segments of the electricity industry: private-owned utilities, federal power agencies, rural electric cooperatives, independent power producers, power marketers, and end-use consumers[17].

As in Mexico the installed capacity is dominated by gas power plants. Big efforts are done to increase renewable energy share, but the political panorama is ever changing.

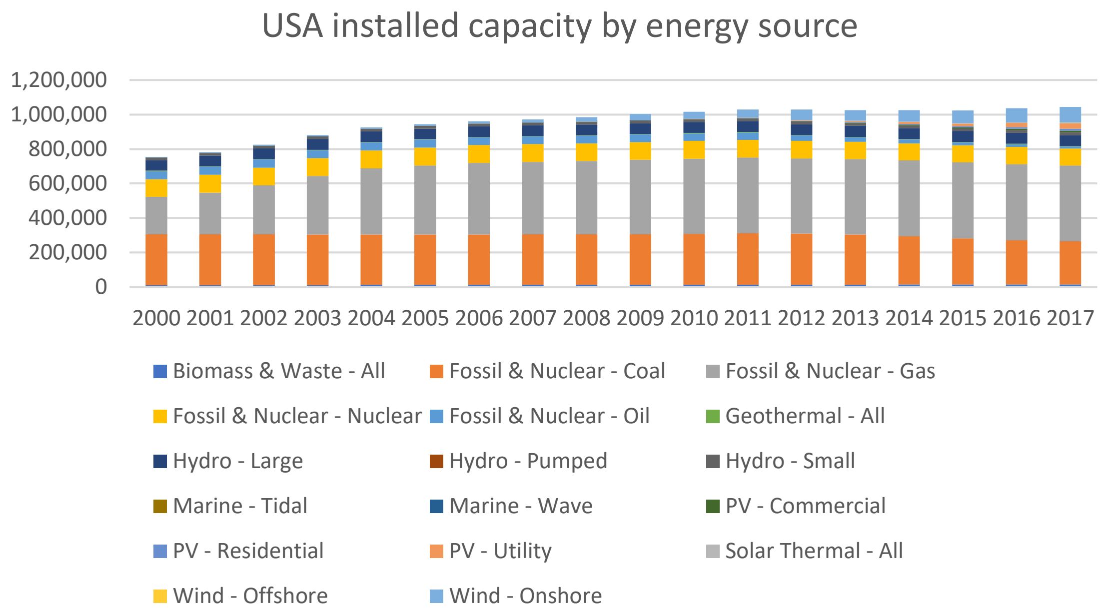

Figure 9: USA installed capacity by energy source. Source: [18]

The energy generation as in all countries is highly correlated by the economic situation of the country and in figure 10, we can see the impact of the 2009 economic recession.

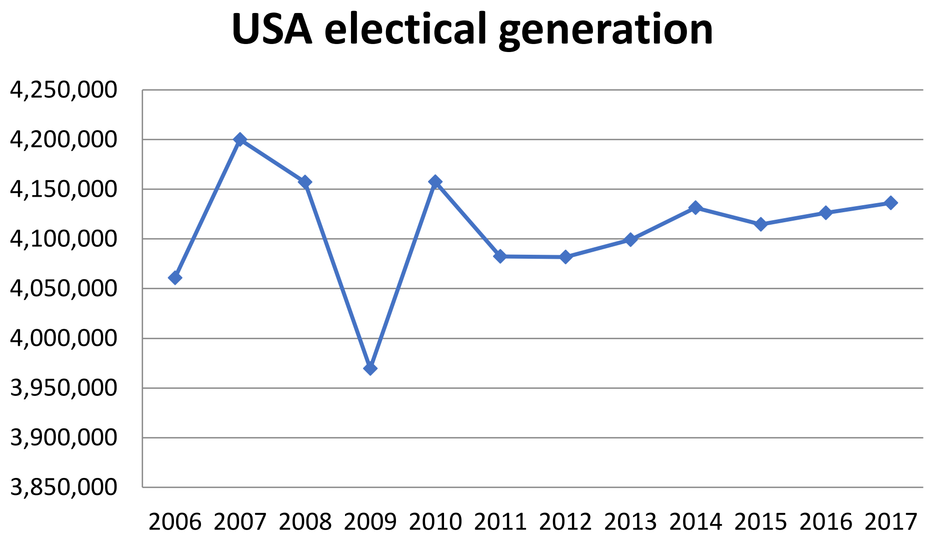

Figure 10: USA electrical generation. Source: [18]

1.2.3 Mexico – U.S. interconnection

Geographical historical, and resource factors have limited the interconnection between Mexico and the US [19]. According to the Energy Information Administration (EIA) in 2013 the US exported 0.68 million MWh to Mexico and imported 1.27 million MWh from the latter[19]. This electricity trade is small compared to the electrical demand of both countries. Currently there are eleven interconnectors alongside the border of Mexico and the US. Five of them are emergency interconnectors to ensure the reliability of the respective system and six of them are permanent.

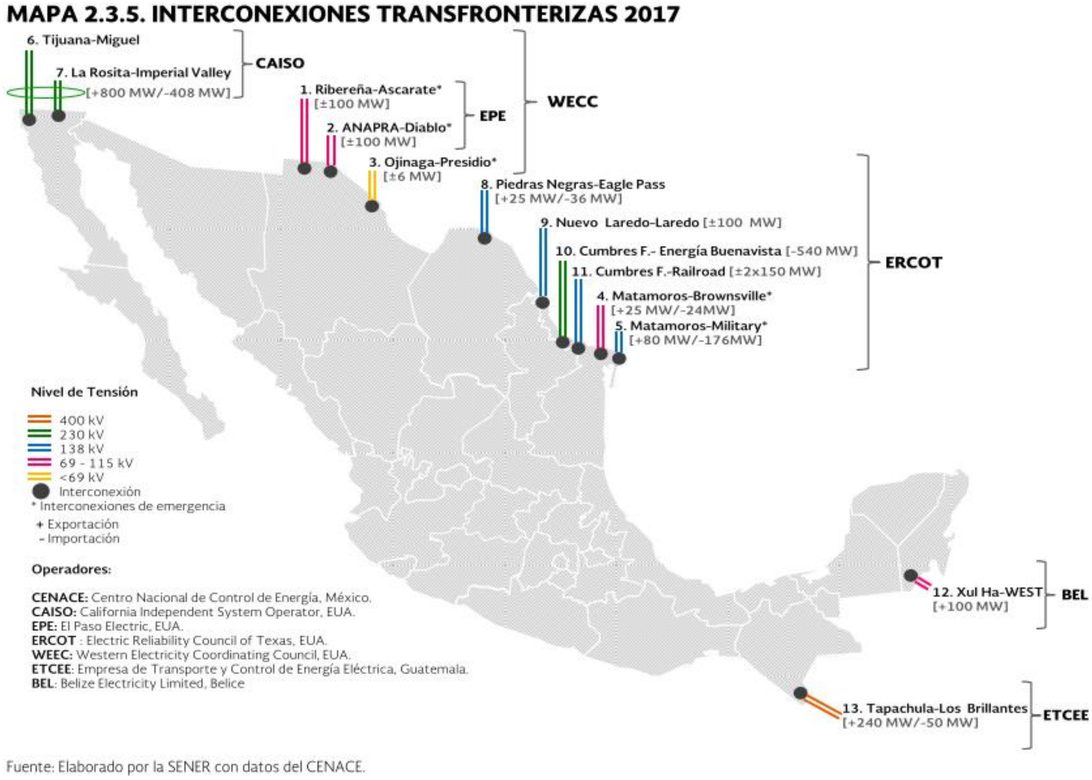

Figure 11: Mexican international interconnections. Numbers 6,7,8,9,10, and 11 are permanent interconnectors that allow commercial transactions on a normal basis. The rest are for emergency power. The "+" sign refers to the capacity from Mexico to the US and the sign "–"vice versa. Source [52]

Only three US states currently trade electricity with Mexico. California, New Mexico and Texas. The electricity trade from Mexico to the US is given by a series of exceptions within the grid structure.

First, as explained before the Baja California transmission system is isolated form the SIN but stull under the responsibility of CENACE. However, this system is highly integrated to the WECC and participates extensively in the US market. Also, the biggest transmission capacities are located in this area.

Second, ERCOT is quite a unique RTO within the US. ERCOT has avoided federal regulation by FERC by establishing a sector that avoids cross-border relationships. This maintained all the grid operations within Texas and is only interconnected to the rest of the US by a series of asynchronous interconnectors. This virtual isolation of ERCOT and the small size of the interconnectors, gives it the ability to have interconnections with Mexico. Even though the Mexican network codes are not fully compliant with those of FERC [19].

Finally, with exceptions of this cases, Mexican electricity does not go to any other state and usually the trade is in the form of bilateral agreements and emergency situations. The big difference in market sizes, and the size of the interconnectors as is, do not pose ideal conditions for further integration on the region. Hence, a frontier condition is stablished, and the market coupling will be linked to these regions (ERCOT, Southwest and California). The frontier conditions will consist that all the exchanges outside the selected zones will be subtracted in real terms from the real hourly data.

One objective of this simulation is to find complementarities between the two markets. And see if an enhanced interconnection is beneficial for all parties. Also, the interconnection between US RTO´s will be used optimally and not only reserved for reliability.

The demand profiles of both countries could be complementary and can enhance the cross-border zonal interexchange between them. This may allow for cheaper prices throughout the interconnected areas and further utilization of generation units, further incentivizing the investment on cheaper sources. All of the demand profiles are set to the central time to be comparable. Furthermore, this time is the one that will be sued as a transaction time for all interchanges within the market clearing algorithm. The demand is of 2018. As Mexico has a LMP pricing and demand methodology (explained after, an average had to be done to get the values presented in this paper.

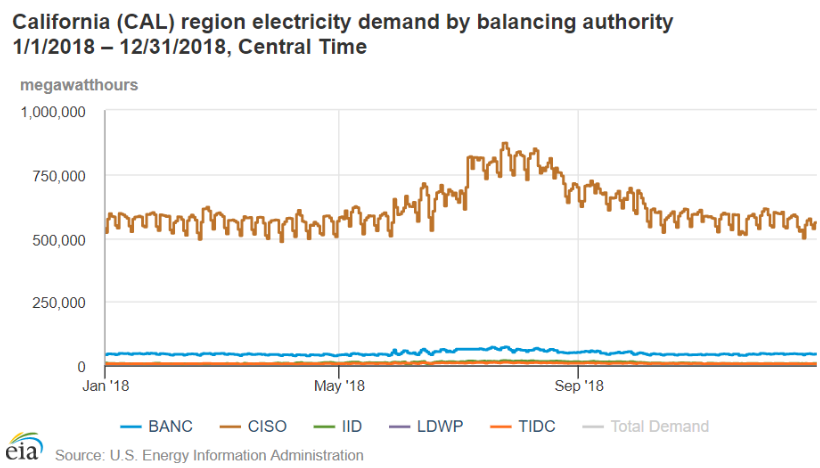

Figure 12: 2018 demand profile of the California region by balancing authority. Source:[46]

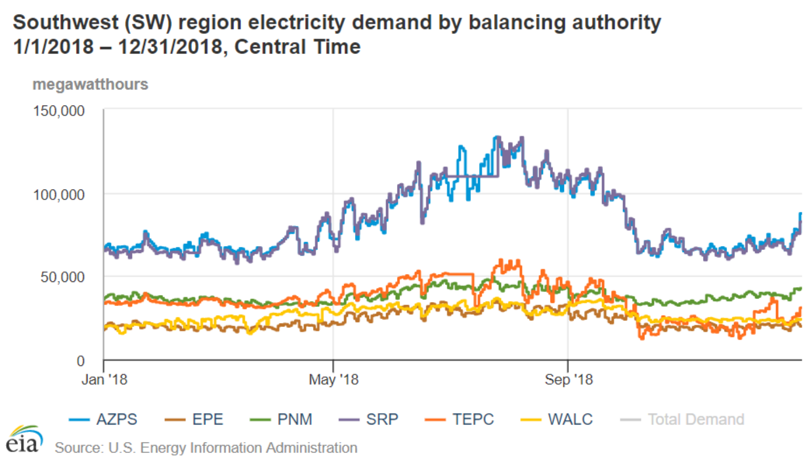

Figure 13: 2018 demand profile of the southwest region by balancing authority. Source: [53].

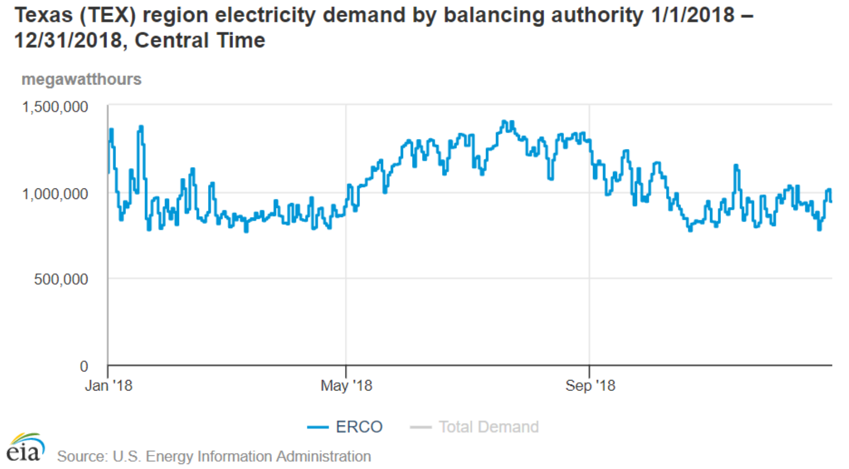

Figure 14: 2018 demand profile of the Texas (ERCOT) region by balancing authority. Source:[45].

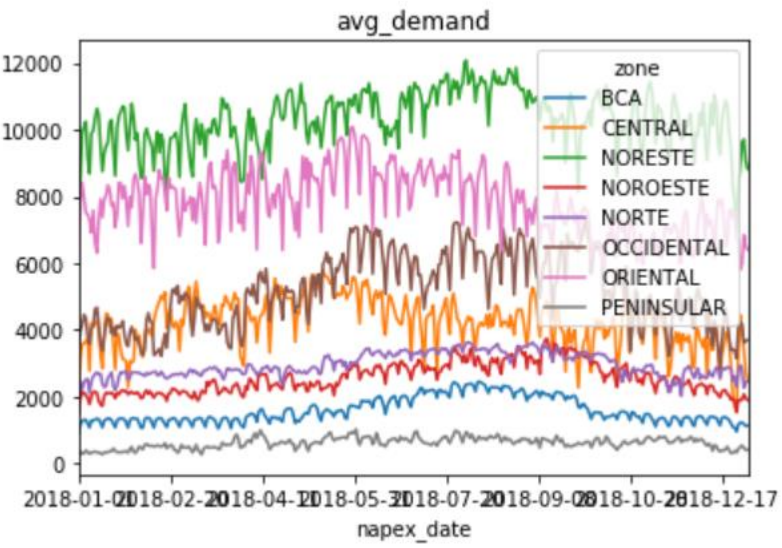

Figure 15: demand profiles of the Mexican transmission regions. Own figure.

Currently the interexchange values between Mexico and the selected regions is small and quite limited, almost reserved for emergencies. This is due to the fact that Mexican electricity is not up to standards and code regulations of the FERC. For the purpose of this study, this will be overseen and assumed that the exchange can be one without regulation limitations.

As we can see on figures 12-15 some complementarity can be found in wintertime October-March, but the peaks somewhat coincide so the interzonal exchange could be affected. For getting the zonal prices from the LMO from Mexico, a weighted average with respect of the installed capacity of each node was done. This will be further explained in chapter 4.

2 Market coupling

"*Electricity should, as far as possible flow between member states as easily as it currently flows within member states".* This extract taken from [20] express in one sentence the fundamental objective of *Market coupling of electricity markets* (referred here after as "market coupling"). In order to achieve this objective, several technical and economical constraints must be met. This section will be dedicated to explaining the complexity and the solutions currently available to make a North American market coupling a reality.

More formally, market coupling can be defined as the optimal use of the available daily cross-border capacity between the participating bidding zones [21]. Even though, the market coupling solutions can be applicable to a wide range of the electricity markets, i.e. intra-day and real-time markets, this paper will be mainly focusing in the solutions and complexities of the day-ahead market.

Market coupling of electricity markets has two main drivers. Improved security of supply and efficiency [22]. Security of supply is understood as the guaranteed supply of electricity to the end-consumer with a certain level of continuity and quality. To detail this further, security of electrical power systems can be subdivided in two groups [23]:

- Sort-term: Known as operational reliability, is used to describe the system resilience to withstand sudden disturbances such as short circuits or unplanned loss of system elements i.e. loss of load or generation capacity [23]. A reliable system should be able to meet the demand within the situations explained above.

- Long-term: known as adequacy, describes the ability of the system to supply the electrical demand at all times of costumers, taking into consideration scheduled and expected unscheduled outages [23]. Access to fuels, generation and network adequacies can be considered subdivisions of the system´s adequacy.

Moreover, in a coupled market, is easier to pool the expensive capacity resources required to maintain reserve margins. By doing this it ensures a broader access to a more diverse portfolio and makes it simpler to find replace capacity then this becomes unavailable, scheduled or not. An equally important requirement is the strong coordination among system operators to maintain the system security over their respective control areas to avoid blackouts and system element damages [22].

On the efficiency front; development, complementarity, generation-capacity mix, market, renewable energy sources (RES), all see improvements and makes the market coupling a more attractive solution. One important feature of this efficiency is exploiting the complementarities between demand patterns across the interconnected zones. This complementarity in a coupled market contribute to reduce the overall cost of the electricity system by the aggregation of demand across zones.

