

KADIR HAS UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING



MARKET PRICE SIMULATIONS FOR TURKISH ELECTRICITY
MARKET USING EQUILIBRIUM MODELS

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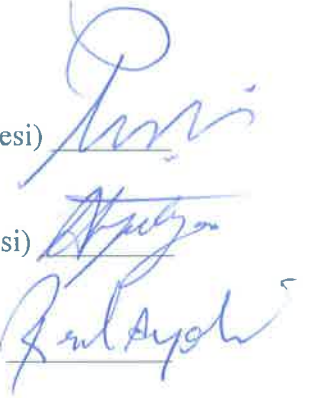
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“I, Hande AKIR, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.”

HANDE AKIR

MARKET PRICE SIMULATIONS FOR TURKISH ELECTRICITY MARKET USING EQUILIBRIUM MODELS

Abstract

Electrical energy, which is known as secondary energy sources, is generated by the conversion of renewable energy sources to potential and chemical energy or is generated by variety processes of fossil fuels. Electricity is an important product in an economy and an important input for production of most of the goods and services. Electricity has unique properties such as non-storability and it has no full substitute and therefore, the electricity industry is different from classical competitive industries. During the last decade, new regulations and developments in the world have initiated various reform movements and a new action plan in Turkey to create a competitive market. The relevant legislation and procedures is created and specific markets are designed within this plan and vertically integrated structure of generation, transmission and distribution activities are separated in this restructuring process. In this study, we focus on many examples and applications in the world about electricity market equilibrium models. Since, there is no market model applied in this way in Turkey, it is created to simulate market prices by using GAMS software and adoption of market price simulations to Turkey's electricity markets are examined. Finally, we have performed price-cost analyses and observe the welfare effects of different market structures.

Key Words: Electricity Markets, Market Price Simulation, Equilibrium Model, Nodal/Zonal Pricing, Mixed Complementarity Problem (MCP)

MARKET PRICE SIMULATIONS FOR TURKISH ELECTRICITY MARKET USING EQUILIBRIUM MODELS

Özet

İkincil enerji kaynağı olarak bilinen elektrik enerjisi yenilenebilir enerji kaynaklarının potansiyel ya da kimyasal enerjilerinin dönüştürülmesi ile ya da fosil yakıtların çeşitli işlemlerden geçirilmesi ile üretilmektedir. Elektrik, hem neredeyse bütün ürün ve hizmetlerin üretilmesinde girdi olması, hem de son kullanıcı tarafından tüketilen nihai bir ürün olması nedeniyle ekonomide çok büyük öneme sahip bir üründür. Elektriğin diğer ürünler de olmayan stoklanamama, tam ikamesinin olmaması gibi kendine has özelliklerinin oluşu nedeniyle, elektrik endüstrisi klasik rekabetçi endüstrilerden çok farklıdır. Son yıllarda dünyada oluşan yeni düzenlemeler ve gelişmelere bağlı olarak Türkiye de rekabetçi bir piyasa oluşturmak için çeşitli reform hareketlerine başladı ve yeni eylem planları oluşturdu. İlk olarak bu yenilenme sürecinde ilgili mevzuat ve prosedürler oluşturulmuş, sektöre özgü piyasalar tasarlanmış, üretim, iletim ve dağıtımdan oluşan dikey bütünleşik yapı ayrıştırılmıştır. Bu çalışmada ise Dünya’da birçok örneği ve uygulaması olan elektrik enerjisi piyasası denge modelleri üzerinde durulmuştur. Türkiye’de bu şekilde uygulanan bir piyasa modeli olmaması nedeniyle Piyasa Fiyat Simülasyonları modeli Türkiye elektrik enerjisi piyasalarına uyarlanmış ve GAMS programı kullanılarak fiyat-üretim simülasyonları oluşturulmuştur. Son olarak da çıkan sonuçlar yorumlanarak fiyat-maliyet analizi ve refah etkileri ölçümlenmiştir.

Anahtar Kelimeler: Elektrik Piyasaları, Piyasa Fiyat Simülasyonları, Denge Modelleri, Bara Bazlı (Nodal)/ Bölgesel (Zonal) Fiyatlandırma, Karışık Tamamlayıcı Problemi

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List of Abbreviations

- AC : Alternating Current
- BO : Build-Operate (Yap-İşlet –Yİ)
- BOT : Build-Operate-Transfer (Yap-İşlet-Devret-YİD)
- CV : Conjectural Variations
- CVaR : Conditional Value at Risk
- DDP : Dual Dynamic Programming
- E&W : England and Wales
- ETL : Electricity Transmission Line (Elektrik Nakil Hattı)
- EMRA: Republic of Turkey Energy Market Regulatory (Enerji Piyasası Düzenleme Kurumu)
- EPK : Electricity Market Law (Elektrik Piyasası Kanunu)
- ETKB : Ministry of Energy and Natural Resources (Enerji ve Tabii Kaynaklar Bakanlığı)
- EÜAŞ : Elektrik Üretim A.Ş.
- HHI : Herfindahl – Hirschman Index
- KKT : Karush–Kuhn–Tucker
- LCP : Linear Complementarity Problem
- LP : Linear Programming

MCP : Market Clearing Price (Piyasa Takas Fiyatı-PTF)

MCP : Mixed Complementarity Problem

MILP : Mixed Integer Linear Programming

MPEC : Mathematical Program with Equilibrium Constraints

MWh : Megawatthour

NETA : New Electricity Trade Arrangements

OECD : Organization for Economic Co-operation and Development

ÖİB : Prime Ministry Privatization Administration (Özelleştirme İdaresi Başkanlığı)

PaR : Profit-at-Risk

PTDF : Power Transfer Distribution Factor

SFE : Supply Function Equilibrium

SMP : System Marginal Price (Sistem Marjinal Fiyatı-SMF)

TEAŞ : Türkiye Elektrik Üretim ve İletim A.Ş.

TEDAŞ: Türkiye Elektrik Dağıtım A.Ş.

TEİAŞ: Türkiye Elektrik İletim A.Ş.

TEK : Turkish Electricity Authority (Türkiye Elektrik Kurumu)

TOR : Transfer of Operating Rights (İşletme Hakkı Devri-İHD)

TSO : Transmission System Operator

VaR : Value-at- Risk

VI : Variational Inequality

Chapter 1

1. Introduction

The energy is the one of the major inputs for the economy and life, can be described as ability to do work. Energy, which is the main part of movement and generation, is an irreplaceable resource that plays very important role in entire parameters of life.

There are many forms of energy such as electricity, light, bioenergy, nuclear energy, chemical energy and these energy forms can be converted into each other. This is one of the most important features of the energy. These energy forms can be classified according to energy loss during transformation between each other. If energy loss is less during transformation, then it is called “high quality energy”.

The electricity has its own features, such as non-storability (i.e., not many efficient ways to store electricity, for example, see “hydro pump storage”), instant balance of supply and demand, its transportation governed by Kirchhoff’s current and voltage laws. That’s the reason why it is not similar to the other competitive industries. Moreover, the electricity industry has many complications (e.g., system security and reliability, market power issues, investment in renewable energy resources, emission limits) that make it harder to find a solution for the overall industry.

The regulations (or reforms) in electricity sector have been developing during the last two decades around the world in order to avoid instability in the restructured markets and infeasibility in technical conditions of the system for sake of public interest and advantage. The purpose of these new regulations is to create a competitive electricity market according to the balance of supply and demand in the market.

This period of change affects developing countries in different ways. Objectives of the electricity deregulation can be stated as to support current agents in the market as well as investors for innovation, to decrease electricity prices and to increase the comfort of consumers (OECD 2000).

The electricity market has been monopolized so many years in a vertically integrated structure by many jurisdictions/countries including Turkey. In recent years, the changes and developments that occurred around the globe force Turkey to reform its current policy and to make new action plans in order to create a new competitive electricity market. Primarily relevant legislations and procedures have been formed, new markets are laid out, specifically for the electricity sector, and lastly the vertically integrated structure that constituted generation, transmission and distribution is separated in this restructuring process. The privatization of the generation and distribution activities which was previously owned by a public monopoly could be seen as the most important indicator of the restructuring process. Specially, the transformation to a competitive market is provided by this privatization of the generation and distribution assets that was previously owned by the government. In addition, the government planned to privatize the generation assets which has a serious market share in electricity generation, launched

the market that is designed specifically for the sector and especially opened the electricity generation market to competition.

We have to be aware of that an advantage or an increase in social welfare or profits is not guaranteed by introducing competition in this market. Particularly, it is more critical for the electricity market which has various parameters and limitations due to the facts that: a) the electricity cannot be stored efficiently, b) the requirement for supply-demand balance is instantaneous, c) also the cost differences for generation technologies as well as the particular features of the transmission network (i.e., the grid) itself allow generation firms to exercise market power and affect the market prices.

Being able to provide the electricity power in a reliable and secure way to the consumers is the main responsibility of the system operators. The generation capacity has to be dispatched and new capacity has to be added for a reasonable growth of economy. Recently, many countries are seeking to provide the most efficient energy with the cheapest cost for their consumers. Nevertheless, it does not mean to supply the electricity with the cheapest price and hence the consumers will pay cheaper utility bills. The most important issue that the regulatory bodies in electricity markets have faced and particularly focused on has been to generate electricity in a cost effective way and to control whether this energy has been consumed with a reasonable price or not. Therefore, a general rule of thumb for regulatory bodies in electricity market liberalization or restructuring process is the decentralization of the electricity markets and mitigation of market power by preventing gaming or monopoly structures in the market (except in transmission services where a natural monopoly is usually preserved).

The electricity markets have a special importance for Turkey, which has very important strategic location and political situation. The supply security of Turkish energy markets and the energy imports that causes deficits in balance of payments of the Turkish economy creates an unsustainable environment. Therefore, the restructuring process that occurs in electricity sector in Turkey has to be analyzed carefully and the effects have to be put forward in both economic and financial terms as well as from the social welfare perspective.

The aim of this study is; to simulate market prices in Turkish electricity markets by applying market equilibrium models under different market structures and to observe the price-cost margins and welfare effects on society. Although there are many examples and applications all around the world (e.g., several states in United States and countries and electricity markets across Europe), there is no such applied model for Turkish electricity market. Forecasts for regulated electricity prices, market power analyses, generation and transmission investment modeling and analyses can be performed by such models.

The data required for this study includes transmission network parameters (e.g., resistance and reactance of transmission lines for a full AC model or power transfer distribution factors –PTDF- for DC approximation), nodal generation capacities and nodal demand (load) parameters which can be estimated using the nominal demand values for a specific period in the past (e.g., peak or minimum demand in 2012).

Unfortunately, the data sources for our models are not readily available for research and regulatory bodies (e.g., TEİAŞ, EPDK) have not published or shared such data due to confidentiality reasons. Although many jurisdictions provide such data for research purposes, we were not able to obtain the data for our study despite numerous applications to regulatory bodies. Therefore, we have estimated the data for the transmission system from the publicly available sources such as Turkish electrification map, total nominal demand and generation capacities from TEİAŞ web site. A more realistic study should have such data from the regulatory bodies, nevertheless we would like to provide insights for regulators and system operators in this study.

The electricity market models are published and highly referred in academic literature. Bertrand, Nash-Cournot, Stackelberg leader–follower games (MPECs) and monopoly models are well studied models in the electricity market literature. For Turkish electricity market studies, readers can refer to Şen (2006), Yaşar (2009), Camadan and Erten (2010) and Sitti (2010).

The thesis is organized as follows. Chapter 2 introduces the electric power and its features. It also includes a brief history of Turkish electricity system and its restructuring process in the last decade with some comparison to other jurisdictions' experiences in this process. Chapter 3 focuses on the electricity restructuring process and the markets. Liberalization in the electricity industry and the transition from a vertically integrated monopoly market to a competitive market is investigated. Moreover, pool versus bilateral market structures are examined and mechanisms for price formation as well as market power issues are studied.

Chapter 4 deals with the electricity market modeling trends with subsections of “Optimization Problem for One Firm” and “Market Equilibrium Considering All Firms”. Finally, Chapter 5 introduces the mathematical models for the market equilibrium (price simulation) models and analyses for a representative model of the Turkish electricity system. Besides formulations, results (price-cost margins, welfare effects) under different market structures (namely, perfect competition, Nash-Cournot and monopoly structures) are presented. The thesis concludes with Chapter 6, where insights and recommendations for Turkish electricity market are summarized and directions for future research areas are presented.

Chapter 2

2. Electrical Energy and History of Electricity Industries in Turkey

2.1. What is Electrical Energy?

Electricity is a physical phenomenon caused by static or dynamic charged particles. Electrical phenomena occur when numerous electrons accumulate in a place or when they move from one place to another. The type of energy which is obtained by the transformation of mechanical, chemical or thermal energy into electricity and offered to the use of the final consumer is called the electrical energy. The main mechanism through which electrical energy is generated is the generation of an electrical current in the stator windings as a result of the turning of the rotor by the driving sources like water turbine, steam turbine, explosion engine and wind turbine which are operated by means of various sources of effect (Akçollu 2000; Camadan and Erten 2010).