The aggregation of demand in North America can complement itself in more than one way. Usually maximum electricity demand occurs at different times in the countries participating in the market coupling. The seasonal variation in electricity demand (Winter and summer peaks in northern and southern countries) together with different time zones throughout the area, provides a quite promising complementarity. This means that the region can share resources instead of building capacity that would be idle for months [22].

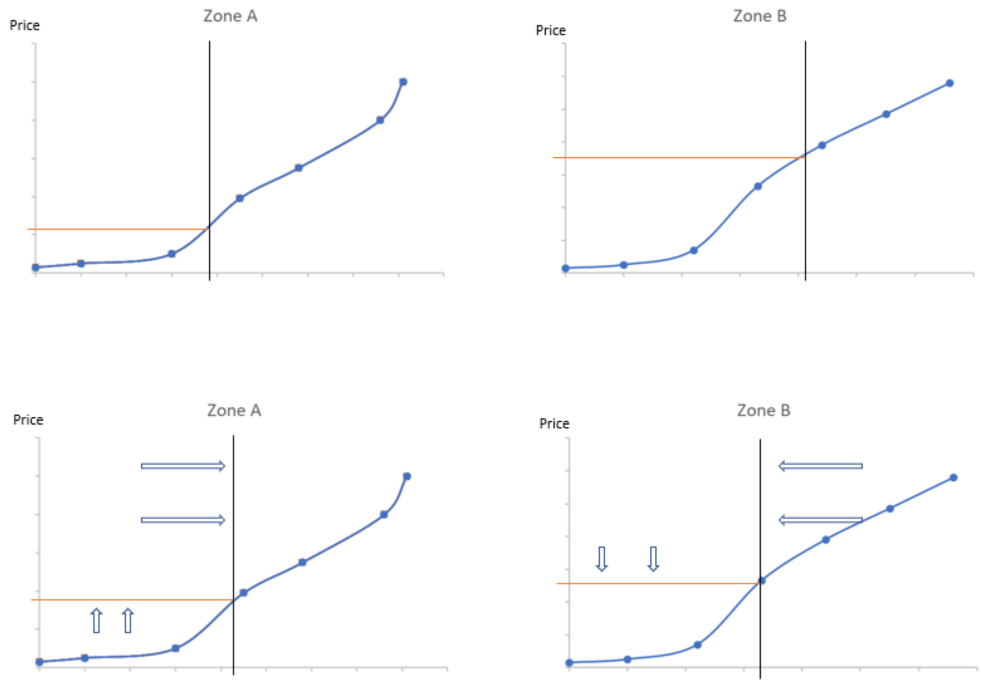

Figure 16: Visualization of the possible effect of the market coupling between two zones (before and after). Blue line supply merit order, black line demand in zone z, red line price point in zone z. Full convergence will yield the same price point.

One other way the demand aggregation helps drive down costs, by smoothening demand variations. This means that the portion of baseload demand is increased and has the contrary effect on peak demand. Hence, cheaper sources are used more to meet the demand thanks to the merit order [22]. the benefits of the merit order working with a well-diversified energy mix are well known and overall dispatching costs are reduced. Priority dispatching is also a common practice, where non-carbon bases energies i.e. green energies, are dispatched first with little regard of their marginal costs.

The synergies that con be observed between generation-capacity mixes are mainly regarding the marginal costs and the fuel savings. Low-cost generator seeks to sell as much energy as possible, meanwhile high-cost generators see fuel costs savings. A market coupling schema helps easing the liberalization of electricity markets in countries that are still dominated by a strong incumbent operator originated by the natural monopoly of a vertical integration e.g. Mexico. Market power mitigation and emphasizing competitiveness are the solutions that a coupled market offers to smoothen the transition [22].

2.1 Calculation methodology

Now that the market coupling concept has been introduced, as well as the drivers for its implementation. I will explain the mathematics behind it that will be, in some sense, the backbone of the model, goal of this diploma thesis. This subsection is based on [13, 24–26].

For making these methodologies to work, network limitations have to be taken into account in a form generally referred to as *congestion management.* It will be assumed that for regular trade (trade within a trading zone), the capacity of the network is sufficient and do not represent any binding constraint to interzonal trade. This assumption is denoted as *copper plate.* With this assumption, the only binding capacity for creating the market clearing solution space is that of the interconnectors asi is far more limited.

Market coupling of liberalized markets creates two different layers of flow that has to be addressed to make a feasible market clearing model. The technical layer is the one that solves the market taking in count Kirchhoff's laws to determine physical flows. These fiscal flows combined with the thermal capacities of the transmission lines determine the congestion of the network. The economic flow subsists on top of the technical layer and determines the transaction flows. The physical flow determines the path form a generator to a sink which can take many paths depending on the topology of the network; while the economic flow delimits the trading of electricity and its described by a single path. These differences allow us to break down every physical flow into economic and non-economic path known as parallel flows.

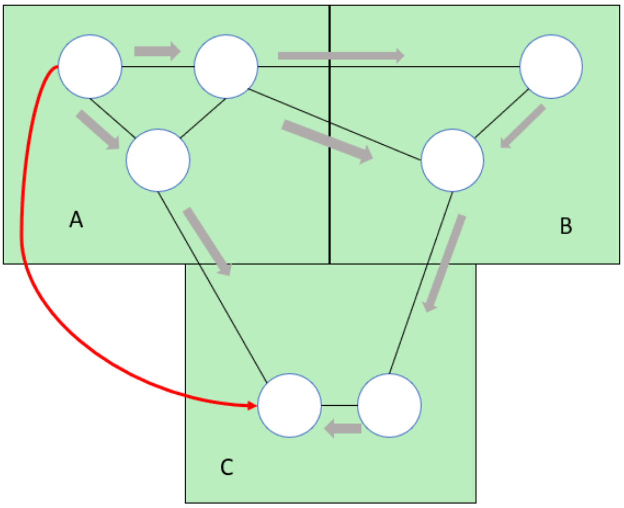

Figure 17: representation of physical flows (grey) and economic flows (red) in cross border capacity. Based on [13].

As explained above, the market coupling can be seen as an effective way of utilizing the existing network to the maximum of its capacity. This is done with the help of cooperating TSOs, power exchanges and interconnection capacity. Coordination among the participants is of vital importance to avoid overloads and other complications in the interconnected network.

To represent this optimal exploitation of the electricity grid, an objective function has to be determined. In this context, the social welfare (w) is to be maximized, where it represents every aspect of the market. Social welfare is defined as producer economic surplus + consumer economic surplus + congestion rents[27]. The last one refers to the price difference when price convergence it´s not reached, times the traded flow and is interpreted as revenues for the TSO. The utility function has its base on the merit order and on the supply-demand aggregation per bidding period (1 hour). Let z and a be both different subset of bidding zones Z, s the index of supply bids S, d the index of demand bids D, L subset of interconnectors between zones a, z (Lz.a) and f the flow between zones a, and z.

$$W = max \sum_{z \in Z} \left[\sum_{d \in Dz} C_d \cdot Q_d \cdot x_d - \sum_{s \in Sz} C_s \cdot Q_s \cdot x_s - \sum_{l \in L_{z.a}} (|P_{l_z} - P_{l_a}) \cdot (f_l) \right] \tag{2.1}$$

Where:

$C_{d,s}$: “cost” of demand/supply bids in bidding zone z.

$Q_{d,s}$: Quantity in MWh of the supply/demand bids in bidding zone z.

$x_{d,s}$: Accepted share of the supply/demand bid in bidding zone z. (0<x<1). Decision variable.

P_{lz} : clearing price in bidding zone z.

P_{la} : clearing price in bidding zone a.

f_l : Flow through interconnector line l.

If we consider that the demand is inelastic and fixed to each node, equation (2.1) will change. In this simplification, the social welfare is changed to a generation cost minimization objective function where congestion rents are still taken in count.

$$W = min \sum_{z \in Z} \left[\sum_{s \in Sz} C_s \cdot Q_s \cdot x_s + \sum_{l \in L_{z.a}} (|P_{l_z} - P_{l_a}) \cdot (f_l) \right] \tag{2.2}$$

Where:

C_s : "cost" of supply bids in bidding zone z.

Q_s : Quantity in MWh of the supply bids in bidding zone z.

x_s : Accepted share of the supply bid in bidding zone z. (0<x<1). Decision variable.

P_{lz} : clearing price in bidding zone z.

P_{la} : clearing price in bidding zone a.

f_l : Flow through interconnector line l

Both equations (1,2) are subject to the constraints set by the capacity allocation method chosen and by the constraint that sum of net position equal 0 (ΣNP=0). Considering that the congestion rent part of the equation (2) can be depreciated because it falls into an investment paradox where the more the TSO invests on interconnection capacity, the less revenue it will perceive due to the market convergence[28]. This allow us to further simplify the social welfare equation *W* to also take in count the demand bids in bidding zone z transform it to a maximization problem.

$$W = max \sum_{z \in Z} \left[\sum_{b \in Bz} C_b \cdot Q_b \cdot x_b \right]$$

(2.3) *based on* [29]

Where:

C_b : "cost" of bids in bidding zone z.

Q_s : Quantity in MWh of the bids in bidding zone z. Generator bids are negative and demand bids positive.

x_s : Accepted share of the bid supply in bidding zone z. (0<x<1). Decision variable.

The market outcome is subject to the market clearing condition, meaning that the zonal generation equals zonal consumption plus the net position (NP)[13]. A negative NP represents and export and a negative NP an import.

$$\sum_{b \in Bz} Q_{bz} \cdot x_{bz} + NP_z = 0 \qquad \forall z$$

(2.4)

The constraints of the market outcomes are set by the available transmission capacity:

$$-F_{l\,max} \leq F_l \leq F_{l\,max} \qquad \forall l$$

(2.5)

$$F_l = f(NP_z) \qquad \forall l$$

(2.6)

Where:

$F_{l\,max}$: The maximum transmission capacity of line l available in the market in [MW].

F_l : Flow through line l.

f : function lining the NP with flows through the network and its specified by the market clearing method to be used. This function has to be solved for every time step pf the electricity market.

Two methods are currently being applied on the EU for day-ahead market clearing in a coupled market (ATC and FBMC) and will be explained on the following subsections together with nodal market clearing. These models works on the assumption that all grid regulators of all bidding zones included comply to the market rules (network codes), that there are not institutional barriers and the markets involved are liberalized[22].

2.2 Nodal market clearing

This market clearing method is the one currently used in Mexico and throughout the transmission regions of USA. Nodal electricity markets make use of locational marginal prices (LMP) which prices the electricity at each node of the system while taking in count transmission congestion in a DC approximation[30] of the real network [31]. In this method, all the relevant parameters (physical) of the network are taking in count for the market clearing algorithm. Therefore, this allows that all commercial transactions are correctly converted to physical flows and constraints are correctly accounted for throughout the entire network [27].

If equation 2.3 is to be applied with this market clearing method, each node will be taken as a market zone and the size of the market clearing algorithm increases to the number of nodes in the network and the critical lines expand to all lines l in the grid. The NP transforms to the nodal injections Pn which represent the generation minus the consumption at each node. Thus, the transmission constraints transform to[27]:

$$-F_{l\,max} \leq F_l \leq F_{l\,max} \qquad \forall\, l \tag{2.7}$$

DC power flow

DC power flow is a linear approximation of an AC power flow system. This method consists in assuming flat voltage profiles and small voltage angles [13]. This allows for a reduction on the AC load flow equations to be reduced in such wat that the active power flows on each line linearly depends on the transmission line reactances and the voltage differences at the end of that line [29]. Also, the losses on the line are omitted enabling useful simplifications on the calculations.

The first approximation is due to the fact that the resistance of the grid is usually much less than the reactance. The second approximation is related to the voltage angles between two buses which normally is also small at stable operation. The third approximation is based on voltage magnitudes whom will be almost equal to the reference voltage [13].

$$F_l = \sum_n PTDF_{l,n}^{node} \cdot P_n \qquad \forall\, l$$

(2.8)

Where:

$F_{l\ max}$: The maximum transmission capacity of line l available in the market in [MW]. Maximum capacity of the line reduced by a security margin.

F_l : Flow through line l.

P_n : Nodal power injections.

$PTDF_{l,n}^{node}$: Nodal power transfer distribution factors (explained below)

The LMP policy allocates implicitly the transmission capacities of all the lines of the system, respecting the grid´s constraints. Meaning that the accepted bids can be implemented without violating any technical constraints[31].

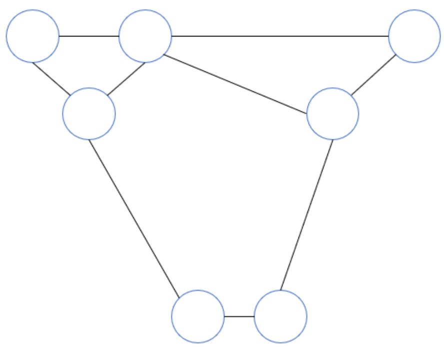

Figure 18: Nodal market representation.

2.2.1 Power flow equations

The PTDF are calculated based on a standard ser of AC power flow equations. This subsection will introduce the PTDF concept and calculation starting from the AC power flow and applying the DC power flow approximations.

The steady state active and reactive flows can be described by the non-linear equations[24]:

$$P_i = V_i \sum_{k=1}^{n} V_k (G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k))$$

(2.9)

$$Q_i = V_i \sum_{k=1}^{n} V_k (G_{ik} \sin(\delta_i - \delta_k) + B_{ik} \cos(\delta_i - \delta_k))$$

(2.10)

Where:

P_i : Active power balance in node I (per unit MW).

Q_i : reactive power balance in node I (per unit MW).

i,k : Node number.

n : number of nodes

V_i : Voltage magnitude in node i.

δ_i : Voltage angle of node i.

δ_k : Voltage angle of node k.

G_{ik} : Conductance between node i and k with negative sign.

G_{ii} : Sum of all conductances connected to node i.

B_{ik} : Suceptance between node i and k with negative sign.

G_{ii} : Sum of all suceptances connected to node i.

Equations 2.9 and 2.10 both are node balance equations in an AC grid at each node. Each line or transformer can be described in a simplified way by a series RL branch, a current flow and a voltage drop[30]. The inverse line parameters are commonly used:

$$Z_L = R_L + j \cdot X_L$$

(2.11)

$$Y_L = G_L + j \cdot B_L = \frac{R_L}{R_L^2 + X_L^2} - j \cdot \frac{X_L}{R_L^2 + X_L^2}$$

(2.12)

Where:

Z_L : Impedance of transmission line L in [ohms].

R_L : Resistance of transmission line L in [ohms].

X_L : Reactance of transmission line L in [ohms].

Y_L : Admittance of transmission line L in [siemens].

G_L : Conductance of transmission line L in [siemens].

B_L : Suceptance of transmission line L in [siemens].

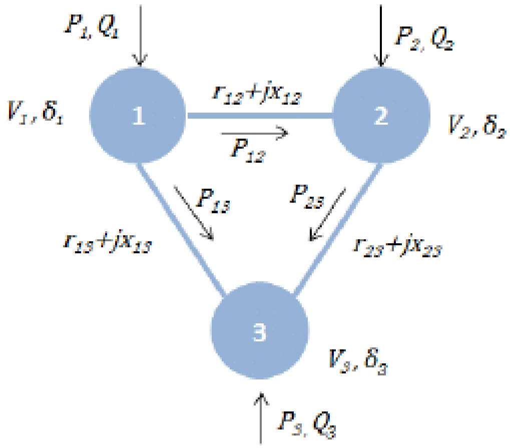

Figure 19: illustration of the node and line parameters used in the power flow eq. this illustration shows the relationship between the concepts previously described in a simplified grid. Source[24].

By applying the DC power flow approximations we can stablish the relationship between the power injection at each node and the flows through the grid[24].

$$First\ aproximation: \quad R < X \quad \rightarrow \quad G \approx 0 \ \therefore \ B \approx \frac{-1}{X}$$

(2.13)

$$Second\ aproximation: \quad \sin\delta \approx \delta \quad and \quad \cos\delta \approx 1$$

(2.14)

$$Third\ aproximation: \quad V_i\ ,V_k \approx 1$$

(2.15)

After considering the DC power flow approximations equations 2.9 and 2.10 will be seriously simplified and will facilitate the calculations:

$$P_i = \sum_{k=1}^{n} B_{ik}(\delta_i - \delta_k)$$

(2.16)

$$Q_i = \sum_{k=1}^{n} -B_{ik}$$

(2.17)

Based on equation 2.17 **Qi** turns into a constant and has no impact on the flow through the grid, allowing me to only take in count Pi (active power) to compute the voltage angles for a determined ratio of supply/demand. This simplification of equations 2.9

and 2.10 is known as the DC power flow method. Is the preferred way of linearization of the AC power flow equations for grid modeling.

Now that the DC power flow equations have been described, it is time to describe the networked to be analyzed where these equations will be applicable. This description of the grid is done by its incidence matrix **A** and its bus admittance matrix **Y**. The incidence matrix is a LINE X NODE (LxN) matrix that describes the topology of the network. The topology of the network refers to the description of which lines are connected to which nodes. The node and line parameters taken in count for the incidence matrix are the current and the voltage in node *n* and line *l.* The admittance matrix is a NODE X NODE (NxN) matrix and its parametrization relates to the nodal voltages and the injected nodal currents. The network description is done in 4 steps[30]:

1. The incidence matrix LxN with $a_{l,n}$ = 1 if the line L starts in node N, $a_{l,n}$ = -1 if line l ends at node N and $a_{l,n}$ = 0 is line l is not connected to node N.

$$A = \begin{bmatrix} a_{1,1} & \cdots & a_{1,n} \\ \vdots & \ddots & \vdots \\ a_{l,1} & \cdots & a_{l,n} \end{bmatrix}$$

(2.18)

2. Kirchhoff's current law is applied at each node:

$$\sum_{k=1}^{n} I_k = 0$$

$$i_N = A^T \cdot i_L$$

(2.19)

3. Kirchhoff's voltage law is applied at each transmission line:

$$\sum_{k=1}^{l} V_k = 0$$

$$V_L = A \cdot V_N$$

(2.20)

4. Substituting equation 2.20 in equation 2.19, yields:

$$i_N = Y \cdot V_N$$

(2.21)

As it can be observed from equation 2.21, knowledge of the admittance matrix is needed in order to describe entirely the grid. The Y-matrix is symmetric as $B_{i,k}$ = $B_{k,}$ and corresponds to the negative suceptance between node i and k. The diagonal elements of the matrix are equivalent to the sum of all suceptances connected to the node. If two nodes are not connected, the impedance between them is infinite and therefore, the admittance between them is zero. Transforms and other grid elements can be added to the matrix and the grid description by their equivalent impedance. The Y matrix can be generally described as:

$$Y = \left[y_{\_N,N'}\right]$$
$$y_{\_N,N'} = \sum_{N'} Y_{\_N,N'}$$
$$y_{\_N,N'} = -Y_{\_N,N'}$$

(2.22)

Where:

$Y_{\_N,N'}$: is the admittance of the line between the nodes N and N´. the relationship between the Y-matrix and the A-matrix is described by the following equation[30]:

$$Y = A^T \cdot Y_d \cdot A$$

(2.23)

Where:

Y_d : refers to q LxL-diagonal matrix that contains the line admittances on the diagonal, its also referred as the primitive admittance matrix.

Now that the concepts of the grid description are explained, is time to merge the DC power flow equations with the grid topology to calculate the nodal PTDF matrix, which connects the flow over each line with the physical constraints of the network for the optimization process. Remembering equation 2.16 in matrix form, it can be expressed as:

$$[\mathbf{P}] = \begin{bmatrix} \mathbf{P_1} \\ \mathbf{P_2} \\ \vdots \\ \mathbf{P_l} \end{bmatrix} = \begin{bmatrix} \mathbf{B_{1,2}} + \mathbf{B_{1,3}} + \dots & -\mathbf{B_{1,2}} & \cdots & -\mathbf{B_{1,n}} \\ -\mathbf{B_{2,1}} & \mathbf{B_{2,1}} + \mathbf{B_{2,3}} + \dots & . & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ -\mathbf{B_{n,1}} & -\mathbf{B_{n,2}} & \cdots & \mathbf{B_{n,1}} + \dots + \mathbf{B_{n,n-1}} \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_n \end{bmatrix} = [B][\delta] = [Y][\delta]$$

(2.24)

Note that δ is the vector that contains the voltage angle at the nodes. At the same time, the voltage angle is given by:

$$[\delta] = [Y]^{-1}[P] = [Z][P]$$

(2.25)

Here, the inverted Y-matrix is referred as Z-matrix or impedance matrix. Due to the dependency of power P to only the difference of voltage angle δ (eq. 2.16) and not on the absolute values, there are infinite solutions of equation 2.24. Therefore, to have a unique solution a reference point must be created for the absolute values of the system. This reference point is commonly known as “slack-node” or “slack-bus” and is set to δ=0. There are two different ways to set the slack-node that yield the same result, the methodology followed by [24] and the one followed by [30]. On the first reference, which is also the methodology selected for the model proposed on this thesis, is to add a single unit “+1” to one of the diagonal elements (selected slack-node) and the second one consist on eliminating the row and column of the selected node in the Y-matrix. If the selected slack-node is node number 1, equation 2.25 will be transformed by both methods accordingly:

$$\begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_n \end{bmatrix} = \begin{bmatrix} \mathbf{1+B_{1,2}+B_{1,3}+\ldots} & \mathbf{-B_{1,2}} & \cdots & \mathbf{-B_{1,n}} \\ \mathbf{-B_{2,1}} & \mathbf{B_{2,1}+B_{2,3}+\ldots} & . & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{-B_{n,1}} & \mathbf{-B_{n,2}} & \cdots & \mathbf{B_{n,1}+\ldots+B_{n,n-1}} \end{bmatrix}^{-1} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix} = [Z][P]$$

(2.26)

$$\begin{bmatrix} \delta_2 \\ \vdots \\ \delta_n \end{bmatrix} = \begin{bmatrix} \mathbf{B_{2,1}+B_{2,3}+\ldots} & \cdots & \mathbf{-B_{2,}} \\ \vdots & \ddots & \vdots \\ \mathbf{-B_{n,2}} & \cdots & \mathbf{B_{n,1}+\ldots+B_{n,n-1}} \end{bmatrix}^{-1} \begin{bmatrix} P_2 \\ \vdots \\ P_n \end{bmatrix} = [Z][P]$$

(2.27)

After the slack-node selection, given the voltage angles in each node, the Active power flowing between two nodes can be calculated by the following equation:

$$P_{ik} = B_{ik}(\delta_i - \delta_k)$$

(2.28)

2.2.2 Nodal PTDF calculation

The PTDF reveals how does a node participates on a certain branch; they function as a type of weight that each node contributes to the grid’s topology. The PTDF matrix includes the PTDF for all lines in the system. The way is derived is by assuming an increase in power and how this increase will affect the network as a whole.

Assuming ΔP_1 is fed to the network at node *n (outside of the diagonal)* and at the slack-node. From eq. 2.27 this delta can be calculated as:

$$\Delta\delta_{sn} = \Delta P_{sn}\left(1 + B_{1,2} + B_{1,3} + \cdots\right) = \Delta P_{sn}(Z_{11})$$

(2.29)

$$\Delta\delta_n = \Delta P_n\left(-B_{n,1}\right) = \Delta P_n\left(Z_{n,1}\right)$$

(2.30)

The change of the active power flow in a branch due to an in injection in node *n* is calculated by combining equations 2.28, 2.29, and 2.30 together.

$$\Delta P_{i,k} = B_{i,k}(\Delta\delta_i - \Delta\delta_k) = B_{i,k}\left(Z_{i,n} - Z_{k,n}\right)\Delta P_n$$

(2.31)

If delta P is set to 2.0 p.u. the PTDF can be expressed as:

$$PTDF = B_{i,k}\left(Z_{i,n} - Z_{k,n}\right)$$

(2.32)

Or in matrix form:

$$PTDF = [A][Y_d][Z]$$

(2.32)

The PTDF has to be calculated for every location of the matrix and the slack node should deliver a column of zeros. For further reference refer to [30][24].

2.3 Available transmission capacity (ATC)

This method is one of the earliest approaches to market coupling and the transmission capacity for the market is calculated ex-ante for each border separately. Using this method, implies a strong simplification of the commercial transactions and the physical constraints of the grid. The zonal electricity markets production and consumption in power systems is simplified using a zonal representation of the underlying nodal electrical network[31].

The ATC is calculated as the maximum exchange that the market can provide between two market areas, that are compatible with physical transmission constraints and network codes. For the ATC calculation, the TSOs approximate the parallel flows that will result from the market coupling. This is heuristic calculation and relays on the base case determination. The ATC capacities are calculated for each of the cross-border branches. By applying this methodology, the set of relevant branches for the market clearing algorithm is reduced to only the cross-border branches instead of the set of all transmission lines as in the nodal market coupling. The change alters the transmission constrains that bound the market clearing algorithm and now become[27]:

$$ATC_{l\,min} \leq F_l \leq ATC_{l\,max} \qquad \forall\, l$$

(2.33)

$$F_l = \sum_{l} A_{l,z} \cdot F_l \qquad \forall\, z$$

(2.34)

Where:

$ATC_{l\,min}$, $ATC_{l\,max}$: Are the negative and positive direction of ATC values respectively.

$A_{l,z}$: is the incidence matrix (see power flow equations).

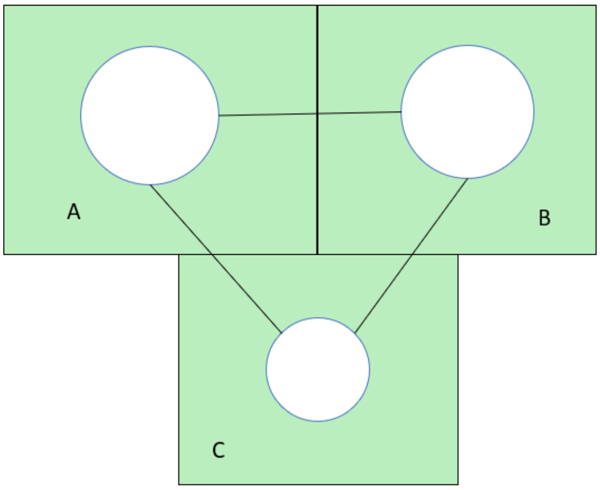

Figure 20: Zonal market model under ATC.

This simplifications and ex-ante nature of the ATC-market coupling yields a rather opaque calculation algorithm for regulators. In this method the interconnector capacity is allocated explicitly. Furthermore, the ACT capacities tend to be conservative to ensure the reliability of the grid. The main differences observed with the nodal market coupling is that the constraints change from nodal to zonal and that the linking function no longer takes in count the contributions of the nodal injections and depends entirely on the precision of the base case. Relying this much on the base case renders this methodology rather inefficient and promotes a sub-utilization of the cross-border capacities. Moreover, the copper plate assumption within the bidding zones, do not allow us to model critical branches within them restricting more the interzonal flow exchange and limiting convergence. Only one equivalent node per zone is considered and only one branch connecting them, the direction of the flow is determined by the sign of the ATC-value constraints.

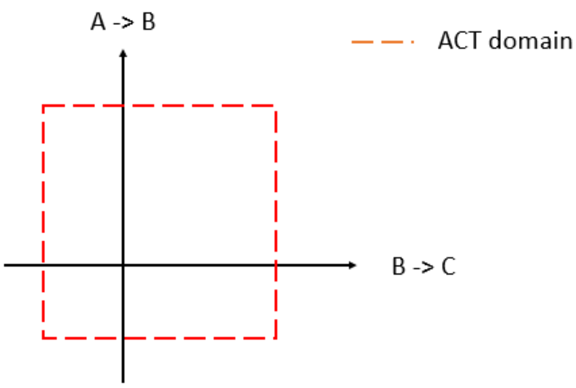

Figure 21: ATC flow domain of a 3-zone market. The dimensions of the rectangle are characterized by the ATC-values. Based on: [27]

2.3 Flow based market coupling

The FB is a grid representation that tries o find the mid-point between nodal and zonal markets [31]. In the FBMC the bids are considered per zone instead per node. This zonal methodology differs from the ATC market coupling by allocating the transmission capacity implicitly. Using this methodology, the nodal injections *Pn* transform to zonal net exchange position *Np* to define the market clearing conditions in equation 2.4. NP describe the difference between the zonal generation injected and the zonal load[13].

$$NP_z = \sum_{z=1}^{Z} \left[\sum_{b=1}^{B} ZB(z,b) \cdot g_b - \sum_{n=1}^{N} ZN(z,n) \cdot d_n \right]$$

(2.35) source [13]

Where:

ZB: bid to zone matrix. Maps generation bids to the nodes.

ZN: node to zone matrix. Maps each node to a zone.

Equation 1,35 can be summarizes as the sum of all nodal injections Pn of a zone proposed in the nodal market coupling algorithm. This allows for the zonal application of equation 2.4.

$$NP_z = \sum_{z=1}^{Z} \left[\sum_{n=1}^{N} ZN(z,n) \cdot P_n \right]$$

(2.36)

Nodal injections Pn stop having sense in a zonal FBMC context to transform to their zonal equivalent. Respectively, the balancing equality constraint adjust to this new definition and states that all interzonal exchanges sum to zero to have a closed system [13].

$$\sum_{z=1}^{Z} NP_z = 0$$

(2.37)

Tow FBMC parameters are needed to characterize the optimization problem: 1) Zonal PTDF 2) Remaining available margin (RAM). To calculate these parameters the Base case is needed. The parameter calculation starts two days before the transaction date and finishes the morning of the delivery. The base case tries to describe the state of the grid topology, net exchange positions and power flows through each CNE for each hour of operation on a nodal level for the delivery day.

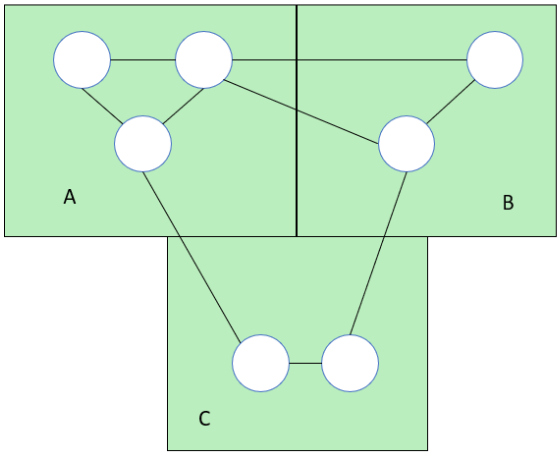

Figure 22: Zonal market model applying FBMC concept.

If equation 2.3 is to be applied with this market clearing method, the market clearing conditions will be described by:

$$-RAM \leq F_l \leq RAM \qquad \forall\, l \tag{2.38}$$

$$F_l = \sum_{z} PTDF_{l,z}^{zone} \cdot NP_z \qquad \forall\, z \tag{2.39}$$

2.3.1 Zonal PTDF calculation

As figure 22 shows, there are differences between the previous methodologies presented so far and the FBMC. Here, the concepts between nodal and zonal market coupling try to find a common ground. Nodal injections in each node of the bidding zones will have different effects depending on the grid´s topology and on which node they exist. The zonal PTDF is the way to mathematically describe these relationships and aggregate all the nodal concepts into zonal ones [24].

The zonal PTDF matrix is derived from the nodal PTDF matrix with the help of the Generation Shift Keys (GSK). The GSK provides the relationship between Pn and the NP. They give the nodal contributions to a change in zonal balance. The GSK is defined as how a change in the NP is mapped to the generating units in a bidding zone, they are used to describe how the net NP of each node influences the NP of the area they belong to [24][13].

According to [13] the mathematical representation of the GSK is the derivative of Pn with respect to the NP of the zone they belong to. This unfortunately requires knowing the market clearing solution NP to be known in order to calculate it analytically creating a circular problem. Furthermore, the sum of GSK of a sum must equal 1.

$$GSK = \frac{dP_n}{dNP_z} \qquad with \qquad \sum_{z=1}^{Z} GSK_z = 1$$

(2.40)

There are various ways to calculate heuristically the GSK to overcome the circular nature of the calculation. The method chosen will have serious impact on the market clearing outcome and they all have pros and cons. When choosing a GSK calculation strategy, it is important to note that this is a linear approximation to a nonlinear problem. To illustrate this linearization, two calculation methods will be presented: Average GSK (flat participation) and marginal GSK presented in [24].

The average calculation as its name suggests, it supposes an equal participation of all nodes in the bidding zone. Choosing this strategy, while simple, can create short comings while clearing the market as it can allocate more generation to a node than the max installed capacity and add fictitious generation to load only nodes. It can be improved by making a weighted average of the GSK with respect of the installed capacity of the node, better representing the grid´s state. As a pro, this strategy yields a more robust assumption and if the market clearing results differ significantly from the real flows, this approximation will handle better the discrepancy.

The marginal GSK strategy relays on an ex-post analysis and tries to predict the marginal node using the base case and historical results to better allocate the GSK weights throughout the bidding zone. This yields a more precise model and if the real flows and NP do not differ much from the base case, this will be the methodology of choice.

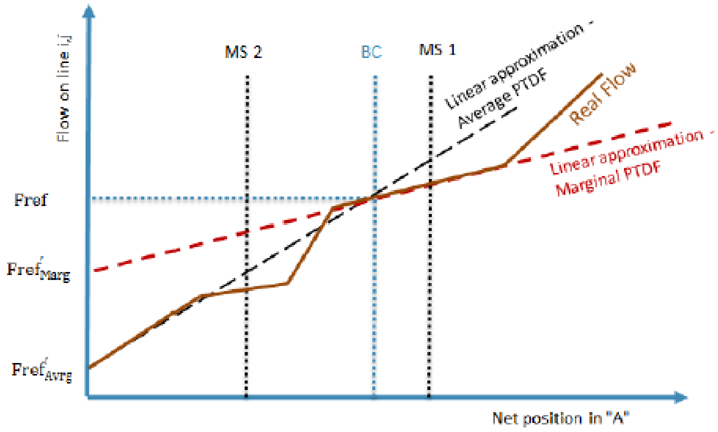

Figure 23: Possible relationships between flows in line l as a function of NP depending on the GSK strategy choice and resulting zonal PTDF. BC refers to base case, MS to market solution one and two respectively. Source: [24].

The relationship between the GSK and the zonal PTDF is given by:

$$PTDF_{l,z}^{zone} = PTDF_{l,n}^{node} \cdot GSK_{n,z} \qquad \forall l \;\; , \;\; \forall z$$

(2.41)

The resulting $PTDF_{l,z}^{zone}$ matrix is an LxZ matrix that maps the CNE and the nodal contributions to the zonal balance.