The need for electrical energy increases every day. For that reason the energy sources required for generating electricity are being searched and care is taken for them to be practically usable and not to cause environmental pollution. Besides the studies carried out to generate electricity from many sources like coal, water potential, nuclear fuel, sun

and geothermal sources, there are also efforts directed at generating cheap electricity. Transmission of the energy generated is another important problem. Joule losses (energy losses) arising from the resistances in the transmission lines still exist even if the voltage is dropped and the current is increased.

Today there are several methods of electricity generation. Electricity is generated by the transformation of the various types of energy existing in nature like thermal, solar, wind energy of which direct use is more difficult. For example, thermal power plants burn natural gas, coal and oil for the generation of heat. Nuclear power plants on the other hand generate heat by pulling uranium fuel into pieces. However all these different types of power plants use the heat, which they generate, for the purpose of transforming water into steam. The steam obtained is given to the turbine linked to the electricity generator. While passing through the thousands of flaps on the turbine shaft, water steam rotates the turbine shaft using the energy that it had obtained from the heat that had been generated before. And this rotation is the mechanical movement that the generator needs for generating electricity. The electricity is transmitted to the point of use through the conductive lines which are called the transmission lines. As far as the hydraulic power plants are concerned, the water which is accumulated in the dams is passed over a water turbine and electricity is generated by turning the electricity generator connected to the turbine (Akçollu 2000; Camadan and Erten 2010).

2.2. Features of Electricity as a Commodity

Due to their specific nature and characteristics, electricity and electricity markets exhibit a totally different and complex structure in comparison to all other markets. While there is no need to take into consideration the physical balances specific to a

definite product regarding the market mechanism through which the price of that product is formed, electricity is probably the only commodity for which the physical balances have to be taken into consideration at the state of the formation of the price in the market. The specific characteristics of electricity which makes it different from all other sources of energy are listed below:

- Electricity is a type of energy which must be consumed at the moment that it has been generated and is consequently almost impossible (or not economically feasible) to be stored. This characteristic of electricity requires the existence of an entity which continuously observes the instant demand and supply for electricity and this entity is in charge of maintaining the balance between them. This entity is called the “system operator”.
- Electricity is a type of energy whose demand flexibility is very low. For example, the flexibility of the household members for electricity is between -0.15 and -0.25 even in the long-term (Hope 2005). The fact that electricity is an irreplaceable product for the consumers (i.e., it is not substitutable with other products) is the main reason for the low level of demand flexibility of electricity.
- Electricity is transmitted to the end-user through the transmission lines. However each transmission line has a finite capacity to transmit electricity. Exceeding that capacity could distort the balance of the system and even lead to a collapse of the system. Transmission constraints may cause different levels of electricity prices to be observed in different regions. This means an additional price risk for both generators and consumers. For example, if a problem arises in one of the transmission lines due to an overload flow in one

direction, the electrical energy generated by some other plants using the same transmission line may not be transmitted in the same flow direction. In turn, such a situation may hinder the efficient operation of the market (i.e., to obtain the optimum level of generation and consumption) and the efficient transmission of the electricity generated. The management of the transmission constraints is also carried out by the system operator (Kölmek 2009).

2.3. History of Turkish Electricity Market

Turkey became familiar with the electricity sector for the first time with the foundation of the first big power plant in Istanbul/ Silahtarağa in 1913. The process of nationalization of the electricity industry began together with the decision to carry out the activities related to electrical energy by the public sector in 1930. Almost all the electricity sector has been dominated by the public sector by the year 1944. ETKB and TEK have been founded in 1963 and 1970 respectively and this enabled Turkey to have an institutional structure in the electricity sector for the first time. TEK became a national monopoly in all the activities of the electricity sector (e.g., generation, transmission and distribution) as a result of the abolishment of the authority of the municipalities to distribute electricity in 1982 (*Akçollu 2000*).

The monopoly of TEK in the electricity sector has ended together with the law enacted in 1984 and the path was paved for the private sector to engage in the electricity market either by means of the BOT or TOR models. While BOT companies were contemplated for the new projects, TOR model prescribed the operation of the existing generation and distribution plants by the private sector

participants provided that their ownership remains in TEK. However the first large-scale project could only be started in 1996 as a result of some legal issues which could not be solved by the law no. 3096.

TEK has been divided into two parts in 1994 and TEAŞ (responsible for the generation and transmission operations) and TEDAŞ (responsible for the distribution operations) have been established. The law no. 4283 enabled the private and public sector to build electricity generation plants on the basis of the BO model. During that period, the decisions of the constitutional court given in the years 1994 and 1995 against the privatization efforts impeded those efforts. As a result of that situation, an amendment has been made on the constitution in 1999 in order to realize the privatizations.

TEAŞ is the only buyer in the electricity market before the entry into force of the new law on the electricity market as seen in the figure below:

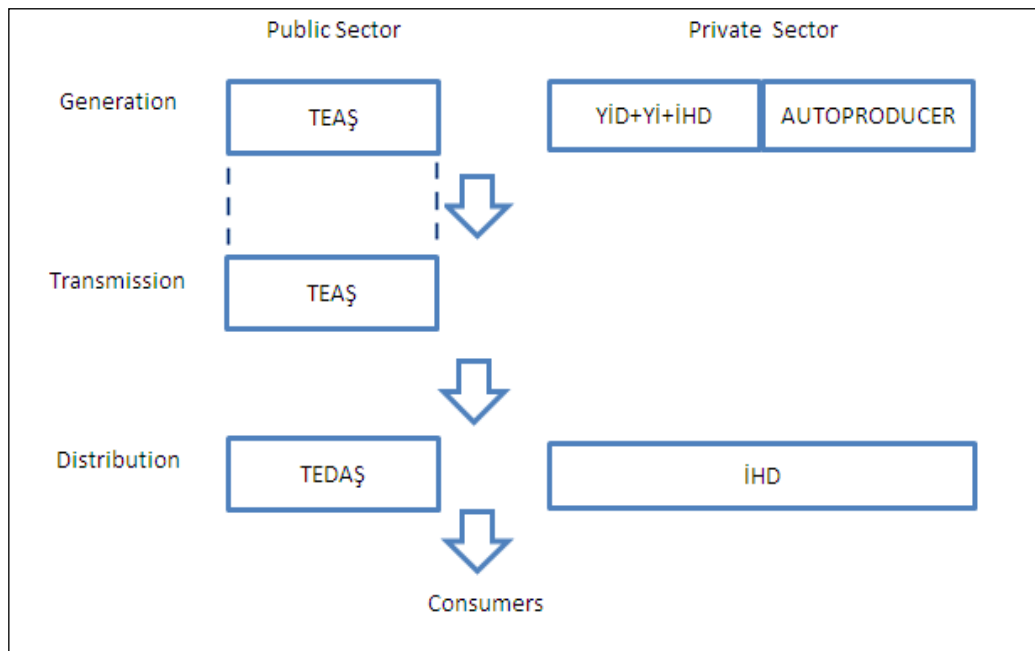


Figure 1: Electricity sector in Turkey before the law no. 4628, Source: Akçollu 2000

It has been aimed at creating a market mechanism on the basis of which the electricity market would operate within the framework of the competitive market principles, by putting the law on the electricity market no. 4628 (EPK) into effect in 2001. The law on electricity market aimed at creating an electricity market which will carry out its activities in a competitive environment according to the provisions of the special law. This electricity market means to be a financially strong, stable and transparent market for the purpose of providing electricity to the consumers in a sufficient amount, with good quality and a cheap price, in an environment friendly manner. It further aims at the provision of an independent regulatory and supervisory body in this market.

The name of the electricity market regulation authority which has been established by the law on EPK, no. 4628 has later been changed as EMRA by the law on natural gas market, no. 4646 (Camadan and Erten 2010). TEAŞ was divided into three independent units (namely EÜAŞ for electricity generation activities, TEİAŞ for electricity transmission activities, TETAŞ for carrying out electricity trade activities) following the electricity market regulation board took office on November 19, 2001.

2.3.1. TEDAŞ

Distribution activities of this company are carried out by the companies which are the holder of electricity distribution licenses of specific regions. Distribution companies also provide retail sales services by getting a license for that purpose. Distribution activities are realized by distribution companies which are active in 21 electricity distribution regions all over Turkey. While 20 distribution companies

among them have been subordinated to TEDAŞ until recently, a privatization process has been started for all of these distribution companies (Camadan and Erten 2010).

2.3.2. EÜAŞ

EÜAŞ is a public company which is 100 % owned by the treasury and has been founded for the purpose of generating electricity in accordance with the general energy and economic policy of Turkey. It provides the major part of the electricity generation in Turkey. Besides, generation activities in the private sector are carried out by the private generation companies, autogenerators, autogenerator groups and contracted generation companies (Akçollu 2000).

2.3.3. TEİAŞ

TEİAŞ is a state-owned enterprise which operates the electricity transmission system at a high voltage level in Turkey. Similar to many jurisdictions around the world, transmission system in Turkey has open access (e.g., a natural monopoly). TEİAŞ also has other responsibilities, such as distribution of loads, control of frequency as well as transmission investments (e.g., new transmission lines) and real-time system reliability and security.

2.3.4. TETAŞ

Trade of electricity in the Turkish electricity market is carried out within the scope of the bilateral contracts or in the balancing and settlement market. The existing structure of the electricity market in Turkey is shown in Figure 2. As depicted in the figure, EÜAŞ sells the electricity that it generates to TETAŞ. Also partnerships and portfolio generation groups subordinated to EÜAŞ sell electricity to the distribution companies. The power plants which operate on the basis of BOT, BO and TOR

contracts sell all the electrical energy they generate to TETAŞ. TETAŞ on the other hand, sell this electricity to distribution companies and eligible consumers. The eligible consumers shall be prohibited from buying electricity from TETAŞ in case they terminate their contracts with TETAŞ. Private generation companies sell the electricity that they generate to the eligible consumers, wholesale companies through bilateral agreements or they can trade in the balancing and settlement market.

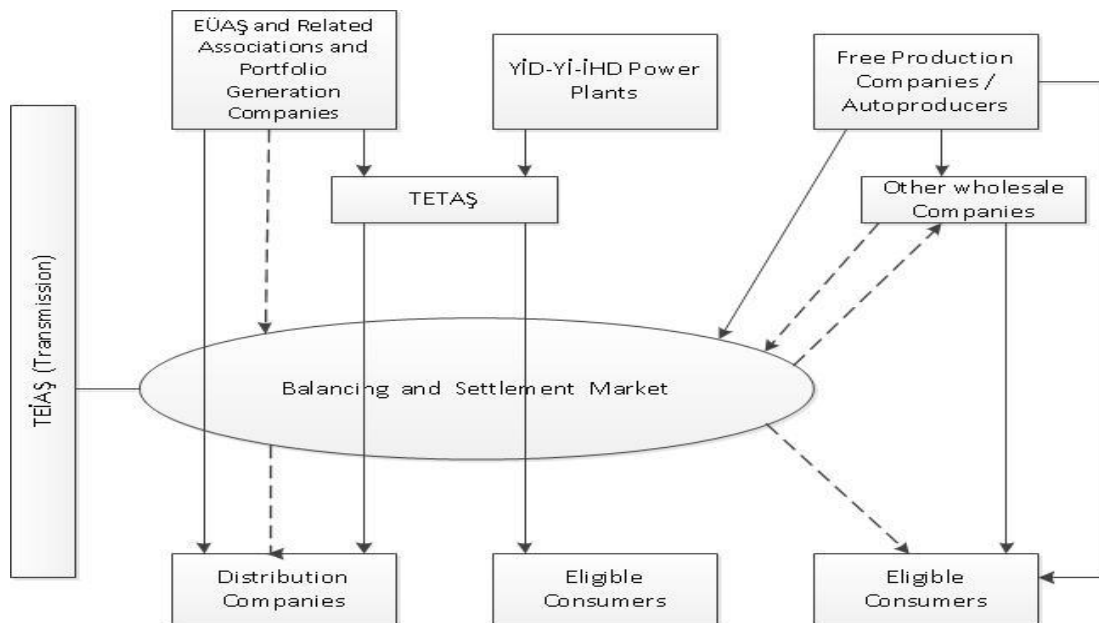


Figure 2: Electricity sector in Turkey after the law no. 4628 Source: Camadan and Erten 2010

Chapter 3

3. Electricity Market

3.1. Participants in the Electricity Markets

The participants in the electricity markets comprises the generators which generate electricity using various energy sources, wholesale and distribution companies which buy electricity from the generators for the purpose of reselling it, large industrial consumers which are in the position of an eligible consumer, traders and system operator. System operator, which is responsible for ensuring the balance between generation and consumption of electricity in the physical structure and the transmission of electricity between the generators and consumers without any congestion in the transmission lines, is also responsible for the financial settlement of the system at the same time (Sağlam 2012). However, this duty has generally been left to the market (exchange) operator as far as structures are concerned in which the restructuring of electricity exchange has not been completed.

Participants other than the system operator use electricity markets for various reasons. For example, the generators may use the market in order to introduce their excess capacity to the market, buy from the markets where part of the electricity amount prescribed by the bilateral contracts that is unavailable from the generator's own sources or buy electricity from the market when the market prices are lower than the generator's own generation cost. On the other hand, if the large

industrial consumers could not meet their need of electricity through a sufficient number of bilateral agreements they can buy the remaining amount from the market. If they have concluded bilateral agreements that may have exceeded their needs or if the market price is higher than the alternative cost of consumption, they can try to sell the excess amount of electricity bought in the market. Traders, on the other hand, take their place in the spot electricity markets in order to make use of the opportunities of arbitrage that occur in different electricity markets and to take a position with speculative purposes (Boisselau 2004). All these participants use, besides the spot market, the derivative electricity markets for the purpose of both protection from the risks and for speculative purposes.