2.3.2 Remaining available margin

The model proposed in this paper only duels in the day-ahead market and therefore, a need to calculate the remaining line transmission capacity of the CNEs to be used in this market is critical. This capacity is known in this context as RAM. The RAM calculation procedure consists of two main steps [29].

1. The CNEs and critical outages have to be determined. The set of lines L for the market clearing algorithm becomes the set of CNEs defined by the base case.
2. The RAM for the CNEs is calculated under the critical outages and loop flows.

The CNE in this concept can be considered as a cross-border transmission line, inter-zonal transmission line or a transformer. The state of the grid can be considered in an N-state or contingency cases such as N-1 state or any other contingency state. A CNE can be identified by a TSO if the zonal PTDF for that element is larger than 5 %. The determination and selection of the CNEs is done by each TSO independently and can be either hourly or in a daily fashion. RAM is defined in Equation 2.42 [29].

$$RAM = F_l^{max} - F_l^{ref} - FAV_l - FRM_l - F_{Ol} \qquad \forall l \tag{2.42}$$

Where:

F_l^{max}: Is the max thermal capacity allowable on CNE in [MW].

F_l^{ref}: The reference flow generated by commercial transactions out of the day-ahead exchange in the market. These flows can be either internal or external in nature and can include bilateral agreements, forward markets, long term nominations, etc.

FAV_l: Refers to the final adjustment value of the CNE. This value is taken in count by the TSO´s experience and its heuristic in nature. Is used for remedial actions.

FRM_l: Refers to the flow reliability margin in [MW]. A safety margin needed for the compensation of the linear approximation of the FBMC to the nonlinear problem.

F_{Ol}: Refers to the loop flows inherently created by the linear approximations and Kirchhoff's law. In this paper the loop flows definitions is taken the as in [10] where loop flows are defined as the difference between the real market flows and the flows assumed in the FBMC algorithm.

2.3.3 Base case

The base case creation consists on the forecast of the state of the electrical network at eh moment of delivery. In this context of each hour of the day-ahead market at the day of delivery. It is also referred as the Day-2 congestions forecast. While also a Day-ahead congestion forecast exists, which is done in the evening of the day-ahead and therefore more precise, the first step is the D-2 forecast.

The base case determination consists of two main steps, 1) each TSO makes an estimation of the base case within their respective zone or control area, 2) all the different base cases are merged into a common base case that will characterize the market comprised of the interconnected zones[13].

The base case estimation starts with the estimation of the local base case based on a reference day. The reference day is defined as a day where the market outcome is already known, it can be a day in the past with similar conditions (weekend/weekday, winter/summer, dry season/ wet season, etc. This known market outcome is updated with the D-2 renewable forecast, load forecast and outage schedules. The outcome of this first step is the TSOs coordination of the NP for the reference day[13].

For the second step, as there exist different methodologies and conditions for the base case conditions, it's the market clearer or power exchanger's job to join them into one common base case that will set the conditions for the delivery day market clearing.

In conclusion, the constraints set in eq. 2.41 and 2.42 impose the zonal NP limitations to export and import hence defining the FB domain. Form figure 24 we can see that the region of feasible solutions of the FBMC domain is bigger and allows for more interzonal exchanges within the interconnected zones.

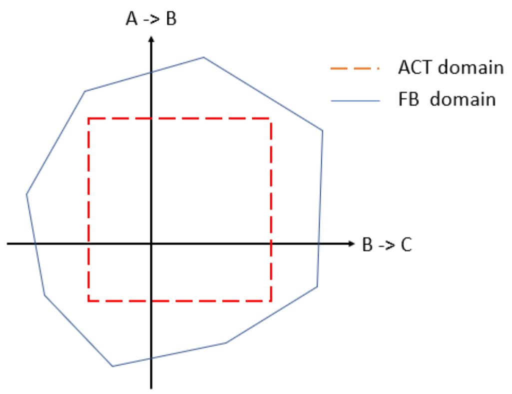

Figure 24: The FBMC domain representation compared to the ATC flow domain of 3 interconnected areas. Based on [29]

2.4 Barriers to Market coupling

It is common knowledge that the key barrier to market integration is the lack of interconnector capacity [22]. Two main reasons for the lack of in integration are mentioned in [21]:

- Inefficient use of existing transmission networks stemming from inefficiencies in cross-zonal capacity allocation, cross-zonal capacity calculation and the assumed definition of possible bidding zones for long- term, day-ahead, intraday and balancing timeframes.
- Lack of investments in electricity network infrastructure that would enable more cross-zonal capacities and more cross-zonal trade between areas with excess supply and areas with excess demand.

While the lack of cross-border transmission lines often reflects regions' physical geography, it can also result from existing institutional barriers[21].

Within these institutional barriers, one of the major difficulties in integrating markets consists in overcoming institutional differences. Market integration within the same country, is often quite challenging because of differences in state-level institutional settings and regulations. Market integration spanning several countries, comes up against even more challenging institutional barriers.

Governments and regulators have a national mandate, or a mandate restricted to an individual state or province. Some regulators affirm that the implementation of measures that optimize social well-being both nationally and internationally is the key challenge to integrate (for example) European markets. The legacy of divergent and inconsistent rules that are difficult to harmonize is an expression of this challenge. Its two most important manifestations are the electrical safety of the supply and Distributional impacts [17].

While this may seem like security of supply could be a combined effort of all the countries involved, this is not entirely true. Governments place great emphasis on ensuring a safe and reliable electricity supply in all their jurisdictions. This is a legitimate concern, given the importance of electricity in modern economies controlled by computers and electronic communications. Electricity still cannot be stored at a reasonable cost. It requires a costly physical infrastructure, so governments remain responsible, in contrast to security of supply for other energies (such as oil and gas), for which governments must rely on global markets.

Although in many aspects security of supply is already a regional problem involving neighboring jurisdictions, policy makers continue to address it in isolation. For example, several governments prefer to generate electricity locally instead of importing it, even if importation is less expensive. Similarly, system operators are often organized at the national level, regardless of the topology of the network or the size of the electrical systems. Local governments are not willing to give up this energy-related competition. In fact, if something goes wrong, government officials will always be responsible. However, this institutional framework must be modernized to reflect the physical and market realities [22].

The market coupling solution for the future of the energy, also present some market barriers as the prices might rise for exporting countries. While increasing interconnector capacity removes congestion, it also triggers wholesale price convergence, thus reducing the overall dispatching cost. While these exchanges improve overall welfare, the price adjustments also generate significant distributive impacts for consumers and producers in different locations.

There is strong empirical evidence that jurisdictions that benefit from cheap coal, nuclear or hydroelectric power are reluctant to participate in the integration of the electricity market or even liberalization. For example, certain states of EE. UU. that benefit from the cheap coal generation do not want to liberalize their markets (in fact, only the states of the East Coast with costly power have decided to liberalize). The province of Quebec in Canada has cheap hydroelectric power and has not liberalized its electricity market, although it exports electricity to the United States. Similarly, France has introduced a wholesale price of regulated electricity for nuclear energy below the market price.

Electricity prices are still a politically sensitive issue. Governments do not aim to act in the interests of neighboring countries, but rather to protect the interests of national consumers. They tend to neglect the distributive impacts of regional market integration, although these are perhaps the main obstacle to greater market integration in many jurisdictions. While in theory economists advocate first increasing overall efficiency and then addressing redistribution, governments rarely do so in practice.

3 Agent based system

In this chapter I will introduce the concept of agents and agency systems (including multiagent systems). It will also include the way agent systems are currently applied to electricity markets and learning methods.

Agents and agency systems are used due to the inherent uncertainty that every computer program encounters when the programmer did not anticipate a specific situation it may occur. For several applications this may be acceptable but sometimes a system that can decide by itself is desired. Here is where agents and agency systems have their cue. This *autonomous* decision refers to what the program needs to do in order to achieve the goals that we have delegate them. These programs are known as agents. Agents have to operate or operate in a robust fashion in an unpredictable and sometimes open environment. When agents act under these conditions there are cataloged as *intelligent agents* that I will discuss further in this paper.

Quoting [32]:

“An agent is a computer system that is situated in some environment and that is capable of autonomous action in this environment in order to achieve its delegated objectives.”

There are some important notes from this quote. And all of them are treated briefly in tis paper. Such notes are: 1) the reference of agents instead of intelligent agents, 2) the definition of environment is open, as the agent can duel in different types of environment, 3) Autonomous is not defined due to its inherent complexity and degree that the agent is capable to act upon. During the extent of this chapter I will be constructing to further constraint the definition of agent.

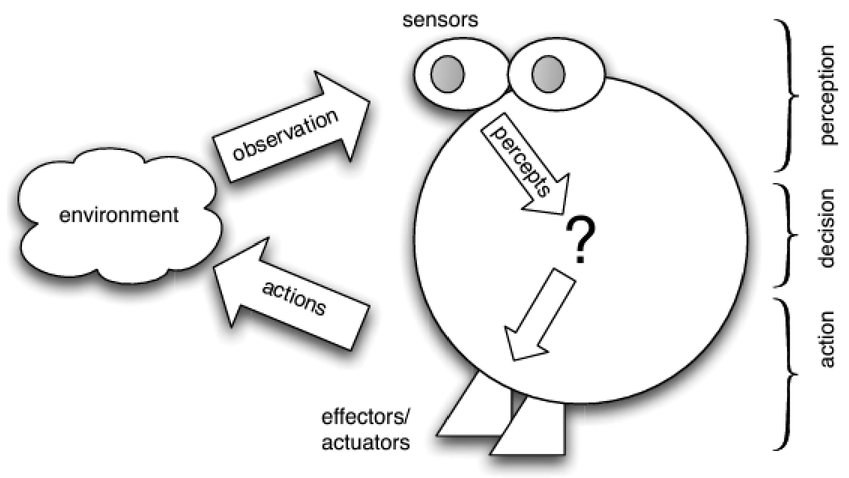

Figure 25: Agent in its environment. Source: [32]

In figure 25 we can see an abstract representation of an agent with its environment. The agent perceives the environment and acts according to these percepts to produce an output in form of actions that affects the environment changing its state. To fully apply the agent definition, in most domains, the agent will not have complete control of its environment. The partial control the agent has over the environment creates an influence over it. The influence, instead of control, implies that the agent has to be prepared to the possibility of failure if the same action is applied to identical situations.

The agent has to have to its disposal normally two or more actions available to interact and modify its environment. These set of actions conform the agent´s *effectoric capability.* The actions within the set are not all applicable to all the situations the agent may encounter. Preconditions associated with each action will define the possible situations where they are applicable [32].

Agent architectures are in charge of solving the agent´s problem of deciding which action is applicable to better satisfy the delegated objectives. Theses decision -making systems are embedded in the environment where the agent develops. Because the actions selecting prosses is based on the environment characteristics. It is necessary to develop further the environment presented in the quote above. According to [33], the following environment classification is presented:

- Fully observable/ Partially observable.
  - If the sensors of the agent give it access to the entire state of the environment needed to choose an action, yields a fully observable environment. The contrary is classified as a partially observable environment.
  - The convince of this environment classification is that the agent is free from tracking the changes in the environment allowing for simpler agents to be built. Unfortunately, most of the complex environments are Partially observable.

- Deterministic/ Stochastic.
  - A deterministic environment is defined as the one where any action has a single effect. In other words, if the following environment state is completely determined by the environment's current state and the action of the agent.
  - Contrary, in a stochastic environment there are multiple unpredictable outcomes for any action. Uncertainty about the state of the environment after aby action the agent choses is inherent to this classification of environments.
  - The uncertainty is avoided in a fully observable, deterministic environment so the agent does not have to deal with it.

- Episodic/ Sequential.
  - Episodic means that the following situation do not depend on the actions occurred in past situations. The agent´s performance depends on discrete episodes.

- Sequential refers to the case where the agent takes in count a series of connected episodes.
    - This allows for a simplification on the agent design as the agent decides what action to take perceiving only the current episode. The interaction between the current and future episode is neglected.

- Static/ Dynamic.
    - If the environment does not change while the agent is deciding which action to perform, the environment is then classified as static.
    - The existence of other processes operating on the environment that changes it beyond the agent´s control, yields a Dynamic environment.
    - If the state of the environment is not changes, the agent does not need to observe the environment while deliberating. The contrary is true otherwise.

- Discrete/ Continuous.
    - If the environment is discrete, there are a limited number of actions and precepts.
    - The contrary is true otherwise.

- Single/ Multi-agent.
    - This realties to the existence of other intelligent agents which the agent needs to be concerned about in either a cooperative or competitive way.
    - MAS are decentralized multi-actor systems where the behavior of each agent is defined and implemented by means of peer-to-peer interactions among rational, autonomous entities.
    - Economic systems are multi-agent.

3.1.1 Intelligent agents

While everyday appliances like thermostats can be considered agents, they are not intelligent agents. In this subsection, the note about the difference between agent and intelligent agent will be explored. Here the definition of agent quoted above will be expanded and described in a more constraint manner.

To be considered an intelligent agent, at least in a weak notion, the agent must fulfill the following properties described on [34]:

- Autonomy: the agents are able to operate without the direct intervention of users and can have some kind of control over the actions they take and internal processes. The given state of an agent its determined by itself.

- Reactivity: the agent´s perception of the environment allows it to respond in near-real-time to the changes that occur in the environment and decide accordingly.
- Social ability: the agent is able to communicate and interact with other agents with the objective of satisfying their delegated goals.
- Proactiveness: agents do not only take action as a response to its environment, but they are rather able to have goal-oriented behavior.

In the model presented in this paper makes use of intelligent agents as they act independently, and the decision-making process is autonomous. Further explanation of the BDI programing driving agency systems and stronger notions of agency can be found at [34] and won't be dealt with within this paper.

3.1.2 Variety of intelligent agent types and architecture

The nature of the problem to *tackle* will define the choice of agent architecture and type. A link exists between the complexity of the task and the minimum requirements the agent architecture should fulfill for implementing a rational agent. Rationality is defined as the choice of actions based on an expected utility of the outcome of the action. Therefore, the agent that chooses the action that provides the maximal expected outcome is a rational one. The agent architectures presented by Russel and Norvig in [33] are:

1) Table-driven agents
2) Simple reflex agents (reactive agents)
3) Agents with memory
4) Agents with goals
5) Utility-based agents

The 1) agent is the simplest form of intelligent agent and works as a table lookup of precept-action pairs. The mapping of these pairs is done for every possible perceived state and the optimal action for that state is taken. this type of agent is not able to adapt to changes in the environment and the whole table (of pairs) has to be updated every time a change is done. It also can't take actions based on previous actions and/or states

Agent 2) chooses the following action based only on the current percept only. Rule-based reasoning maps from the precepts to the best action. It has the same shortcomings as 1).

Memory in 3) encodes an internal state of the conditions to remember the past as contained in previous precepts. The *memory* is needed because the majority of environments are partially observable, and this knowledge improves the decision-making process.

As the complexity of the agents is growing, 4) has the ability to choose actions to achieve a goal and fulfill the delegated responsibilities. In this type of agent, we change from reactive to deliberative which means that they do not only react to the current state of the environment but act and *influence* it in order to achieve its goals. It is able to consider long sequences of actions before making a decision that will have impact on the future.

Finally, 5) sets the template to decide the best alternative when multiple exist. In distinction with 4) not only the goal has to be fulfilled but the quality of the state is considered in a function called utility. If one state yields a higher utility than the other, the agent will choose the first one. The introduction of the utility on the agent architecture ensures not only the seeking of fulfilling the goal but ensures the best *way* to get there. 5 chooses the most desirable action to take in order to fulfil its delegated responsibilities. Allow decisions that compare the choice between conflicting objectives and the choice between the probability of success and the importance of the objective (if the achievement is uncertain).

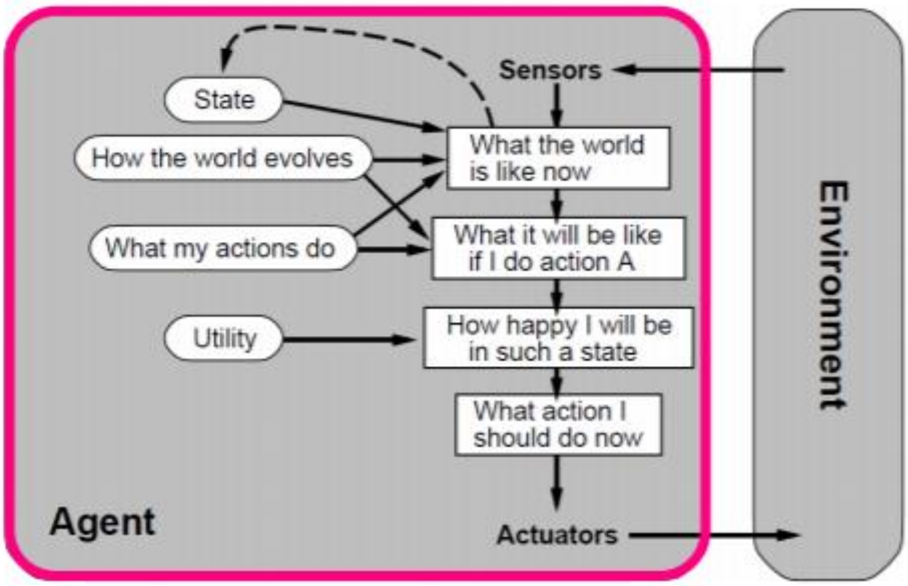

Figure 26: Utility-based agent architecture. Source:[33]

We can see on figure 26 a top-level abstraction of the 5) agent interacting with its environment. It can be observed the *intelligent* differences between figure 26 and 25, where the internal state of the agent is able to take deliberate actions, learn from its environment and take the optimal action that will yield the highest expected utility.

3.1 Agent based systems in electricity markets

Electricity markets involve several entities that all act in an economical way trying to get the best advantages and profits while limited by technical power grid constraints [35]. The complex nature of this technical-economical relationship of electricity markets makes them a great candidate to be modeled by a MAS. Because MAS is able to work in open systems and is able to deal with the uncertainties inherent to competitive markets, a multi-agent simulation of competitive markets (MASCEM) is created.

A series of different MASCEM models exist with different rules and considerations which try to foresee market behaviors. The analysis of this type of systems allows regulators and market players alike to test the market´s conditions in advance. allowing rules to be verified on the regulator´s side and market players can obtain the most profitable outcome from the market.

In the model proposed on this paper, the market player side is the one to be modelled with a MAS. Recently, electricity market players have opted to use rather simple bidding strategies. A great majority of them opt to bid price and quantity in a constant way. However, some market players bid prices in the generation costs and go as far as simple averages or regressions of historic market prices [36]. Even this rather simple strategies do not maximize the participants profits and remains a highly unexplored issue. Here, the usage of MAS enables a way to find market inefficiencies and explores different bidding strategies for market players. Through individual agent behavior simulation, a possible new bidding strategy can be tested beforehand and have an expected outcome of applying such strategy.

In a competitive market, all players are expected to act economically and for the maximization of their own interest. By economically I am referring that the actors will always act on an analytically justifiable way and that their risk adversity is low. This being said it is the task of the developer to build suitable competitor agent profiles with strategic and stochastic capabilities to deal and adapt their actions within the ever-changing environment that is electricity markets. Forecasting technics such as neural networks, data mining, etc. can yield bidding strategies by themselves but intelligent behavior is needed to make a MASCEM.

MASCEM makes used of what's known as agent based computational economics (ACE) to model their complexity. Within this MAS the electricity market proposed in this paper (Mexico-USA) will be analyzed by means of reinforcement learning. There exist different types of reinforcement learning, such as Erev & Roth probability of choice and Q-learning. While both deliver a result within the MAS in this paper only Q-learning will be traded and proposed.

Q-learning, as other reinforce learning techniques, is learning the policy of what has to be done to obtain the maximum reward. Q-learning gives intelligent agents the capability to act optimally in Markovian domains trough the experiences and consequences the actions without the need to build maps of the domains [37].

The ground-work and definition of q-learning was stated by Watkins on [37]. In this paper the q-learning methodology will follow the one proposed by [38]. What will be presented here is a computational model formulation of the Q-learning concept.

The environment is comprised by a finite construct of Markov decision processes with state set S and action set A. by characterizing the environment as a discrete one, it is assumed that the set s ∈ S and a ∈ A are finite. Each timestep *t,* the agent observes the current state of the environment $s_t = s \epsilon S$ and decides to take action $a_t = a \epsilon A$. Because agents are able to *influence* its environment, state s changes to $s_{t+1} = s' \epsilon S$. The uncertainty of the market is dealt by transition probability $P_{ss'}^{a}$ which refers to the chance that one state will change to another by means of action *a* within the Markov process. The change of state also delivers and immediate reward to the agent $R_{ss'}^{a}$. Because the action to be taken by the agent will affect the state of the environment $a_{t+1} = a' \epsilon A$. [38]

A value is assigned to each pair of (*s,a*) that fulfill the preconditions and thus being admissible to be taken by the agent. This value receives the name of Q value (equation 3.1). After each action and earning the respective reward, the Q value for the associated pair is updated. The updating of the Q value lookup table is an attempt of each agent to find the optimal policy $\pi^*(s) \epsilon A$ (equation 3.2). The optimization of the policy is in other words maximizing the total reward in the long run [38].

$$Q^* = \sum_{s'} P_{ss'}^{a} [R_{ss'}^{a} + \gamma \cdot \max_{a'} (Q^*(s', a'))]$$

(3.1)

$$\pi^*(s) = arg\ max_a(Q^*(s, a))$$

(3.2)

Where:

γ: is the discount factor. This factor can be interpreted as how important are expected future rewards for the agent. Future rewards have less value than current rewards if this factor is less than one.

By means of the known transition probability and the immediate reward the environment is identified. The only available information for the q value updating is s_t, a_t, s', $R_{ss'}^{a}$. With this information and the introduction of learning rate α (which can be understood as how much the Q value *learns* or its modified by new data) the Q value updating equation can be constructed [38].

$$Q'(s_t, a_t) = Q_t(s_t, a_t) + \alpha \Delta Q(s_t, a_t)$$

(3.3)

$$\Delta Q(s_t, a_t) = R^a_{ss'} + \gamma \max_{a'} Q(s', a') - Q_t(s_t, a_t)$$

(3.4)

By substituting 3.4 on 3.3 and introducing learning.

$$Q'(s_t, a_t) = (1 - \alpha) \cdot Q_t(s_t, a_t) + \alpha \cdot (R^a_{ss'} + \gamma \max_{a'} Q(s', a'))$$

(3.5)

On the Q value lookup table where equation 3.5 acts, each row represent the observed states and the columns represent the set of actions that are allowable. For the Q values to be updated the Q value table needs to be initialized. Some common ways to initialize the table are based on knowledge or random choice. Nevertheless, setting the values of the table to zero is also possible.

However, always choosing the optimal may leave potential long-run gains unexplored. In order to do this a parameter ε, denominated greedy parameter/strategy, is introduced. This parameter can also be a solution to potential locks the equation 3.6 may encounter if two Q values are identical. The greedy parameter balances the agent's decision between exploration and exploitation [39].

- Exploitation: choses the optimal decision (highest Q value) given the current information.
- Exploration: discovers new information by performing random action $a \epsilon A$.

This parameter is introduces in the Q-learning algorithm by the following equation [39]:

$$a_t = \begin{cases} \pi^*(s), & P(1 - \varepsilon) \\ a \epsilon A, & P(\varepsilon) \end{cases}$$

(3.6)

According to the convergence proof presented on [37] if each action of set A is performed in each state of set S for an infinite number of times on an infinite run the Q values will converge with P=1 to the best Q value. This shortcoming of the Q-learning algorithm is known as the curse of dimensionality. The stationary and Markovian environment background of Q-learning simplifies and helps solve this shortcoming. Even with this, Q-earning is easier to implement, and appears to be the most efficient model-free reinforcement learning algorithm [38].

Now that the algorithm and methodology have been defined, it is time to define the environment, agents, states and actions that will comprise the model.

The environment will be the electricity market itself and it can be classified as partially observable, stochastic, episodic, dynamic, and discrete. The selection of such characteristics of the environment definitely represents a simplification of reality but will yield the results needed for the purpose of this model.

The environment is partially observable because the agent only knowns if it was selected for dispatch or not and has only access to its own internal information i.e. marginal cost. The markets do not render and shares enough information for the agents to foresee the day-ahead outcomes. It is stochastic because every action of set A does not guarantee an outcome but instead an expected one on the state of the environment and it rather influence it than control it. The episodic characteristic is set due to the nature of the day-ahead electricity markets and the time step of day and hour. However, setting the characteristic to an episodic environment leaves out any intention for further investment as the environment does not duel on the future, it rather seals in the short run. This is a dynamic environment because the market is not only influenced by the actions of the agent as the forecasting of the renewable energies and load is not guaranteed to be true all times. In fact, these are known to vary widely, and the forecasting and seasonality are extremely hard to set into acceptable parameters, even more on the long run. The fact that the agents have just a limited amount of actions on set *A* at their disposal and the percept is in fact just one, the environment is a discrete one.

With the environment described, the agent type must be selected in order to ensure that it has sufficient intelligence to interact and influence its environment. In the model proposed in this paper, the electricity market entity to be modeled within the MASCEM is exclusively the generation units. By doing this, while simplifying the model due to the exclusion of demand side management, the market clearing algorithm will be further simplified and equation 2.3 is true for the social welfare, as well as the concepts treated on chapter 2. It is then clear than a type 5) agent is then needed to fulfill its delegated responsibility of profit maximization.

The states for the Q-learning algorithm that will make the rows of the Q values table will be given by the day-ahead price prediction of the date of the delivery on D-1. Because the agents bid one day before delivery, the price for each zone needs to be forecasted to set the state s_t of the environment so the agents can act accordingly. For the price forecasting a dynamic artificial neural network (NN) like the one presented in [40] (see appendix 3) will be implemented. As said above, reinforcement learning can be enhanced by the use of machine learning.

Finally, the effectoric capabilities and percepts of the agent have to be defined in order to fully define the bidding strategies of the agents and the MAS. In here, an in alignment with chapter 2 concepts, the actions a_t will be limited only changing the bid price of each agent. The percepts will become the state of the environment, so the observations will be the forecasted day-ahead price. As said before, they have to act economically and in a competitive way, therefore, a minimum bound has to be set at less the marginal costs of electricity generation of each agent. It is important to note that the intentions for future investments are omitted in this model, but it is definitely a concept to be explored, maybe with the help of a "*greedy*" parameter to further expand the capabilities of the model.

4 Modelling

In this chapter the methodology, assumptions and objectives of the model proposed in this thesis will be described. The introduction of the North American Power Exchange (NAPEX) will be also specified.

4.1 NAPEX

The model proposed here needs the creation of a virtual entity to overtake the duties of making several bidding zones work as one electricity market. In other words, the creation of an international power exchange is needed between USA and Mexico. The current situation of both markets and the current state of the interconnection of both is explained toughly on chapter 1. From there it is understood that the current exchange between Mexico and USA is quite limited and almost always (except Baja California system Integrated to WECC) the trade is a result of a scheduled bilateral agreement. This causes that the interconnection capacity between both countries is limited and underutilized. Similarly, USA RTO´s have also limited and restricted interconnector capacity i.e. ERCOT is not currently interconnected with WECC.

The area where NAPEX will operate was selected by two factors, interconnection and geography. Combining both factors a selection of the Mexican national interconnected system (SIN) and USA´s regions of California (CAL), Southwest (SW) and ERCOT (TX) was done to be modelled and under the assumption of NAPEX. Further international and national interconnections are taken as frontier constraints and interact with their interconnected counterparts without being part of the model and therefore out of the scope of NAPEX and this thesis.

NAPEX will act as the power exchange agent in charge of clearing the day-ahead market. NAPEX also has to deal with the time differences that exist on the interconnected regions that will be modeled. Four different time zones are acknowledged by NAPEX. To solve this issue the Central time (GMT-7) was selected as the time where all the transactions are held. The time difference experienced within the interconnected zones can further enhance the complementarity between zones and can increase the operation hours of cheaper sources making them more profitable.

Under NAPEX international borders and national entities i.e. TSO, blur to allow the creation of 11 Biding zones. Each bidding zone, as required, will have the necessary zonal authorities in charge of maintaining the reliability and security of the grid. The isolated systems on Mexico i.e. Mugelé and Baja California Sur are expected to function normally.

The creation of NAPEX also assumes a compliance to all regulatory and institutional frameworks (network codes) where zonal authorities, TSOs or RTOs do not limit or oppose the interzonal trade further than the technical constraints. This assumption is important to mention to limit the model only by the calculation methodology and no external aspects interfere with the FBMC.

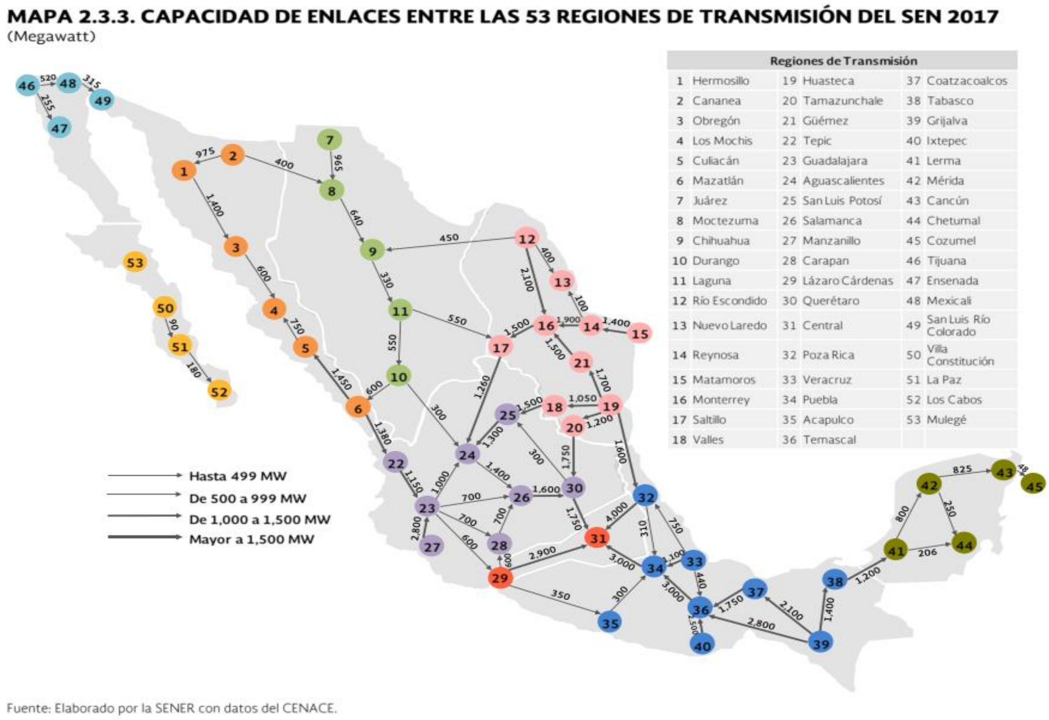

Figure 27: Mexican Grid topology. Source: [54]

On figure 27, the grid topology used in the model is introduced. Three things are important to note for here, some of which will be further explained in subsection 4.2. First of all, NAPEX only takes in count *nodes* 1 through 49, the rest is excluded as they are currently isolated systems. Second, if figure 27 ang figure 5 are combined it is clear that each color is a bidding zone and here the same logic applies. Finally, the maximum transmission capacity for each line is specified on figure 27.

Figure 28: California, Southwest and ERCOT regions source: [41]

Figure 28 shows the selected regions to be under NAPEX and a proposed grid topology joining Balancing Authority (BA) to another BA. The balancing authorities are in charge of the reliability and security of the grid in their control areas. NAPEX takes them as nodes within the bidding zone z. ERCOT (Texas) is a special case because it only consists of a single BA and there for it's a zone of one node only. It can be observed form figure 28 that ERCOT its only communicated to the Mexican grid and not to the other two USA regions selected. The lines inside the red circle in figure 28 where added to comply fully with figure 11 and represent on the model all the interconnection capacity available. The capacity of the lines connecting the nodes will be calculated as the maximum historical interchange value plus 15%

Figures 27 and 28 show the 11 zones that conform NAPEX. The time differences between them are the existing ones and only set to englobe the complete zone within one time zone only.

4.2 Model description

The purpose of the model in this thesis is to simulate an interconnected electricity market on North America by means of an agency system. More specifically the Interconnected zoned under NAPEX. In this subsection the concepts of Chapter 2 and 3 will combine to stablish the outline of what is modelled. It is important to note that some information required for the FBMC was not readily available as the current pricing and market schemes un Mexico and USA are LMP. Description of all assumptions and steps taken to derive the FBMC parameters will be explained.

4.2.1 Assumptions and fixed inputs

Let's start by setting the framework that will enable the modeling of the market and that will be constant throughout the calculations:

- An assumption of network code compliance will be assumed, and no limits to the electricity trades are imposed by any RTO or ISO.
- The agent behavior will be the same in every case. The learning algorithm should be able to adapt to the difference in the market structure.
- Due to the lack of information regarding bilateral agreements and forward trading the forward market will be cleared in the sense of demand and generation capacity reduction. Further explanation in 4.2.2.
- All the electricity from intermittent sources will be traded on the day ahead market. Only wind and solar energies will be considered.
- Hydro generators will have the same behavior as traditional sources and the water amount will not be considered but their capacity will be reduced to try and simulate the source availability.

- An independent entity will be created and will be in charge of clearing the market, North American power exchange. This entity will work on only one time zone. This means that each transaction will be done in local time but cleared in central time.
- As the allocation of forward generation is unknown, each base and peak load generation capacities will be reduced. Further explanation in 4.3.4.
- The simulation will be restricted only to the year 2018.
- All the transactions are done in US dollars. The exchange rates from Mexican peso to US dollars are taken from historical values to the exact values taken from [42].
- Generation units are only traditional sources.
- The model only evaluates electricity only markets [MWh]. Related products are not considered.
- To better define the state of the environment (market), the forecasted market prices will be rounded to integer numbers.
- All lines in figures 27 and 28 will be considered as CNEs due to the missing operational grid information.

These assumptions will help us bound the problem and focus on the day-ahead market and agent behavior. They, as well set the characteristic of the environment.

4.2.2 Agent behavior.

Following up on what was said on section 3.1 where the agent and environment was described, here a comprehensive explanation of the agent behavior on the electricity market will be presented.