3.2. Transition from a Monopoly to a Competitive Market

No country has opened its electricity markets to competition all at once. In other words, if we take into consideration that the final competitive step in opening the electricity market to competition is giving the final consumers the right to choose their own supplier of electricity, many other applications must have been realized by that time. In many countries, generally, electricity market is moving away from its traditional structure and competition has been introduced by means of such reforms as the commercialization of the markets, privatization and foundation of independent companies (Çetintaş and Çetin 2004). These reforms are shortly outlined below:

3.2.1. Commercialization

Commercialization is a measure which is applied for a monopoly company with a traditional structure. The markets of many countries use commercialization activity as an intermediary step for transition to privatization and other reforms. Together with the commercialization, the company which is responsible for providing the

service, should gain a relatively more independent structure and is subject to the same tax laws, prices and rules as the private sector companies (Çetintaş and Çetin 2004). The company should be subject to different cost calculations for generation, transmission and distribution services and in this way the stage at which the electricity has a higher cost is determined and the monopoly company, which behaves with commercial drives, is expected to develop cost-reduction techniques in this field and implement the corresponding measures.

3.2.2. Privatization

The term privatization expresses the transfer of the assets owned by the state to the private sector (Çetintaş and Çetin 2004). Electricity market is traditionally owned by the state and mainly operated by means of central planning in many countries. Through privatization, some countries have opened only generation to the private sector while some others have opened transmission and distribution to the private sector and some others ensure competition within the process of restructuring and adopt an independent regulatory structure and aim at a competitive electricity market. Within this framework in Turkey, the first step taken was the transfer of some facilities owned by the municipalities to TEK by means of the law, no. 2705 that went into effect in 1982. The purpose of this transfer is to bring together various establishments which are active in various segments of the electricity sector and to create a structure which facilitates privatization and to ensure that a public monopoly company carries out its activities under conditions that also apply for the private sector before the realization of privatization.

The purposes of the privatization of the generation plants in Turkey are to mobilize the sources of the private sector for the purpose of development of the electricity

generation capacity, increase the availability of the existing generation plants and increase the capacity usage factors as well as the competition in the sector.

Reform of Electricity Sector and the Benefits Expected from Privatization

The main objectives of the document titled “Reform on the electricity energy sector and the privatization strategy, dated 17/03/2004 are to:

- Ensure cost reduction by operating the assets of electricity generation and distribution efficiently and productively;
- Ensure the security of the supply and increase the quality of electrical energy;
- Reduce the technical losses in the distribution sector to the average level in OECD countries and prevent the leakages;
- Ensure that the renewal and expansion investments required are realized only by the private sector without imposing any obligations on the governmental establishments;
- Reflect the benefits which are obtained by creating a competition in the field of the generation and trade of electrical energy and regulation of the service quality to the consumer.

3.2.3. Division of the Vertical Structure or Independence

When the electricity market has been liberalized, the companies which have been integrated vertically should be separated as independent companies which provide generation, transmission, distribution and retail services in legal and functional terms. This separation may show differences from country to country. In this context, TEK has been restructured as two separate state economic enterprises, namely TEAŞ and TEDAŞ.

3.2.4. Competition

The final phase of the liberalization of the electricity industry is the opening of the market to competition. In a competitive electricity industry transmission and distribution may remain as a monopoly but the wholesale market which sells electricity through the network should be opened to competition. A competitive practice for the wholesale market can be that the independent electricity generators submit bids for the long-term contracts to be signed with the buyers of electricity. Another practice can be setting up spot or short-term markets for wholesale markets. In this method, different generators may submit bids for transmitting electricity to the distributor through the independent transmitter of a transmission company or transmission system.

EPK which went into force in March, 2001 for the purpose of opening the Turkish electricity market to competition aimed at giving priority to the large industrial users (and then to the small consumers and households) the possibility to choose their own electricity supplier. This legislation aims at ensuring an efficient competition in the generation, wholesale and retail activities and is subject to transmission and distribution activities. Distribution will be privatized on a regional basis under regulation and the legislation accepts that electricity is a strategic product which is sold and bought within the framework of the market structure that is open to competition (Çetintaş and Çetin 2004).

“Process of Liberalization of the Electricity Market in Turkey”

Regulations on Turkish market in the process of liberalization in 2001 and thereafter are mentioned below:

- The privatization of the generation and distribution assets (like networks and power plants) have been left to prime ministry privatization administration (ÖİB).
- Transparency of the market rules and regulations has been ensured by means of the laws and regulations that had went into force.
- Regulations have been introduced which ensure that the distribution companies and TEİAŞ provide services and the right of access to all users under equal conditions.
- Licensing, which means a one sided administrative permission, has been adopted as the only means of authorizing to engage in electricity related business activities.
- The eligible consumer who has the option to select its own supplier has been defined through bilateral agreements as well as the minimum consumption level of eligible consumer. Hence, the scope of the liberalization of the market has been expanded. It has been planned to create a competitive environment in the wholesale and retail trading of electricity.
- It has been ensured that the vertically integrated structure in the sector to be eliminated as well as the generation, transmission and distribution activities have been separated from each other.

3.3. Types of Tenders in the Electricity Markets According to the Participants

Another factor which has an impact on the structure of the market when we consider the participants that take part in the system is the level of participation in the market

from the supply or demand side. If the tender mechanism which determines the market requires that only the participants in the supply side can offer price-quantity pairs and demand appears only as a forecasted quantity, then it is called “an electricity market with one-sided tender”. Whereas, it is possible for both the supply and demand side to participate in the tender, then it is called “an electricity market with double-sided tender” (Madlener and Kaufmann 2004). For example, in the NordPool market (i.e., Scandinavian electricity exchange) it is possible for both the supply and the demand side to participate in the market. Whereas it was only possible for the supply side to offer a quotation for prices and amounts during the pool practice that was in force in England before the NETA.

3.4. Configurations of the Electricity Market

The structure of the electricity market of England-Wales before NETA that was mentioned above and the structure of the electricity exchange in NordPool are two different formations which are observed in the restructuring process of the electricity markets. In fact, the pool system is the pioneering configuration of the electricity market and it has transformed into the electricity exchange through an evolution process.

3.4.1. A Comparison of the Structures Pool and Electricity Exchange

The main differences between the pool system and electricity exchange are stated below:

- Generally, participation in the pool system is compulsory while participation in the electricity exchange is optional. In other words, in the pool system, it is

compulsory for all generators to sell electricity to the pool and for all consumers to buy electricity that they need from the pool.

- The tender mechanism in the pool system is based on one-sided tender system while the tender mechanism in the electricity exchange is based on the two-sided tender system.
- While the pool system is a structure in which the physical and technical specifications of electricity are taken into account, the electricity exchange is a market structure where solely the electrical energy is bought and sold without any technical constraints such as the transmission constraints (Camadan 2009). It is the duty of the system operator to take into consideration and regulate the technical constraints which are not taken into account by the electricity exchanges (Bouisseleau 2004).
- While there are supplementary payments such as capacity payments in the pool system there are no supplementary payments in the electricity exchange.
- The mechanism of fixing the price and offers are complex and multi-parameter based in the pool system. However, the structure of making offers in the electricity exchange is much simpler than the pool system (Camadan 2009).
- The configuration of the pool is a structure which is formed by only one market, where the system operator plays a central role in ensuring the balance of the system (Sağlam 2012). On the other hand, electricity exchange structure both imposes more responsibility on the participants and offers them more possibilities with more than one market.

- While there is no room for bilateral agreements in the pool system, the structure of the electricity exchange allows the parties to sign bilateral contracts (Camadan 2009).
- Transparency is missing in the pool system to a significant extent in comparison to the electricity exchange. This situation not only creates obstacles in entry to the market for the potential participants but also allows local generators to exercise market power (Bouisseleau 2004).

3.5. Wholesale Electricity Markets

As a result of the specific characteristics of the electricity industry an organized system is needed in order to provide the electricity market to function in a balanced manner. Besides this organized system, it should be also allowed that the electricity can be the subject of trade independently by means of the mutual declaration of intended parties. Within this framework, it is observed that the wholesale trade of electricity is possible to be carried out in several markets.

Electricity wholesale markets have been classified and examined under very different forms in the literature. In this study, electricity wholesale markets are examined under the following subsections:

3.5.1. Spot (Organized) Markets

Short-term markets which comprises the physical trade of electricity and market price formation within the framework of a system operated by an independent central administration is called spot (organized) markets. Within this framework, the spot

markets shall be examined under two subsections depending on the purpose for which they have been established.

3.5.1.1. Energy Exchanges (Day Ahead Market)

Energy exchanges are generally defined as the markets in which the traditional short-term trade is carried out. Even if the term “spot market” defines the instant physical trade for other commodities and services, it is impossible to establish a spot market where instant delivery is possible. Hence, in electricity markets, the transactions are carried out at a definite time before the delivery. The market in which such trade is carried out needs a central administration system and organization. This administrative function is undertaken by a market operator. Although it is possible to call the market of short-term bilateral contracts as a spot market, energy exchanges are generally organized under the name of “day ahead” market as a mechanism which usually functions 24 hours before the physical delivery of electricity (Yücel 2011).

In many countries, spot markets are form of exchanges which are operated as day ahead markets. Day ahead market is a mechanism where each participant in the market makes offers for purchase & sale in terms of price and amount within the framework of the predefined standard rules relating to each hour of the next day and the market price is determined by letting the supply & demand curves overlap with each other. This market is the last opportunity, for the generators and consumers who does not want to endure the price risk in the real-time market. It also provides an opportunity for eliminating the energy imbalances which have not been set through bilateral contracts (Sitti 2010). In addition, a market in which only electricity is

bought & sold and hourly prices are determined is established in the electricity exchange without considering any technical constraints such as transmission constraints.

3.5.1.2. Equilibrium Prices (Day Ahead and Real-Time Markets)

As a result of the need for instantaneous balance of generation and consumption of electricity, markets have been created which are generally opened following the closing of the day-ahead market and in which the system operator buys and sells electricity. The real-time balancing has two components: balancing power market and ancillary services. The functioning of these markets is based on the instant matching of generation and consumption by the system operator.

In real-time terms and in parallel to the increase in consumption, some of the generation plants are given the instruction to increase their generation (taking load) while others are given the instruction to reduce their generation when there is a continuous decrease in consumption (discharge the load). Even if it may be claimed that the balancing markets are something more than merely being a market and that they are a mechanism that has been formed as a result of a physical balancing requirements, we may conclude that the system exhibits itself as a very short-term organized market considering the tender method used during the process of the formation of price and the fact that the participants behave with the purpose of profit maximization and with competitive instincts (Yücel 2011).

Due to the fact that the spot markets which have been dealing with balancing activities are short-term markets, they appear as a structure in which even the

generators with a low market share may have a high market power and use that power because of the characteristic features of the electricity.

3.5.2. Bilateral Contracts

As shall be understood from its name, there are two sides (namely the buyer and the seller) in the market of bilateral contracts. The trade of electrical energy is carried out by means of physical contracts in which the generators and buyers sign by either using an intermediary or an exchange market. These contracts, in general, have no standard features and may differentiate from each other in terms of the beginning date, duration, delivery regions and may have terms which are specific to the buyer and the seller (Şen 2006; Boisselau 2004). The most important benefit provided by that market is to prevent the generators and consumers to be effected from the price fluctuations in the spot markets by means of the long-term contracts signed between them. The market of bilateral contracts has been called “forward market” due to its forward structure. System operator must be informed of all the transactions realized in the market of bilateral contracts. However, the role of the system operator is very restricted within the structure of this market and the main task of the system operator is to ensure the technical reliability of the system and operate the real time market.

3.5.3. Derivative (Financial) Markets

Electricity trade in the organized markets or the markets of bilateral contracts may indeed be accepted as the physical trade of electricity; because the electrical energy is directly traded in these markets. However derivative markets which do not include a physical delivery have also been developed.

Besides the purchase and sale of electricity as a commodity, some instruments for risk-bound financial protection (hedge) and risk management may be used especially due to the uncertainty between long-term and short-term trade.

The primary instrument used in the derivative markets within this framework is the “contracts for differences” (Sağlam 2012). This type of contracts is based on the capitalization of the difference that arises between the contracted price and market price as a result of the fluctuations in the spot markets and its being transacted upon in the exchanges. “Futures transactions”, in which the bilateral contracts that are standardized and have a forward nature subject to trade transactions, may be cited as another financial instrument. It is noted that these derivative instruments may be traded both in the exchanges and the bilateral (over the counter - OTC) markets. However, it may be observed that the transactions related to the derivative markets are generally carried out in the energy exchanges together with the physical trade of electricity.

3.6. Mechanisms of Price Formation

The prices in the electricity wholesale markets are generally formed by means of two different mechanisms, namely the mutual contracts and merit order.