There are two main agents within the model. The market coupling agent that will clear the day ahead market and the trading agents that can submit supply or demand bids. As said before, the market area is comprised by several bidding zones. Each bidding zone has a market authority that will respond to a higher agent, the market coupling agent NAPEX. The demand bids are artificially set to a single ask-offer per bidding zone set at 9999 USD/MWh in order to ensure that it will always be satisfied if there´s enough installed capacity. The demand bids are considered inelastic and the real demand values are considered. The generation bids will be given by each generation unit that will act as a single agent in every case. These generation agents will search economic benefits and thus their rewards for the Q-learning algorithm will come on the form of profit earned by adding a markup to their marginal costs m_t = {0, .1, .2,…} US dollars. This markup can be negative or positive with a lower bound of the marginal cost. This is justified by the fact that almost all generation units earn most of the profit from future markets so only marginal cost are applicable. No generation agent can bid below this number. Startup costs are not considered. The renewable energy sources will always be dispatched and reduce the demand bids by their real values at the time of the delivery. However, the forecasting of these sources is important for the agent's behavior.

$$P_t = C_{Mar} + m_t \qquad\qquad if \quad \widehat{P_h} > C_{Mar}$$

(4.1)

Now the question remains on how the agent will determine the markup. The environment description set on 3.1 allows us to determine the state of the agent by knowing the price of the market. The price can be forecasted by means of the demand and renewable energy generation forecast (given by the TSO and found on [41] for USA and [43]) and with help of a NN (see appendix 1). This forecasted price $\widehat{P}_h$ will help decide the agent what to do, do nothing, reduce or augment the price. To further increase the competitivity, the model will be pay as bid.

Table 1: *Q-learning parameter values*

Parameter	Value
ε	0.25
α	0.3
γ	0.95

Table 1 shows the selected values for the agent characteristic in reinforcement learning. The values where chosen heuristically but following common values. The sensitivity of this values in not investigate but it can be left for future work.

As said above, Mexico and the US work under an LMP scheme so in order to have all the inputs required for FBMC the demand of the control regions presented on figure 27 was aggregated into NAPEX zones. US EIA already gives the aggregated demand by region selected so it was taken directly. Regarding the prices in Mexico a weighted average was done with respect to the installed capacity of each pricing node into transmission regions and then converted into zonal prices following the same logic. In the case of USA because no information was available the zonal prices where set proportional to the Mexican prices considering installed capacity and demand of each zone.

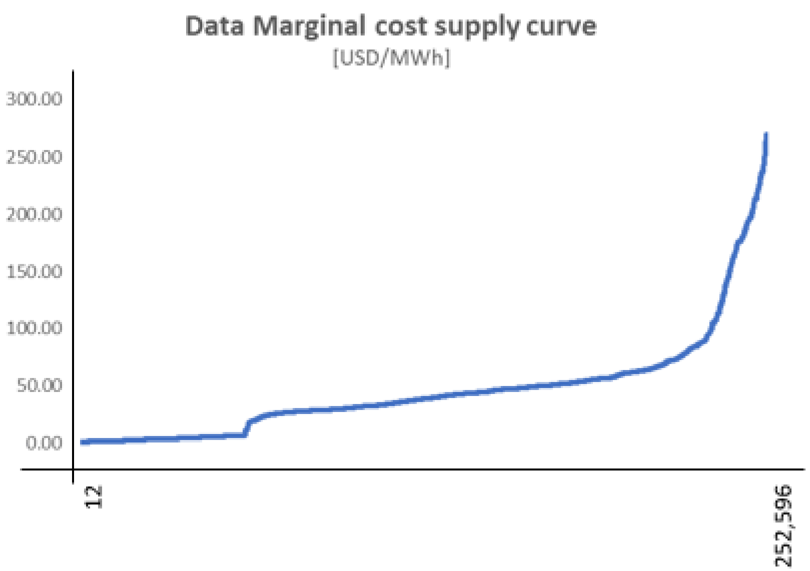

Figure 29: Marginal cost of the generation units used in the model.

The generation agents as set by equation 4.1 are only to modify autonomously the bid price. However, if they bid their installed capacity for energy generation, it would be unrealistic. Therefore, the agent's capacity for bidding in each hour of the day-ahead market has to be reduced. Lack of information regarding forward markets and bilateral agreements makes it quite hard to solve this. For simulating this each agent installed capacity will be randomly reduced by two factors following two different normal distributions. The first factor is regarding the capacity already sold in forward markets which is determined by a normal distribution with parameters μ= .15 and σ=.05. The parameters where selected heuristically and where set so that ~85% of the electricity is traded on forward markets. The second factor is related to the availability of the source. This factor is also determined by a normal distribution with parameters μ= .95 and σ=.15.

The agent communication will come from the storage and knowledge of the market clearing results.

4.2.3 Market coupling

The market clearing algorithm is the solution to equation 2.3 constraint by the FBMC parameters described in chapter 2.

Reinterpreting equation 2.3 for better formatting in the LP problem (objective function) yields:

$$\max \sum_{z \in Z} \left[\sum_{d \in Dz} P_d \cdot Q_d \cdot x_d - \sum_{s \in Sz} C_s \cdot Q_s \cdot x_s \right] \tag{4.2}$$

Equation 2.3 defers form 4.2 in the sense that demand and supply bids are separated and its clearer the relationship between them. P and C are equivalent (price and cost).

The market clearing condition set in equation 2.4 allow us to visualize the NP within the LP problem. Combining the concept of 4.2 in 2.4 we get:

$$\sum_{d \in Dz} Q_d \cdot x_d - \sum_{s \in Sz} Q_s \cdot x_s + \sum_{i \in Zz} NP_i = 0 \qquad \forall z \in Z \tag{4.3}$$

Moreover, line complementarity has to be introduced for evaluation reasons for each exchange direction. This will create the need for a new decision variable that will decide the direction of the flow.

$$NP_{z,i} = NP_{i,z} \qquad \forall z, i \in Z \tag{4.4}$$

The model only considers FBMC so only the constraints and parameters for this type of MC are of use.

Recalling constraints determined on chapter 2 for FBMC two Parameters where needed. Zonal PTDF and RAM. For the correct application of the zonal PTDF a transfer matrix has to be created. The receiving zone *z* PTDF is subtracted from the PTDF of the injecting zone *i*. This will construct hub-to-hub PTDF and will set the capacity constraints linking the flows Fl with the RAM. These relationships are given by [44]:

$$Cap_l = \sum_{z,i \in Z} (PTDF_l^z - PTDF_l^i) \cdot NP_{z \to i} \qquad \forall l \in L \tag{4.5}$$

$$-RAM \leq Cap_l \leq RAM \tag{4.6}$$

The mode will be solved using the Python library PuLp, which makes use of the standard solver CBC to find the optimal solution to the problem presented above.

4.2.4 Base case creation

For calculating the parameters of the FBMC a base case had to be created because this form of MC is not utilized on America. Furthermore, the creation of NAPEX demands the calculation for the FBMC as it does not exists in reality

Nodal PTDF

Even though the nodal PTDF is not used directly in the FBMC its calculation is necessary to obtain the zonal PTDF. Following the methodology described in chapter 2 and the information found on appendix 2, which contains the characteristics of the line, the Nodal PTDF was calculated. This matrix is to remain constant throughout the entire simulation as it only depends on the grid's topology and on the admittance matrix which is assumed to be constant in time. The grid topology follows figure 27 and 28 and more information can be found on appendix 2.

GSK

Regarding the GSK as no past or historical information is available the model was initialized with a weighted average regarding the installed capacity on every transmission region or BA. This strategy was preferred over flat participation because I believe it better represents the state of the grid without information. The GSK values where given per day rather than per hour. The value of the GSK is updated every depending on the results of the market. The updating consists on incrementing the value of the installed capacity of the selected sources every time they are selected. This changes the weights on the weighted average and further changing the Zonal PTDF. This process is done on D-1 after the market coupling results are given. This ex-post analysis represented for me, the best way to obtain the GSK without full knowledge of the grids state.

RAM

Similar to the logic behind the forward market clearing presented on 4.2.1 the RAM is reduced by the same factor as the capacity related to the forward market minus a random selection of a uniform distribution from 5% to 10% to further represent uncertainty of loop flows and security margins.

5 Analysis and results

In this section, a comparison will be made with the actual values and the modeled ones. While the results from the model above are not directly comparable to reality due to the assumptions and simplifications taken, they can give us an idea of the effects of implementing a FBMC policy.

First, let's set the real case values for comparing after with the modelled ones. Figure 30 and 32 show the real exchanges for the selected day between Mexico and USA.

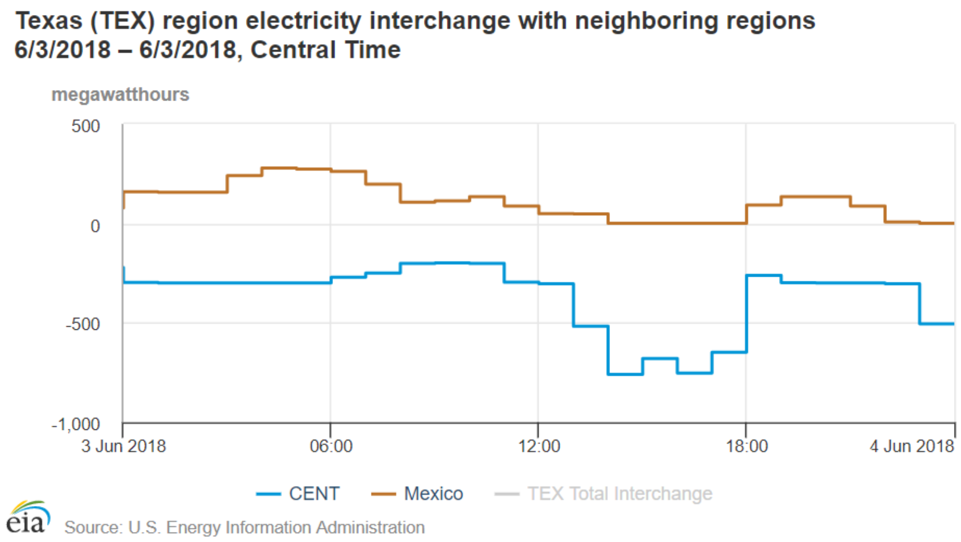

Figure 30: Texas region electricity interexchange. Source: [45]

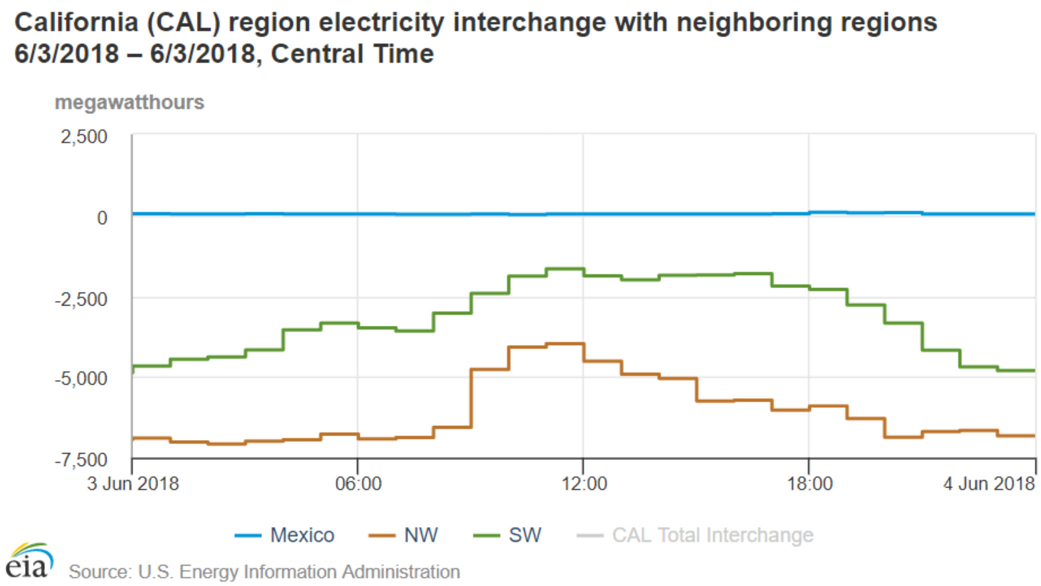

Figure 31: CAL region electricity interexchange. Source:[46]

In figure 31 and 32 a total hourly net interchange between the selected region and neighboring regions is presented. Negative values indicate net inflows from neighboring regions, and positive values indicate net outflows to neighboring regions.

We can notice form here that the current exchange between the two countries is fairly limited and not only because of the limited transmission capacity as the max values are not achieved. It is worth noticing that even though the BCA system is highly interconnected with CAISO the exchange volumes, at least for the selected day are smaller than the Texas interconnection. In the Texas interconnection the exchange is done explicitly and in forward markets only.

Now to compare with the results from the model, the information obtained after the simulation will be presented.

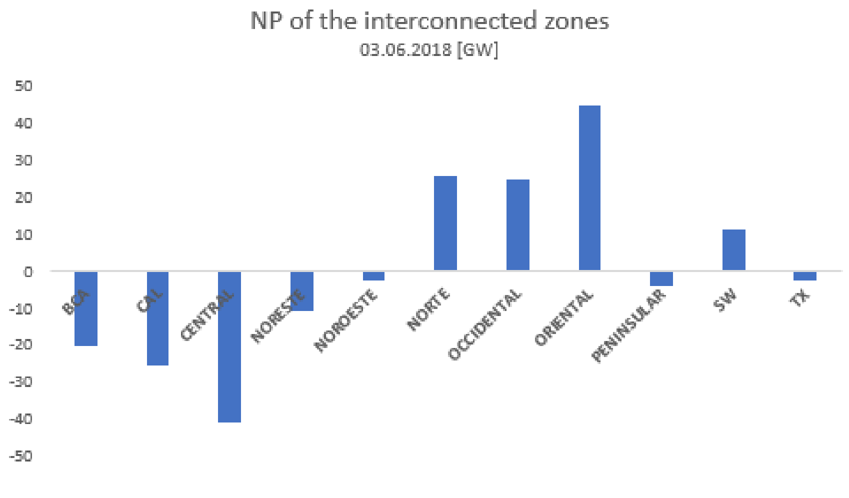

Figure 32: Net exchange position of the interconnected zones.

Figure 30 shows us the NP of the interconnected zones. we can see that California has high import values which can mean an energy dependency. But as seen above on figure 32 California actually import big amounts of energy so this is congruent. The NP can be modified by a series of factors like increased interconnector capacity or simply the installed capacity of cheap sources is more in the model than in reality. This can distort the shape of the results.

To further investigate the flows between USA and Mexico, the modelled flows of the selected day are presented.

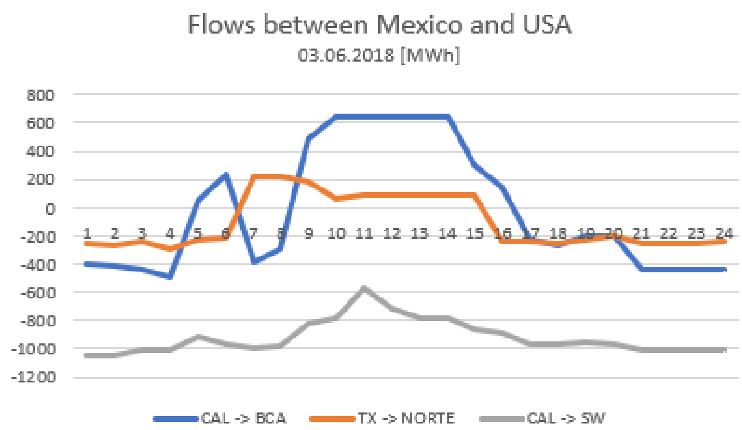

Figure 33: Modelled flows between CAL BCA TX and SW

Figure 33 is interesting because shows the effects of the availability factor applied to the generation units and the RAM. While we can see an increase on the interconnection (the value is less because this is only DA and figures 30 and 31 are the rea flows) it's important to see the shape of the curves. Here we can see that NAPEX by dueling in one time zone can have some complementarity effects.

Other important factor that has great impact on the results is the GSK strategy. As established on chapter 2, the strategy selected for this FBMC parameter has direct impact on the MC results. On chapter 4 the GSK updating strategy was described. Hence the question remains on how this parameter changed the zonal PTDF matrix over time. Figure 34 shows the change in percentage that the zonal PTDF matrix suffered during th simulation.

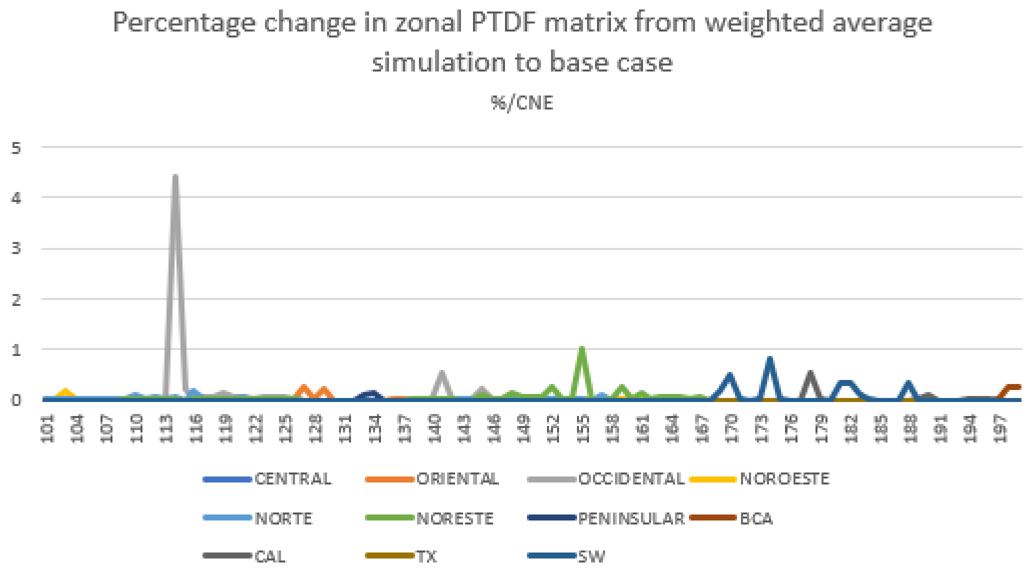

Figure 34: % change of the zonal PTDF matrix

This difference makes the representation of the grid more precise and help identify CNEs.