3.6.1. The Mechanism of Mutual Contracts

As has been explained above, the first mechanism is based on the formation of the price by means of the mutual declaration of intent of the parties in the market of bilateral contracts and derivative market. In this method, the parties come to an agreement through intermediaries, telephone or electronic environment and mutual bargaining is made especially for the long-term transactions. Besides, it is observed

that standardized bilateral contracts and derivatives are subject of trade activities in the structures such as exchanges. With this structure, the price formation in the market of mutual contracts and the derivative markets has no significant differences from the mechanisms of price formation in other commodity and service markets.

3.6.2. Mechanisms of Merit Order

The amount of electricity supplied by the different generation units of the generators can be ordered by marginal cost until the demand has been completely met and this is called “merit order”. The marginal cost of the generation unit which had ensured the demand to be completely met constitutes the price which shall be paid to all generators in the system (Rothwell and Gomez 2003).

The merit order mechanism is based on the principle of tender (bid and auction) in the spot markets. The main dynamics determining the formation of price is generally the same, although there are differences related to the functioning of this mechanism which is operated in an organized manner in many countries. In this mechanism, the prices are determined according to a tender system in which the balance price applicable in the near future (generally a day ahead) and for a definite period of time (generally hourly) is formed according to the price quoted by the last power plant whose offer has been accepted. The stages of price formation within the framework of this mechanism which is called “tender for marginal price” are as follows (Kirschen and Strbac 2005):

- The mechanism is managed by a system operator or a market operator (the central administration).

- The central administration, first of all, estimates the amount of demand for electrical energy during each hour of the following day.
- A general tender is announced for the purpose of supplying the amount of electrical energy needed for each hour of the next day.
- Generation companies offer a definite capacity and price on the basis of the cost structure of the generation units in their portfolio and the idle capacity that they have in the physical state.
- The bids which are submitted for each hour separately are ordered by the central administration according to increasing price.
- Within the framework of this system, a curve is formed which shows the quoted price as a function of the amounts of cumulative offer. That curve is the “supply curve” of the market.
- The central administration determines the amount of supply that meets the amount of forecasted demand for the relevant hour. The intersection of supply and demand curves forms the market equilibrium. The combination of price & quantity at the point of intersection is the point at which the market is in equilibrium.
- All offers for supply which are equal or under this price which is called the MCP (market clearing price) are accepted and the generators whose offers have been accepted and they are instructed to “be online” for the real-time delivery for the next day.

- MCP may also be called the SMP since it reflects the price of the last accepted MWh. Generators pay this price for each MWh electricity that they generate while the consumers also pay the same price for each MWh electricity that they consume.

In general, it is possible to develop regional price formation mechanisms geographically besides the mechanism for determining a single price in the network. Indeed, it is possible that the constraints in the transmission system which is generally neglected because of the sufficiency of the network resources in the system becomes a serious problem as a result of the restructuring (i.e., congestion) and the differences that arise in the generation of and demand for electricity in geographical terms. Within this framework, it is possible to operate the mechanism for price formation related to organized markets stated above for each region (or zone) separately (instead of determining a single price that can apply to the overall network). This model is called the **zonal pricing model**. In this model, the incentive aims at encouraging the generation investments in the zones where the prices are formed and trading of the transmission capacities may also come to the agenda because of the constraints that may arise in the network.

3.7. Market Power in Electricity Markets

Even if the electricity generation market is not accepted as a natural monopoly, it is possible that generation companies or wholesale companies and even the small generators may exercise market power. The fact that the supply of and demand for electricity is not flexible in the short-term and the necessity of the existence of a real-

time supply & demand balance in the electricity markets and the existence of network limitations makes the electricity markets suitable for the use of market power .

Expressed in simple terms, market power is the capability to increase the prices over the competitive levels. Camadan and Erten defines market power as follows: “Market power is, basically, the ability of a single or several companies to increase the market prices over the competitive price level” (2010: 65).

3.7.1. Analysis of Competition and the Determination of Market Power

Static models, concentration measurements, analysis of price & cost margins and analysis of residual demand are used to determine the market power in electricity markets. These methods are explained in the next subsections.

3.7.1.1. Static Models

Static models are those models which makes an analysis of competition for only short term (such as hourly or daily) and they do not take into account the long-term dynamics (e.g., the opportunities for harmonic action, obstacles against entry to market, long-term contracts, investment incentives) (Akçollu 2000).

In the Cournot model, the companies accept the generation levels of each other as given and try to compete using generation quantities as their only strategic variable only. The prices in the market are regulated by an auctioneer outside the firms in the market for the purpose of balancing the supply and demand. These firms in the market are able to use their market power by reducing the amount of electricity that they offer to the market and consequently increase the electricity prices and their

own profits. In other words, according to the Cournot model, as the concentration level in the market increases, the price differences away from equilibrium level of perfect competition arise and reach close to the levels of monopolist market structure.

In the Bertrand model, however, the companies accept the prices of each other as given and determine the price of the product that they sell by themselves (i.e., price is their strategic variable). Companies are able to use their market power by determining prices over the marginal costs and consequently generate less than the amount for the perfect competition case. Static competition models such as Cournot and Bertrand are not suitable for electricity markets which are totally decentralized. In the existing situation, all decentralized electricity wholesale markets initiate firm's price auctions where the generation companies offer price & generation amounts and the wholesale equilibrium is realized at the same market clearing price. It is not Cournot and Bertrand models but Nash equilibrium which fits this system the most. Three situations are examined in Nash equilibrium:

- The situation where the sale prices offered by all companies in the low-demand periods are equal to their marginal cost;
- The situation where all companies except one of them want to sell all their capacity at a price equal to the marginal price and only one company realizes generation / sale under its capacity and made an offer at a higher price;
- The situation where all companies determine complex and casual pricing strategies in which the price fluctuates in the price interval that is under the cost and as high as possible (Harbord and Fabra 2000).

The most important issue that Nash equilibrium puts forward for electricity market participants is that the determination of the strategic variables (i.e., price or quantity) of the firms which exercise market power is not the same as the determination of these variables by other firms. In the second and third cases, the companies which bid a low price and make use of the high price given by other companies by means of “free-ride” are the companies which use their market power in the most successful manner. On the other hand, in the first case, all companies offer competitive prices and the company which determines the market price is dependent on the place where the demand curve overlaps the competitive industry output at a given time. It is also possible that the equilibrium price equal to the price offered by a small company with no market power.

3.7.1.2. Concentration Measurements

Concentration measurements, market share and concentration rate measurements are market power measures such as Herfindahl – Hirschman Index (HHI). HHI is the most frequently used measure in competition and regulation context. Concentration measurements are only calculated using the existing market shares of the companies. Concentration measurements do not consider the following facts while taking into account the number and dimensions of the companies in the market:

- Flexibility of demand
- The structure of the companies in the generation market
- Strategies of the competitors
- Obstacles to entry to the market

3.7.1.3. Analysis of the Price-Cost Margin

The analysis of price-cost margin is used in the measurement of the extent to which the prices exceed the marginal costs. Borenstein and Bushnell (1999) think that the price-cost margin is the most suitable method to understand whether market power has been used or not.

3.7.1.4. Analysis of Residual Demand

Residual demand curve measures the impact of the changes in the prices applied by a company on the sales. In a traditional analysis of residual demand, the market power of a company is measured by the degree of its capacity to pull its price over the competitive levels in a profitable way.

Chapter 4

4. Electricity Market Modeling Trends

There are different approaches for electricity market modeling trends which can be categorized as in Figure 3.

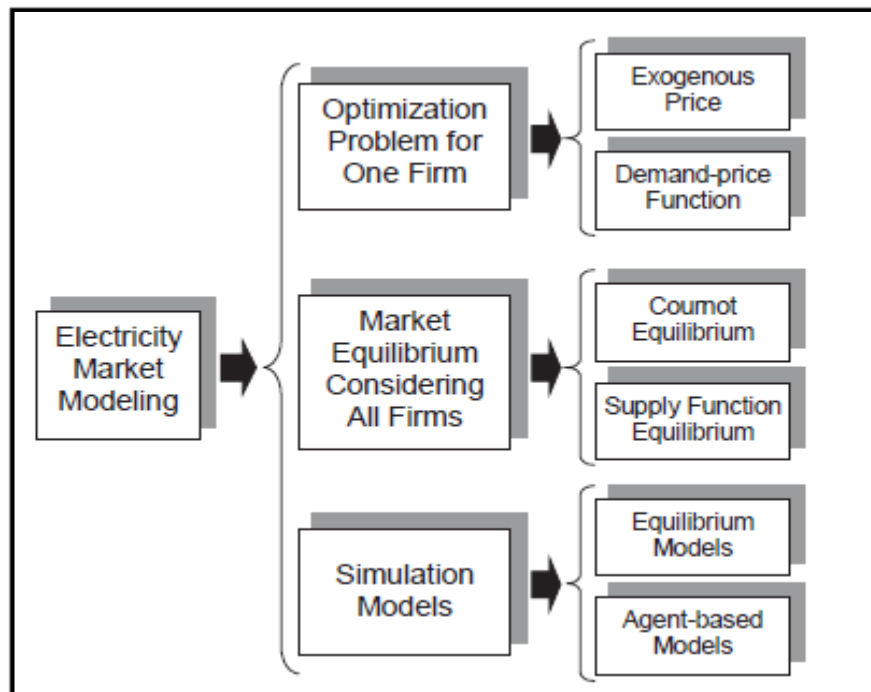


Figure 3: The electricity market modeling Source: (Ventosa et al. 2005)

In fact, there is many other categorization, but we can categorize modeling approaches on three main trends:

- *Optimization Models (Profit Maximization for One Participant)*
- *Equilibrium Models (Competition between Participants)*
- *Simulation Models (Due to complexity)*

In this study, we will focus on market equilibrium models and especially Cournot equilibrium model. Also the Stackelberg leader–follower games, monopoly model and perfect competition model can be studied under the equilibrium modelling approach.

Mathematical Structure

As mentioned, the aim of optimization models is to maximize the profit for one of the participants competing in the market. Whereas, in the equilibrium models, the aim is to find an equilibrium solution for all players in the market and no player has an incentive to deviate from this equilibrium solution (as this may worsen their profits).

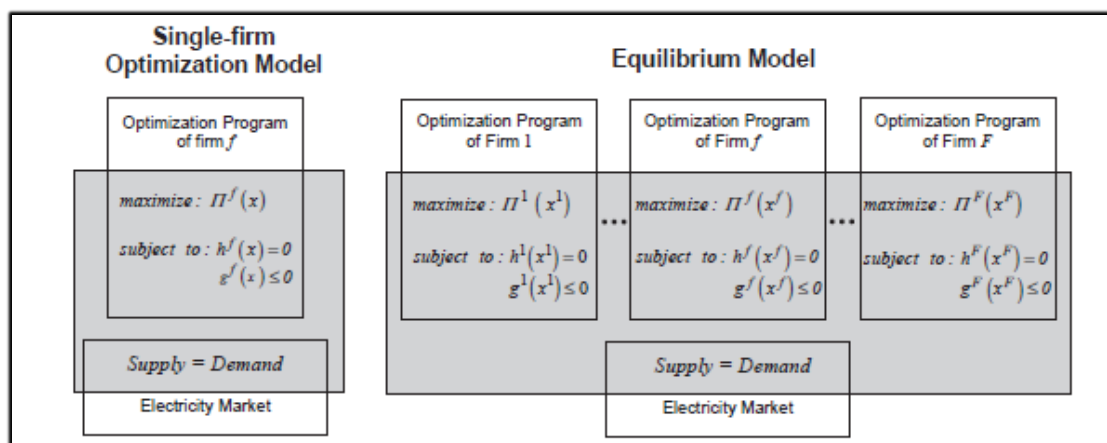


Figure 4: Mathematical structure Source: (Ventosa et al. 2005)

4.1. Market Equilibrium Considering All Firms

4.1.1. Cournot Equilibrium

This model, which was originally formulated by Cournot in 1838, is based on the assumptions below;

- *Each firm knows the inverse demand function for the entire market,*
- *Each firm assumes fixed values for the generation of the other firms,*
- *The firms are economically rational and act strategically,*
- *The number of firms is fixed,*
- *Firms do not cooperate,*
- *There is more than one firm and all firms generate a homogeneous product,*
- *Firms compete in quantities and choose their quantities simultaneously.*

Lately, the idea that each firm takes the other firms' decision as beyond its control was investigated by Nash in 1951, in a much more general setting, which is the key foundation of the modern game theory.

In general terms, the strategic variables are the firms' generation quantities in this model. Firm chooses its generation quantity in order to maximize its profit and firms do not respond to price changes. In Cournot model, a firm uses its knowledge of the inverse demand curve, but assumes that it has no influence over other firms' output decisions. Thus, this makes Cournot model a less intense form of competition.

The publications devoted to these models concentrate on four areas:

- *Market power analysis,*
- *Hydrothermal coordination,*
- *Influence of the transmission network constraints, and*
- *Risk assessment*

4.1.1.1. Market Power Analysis

Market power measurement was the earliest application of Cournot-based model to electricity markets. Borenstein et al. employed this theoretical market model to analyze Californian electricity market power instead of using the more traditional Hirschman–Herfindahl Index (HHI) and Lerner Index, which measure market shares and price-cost margins, respectively (1995). Later, Borenstein and Bushnell have extended this approach by developing an empirical simulation model that calculates the Cournot equilibrium iteratively: the profit-maximizing output of each firm is obtained assuming that the generation of the remaining firms is fixed (1999). This is repeated for each supplier until no firm can improve its profit. A collection of models—most of them based on Cournot competition—for measuring market power in electricity can be found in Bushnell et al. (1999).

4.1.1.2. Electricity Power Network

Both Hogan (1997) and Oren (1997) formulate a spatial electricity model in which firms compete in a Cournot manner for congestion pricing in transmission networks. Wei and Smeers use a variational inequality (VI) approach for computing the spatial

market equilibrium (1999). In their study, electrical network considering only power is modeled. This type of electricity network model is known as transshipment model.

Moreover, Hobbs models imperfect competition among electricity generators in bilateral and POOLCO-based power markets as a linear complementarity problem (LCP) (2001). That model includes a congestion-pricing scheme for transmission in which load flows are modeled considering both the first and the second Kirchhoff's laws. This kind of modelling approach for the transmission networks is called as DC approximation model.

In all these models, it is assumed that the generation units of each firm are located at only one node of the network. Unfortunately, equilibrium does not exist due to each firm is allowed to own generation units in more than one node. Neuhoff has focused on that topic (2003).

4.1.1.3. Risk Analysis

Battle et al. present a procedure capable of taking into account some risk factors, such as hydraulic inflows, demand growth and fuel costs (2000). Cournot market behavior is considered using the simulation model described in Otero-Novas et al., which computes market prices under a wide range of scenarios (2000). His model provides risk measures such as value-at-risk (VaR) or profit-at-risk (PaR).

4.1.1.4. Extensions of Cournot Equilibrium

The most important point under the Cournot approach is that the generators' strategies are expressed in terms of quantities and not in terms of offer curves. Hence, equilibrium prices are determined only by the demand function which is

highly sensitive to demand representation. This shortcoming seems to reinforce the idea that the supply function equilibrium (SFE) approach is a better alternative to represent competition in electricity markets (Rudkevich et al. 1998).

Incorporating the conjectural variations (CV) approach described in traditional microeconomics theory is another way to overcome this limitation (Vives, 1999). The CV approach changes the conjectures that generators are expected to assume about their competitors' strategic decisions, in terms of the possibility of future reactions. It is suggested to improve Cournot pricing in electricity markets.

4.1.2. Bertrand Game

This model, which signifies that firms' strategic variables are the prices each firm charges, was published by Joseph Bertrand in the late nineteenth century.

The Bertrand model is another kind of Nash game in which each firm takes other firms' strategic price variables as fixed and beyond its control. If the commodity is homogeneous, customers believe that the product of one firm is physically identical to the product of any other firms. Then, customers will choose the firm that offers the lowest price. If not, the commodity is heterogeneous, and then there may be nonzero cross price elasticities. Therefore, each firm has an incentive to undercut other firms' prices, even by a small amount as long as the price does not fall below its marginal cost (Gabriel et al., 2013).

Bertrand model can be applied to power markets where the competition is the most intense. The participant specifies a single price for each generator or area served.

In addition, it assumes that other participants will not change their prices in response. The price falls to marginal cost due to the competition if there are no capacity limits and transmission costs.

4.2.3. Stackelberg Leader – Follower Games (MPECs)

This model defines a leader that could use its knowledge of inverse demand curve and it could also anticipate the reactions of other firms (i.e., followers) to the leader's decisions. This means that the leader firm knows both the inverse demand curve and the followers' reaction to its strategy. The mathematical form of this model is usually called a MPEC and the solution for these models are still an active research area where multiple equilibria and non-tractability are important issues (see Gabriel et al, 2013 for further details).

4.2.4. Monopoly Model

This model supposes that all firms merge into one single firm, a monopolist. All of the original firms' generation facilities still exist as before. If this monopolist firm acts as a price-taker, then the resulting market equilibrium would be the same as the separate firms case. But, if this monopolist firm can estimate the inverse demand function, then it would be better off by anticipating the effect of its total generation on the market price (Gabriel et al., 2013). This is the objective of monopoly model.

Chapter 5

5. The Mathematical Model

5.1. Short – Run Perfectly Competitive Market

In this section we have explained the details of the mathematical model for the electricity market price simulations. This model is due to Gabriel et al. (2013) and more generally due to Hobbs (2001). According to this model, we introduce an elementary model of perfect and imperfect (oligopolistic) competition among power generators. Below, we introduce the notation for the model in details:

Sets

- f index for firms
- i, j indices for nodes (buses)
- h index for generating units
- I_f is the set of nodes i at which firm f owns generation
- K is the set of transmission lines

Decision Variables

- p_i is the electricity price at node i
- x_{fih} firm f 's generation at node i by generating unit h , in MW
- s_{fi} represents firm f 's sales at node i
- w_i transmission price at node i

- y_i power injection/withdrawal at node i , in MW of transmission services
- μ_f is the dual of the capacity constraint
- $C_{fih}(x_{fih})$ is the cost function of firm i generation unit h at node i
- $f_{d,i}^{-1}$ linear inverse demand function at node i

Parameters

- α_i non-price effects at node i for the linear inverse demand function (weather, socio-demographic factors, the appliance stock)
- β_i constant price coefficient for the linear inverse demand function at node i
- T_k is the upper level to the flow through transmission line k
- λ_k^+ is nonnegative dual variable for the transmission line flow limit
- λ_k^- is negative dual variable for the transmission line flow limit
- $PTDF_{ik}$ is a linear response coefficient, translating net power injections/withdrawals at the nodes into flow on a transmission line k in the network
- K_{fih} available capacity of firm f generating unit h at node i

The perfect competition model is generalized with the following features:

The model has generators selling to consumers at locations throughout the network. For this reason, a new variable s_{fi} is defined, the MW sales by generating firm f to consumer at node i . Therefore, both generators and the TSO can sell directly to consumers and satisfy their demand.

For the Nash-Cournot model, each firm f assumes that the other firms will not change the amount they sell. Thus, generators play a quantity game against other generators.

Firms realize that if more or less power is sold at a node, then price will fall or rise, respectively, following the inverse demand curve. This provides an incentive to restrict sales and increase price.

In the general framework of the model, generators pay the TSO for transmission services. The TSO's prices ration scarce transmission capacity. A property of congestion pricing is the price of moving power from node j to node i is -1 times the price of moving it in the opposite direction. Furthermore, the price of moving power from j to i is equal to the price of moving it from j to an arbitrary node k (i.e., defined as a reference or slack or hub node) and then from k to i , and is the same for all k (i.e., principle of superposition applies). This price is w_i \$/MWh from the hub node to node i . All power is routed through the hub, so that a generator wishing to produce power at node j and sell it at node i pays $-w_i + w_j$ \$/MWh as the transmission price. Each generating company assumes that its sales and output actions will not affect the values of w_i . If a large generator tried to send more power to other locations, congestion would increase, causing the price of transmission services to that location to go up.

Consumer (demand) side:

$$p_i = f_{d,i}^{-1} \left(\sum_{f \in F} s_{fi} \right) = \alpha_i - \beta_i \left(\sum_{f \in F} s_{fi} \right) \quad (5.1)$$

Generation Firm i 's Problem

$$\text{Maximize}_{x_{fih}, s_{fi}} \sum_i [p_i - w_i] s_{fi} - \sum_{i \in I_f} \left(\sum_h C_{fih}(x_{fih}) - w_i x_{fih} \right) \quad (5.2)$$

Subject to.

$$\sum_{i \in I} s_{fi} - \sum_{i \in I_f} \sum_{h \in H} x_{fih} = 0 \quad (v_f) \quad \forall f \in F \quad (5.3)$$

$$x_{fih} - K_{fih} \leq 0 \quad (\mu_{fih}) \quad \forall i \in I_f \quad (5.4)$$

$$x_{fih} \geq 0 \quad \forall i \in I_f \quad (5.5)$$

TSO's Problem

$$\text{Maximize}_{y_i} \sum_{i \in I} w_i y_i \quad (5.6)$$

Subject to.

$$\sum_{i \in I} y_i = 0 \quad (\gamma) \quad (5.7)$$

$$\sum_{i \in I} PTDF_{ik} y_i \leq T_k \quad (\lambda_k^+), \quad \forall k \in K \quad (5.8)$$

$$-\sum_i PTDF_{ik} y_i \leq T_k \quad (\lambda_k^-), \quad \forall k \in K \quad (5.9)$$

Market Clearing Condition

$$\sum_{f \in F} s_{fi} - \sum_{f \in F} \sum_{h \in H} x_{fih} - y_i = 0 \quad (w_i) \quad \forall i \in I \quad (5.10)$$

Generating Firm; is a price-taker (for the perfect competition model) and it views price at each and every node as an unchangeable parameter in its objective function, even though from the market's point of view those prices are variable and are adjusted to balance supply and demand at each node.

Basically, we consider the possibility of more than one firm and generation units at each node. However, the unit commitment constraints and costs are disregarded. The latter can be readily modeled by defining multiple periods in chronologic order and adding constraints that limit the change in generator's output from period to period. In theory, start-up and minimum load costs need to use binary (0 and 1) variables to represent the decision. Therefore, they are not included in the model (as it will destroy the convexity of the overall model).

Consumer side; the response of the consumer to price changes is formulated by its demand function (i.e., utility maximization problem for the consumer is represented by this demand equation).

Transmission provider; its objective is to allocate transmission capacity to maximize the value that the market receives. This behavior is represented by modeling the TSO as a market agent who believes it can not affect the market price, even though, in fact, price is a variable that is endogenous to the market. Basically, TSO operates a market that auctions off the capacity of individual transmission components. It is similar to the "flowgate" market which is proposed by Chao and Peck (Gabriel et al. 2013).

The y_i variable of TSO model is the power injections/withdrawals of the TSO for the transmission service at node i . These variables are used to model the flow in a particular direction through a particular branch of the network, where there are K branches. These branches may represent distinct components of the transmission network such as transmission lines and transformers or can model aggregations of lines or other constraints.

The flows $flow_k$ are dependent on the nodal power injections/withdrawals y_i as follows. The DC load flow model install a system of K independent linear equations that determines the K flow as a function of the TSO's transmission service at the I nodes. The model assumes that resistance is much less than reactance and the nominal voltage levels for buses (i.e., nodes) are same as the actual voltage magnitudes. Basically, the K equations are derived from $I-1$ independent energy balances at the nodes and $K-I + 1$ independent loop equations while there are only constraints on flows on individual lines (Gabriel et al. 2013). Due to Kirchhoff's current law (Schweppe et al. 1988), the sum, over all links in a loop in a network, of the MW link flow times the link impedance must equal to zero. So that

$$flow_k = \sum_i PTDF_{ik} y_i \quad \forall k \quad (5.11)$$

The $PTDF_{ik}$ is a linear response coefficient, translating net power injections/withdrawals at the nodes into flow on a branch k in the network. It's called "swing factors" or "power transfer distribution factors" by engineers. They can be interpreted as the MW flow through component k that results from a 1 MW withdrawal at node i and a matching 1 MW injection at the "hub" node, which is the node whose energy balance is not included in the K independent equations. Swing

factors can be used for approximation of the actual flows which are managed by nonlinear equations. The resulting pattern of flow is very different than what a transportation network might generate in which flow can be directed along different paths of a network (Gabriel et al. 2013).

These K equalities can be used to eliminate the flow variables, so that the bounds on flows in the TSO's optimization model become bounds on $\sum_{i \in I} PTDF_{ik} y_i$ instead.

The generators adopt a Bertrand (price-taking) conjecture regarding the price of transmission services. That is, each generating company assumes that its sales and output actions will not affect the values of w_i . This is of course a strong assumption, in that a large generator might naturally assume that if it tried to send more power to another location, congestion would increase, causing the price of transmission services to that location to go up (Gabriel et al. 2013).

5.2. Market-Clearing Conditions and the Equilibrium Problem

Basically, the market-clearing conditions (5.10) depend on supply and demand balance at each node i and in the complementarity problem they are associated with the transmission price w_i . The equilibrium problem consists of the first order (KKT) conditions for the generation firms (5.2-5.5) and TSO's problem (5.6-5.9) together with the market clearing condition (5.10) and the demand equation (5.1).

Note that the equation (5.7) is satisfied together by equations (5.3) and (5.10), i.e., sum equation (5.10) over all nodes (i) and sum equation (5.3) over all firms (f) to get equation (5.7). Hence, it is redundant. Inclusion of redundant constraints in the problem may cause two important problems: numerical problems due to linear dependency of constraints and ambiguity problem in the form of multiple solutions

for the dual variable associated with this redundant constraint. To avoid these problems, this constraint is omitted from the overall complementarity problem.