5.1 Future work

The model presented here, while made on the most logic way possible, still has shortcomings.

First of all, the lack of information from zonal prices affected the development of this model as they have been artificially created. Therefore, for better modeling more information is required. Furthermore, the forward market clearing is still an open issue in the model proposed and by altering randomly the capacities of the agents, unrealistic results can be yielded.

The grid elements and the FBMC parameter calculation can be improved by having access to the complete grid´s topology and their characteristics. In this model and as it can be seen on appendix 2, the reactance values are based not on the grid to be studied but rather on an analysis made to a grid. Undoubtably this affects the end result.

Regarding the GSK a more complete forecasting can be done in order to obtain a better result for each day.

Definitely something to study shall be the possibility of demand-side management and portfolio optimization for agents with multiple generation units. This will add more real characteristics to the simulation and will prepare the model for better policy analysis.

Regarding the bidding strategies, more complex and data driven strategies can me researched. Furthermore, the model can be expanded to model a different strategy for each agent. This can be further enhanced by including a NN to each agent that will make the day ahead price prediction differs hence, making similar sources act different under the same market conditions.

Also, marginal source analysis can be done to characterize the market and give price signals to investors to see where and which type of energy source is needed. The inclusion of renewable sources agents, a more sophisticated hydro and more type of bids (not only hourly) can be a further expansion to the generation agent.

Future investment thinking can be added to the agents to make more realistic bids and scenarios. This could have the features to change the environment characteristics and the agent design could have to change as a future expectation and goal is also desired. In reality, big utility companies, as said above, make the majority of their profits through bilateral agreements and forward markets, would not benefit much from this application on the day-ahead market, but renewable sources, and storage can show some interest on this type of strategy.

Finally, directly directed for the market zones within this model, an expansion to the rest of USA and connecting the isolated systems of Mexico can be of interest for both countries and attempt to create an interconnected America. Furthermore, new policies could be tested and the impact of increased interconnection on the local economies.

Conclusion and annotation

Electricity markets coupling has been proven to increase the social welfare and to use optimally existing electrical infrastructure. While the investment in new transmission capacity seems counter intuitive because of the reduction of congestion rents, the benefits that can be enjoyed by a price convergence will help more people. During the development of this thesis, several concepts where explored and brought together to try and find a solution to a very complex problem.

While the model proposed in this thesis can be expended in a series of ways to better represent reality, the groundwork and the interest of an interconnected North America is set. In line with the motivation of this thesis an increase in social welfare by a methodology not currently used in this part of the world was done by means of an agent-based system to try and model the economic behavior generation units my present if this interconnection arrives.

Different learning methodologies are included in this thesis to try and represent the best way possible the electricity markets within the scope of the thesis. Challenges regarding data scraping and missing information where faced but solved with creativity to yield a satisfactory outcome. As a stochastic agent, we also have to make decisions in the face of uncertainty and use our previous experience to produce the best outcome for us and the society. This paper is my bet to set in motion a more interconnected North America.

The solution of the technical and economical complex situations faces within this thesis offer a new way of thinking in the North American region. While it can take some time to see a true interconnection in the entire region, first steps are being made and cooperation is in the table. One of my goals while doing this thesis was to show that more interconnection means more welfare, with the hope that people reading this will be interested in working towards this future.

Bibliography and references

[1] ELLIS, James. *Mexico Energy Market Reform* [online]. Dostupné z: https://www.bnef.com/core/themes/121

[2] ORECCHINI, Fabio. The era of energy vectors. *International Journal of Hydrogen Energy* [online]. 2006, **31**(14), 1951–1954. ISSN 03603199. Dostupné z: doi:10.1016/j.ijhydene.2006.01.015

[3] UNFCCC. *GHG total without LULUCF, in kt CO_2 equivalent* [online]. Dostupné z: http://di.unfccc.int/time_series

[4] OCHOA, Camila a Ann VAN ACKERE. Does size matter? Simulating electricity market coupling between Colombia and Ecuador. *Renewable and Sustainable Energy Reviews* [online]. 2015, **50**, 1108–1124. ISSN 18790690. Dostupné z: doi:10.1016/j.rser.2015.05.054

[5] OCHOA, Camila a Ann VAN ACKERE. Winners and losers of market coupling. *Energy* [online]. 2015, **80**, 522–534. ISSN 03605442. Dostupné z: doi:10.1016/j.energy.2014.11.088

[6] B, Andreas Bublitz, Philipp RINGLER, Massimo GENOESE a Wolf FICHTNER. Agent-Based Simulation of Interconnected Wholesale Electricity Markets: An Application to the German and French Market Area [online]. 2014, **449**, 32–45. ISSN 18650929. Dostupné z: doi:10.1007/978-3-642-36907-0

[7] KPMG. Oportunidades en el sector eléctrico en México Contenido. 2016.

[8] SHAHIDEHPOUR, Mohammad, Hatim YAMIN a Zuyi LI. *Market Operations in Electric Power Systems* [online]. 2002. ISBN 0471443379. Dostupné z: doi:10.1002/047122412X

[9] HOGAN, W W. Independent System Operator: Pricing and Flexibility in a Competitive Electricity Market. *Mimeo* [online]. 1998, (February), 52. ISSN 2327-6924 2327-6886. Dostupné z: doi:10.1111/1745-7599.12000

[10] BOURY, Jonas. Methods for the determination of flow-based capacity parameters : description , evaluation and improvements (Msc thesis). *Researchgate.Net* [online]. 2015. Dostupné z: doi:10.13140/RG.2.2.23785.70248

[11] KIOSE, Daniil a Vlasios VOUDOURIS. The ACEWEM framework: An integrated agent-based and statistical modelling laboratory for repeated power auctions. *Expert Systems with Applications* [online]. 2015, **42**(5), 2731–2748. ISSN 09574174. Dostupné z: doi:10.1016/j.eswa.2014.11.024

[12] © OECD/IEA, 2016; International Energy Agency. LARGE-SCALE ELECTRICITY INTERCONNECTION - Technology and prospects for cross-regional networks. *2016* [online]. 2016. Dostupné z: https://www.iea.org/publications/freepublications/publication/Interconnection.pdf

[13] BOURY, Jonas. Methods for the determination of flow-based capacity parameters : description , evaluation and improvements (Msc thesis). *Researchgate.Net* [online]. 2015. Dostupné z: doi:10.13140/RG.2.2.23785.70248

[14] KUL ENERGY INSTITUTE. The current electricity market design in Europe. *KU Leuven Energy Institute* [online]. 2015, 4. ISSN 0272-7714. Dostupné z: doi:10.1016/j.ecss.2018.07.008

[15] NORD POOL SPOT. Explicit and implicit capacity auction. 2012.

[16] FERC. *FERC* [online]. 2019. Dostupné z: https://www.ferc.gov/about/ferc-does.asp

[17] NERC. *NERC key players* [online]. 2019. Dostupné z: https://www.nerc.com/AboutNERC/keyplayers/Pages/default.aspx

[18] BLOOMBERG NEW ENERGY FINANCE. *United States country profile* [online]. 2017. Dostupné z: https://www.bnef.com/core/country-profiles/USA

[19] VIDANGOS, Natasha, Lindsey GRIFFITH, Francisco FLORES-ESPINO a James MCCALL. Electricity in North America [online]. 2016, (July), 135. Dostupné z: https://www.energy.gov/sites/prod/files/2017/01/f34/Electricity in North America Baseline and Literature Review.pdf

[20] EUROPEAN COMISSION. *MEDIUM TERM VISION FOR THE INTERNAL ELECTRICITY MARKET*. 2012.

[21] ACER. *ACER / CEER Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2013 A N N U A L R E P O R T O N T H E R E S U LT S O F M O N I TO R I N G T H E I N T E R N A L E L E C T R I C I T Y A N D N AT U R A L G A S M A*. 2013. ISBN 9789295083172.

[22] IEA. Seamless power markets. 2014.

[23] SHEET, Ei-fact, Federal ACT, F O D ECONOMIE, The FEDERAL, Energy OBSERVATORY, The BELGIAN a The CREG. Security of electric power supply. 2013, 2–5.

[24] ENERGINET DK, FINGRID, STATTNET, Svenska Kraftnet. Methodology and concepts for the Nordic Flow Based Market Coupling Approach. 2016.

[25] CHATZIGIANNIS, Dimitris I., Grigoris A. DOURBOIS, Pandelis N. BISKAS a Anastasios G. BAKIRTZIS. European day-ahead electricity market clearing model. *Electric Power Systems Research* [online]. 2016, **140**, 225–239. ISSN 03787796. Dostupné z: doi:10.1016/j.epsr.2016.06.019

[26] BELPEX. Basic Market Coupling Concept [online]. nedatováno, **i**, 1–4. Dostupné z: https://www.belpex.be/wp-content/uploads/Basic-Market-Coupling-Concept.pdf

[27] VAN DEN BERGH, Kenneth, Jonas BOURY a Erik DELARUE. The Flow-Based Market Coupling in Central Western Europe: Concepts and definitions. *Electricity Journal* [online]. 2016, **29**(1), 24–29. ISSN 10406190. Dostupné z: doi:10.1016/j.tej.2015.12.004

[28] PÉREZ-ARRIAGA, Ignacio J. a Luis OLMOS. A plausible congestion management scheme for the internal electricity market of the European Union. *Utilities Policy* [online]. 2005, **13**(2 SPEC. ISS.), 117–134. ISSN 09571787. Dostupné z: doi:10.1016/j.jup.2004.12.003

[29] VAN DEN BERGH, Kenneth, Jonas BOURY a Erik DELARUE. The Flow-Based Market Coupling in Central Western Europe: Concepts and definitions. *Electricity Journal* [online]. 2016, **29**(1), 24–29. ISSN 10406190. Dostupné z: doi:10.1016/j.tej.2015.12.004

[30] VAN DEN BERGH, Kenneth, Erik DELARUE a William D'HAESELEER. DC power flow in unit commitment models. *TME Working Paper-Energy and Environment*. 2014, (May), 1–38.

[31] SOL, Aravena. Analysis of renewable energy integration in transmission-constrained electricity markets using parallel computing. nedatováno.

[32] WEISS, Gerhard. *Multiagent systems* [online]. Second Edi. Massachusetts: Massachusetts Institute of Technology, 2013. Dostupné z: https://ebookcentral.proquest.com/lib/cvut/detail.action?docID=3339590.

[33] RIECKEN, Doug. Intelligent agents. *Communications of the ACM* [online]. 1994, **37**(7), 18–21. ISSN 15577317. Dostupné z: doi:10.1145/176789.176790

[34] WOOLDRIDGE, Michael, Chester STREET, M MANCHESTER, Nicholas R JENNINGS, Mile End ROAD a E LONDON. Intelligent Agents: Theory and Practice. 1995, (January), 1–62.

[35] VALE, Zita, Tiago PINTO, Isabel PRAÇA a Hugo MORAIS. MASCEM : Electricity Markets Simulation with Strategic Agents. 2011, (April), 9–17.

[36] PINTO, Tiago, Isabel PRAÇA, Zita VALE, Hugo MORAIS a Tiago M. SOUSA. Strategic bidding in electricity markets: An agent-based simulator with game theory for scenario analysis. *Integrated Computer-Aided Engineering* [online]. 2013, **20**(4), 335–346. ISSN 10692509. Dostupné z: doi:10.3233/ICA-130438

[37] WATKINS, Christopher J C H. Q-Learning. 1992, **292**, 279–292.

[38] RAHIMIYAN, Morteza a Habib Rajabi MASHHADI. An Adaptive Q -Learning Algorithm Developed for Agent-Based Computational Modeling of. 2010, **40**(5), 547–556.

[39] POWELL, Warren B. Exploration vs. Exploitation. *Approximate Dynamic Programming* [online]. 2007, 323–350. Dostupné z: doi:10.1002/9780470182963.ch10

[40] PINTO, T., T. M. SOUSA a Z. VALE. Dynamic artificial neural network for electricity market prices forecast. *INES 2012 - IEEE 16th International Conference on Intelligent Engineering Systems, Proceedings* [online]. 2012, 311–316. Dostupné z: doi:10.1109/INES.2012.6249850

[41] U.S. ENERGY INFORMATION ADMINISTRATION. *Grid operation data* [online]. Dostupné

z: https://www.eia.gov/beta/electricity/gridmonitor/dashboard/electric_overview/regional/REG-SW

[42] BANXICO. *Banco de México tipos de cambio* [online]. Dostupné z: https://www.banxico.org.mx/tipcamb/main.do?page=tip&idioma=sp

[43] CENACE. *Datos operativos cenace* [online]. Dostupné z: https://www.cenace.gob.mx/SIM/VISTA/REPORTES/DemandaRealSist.aspx

[44] DUFOUR, Aurélie. Capacity allocation using the flow-based method. *Science*. 2007.

[45] U.S. ENERGY INFORMATION ADMINISTRATION. *Texas (ERCOT) demand profile by Balancing Authority* [online]. 2019 [vid. 2019-02-12]. Dostupné z: https://www.eia.gov/beta/electricity/gridmonitor/expanded-view/electric_overview/regional/REG-TEX/ElectricityRegionDemand-8/edit

[46] U.S. ENERGY INFORMATION ADMINISTRATION. California demand profile by Balancing Authority. *2019* [online]. [vid. 2019-02-12]. Dostupné z: https://www.eia.gov/beta/electricity/gridmonitor/expanded-view/electric_overview/regional/REG-CAL/ElectricityRegionDemand-8/edit

[47] CROSS, S. S., R. F. HARRISON a R. L. KENNEDY. *Introduction to neural networks* [online]. 1995. ISBN 0203451511. Dostupné z: doi:10.1016/S0140-6736(95)91746-2

[48] DAVID KRIESEL. A Brief Intoduction to Neural Networks. *A* [online]. 2001, 239–297. Dostupné z: doi:10.1007/978-3-662-04323-3_10

[49] LOWELL, A. Lawrence. LOAD FLOW ANALYSIS OF RADIAL DISTRIBUTION NETWORK USING LINEAR DATA STRUCTURE. *University of Pennsylvania Law Review and American Law Register* [online]. 2013, **83**(6), 824. ISSN 07499833. Dostupné z: doi:10.2307/3308504

[50] BLOOMBERG NEW ENERGY FINANCE. *Mexico country profile* [online]. 2017. Dostupné z: https://www.bnef.com/core/county-profile/MX

[51] SENER. Prospectiva del sector eléctrico 2017-2031. 2017.

[52] SENER. PROSEDEN Programa de desarollo del sistema eléctrico nacional. 2018.

[53] AUTHORITY, U.S. Energy Information. *Southwest demand profile by Balancing Authoirty* [online]. 2019. Dostupné z: https://www.eia.gov/beta/electricity/gridmonitor/expanded-view/electric_overview/regional/REG-SW/ElectricityRegionDemand-8/edit

[54] SENER. Programa de Apliación y Modernización de la RNTy RGD del Mercado Eléctrico Mayorista (PRODESEN 2018 - 2029). 2018, 648.

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Appendix

Appendix 1: Artificial neural network for electricity price forecasting.

Forecasting in electricity systems can be done by a series of methodologies and all of them have their own pros and cons. Depending on the application an on the component to be forecasted, a forecast methodology is selected.

Artificial neural networks get their inspiration form the biological workings and processes of the brain. A neural network is an interconnected system of simple processing neurons or nodes, whose functionality is stores in the interunit connection [47]. It is a sorted triple (N,V,w) where N and V represent to sets, N is the set of neurons, V a set of $\{(i,j)|i,j \in \mathrm{N}\}$ comprised of connections between neuron *i* and *j,* and finally a function *w*. Function *w* defines the weights of the connection between neuron *i* and *j* *(*$w_{i,j}$) A weight of 0 would mean that the connection does not exist on the network [48].

Within a neural network, each neuron does a simple operation. The neuron processes the data in three main stages, propagation function, activation function and output function. The sending and receiving data from one neuron to another is a basic concept and plication of neural networks. The learning comes from adjusting the weights $w_{i,j}$ to have the desired output. This adjustment is based on *training* the data with a large number of correct examples (the larger the better) so the network can do a comparison and adjust accordingly. This way, basic rules can be extracted form the data and even unexplored paths or relationships within the data can emerge [40].

The dynamic part of the name of this appendix, comes from the re-adaptation of the network to train in each execution so that the network always considers the most recent data. This allows the network to adjust the forecast to the evolution of the system within time [40].

The way a NN was implemented in this thesis is closely related to with is exposed in [40]. In this paper it is mention the suitability between NN and MAS. Therefore, this method was chosen to forecast electricity prices due to its dynamic nature and adaptability for the bidding strategies. The constant evolution of electricity system makes good use of the retraining presented in this paper and ensures that the bidding strategy is up to date with the market. the retraining concept is presented in figure 35.