The MCP problem for the perfect competition model is given below:

MCP: Find $s_{fi}, x_{fih}, v_f, \mu_{fih}, y_i, \lambda_k^+, \lambda_k^-, w_i, p_i$ that satisfy

$$\begin{aligned}
s_{fi} \geq 0 \perp -p_i + w_i + v_f &\geq 0 & \forall f \in F, i \in I \\
x_{fih} \geq 0 \perp \frac{dC_{fih}}{dx_{fih}} - w_i - v_f + \mu_{fih} &\geq 0 & \forall f \in F, i \in I_f, h \in H \\
v_f \text{ free} \perp \sum_{i \in I} s_{fi} - \sum_{i \in I_f} \sum_{h \in H} x_{fih} &= 0 & \forall f \in F \\
\mu_{fih} \geq 0 \perp x_{fih} - K_{fih} &\leq 0 & \forall i \in I_f \\
y_i \text{ free} \perp -w_i + \sum_{k \in K} PTDF_{ik} (\lambda_k^+ - \lambda_k^-) &= 0 & \forall i \in I \\
\lambda_k^+ \geq 0 \perp \sum_{i \in I} PTDF_{ik} y_i &\leq T_k & \forall k \in K \\
\lambda_k^- \geq 0 \perp -\sum_{i \in I} PTDF_{ik} y_i &\leq T_k & \forall k \in K \\
w_i \text{ free} \perp \sum_{f \in F} s_{fi} - \sum_{f \in F} \sum_{h \in H} x_{fih} - y_i &= 0 & \forall i \in I \\
p_i = f_{d,i}^{-1} \left(\sum_{f \in F} s_{fi} \right) &= \alpha_i - \beta_i \left(\sum_{f \in F} s_{fi} \right) & \forall i \in I
\end{aligned} \tag{5.12}$$

It can be easily verified that the MCP problem (5.12) has equal number of conditions and variables. Note that the p_i variables can be eliminated from the problem by replacing it with the inverse demand function, $f_{d,i}^{-1}(\sum_{f \in F} s_{fi})$.

5.3. Solution Properties

Economic interpretations may be given for the equilibrium conditions (Gabriel et al., 2013);

- The “price equals marginal cost” is result of microeconomic models of the perfect competition. This model generalizes this result to spatial markets in which the commodity is transported according to Kirchoff’s laws. (5.11)
- Price at each location i is equal to the system energy price plus a weighted sum of shadow prices for binding transmission constraints (Hogan 1992). This sum represented the cost of bringing power from the hub node to node i .
- Due to further analysis equilibrium conditions can present that TSO’s profit is equal to difference between consumer’s payments for power and payments to generators which is in turn equal to the sum of the transmission constraints times their shadow prices (Hogan 1992).

Uniqueness and existence are desirable properties for models that are used in policy analyses or regulatory proceedings because multiple solutions make conclusions ambiguous. Multiple solutions for market operations models are also undesirable if different solutions imply different distributions of income among market participants; political issues then arise (Johnson, Oren and Svoboda 1997).

The uniqueness and existence of solutions of the MCP problem (5.12) can also be verified. Continuous and decreasing demand curves (for the consumer side) and strictly convex cost functions (for generating firms) are sufficient to ensure that a solution exists and that the quantities and prices are unique. Multiple dual solutions for some dual variables are possible if their associated constraints are degenerate.

Chapter 6

6. Market Price Simulations for Turkish Electricity Market

6.1. Data and Assumptions

The data for the Turkish electricity system is compiled from different sources. TEİAŞ provide us the Turkish Generation-Transmission system map, where we have analyzed the transmission system according to control (load dispatch) areas of the TEİAŞ system. There are 9 control areas as presented in Figure 5.

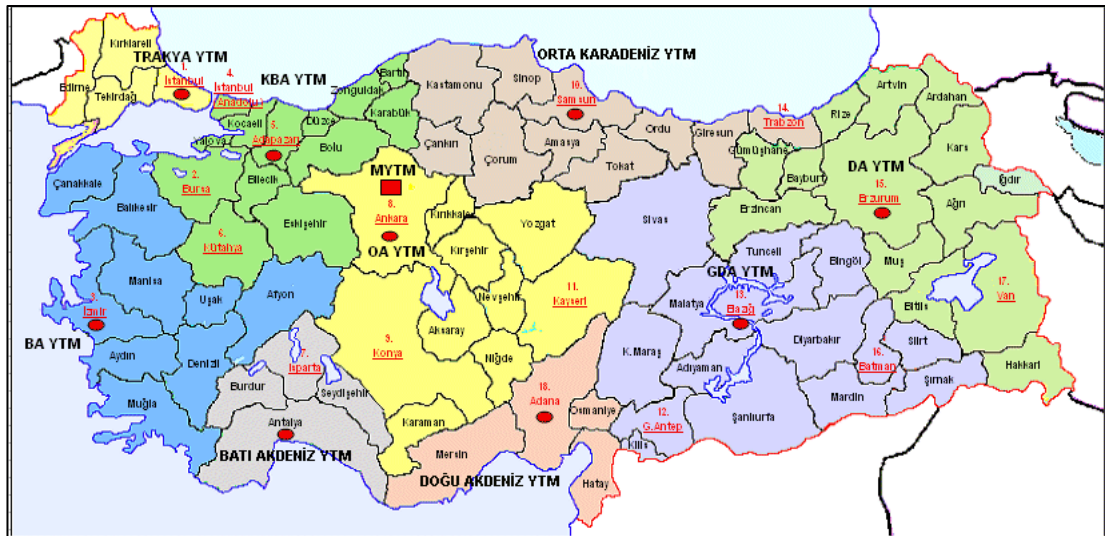


Figure 5: TEİAŞ Control Areas Source: TEİAŞ

We have assumed a 9-bus transmission system where each bus corresponds to these control areas. Then, we have estimated the 400kV transmission lines between these control areas and the following 9-bus system is prepared for our simulation purposes.

As mentioned before, we were not able to get the network data (or data for a test system) for research purposes from the TEİAŞ despite numerous attempts and contact with TEİAŞ and EÜAŞ representatives and managers. Therefore, we have made a crude but useful estimation of the transmission system as depicted in Figure 6.

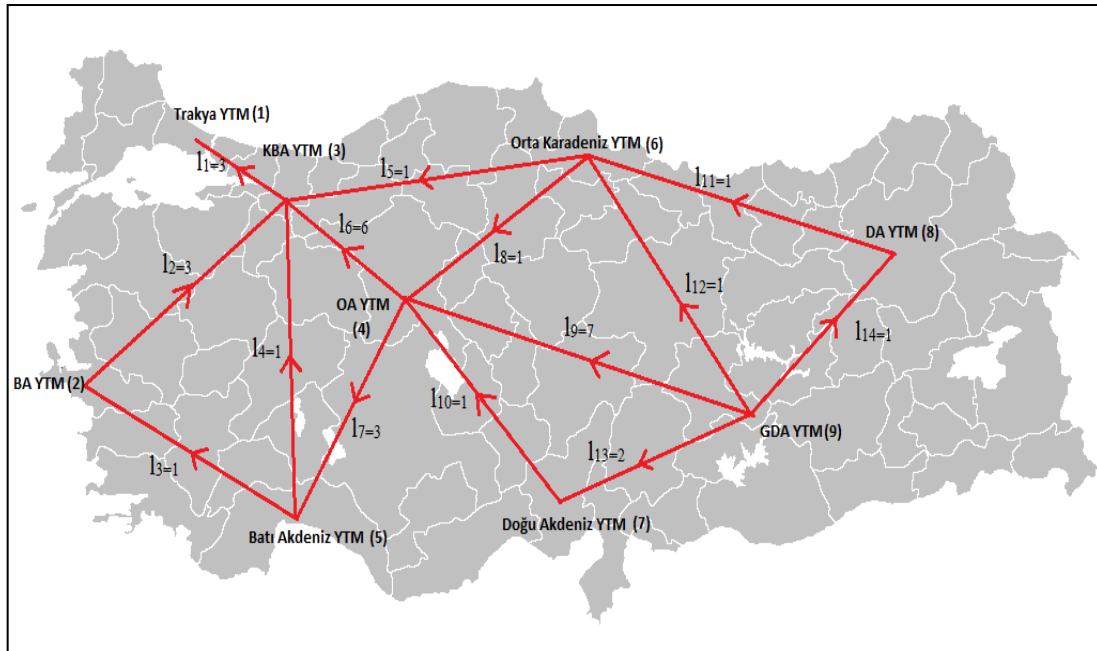


Figure 6: 9-Bus System

After this step, we have computed PTDF matrix for the DC load flow approximation of the system (by assuming equal line reactances of $X=0.1$ p.u. and TRAKYA=n1 as the reference/slack bus). The calculation method is explained in details in Gabriel et al. (2013, pp.607-611). The PTDF matrix is given in the following Table 6.1.1.

Table 6.1.1: PTDF Matrix

PTDF Matrix (Reference Bus n1: TRAKYA)								
	n2	n3	n4	n5	n6	n7	n8	n9
11	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
12	0.6179	0.0	0.0894	0.2358	0.0569	0.0813	0.065	0.0732
13	-0.3821	0.0	0.0895	0.2357	0.0569	0.0813	0.0651	0.0731
14	0.2358	0.0	0.1789	0.4715	0.1138	0.1626	0.1301	0.1463
15	0.0569	0.0	0.2846	0.1138	0.5447	0.3496	0.4797	0.4146
16	0.0894	0.0	0.4472	0.1789	0.2846	0.4065	0.3252	0.3659
17	-0.1464	0.0	0.2683	-0.2926	0.1708	0.2439	0.1951	0.2196
18	-0.0325	0.0	-0.1626	-0.0651	0.2601	-0.0569	0.1545	0.0487
19	-0.0162	0.0	-0.0813	-0.0326	0.13	0.1382	0.2439	0.3577
110	-0.0081	0.0	-0.0407	-0.0163	0.065	0.5691	0.122	0.1788
111	0.0081	0.0	0.0406	0.0163	-0.065	0.0976	0.5447	0.1545
112	0.0163	0.0	0.0813	0.0325	-0.1301	0.1951	0.0894	0.309
113	-0.0081	0.0	-0.0406	-0.0163	0.065	-0.4309	0.1219	0.1789
114	0.0082	0.0	0.0407	0.0162	-0.0651	0.0975	-0.4553	0.1545

Line limits are assumed to be 1000MW per each 400kV as depicted in the map of “Generation-Transmission System of Turkey, 2012” and in below figure 7. The data for the line limits are presented in the following Table 6.2.

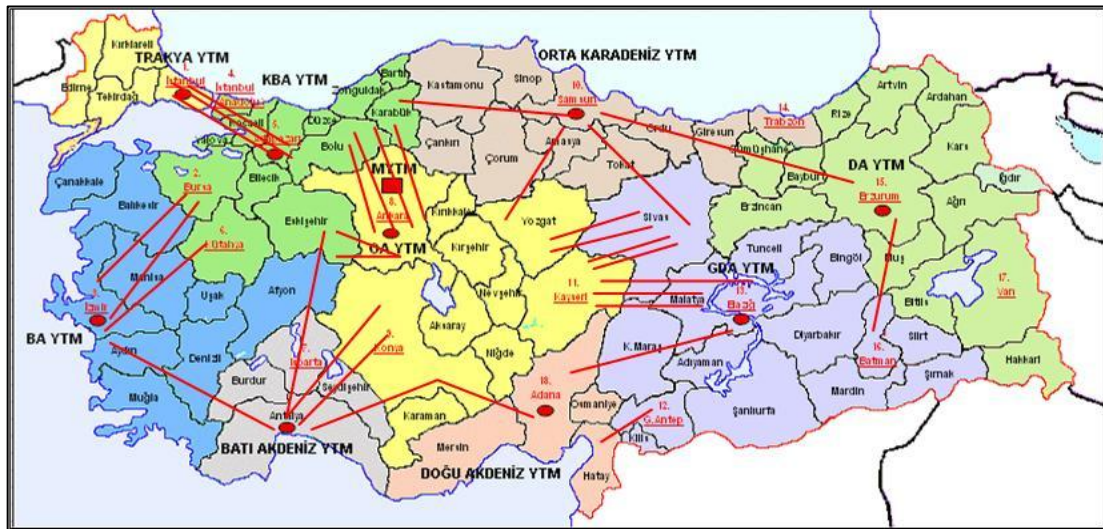


Figure 7: Map of “Generation-Transmission System of Turkey, 2012”

Table 6.1.2: Line Limits

$T(k)$ Line Limits (in MW)	
I1	3000
I2	3000
I3	1000
I4	1000
I5	1000
I6	6000
I7	3000
I8	1000
I9	7000
I10	1000
I11	1000
I12	1000
I13	2000
I14	1000

We have assumed only 6 categories of generation technologies, namely, wind, hydro, coal, oil, gas and other (includes geothermal, solar, biogas and any other generation type available in Turkey). Finally, we have computed the median values for the cost estimation (operation, maintenance and fuel costs in US\$ per MW and converted to TRY using an exchange rate of 2 TRY/US\$) for different generation technologies from “IEA-OECD-NEA” report (2010).

Table 6.1.3: The Median Values for the Cost Estimation

	Fuel	O&M	Total (Fuel+O&M)	Median (Total)	Mean	Availability
Small Hydro		4.25	4.25	6.97	23.65	59%
		6.97	6.97			60%
		59.73	59.73			50%
Large Hydro		6.39	6.39	5.2	8.8	60%
		36.11	36.11			45%
		15.17	15.17			40%
		2.31	2.31			55%
		2.31	2.31			55%
		5.2	5.2			55%
		9.85	9.85			53%
		2.54	2.54			34%
		1.37	1.37			57%
		5.02	5.02			80%
	10.55	10.55	29%			
Geothermal		19.02	19.02	18.21	14.23	70%
		18.21	18.21			87%
		5.47	5.47			85%
Biogas	2.65	41.18	43.83	44.61	48.22	80%
Biomass		24.84	24.84			90%
	74.82	4.49	79.31			85%
	69.06	4.52	73.58			85%
	6.73	15.66	22.39			87%
	19.13	26.25	45.38	85%		
Source: IEA_OECD_NEA 2010 "Projected Cost of Generating Electricity" Report						
Wind		21.92	21.92	21.92		26%
Coal	18.21	6.02	24.23	24.23		85%
Oil	50.37	19.91	70.28	70.28	42.40	85%
Gas	61.12	4.48	65.6	65.6		85%
Pv		29.95	29.95	29.95		13%

Table 6.1.4: Generation Costs (\$/MWh)

Technology	Generation (Fuel+Operation&Maintenance) Costs (\$/MWh)
Wind	21.92
Hydro	6.09
Coal	24.23
Oil	70.28
Gas	65.6
Other	30.92

Generation capacities for each firm and for each node are compiled by using the data from the Ministry of Energy and Natural Resources, General Directorate of Renewable Energy (EIE) web site. This website has the data for each city in Turkey, where we can aggregate the data for each firm and each generation category at each node. For confidentiality reasons, we denote the nodes and firms by n and f in the Appendix Table A.1

The percent consumption data for the demand side is similarly acquired from the Ministry of Energy and Natural Resources, General Directorate of Renewable Energy website. Finally, we have assumed a load factor for each generation category to account for the available capacity (IEA-OECD-NEA, 2010). The load factors are presented in the next Table 6.5

Table 6.1.5: Load Factors

Technology	Load Factor
Wind	26%
Hydro	55%
Coal	85%
Oil	85%
Gas	85%
Other	85%

Source: IEA-OECD-NEA 2010

Because there are no available nodal demand parameters for this test system (nor is nodal demand and price data available), we have constructed plausible demand parameters (suitable for computational tests) for each node by the following procedure: First, we have solved a cost minimization problem with a total load of 37,000 MW. Then we have assumed inverse of the price elasticities of demand at each node i as $B_i = 0.1$ to compute the constant term for the inverse of the constant elasticity demand model, $p_i = f_{d,i}^{-1}(\sum_{f \in F} s_{fi}) = A_i(\sum_{f \in F} s_{fi})^{-B_i}$, by using the optimal solution of the cost minimization model. Then we have solved the market price simulation model (as described in Section 5) with this calculated demand parameters to find the same solution of the cost minimization model. Finally, we have linearized the solution of this model around the equilibrium solution (denoted by superscript $*$) to compute the linear demand parameters:

$$\beta_i = B_i \frac{p_i^*}{\sum_{f \in F} s_{fi}^*} \quad \text{and} \quad \alpha_i = p_i^* + \beta_i \sum_{f \in F} s_{fi}^*$$

In other words, we have calibrated the demand parameters by using the cost minimization model results and compute the constant elasticity demand model and then

the linear demand model for perfect competition model of Section 5. This calibration process for the demand parameter estimation can be used for simulation purposes. But in a real-world application, a careful econometric study would be needed, to establish the best functional form of the demand model and its parameters.

We have formulated the models using different market structures. The MCP model in section 5 is used for the perfect competition model. Note that the first condition of the MCP model in 5.12 does not include the extra term for the marginal revenue of firm f (i.e., recognizing that p_i is a function of $\sum_{f \in F} s_{fi}$) that appears in monopoly and Cournot models and its variants. Because all firms are price takers in a perfect competition structure, this condition only has the p_i term as the marginal revenue term. For the other market structures same model is used except the first condition is modified as follows:

Nash-Cournot behavior for all firms

$$s_{fi} \geq 0 \perp -p_i + \beta_i s_{fi} + w_i + v_f \geq 0 \quad \forall f \in F, i \in I \quad (6.1)$$

Monopoly (all firms merged into a one single firm)

$$s_{fi} \geq 0 \perp -p_i + \sum_{f \in F} \beta_i s_{fi} + w_i + v_f \geq 0 \quad \forall f \in F, i \in I \quad (6.2)$$

Only firm 1 as Nash-Cournot, the rest of the firms as price-taker

$$\begin{aligned} s_{fi} \geq 0 \perp -p_i + \beta_i s_{fi} + w_i + v_f \geq 0 & \quad \forall f = \text{firm1}, i \in I \\ s_{fi} \geq 0 \perp -p_i + w_i + v_f \geq 0 & \quad \forall f \in (F - \text{firm1}), i \in I \end{aligned} \quad (6.3)$$

Only firm 11 as price taker, the rest of the firms behave in Nash-Cournot fashion:

$$\begin{aligned}
 s_{fi} \geq 0 \perp -p_i + w_i + v_f \geq 0 & \quad \forall f = \text{firm11}, i \in I \\
 s_{fi} \geq 0 \perp -p_i + \beta_i s_{fi} + w_i + v_f \geq 0 & \quad \forall f \in (F - \text{firm11}), i \in I
 \end{aligned} \tag{6.4}$$

The models are coded in the GAMS/MCP framework and solved by the PATH solver. All models are solved in less than a second on a 2.0 GHz Windows 2007 PC with 4 GB memory and 4 CPUs.

6.2. Results

In this section, we have summarized the numerical results of the market price simulations for perfect competition, Nash-Cournot and monopoly market structures. For the other market structures' results, see Appendix A.2 and A.3. The perfect competition and monopoly models represent the two extreme market structures. The Nash-Cournot models with firm 1 as the only Nash-Cournot player or all firms as Nash-Cournot players except firm 11 are in between these two extreme market structures. Results for the perfect competition market structure are used as a benchmark in the next section (in PCM and welfare analyses), as it provides the most efficient market outcomes.

We also note that the results for the perfect competition model and the market structure where all firms acts as price-taker except firm 1 acting in Nash-Cournot behavior has the same results. In general, firms recognize that if more or less power is sold at a node then price will fall or rise, respectively, following the inverse demand curve. This provides an incentive to restrict sales and increase price. However, in our case, this is not achieved, most probably, due to large number of players in the market that drives the prices down.

6.2.1. Perfect Competition Market Modeling

Table 6.2.1: Results for the Perfect Competition Model (Linear demand)

	Demand at each Node (MWh)												
Transmission Case	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9				
T_1 =with line limit	5,886.10	6,667.55	9,247.37	4,528.27	1,517.03	1,576.18	2,912.13	910.23	3,751.79				
T_1 =without line limit	7,291.73	7,726.94	11,455.69	3,738.67	1,634.89	855.13	1,997.70	493.73	2,035.07				
	Sales by Firm f (MWh)												
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}		
T_1 =with line limit	13,944.75	445.55	1,399.29	348.50	242.25	1,266.50	1,156	854.25	527	472.70	16,339.86		
T_1 =without line limit	13,932.60	445.55	1,499.14	348.50	242.25	1,266.50	1,156	854.25	527	472.70	16,485.06		
	Energy Price ₹/MWh										Transmission Dual ₹/MWh		
Transmission Case	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	λ_k^+	λ_k^-		
T_1 =with line limit	140.56	139.42	140.56	134.85	138.28	131.20	133.03	131.20	131.20	0	15: 18,49	112: 5,48	
T_1 =without line limit	137.20	137.20	137.20	137.20	137.20	137.20	137.20	137.20	137.20	0	0		
	Transmission Price ₹/MWh										TSO Profit	Consumer Surplus	Social Surplus
Transmission Case	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	₹/hr	₹/hr	₹/hr	
T_1 =with line limit	0.00	-1.14	0.00	-5.71	-2.28	-9.36	-7.53	-9.36	-9.36	23,972.14	254,150.07	2,535,848.51	
T_1 =without line limit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	279,794.35	2,556,067.73	
	Generator Profit ₹/hr											Producer Surplus	
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	₹/hr	
T_1 =with line limit	1,332,170.75	20,588.61	14,418.38	3,261.96	653.73	26,441.76	106,467.60	77,701.33	45,528.54	11,037.55	619,456.09	2,257,726.31	
T_1 =without line limit	1,367,407.55	19,969.90	14,783.63	2,092.17	1,454.31	25,566.36	102,587.32	75,809.01	46,767.75	11,119.22	608,716.17	2,276,273.38	

6.2.2. Nash-Cournot Market Modeling

Table 6.2.2: Results for the Nash-Cournot Model (Linear demand)

	Demand at each Node (MWh)											
Transmission Case	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9			
T_1 =with line limit	5,856.41	6,556.65	9,200.73	4,233.68	1,473.88	1,233.63	2,778.03	796.54	3,652.45			
T_1 =without line limit	7,030.98	7,479.20	11,046.04	3,769.13	1,589.74	1,015.24	2,142.99	586.23	2,416.34			
	Sales by Firm f (MWh)											
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	
T_1 =with line limit	13,932.60	445.55	1,399.69	348.50	242.25	1,266.50	1,156	854.25	527	472.70	15,136.96	
T_1 =without line limit	13,932.60	445.55	1,499.14	348.50	242.25	1,266.50	1,156	854.25	527	472.70	16,331.41	
	Energy Price ₹/MWh									Transmission Dual ₹/MWh		
Transmission Case	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	λ_k^+	λ_k^-	
T_1 =with line limit	140.63	139.65	140.63	135.73	138.67	134.05	133.64	132.84	131.55	0	15: 13,76	112: 10,57
T_1 =without line limit	137.83	137.72	137.83	137.11	137.61	135.87	136.54	135.87	135.87	0	0	
	Transmission Price ₹/MWh									TSO Profit	Consumer Surplus	Social Surplus
Transmission Case	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	₹/hr	₹/hr	₹/hr
T_1 =with line limit	0.00	-0.96	0.00	-4.78	-1.91	-6.12	-6.87	-7.55	-8.97	24,336.40	238,681.75	2,531,916.67
T_1 =without line limit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	270,375.99	2,554,390.97
	Generator Profit ₹/hr											Producer Surplus
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	₹/hr
T_1 =with line limit	1,339,614.62	20,801.46	15,404.99	3,277.32	807.76	26,809.22	106,497.00	77,885.96	46,039.03	11,320.52	620,440.64	2,268,898.52
T_1 =without line limit	1,369,701.84	20,234.64	15,614.83	2,300.75	1,600.98	26,289.07	103,258.50	76,310.26	47,079.62	11,399.67	610,224.80	2,284,014.98

6.2.3. Monopoly Market Modeling

Table 6.2.3: Results for the Monopoly Model (Linear demand)

	Demand at each Node (MWh)												
Transmission Case	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9				
T_1 =with line limit	2,968.07	3,708.28	4,663.00	3,498.30	923.67	1,283.10	2,650.06	848.98	3,944.52				
T_1 =without line limit	5,338.48	5,496.26	8,387.03	2,172.40	1,123.17	294.78	976.61	170.13	701.25				
	Sales by Firm f (MWh)												
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}		
T_1 =with line limit	12,797	445.55	1,190.59	348.50	242.25	1,165.33	1,156	854.25	527	472.70	5,288.82		
T_1 =without line limit	12,797	445.55	1,499.14	348.50	242.25	1,266.50	1,156	854.25	527	485.45	5,038.45		
	Energy Price ₹/MWh										Transmission Dual ₹/MWh		
Transmission Case	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	λ_k^+	λ_k^-		
T_1 =with line limit	147.53	145.61	147.53	137.92	143.69	133.64	134.22	132.08	130.53	0	15: 29.26	112: 15.76	
T_1 =without line limit	141.87	141.87	141.87	141.87	141.87	141.87	141.87	141.87	141.87	0	0		
	Transmission Price ₹/MWh										TSO Profit	Consumer Surplus	Social Surplus
Transmission Case	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	₹/hr	₹/hr	₹/hr	
T_1 =with line limit	0.00	-1.92	0.00	-9.61	-3.84	-13.89	-13.30	-15.45	-17.00	45,023.72	118,823.66	2,393,893.49	
T_1 =without line limit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	135,456.49	2,451,175.25	
	Generator Profit ₹/MWh											Producer Surplus	
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	₹/hr	
T_1 =with line limit	1,348,437.47	23,150.85	21,010.13	5,690.39	1,105.61	32,421.57	114,522.88	82,987.29	47,144.98	13,182.86	540,392.06	2,230,046.12	
T_1 =without line limit	1,420,279.98	22,048.10	21,776.16	3,717.70	2,584.25	31,473.77	107,979.32	79,793.54	49,225.87	13,340.74	563,499.32	2,315,718.76	

6.2.4. Price-Cost Margins (PC versus NC)

In order to measure the efficiency of the market structures, we have computed the PCMs, defined as the difference between a market structure's price and perfect competition price divided by the market structure's price (Bompard et al. 2005; Helman and Hobbs 2010). PCMs for each node and averages over all nodes are presented in the Table 6.9. Note that the Nash-Cournot market structure with firm 1 as the single Nash-Cournot player has the lowest margins, and the monopoly market structure has the highest.