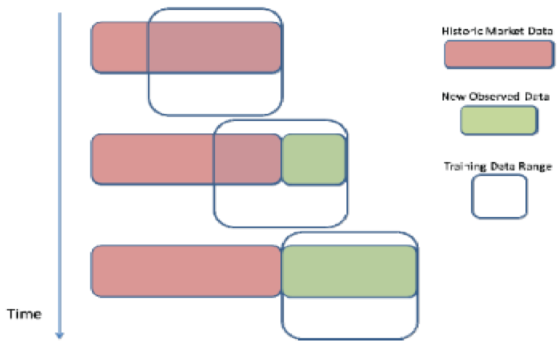

Figure 35: selection of the training set for the NN over time. source:[40]

The proposed NN makes use of the forecasted demand and renewable generation of wind and solar sources and is feedforward. A crucial difference with the proposed NN which take in count the price of the past. while this dynamism is worthwhile. It will take much computing power to do the entire yearly simulation. Therefore, the classical approach of training once is preferred. A NN is done for each bidding zone and each one tries to predict the price of the electricity within its bidding zone. All of the NN follow the e same topology of three layers an impute layer, one hidden layer and an output layer with a single node, the price. On the input layer each input feature is represented by a neuron.

Appendix 2: Line characteristics used in the model.

The values here presented where based on information taken from [49]. Cross-border links in yellow

branch_no	start (i)	end (k)	reactance	max_cap
1	2	1	0.1563	975
2	1	3	0.1157	1400
3	3	4	0.2609	600
4	5	4	0.0043	750
5	6	5	0.2352	1450
6	2	8	0.0168	400
7	7	8	0.2330	965
8	8	9	0.2565	640
9	9	11	0.3474	330
10	11	10	0.2400	550
11	10	6	0.1441	600
12	6	22	0.1230	1380
13	10	24	0.1144	300
14	22	23	0.2316	1150
15	27	23	0.1469	2800
16	23	24	0.2328	1000
17	23	26	0.0318	700
18	23	28	0.2050	700
19	23	29	0.1106	600
20	29	28	0.2532	600
21	28	26	0.0548	700
22	24	26	0.1690	1400
23	29	35	0.2042	350
24	29	31	0.1829	2900
25	35	34	0.2643	300
26	36	34	0.1731	3000
27	40	36	0.0657	2500
28	39	36	0.2688	2800
29	39	38	0.0192	1400
30	38	41	0.1126	1200
31	41	44	0.0068	206
32	42	44	0.1910	250
33	42	43	0.0927	825
34	43	45	0.0524	48
35	41	42	0.1688	800
36	39	37	0.1222	2100
37	37	36	0.1193	1750
38	33	36	0.1926	440
39	33	34	0.1649	1100
40	33	32	0.0762	750
41	34	31	0.1300	3000

42	32	34	0.0372	310
43	32	31	0.0679	4000
44	19	32	0.1215	1600
45	30	31	0.3981	1750
46	26	30	0.3043	1600
47	20	30	0.0404	1750
48	30	25	0.1124	300
49	25	24	0.1608	1300
50	17	24	0.1329	1260
51	18	25	0.1486	1500
52	19	18	0.1425	1050
53	19	20	0.2582	1200
54	19	21	0.0692	1700
55	21	16	0.2673	1500
56	16	17	0.1988	1500
57	11	17	0.1014	550
58	12	9	0.1231	450
59	12	16	0.0281	2100
60	12	13	0.1107	400
61	14	13	0.2660	100
62	14	16	0.1112	1900
63	15	14	0.1236	1400
64	15	65	0.1284	200
65	14	65	0.3058	840
66	13	65	0.1262	100
67	12	65	0.2502	50
68	7	64	0.2669	206
69	64	63	0.0340	700
70	64	62	0.1242	700
71	63	60	0.0290	800
72	63	62	0.2416	800
73	62	60	0.1560	850
74	62	55	0.2098	450
75	62	61	0.2116	1500
76	60	61	0.0427	2700
77	60	50	0.1012	2200
78	60	54	0.2019	1500
79	60	55	0.0467	3000
80	60	53	0.1456	1600
81	61	57	0.1697	2600
82	61	58	0.1327	2500
83	60	59	0.3461	2500
84	61	55	0.2352	2200
85	61	50	0.0662	2800
86	55	50	0.1295	650
87	55	53	0.1606	2650

88	55	56	0.1539	600
89	54	50	0.2253	300
90	55	54	0.1792	900
91	53	50	0.2541	5500
92	50	48	0.0242	800
93	50	46	0.2081	800
94	50	51	0.3285	700
95	50	52	0.1846	2300
96	51	52	0.1884	500
97	46	48	0.0581	520
98	48	49	0.1179	315
99	46	47	0.2197	255

Appendix 2: Example zonal PTDF and Fmax,allow

CNE	CENTRAL	ORIENTAL	OCCIDENTAL	NOROESTE	NORTE	NORESTE	PENINSULAR	BCA	CAL	TX	SW	Fmax
101	-0.0284	-0.0283	-0.0300	-0.7087	-0.0126	-0.0203	-0.0283	0.0000	0.0000	-0.0172	0.0000	975
102	-0.0284	-0.0283	-0.0300	-0.2824	-0.0126	-0.0203	-0.0283	0.0000	0.0000	-0.0172	0.0000	1400
103	-0.0284	-0.0283	-0.0300	-0.0689	-0.0126	-0.0203	-0.0283	0.0000	0.0000	-0.0172	0.0000	600
104	0.0284	0.0283	0.0300	-0.1980	0.0126	0.0203	0.0283	0.0000	0.0000	0.0172	0.0000	750
105	0.0284	0.0283	0.0300	-0.2093	0.0126	0.0203	0.0283	0.0000	0.0000	0.0172	0.0000	1450
106	0.0284	0.0283	0.0300	0.7370	0.0126	0.0203	0.0283	0.0000	0.0000	0.0172	0.0000	400
107	-1.0000	-1.0000	-1.0000	-1.0000	-0.8661	-1.0000	-1.0000	0.0000	0.0000	-1.0000	0.0000	965
108	-0.9716	-0.9717	-0.9700	-0.2630	-0.7125	-0.9797	-0.9717	0.0000	0.0000	-0.9828	0.0000	640
109	-0.7281	-0.7240	-0.7410	-0.2159	-0.3285	-0.4658	-0.7237	0.0000	0.0000	-0.3162	0.0000	330
110	-0.4764	-0.4712	-0.5050	-0.1818	-0.1027	-0.2130	-0.4705	0.0000	0.0000	-0.1247	0.0000	550
111	-0.1625	-0.1655	-0.2124	-0.1808	0.0213	-0.0569	-0.1645	0.0000	0.0000	-0.0291	0.0000	600
112	-0.1909	-0.1938	-0.2424	0.0822	0.0087	-0.0772	-0.1928	0.0000	0.0000	-0.0463	0.0000	1380
113	-0.3139	-0.3057	-0.2926	-0.0010	0.0305	-0.1561	-0.3060	0.0000	0.0000	-0.0956	0.0000	300
114	-0.1909	-0.1938	-0.0938	0.0822	0.0087	-0.0772	-0.1928	0.0000	0.0000	-0.0463	0.0000	1150
115	0.0000	0.0000	0.2308	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	2800
116	0.1769	0.2068	0.3007	0.0517	0.0025	-0.0022	0.2015	0.0000	0.0000	-0.0134	0.0000	1000
117	-0.0258	-0.0138	0.0088	0.0055	0.0008	-0.0085	-0.0150	0.0000	0.0000	-0.0041	0.0000	700
118	-0.1727	-0.1898	-0.0593	0.0139	0.0028	-0.0349	-0.1866	0.0000	0.0000	-0.0153	0.0000	700
119	-0.1693	-0.1970	-0.0116	0.0111	0.0025	-0.0317	-0.1927	0.0000	0.0000	-0.0136	0.0000	600
120	0.1743	0.2168	-0.0466	-0.0081	-0.0023	0.0295	0.2107	0.0000	0.0000	0.0122	0.0000	600
121	0.0016	0.0270	0.0310	0.0058	0.0006	-0.0053	0.0241	0.0000	0.0000	-0.0030	0.0000	700
122	-0.2660	-0.2234	-0.1715	-0.0082	0.0023	-0.0436	-0.2258	0.0000	0.0000	-0.0123	0.0000	1400
123	-0.0678	-0.3789	0.0233	0.0072	0.0022	-0.0281	-0.3463	0.0000	0.0000	-0.0118	0.0000	350
124	-0.2757	-0.0349	0.0117	0.0119	0.0026	-0.0332	-0.0571	0.0000	0.0000	-0.0140	0.0000	2900
125	-0.0678	-0.2062	0.0233	0.0072	0.0022	-0.0281	-0.3463	0.0000	0.0000	-0.0118	0.0000	300
126	-0.0113	0.3642	-0.0090	-0.0015	-0.0006	0.0079	0.5780	0.0000	0.0000	0.0033	0.0000	3000
127	0.0000	0.0058	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	2500
128	0.0000	0.2409	0.0000	0.0000	0.0000	0.0000	0.8166	0.0000	0.0000	0.0000	0.0000	2800
129	0.0000	-0.0442	0.0000	0.0000	0.0000	0.0000	-1.0000	0.0000	0.0000	0.0000	0.0000	1400
130	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-1.0000	0.0000	0.0000	0.0000	0.0000	1200
131	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0273	0.0000	0.0000	0.0000	0.0000	206
132	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0062	0.0000	0.0000	0.0000	0.0000	250
133	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0933	0.0000	0.0000	0.0000	0.0000	825
134	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0248	0.0000	0.0000	0.0000	0.0000	48
135	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.6806	0.0000	0.0000	0.0000	0.0000	800
136	0.0000	0.0541	0.0000	0.0000	0.0000	0.0000	0.1834	0.0000	0.0000	0.0000	0.0000	2100
137	0.0000	0.0541	0.0000	0.0000	0.0000	0.0000	0.1834	0.0000	0.0000	0.0000	0.0000	1750
138	-0.0113	-0.2521	-0.0090	-0.0015	-0.0006	0.0079	-0.4220	0.0000	0.0000	0.0033	0.0000	440
139	-0.0204	0.1311	-0.0163	-0.0027	-0.0011	0.0143	0.1894	0.0000	0.0000	0.0060	0.0000	1100
140	0.0316	0.1851	0.0253	0.0042	0.0017	-0.0221	0.2326	0.0000	0.0000	-0.0093	0.0000	750
141	-0.1195	0.3179	-0.0180	0.0003	-0.0006	0.0081	0.3503	0.0000	0.0000	0.0034	0.0000	3000
142	-0.0200	-0.0608	-0.0160	-0.0027	-0.0011	0.0140	-0.0708	0.0000	0.0000	0.0059	0.0000	310
143	-0.0989	0.0550	-0.0386	-0.0048	-0.0023	0.0298	0.0536	0.0000	0.0000	0.0126	0.0000	4000
144	-0.1506	-0.2483	-0.0799	-0.0117	-0.0052	0.0660	-0.2498	0.0000	0.0000	0.0278	0.0000	1600
145	-0.5059	-0.3379	0.0449	-0.0075	0.0004	-0.0047	-0.3469	0.0000	0.0000	-0.0020	0.0000	1750

146	-0.2903	-0.2102	-0.1311	0.0031	0.0036	-0.0574	-0.2167	0.0000	0.0000	-0.0195	0.0000	1600
147	-0.0498	-0.0135	-0.0468	-0.0052	-0.0027	0.0451	-0.0138	0.0000	0.0000	0.0147	0.0000	1750
148	0.1658	0.1143	0.1071	0.0055	0.0005	-0.0076	0.1164	0.0000	0.0000	-0.0028	0.0000	300
149	0.1693	0.1601	0.0793	-0.0017	-0.0048	0.0827	0.1629	0.0000	0.0000	0.0259	0.0000	1300
150	-0.2984	-0.2846	-0.3103	-0.0572	-0.0260	0.0320	-0.2842	0.0000	0.0000	0.0708	0.0000	1260
151	0.0035	0.0459	-0.0281	-0.0072	-0.0053	0.0904	0.0465	0.0000	0.0000	0.0287	0.0000	1500
152	0.0035	0.0459	-0.0281	-0.0072	-0.0053	0.0453	0.0465	0.0000	0.0000	0.0287	0.0000	1050
153	-0.0498	-0.0135	-0.0468	-0.0052	-0.0027	-0.0313	-0.0138	0.0000	0.0000	0.0147	0.0000	1200
154	0.1969	0.2159	0.1548	0.0240	0.0132	-0.0145	0.2170	0.0000	0.0000	-0.0712	0.0000	1700
155	0.1969	0.2159	0.1548	0.0240	0.0132	0.0427	0.2170	0.0000	0.0000	-0.0712	0.0000	1500
156	-0.0466	-0.0317	-0.0743	-0.0231	-0.0295	0.2485	-0.0310	0.0000	0.0000	0.2622	0.0000	1500
157	-0.2518	-0.2529	-0.2360	-0.0341	0.0035	-0.2527	-0.2532	0.0000	0.0000	-0.1914	0.0000	550
158	0.2435	0.2476	0.2290	0.0471	0.0427	0.5139	0.2480	0.0000	0.0000	0.6666	0.0000	450
159	-0.0665	-0.0677	-0.0626	-0.0129	-0.0117	-0.0256	-0.0678	0.0000	0.0000	0.0365	0.0000	2100
160	-0.0586	-0.0596	-0.0551	-0.0113	-0.0103	-0.1079	-0.0596	0.0000	0.0000	-0.1427	0.0000	400
161	0.0656	0.0667	0.0617	0.0127	0.0115	0.0135	0.0668	0.0000	0.0000	0.0226	0.0000	100
162	-0.1770	-0.1800	-0.1665	-0.0343	-0.0311	0.0129	-0.1802	0.0000	0.0000	0.2969	0.0000	1900
163	-0.0190	-0.0193	-0.0179	-0.0037	-0.0033	0.0858	-0.0194	0.0000	0.0000	0.0546	0.0000	1400
164	0.0190	0.0193	0.0179	0.0037	0.0033	0.1166	0.0194	0.0000	0.0000	-0.0546	0.0000	200
165	0.0924	0.0939	0.0869	0.0179	0.0162	0.0655	0.0941	0.0000	0.0000	-0.2650	0.0000	840
166	0.0070	0.0071	0.0066	0.0014	0.0012	0.0206	0.0071	0.0000	0.0000	-0.1201	0.0000	100
167	-0.1184	-0.1204	-0.1114	-0.0229	-0.0208	-0.2028	-0.1206	0.0000	0.0000	-0.5604	0.0000	50
168	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	1.0000	0.0000	206
169	0.2004	0.2004	0.2004	0.2004	0.2004	0.2004	0.2004	0.0000	0.0000	0.2004	0.0048	700
170	0.7996	0.7996	0.7996	0.7996	0.7996	0.7996	0.7996	0.0000	0.0000	0.7996	0.0433	700
171	0.0692	0.0692	0.0692	0.0692	0.0692	0.0692	0.0692	0.0000	-0.0003	0.0692	0.0253	800
172	0.1312	0.1312	0.1312	0.1312	0.1312	0.1312	0.1312	0.0000	0.0003	0.1312	0.0502	800
173	0.2880	0.2880	0.2880	0.2880	0.2880	0.2880	0.2880	0.0000	-0.0017	0.2880	0.1040	850
174	0.3682	0.3682	0.3682	0.3682	0.3682	0.3682	0.3682	0.0000	-0.0009	0.3682	0.1008	450
175	0.2747	0.2747	0.2747	0.2747	0.2747	0.2747	0.2747	0.0000	0.0029	0.2747	-0.0424	1500
176	-0.0234	-0.0234	-0.0234	-0.0234	-0.0234	-0.0234	-0.0234	0.0000	0.0010	-0.0234	-0.0370	2700
177	0.1647	0.1647	0.1647	0.1647	0.1647	0.1647	0.1647	0.0000	0.0149	0.1647	0.1565	2200
178	0.1166	0.1166	0.1166	0.1166	0.1166	0.1166	0.1166	0.0000	0.0026	0.1166	0.1049	1500
179	-0.0043	-0.0043	-0.0043	-0.0043	-0.0043	-0.0043	-0.0043	0.0000	0.0003	-0.0043	-0.0087	3000
180	0.1036	0.1036	0.1036	0.1036	0.1036	0.1036	0.1036	0.0000	-0.0209	0.1036	0.0943	1600
181	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0331	2600
182	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0178	2500
183	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0618	2500
184	0.1074	0.1074	0.1074	0.1074	0.1074	0.1074	0.1074	0.0000	-0.0042	0.1074	0.1601	2200
185	0.1439	0.1439	0.1439	0.1439	0.1439	0.1439	0.1439	0.0000	0.0081	0.1439	0.1596	2800
186	0.2225	0.2225	0.2225	0.2225	0.2225	0.2225	0.2225	0.0000	0.0183	0.2225	0.2244	650
187	0.1289	0.1289	0.1289	0.1289	0.1289	0.1289	0.1289	0.0000	-0.0241	0.1289	0.1339	2650
188	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0164	600
189	0.2364	0.2364	0.2364	0.2364	0.2364	0.2364	0.2364	0.0000	0.0304	0.2364	0.2313	300
190	0.1198	0.1198	0.1198	0.1198	0.1198	0.1198	0.1198	0.0000	0.0011	0.1198	0.1264	900
191	0.2325	0.2325	0.2325	0.2325	0.2325	0.2325	0.2325	0.0000	0.0740	0.2325	0.2282	5500
192	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.1797	0.0000	0.0000	0.0000	800
193	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.8203	0.0000	0.0000	0.0000	800

194	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0279	0.0000	0.0000	700
195	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0303	0.0000	0.0000	2300
196	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0149	0.0000	0.0000	500
197	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.2025	0.0000	0.0000	0.0000	520
198	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0837	0.0000	0.0000	0.0000	315
199	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.4125	0.0000	0.0000	0.0000	255