Table 6.2.4: Price-Cost Margins and Averages for Each Node

Market Structure \ PCMs	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9	Average
NC With LL	0.05%	0.17%	0.05%	0.65%	0.28%	2.13%	0.46%	1.23%	0.26%	0.59%
NC Without LL	0.45%	0.38%	0.45%	-0.07%	0.30%	-0.98%	-0.49%	-0.98%	-0.98%	-0.21%
MON With LL	4.72%	4.25%	4.72%	2.22%	3.76%	1.83%	0.89%	0.67%	-0.52%	2.51%
MON Without LL	3.29%									3.29%
OnlyF1-NC With LL	0.00%									0.00%
OnlyF1-NC Without LL	0.00%									0.00%
OnlyF11-PC With LL	-0.01%	0.01%	-0.01%	0.08%	0.03%	0.35%	0.04%	0.18%	0.00%	0.07%
OnlyF11-PC Without LL	0.01%	0.01%	0.01%	0.01%	0.01%	-0.04%	0.01%	-0.04%	-0.04%	-0.01%

6.2.5. Welfare Analyses

Table 6.10 summarizes the welfare analyses (i.e., change in consumers', producers' and total surpluses as percentage of the perfect competition model's corresponding surplus values) for different market structures. Total surplus decrease for all market structures except for the last market structure where firm 11 (an aggregation of small size generators represented as "other" firms) acts as price-taker (i.e., it has remained

unchanged). Similarly, consumers' surplus decreases for all market structures except for the market structure where firm 1 acts as the sole Nash-Cournot player. It is obvious from the results that the monopoly structure decreases the consumers' surplus the most (more than 50% decrease).

Suppliers' surplus increases only for the market structures where all players behave in Nash-Cournot fashion and where only firm 11 behaves as price-taker. Also, in monopoly structure without line limits, it has increased.

Note that the percent changes among different market structures are not very significant. The model with 11 firms should be the reason for this, as there are many firms competing in the market that drives the market prices down.

Table 6.2.5: Welfare Analyses for Different Market Structures

Welfare Market Structure	Consumers' Surplus	Producers' Surplus	Total Surplus
NC With LL	-6.09%	0.49%	-0.16%
NC Without LL	-3.37%	0.34%	-0.07%
MON With LL	-53.25%	-1.23%	-5.60%
MON Without LL	-51.59%	1.73%	-4.10%
OnlyF1-NC With LL	0.00%		
OnlyF1-NC Without LL	0.00%		
OnlyF11-PC With LL	-0.60%	0.06%	0.00%
OnlyF11-PC Without LL	-0.07%	0.01%	0.00%

Chapter 7

7. Conclusions and Summary

Market price simulations for the electricity markets under different market structures (from perfect competition to monopoly models) are illustrated with realistic data from the Turkish market. A comparative price-cost margin and welfare analyses are conducted for different market structures over the perfect competition market structures. It is concluded that for this illustrative example, overall welfare gains for consumers can be realized when the market structure has changed from Nash-Cournot or monopoly market structures to perfect competition. Break-up of the larger firm (firm 1) into two or more parts may not increase this gain. As the illustrative example suggested, the number of firms modeled are enough to lower the prices closer to the levels of perfect competition structure.

Market power is widely viewed as one of the most serious imperfections in new power markets. Therefore, models for projecting prices and other market outcomes should explicitly consider the potential for strategic behavior by power producers (Gabriel et al. 2013). The proposed models would be useful for jurisdictions (e.g., Turkey) to assess market power issues by regulatory bodies, to forecast future prices and to examine welfare changes.

By introducing a large-scale linearized DC network (i.e., a test model from TEİAŞ) line limits, and ramp limits, a more realistic model can be built and the impact of transmission network can be examined in detail, such as the market power issues in load pockets (Bompard et al. 2005; Helman and Hobbs 2010).

We can also model other market structures, such as Stackelberg leader-follower model in an MPEC format. But in this case, there may be no or multiple solutions and computational issues may arise due to equilibrium constraints that are mostly non-convex.

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Appendix A: Further Results

Table A.1: Generation Capacities, Source: YEGM and TEİAŞ Websites

Source: TEİAŞ									
Node 1		Node 2		Node 3		Node 4		Node 9	
f1.gas.n1	1156	f1.coal.n2	3034	f1.coal.n3	1475	f1.hydro.n4	457	f1.hydro.n9	6658
f1.oil.n1	630	f1.hydro.n2	179	f1.hydro.n3	288	f9.coal.n4	620	f1.coal.n9	3252
f10.gas.n1	123	f1.gas.n2	180	f6.gas.n3	120	f10.gas.n4	239	f6.hydro.n9	142
f5.gas.n1	33	f6.wind.n2	30	f7.coal.n3	1360	f11.wind.n4	0	f10.hydro.n9	35
f2.gas.n1	98	f6.gas.n2	995	f3.coal.n3	25	f11.hydro.n4	360	f3.oil.n9	56
f11.wind.n1	128	f8.coal.n2	1005	f3.gas.n3	60	f11.coal.n4	25	f3.gas.n9	117
f11.hydro.n1	0	f2.wind.n2	15	f2.hydro.n3	100	f11.oil.n4	37	f2.hydro.n9	7
f11.coal.n1	0	f2.gas.n2	127	f2.gas.n3	127	f11.gas.n4	987	f11.wind.n9	0
f11.oil.n1	0	f3.wind.n2	104	f4.gas.n3	410	f11.other.n4	42	f11.hydro.n9	1900
f11.gas.n1	3433	f3.gas.n2	115	f10.gas.n3	106	Node 8		f11.coal.n9	141
f11.other.n1	22	f10.other.n2	15	f10.hydro.n3	17	f1.hydro.n8	616	f11.oil.n9	261
Node 5		f11.wind.n2	1104	f11.wind.n3	2	f1.oil.n8	50	f11.gas.n9	174
f1.hydro.n5	159	f11.hydro.n2	279	f11.hydro.n3	128	f10.hydro.n8	55	f11.other.n9	6
f6.hydro.n5	29	f11.coal.n2	0	f11.coal.n3	227	f10.oil.n8	15		
f3.gas.n5	1150	f11.oil.n2	131	f11.oil.n3	101	f3.gas.n8	115		
f11.wind.n5	0	f11.gas.n2	2932	f11.gas.n3	5541	f3.oil.n8	24		
f11.hydro.n5	681	f11.other.n2	120	f11.other.n3	14	f11.wind.n8	0		
f11.coal.n5	0	Node 6		Node 7		f11.hydro.n8	786		
f11.oil.n5	0	f1.hydro.n6	1730	f1.hydro.n7	1186	f11.coal.n8	0		
f11.gas.n5	125	f3.hydro.n6	15	f6.hydro.n7	93	f11.oil.n8	1		
f11.other.n5	0	f3.gas.n6	131	f6.gas.n7	195	f11.gas.n8	0		
		f2.hydro.n6	83	f5.gas.n7	252	f11.other.n8	0		
		f10.hydro.n6	6	f2.hydro.n7	69				
		f11.wind.n6	40	f3.wind.n7	30				
		f11.hydro.n6	455	f11.wind.n7	277				
		f11.coal.n6	0	f11.hydro.n7	625				
		f11.oil.n6	8	f11.coal.n7	1320				
		f11.gas.n6	377	f11.oil.n7	220				
		f11.other.n6	0	f11.gas.n7	48				
				f11.other.n7	12				

Table A.2: Results for the Perfect Competition Model with Firm 1 as the only Nash-Cournot Player

	Demand at each Node (MWh)													
Transmission Case	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9					
T_1 =with line limit	5,886.10	6,667.55	9,247.37	4,528.27	1,517.03	1,576.18	2,912.13	910.23	3,751.79					
T_1 =without line limit	7,291.73	7,726.94	11,455.69	3,738.67	1,634.89	855.13	1,997.70	493.73	2,035.07					
	Sales by Firm f (MWh)													
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}			
T_1 =with line limit	13,932.60	445.55	1,397.84	348.50	242.25	1,266.50	1,156.00	854.25	527.00	472.70	16,353.46			
T_1 =without line limit	13,932.60	445.55	1,499.14	348.50	242.25	1,266.50	1,156.00	854.25	527.00	472.70	16,485.06			
	Energy Price ₪/MWh										Transmission Dual ₪/MWh			
Transmission Case	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	λ_k^+	λ_k^-	
T_1 =with line limit	140.56	139.42	140.56	134.85	138.28	131.20	133.03	131.20	131.20	131.20	131.20	0	15: 18,49 112: 5,48	
T_1 =without line limit	137.20	137.20	137.20	137.20	137.20	137.20	137.20	137.20	137.20	137.20	137.20	0	0	
	Transmission Price ₪/MWh										TSO Profit	Consumer Surplus	Social Surplus	
Transmission Case	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	w_{10}	w_{11}	₪/hr	₪/hr	₪/hr
T_1 =with line limit	0.00	-1.14	0.00	-5.71	-2.28	-9.36	-7.53	-9.36	-9.36	-9.36	-9.36	23,972.14	254,150.07	2,535,848.51
T_1 =without line limit	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	279,794.35	2,556,067.73
	Generator Profit ₪/hr											Producer Surplus		
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	₪/hr		
T_1 =with line limit	1,332,170.75	20,588.61	14,418.38	3,261.96	653.73	26,441.76	106,467.60	77,701.33	45,528.54	11,037.55	619,456.09	2,257,726.30		
T_1 =without line limit	1,367,407.55	19,969.90	14,783.63	2,092.17	1,454.31	25,566.36	102,587.32	75,809.01	46,767.75	11,119.22	608,716.17	2,276,273.38		

Table A.3: Results for the Nash-Cournot Model with Firm 11 as the only Price-Taker

	Demand at each Node (MWh)												
Transmission Case	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9				
T_1 =with line limit	5,890.93	6,661.68	9,254.97	4,492.07	1,513.06	1,520.89	2,900.32	894.26	3,751.79				
T_1 =without line limit	7,286.99	7,721.53	11,448.24	3,734.87	1,633.65	861.46	1,995.23	497.40	2,050.19				
	Sales by Firm f (MWh)												
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}		
T_1 =with line limit	13,932.60	445.55	1,243.74	348.50	242.25	1,266.50	1,156	854.25	527	472.70	16,390.89		
T_1 =without line limit	13,932.60	445.55	1,499.14	348.50	242.25	1,266.50	1,156	854.25	527	472.70	16,485.06		
	Energy Price ₹/MWh										Transmission Dual ₹/MWh		
Transmission Case	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	λ_k^+	λ_k^-		
T_1 =with line limit	140.55	139.43	140.55	134.96	138.31	131.66	133.08	131.43	131.20	0	15: 17.83	112: 6.33	
T_1 =without line limit	137.21	137.21	137.21	137.21	137.21	137.15	137.21	137.15	137.15	0	0		
	Transmission Price ₹/MWh										TSO Profit	Consumer Surplus	Social Surplus
Transmission Case	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	₹/hr	₹/hr	₹/hr	
T_1 =with line limit	0.00	-1.12	0.00	-5.59	-2.23	-8.89	-7.47	-9.12	-9.35	24,161.23	252,624.97	2,535,831.42	
T_1 =without line limit	0.00	0.00	0.00	0.00	0.00		0.00			0.00	279,590.89	2,556,066.93	
	Generator Profit ₹/hr											Producer Surplus	
Transmission Case	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	₹/hr	
T_1 =with line limit	1,332,759.18	20,610.20	14,483.05	3,257.93	664.96	26,463.34	106,454.25	77,711.81	45,585.35	11,065.73	619,989.42	2,259,045.22	
T_1 =without line limit	1,367,409.16	19,971.51	14,785.24	2,093.78	1,455.92	25,567.97	102,588.93	75,810.62	46,769.36	11,120.83	608,902.71	2,276,476.03	

Appendix B: The GAMS Code for the Perfect Competition Model

```
option limrow=0, limcol=0;
option solprint=off;
```

```
Sets
```

```
i      nodes      / n1*n9 /
f      firms      / f1*f11 /
h      generating units      / wind,hydro,coal,oil,gas,other/
k      transmission lines      /l1*l14 /
jg(i)  generation nodes      / n1*n9 /
```

```
Alias( i, ii );
```

```
Alias( f, g );
```

```
Parameter Cc(h)  generation (operation & maintenance + fuel) costs ($ per MWh)
/wind 21.92, hydro 6.09, coal 24.23, oil 70.28, gas 65.60, other 30.92/;
```

```
Parameter C(f,h,i) generation (operating) costs at each node for each firm (TL per MWh);
*COMPUTED AFTER XK(f,h,i)
```

```
Parameter XK(f,h,i) generation capacities (from EXCEL report by H.Cakir_ EIE and TEIAS reports)
*(See Table A.1)
```

```
parameter lf(h) capacity factor
```

```
*from IEA_OECD_NEA 2010 "Projected cost of generating electricity" report)
```

```
/wind      0.26
hydro      0.55
coal       0.85
oil        0.85
gas        0.85
other      0.85/ ;
```


*AVAILABLE CAPACITY per GENERATION TECH.

XK(f,h,i)=lf(h)*XK(f,h,i);

C(f,h,i)=1000;

C(f,h,i)=2*Cc(h)\$XK(f,h,i);

*exchange rate: 2.7 tl/euro 2 tl/USD

****LINEAR DEMAND MODEL PARAMETERS****

PARAMETER alpha(i) inv dem intercept (for fixed elasticity of 0.1)

/n1 154.616000

n2 153.360388

n3 154.616000

n4 148.337113

n5 152.105379

n6 144.321429

n7 146.328858

n8 144.320000

n9 144.320000/

PARAMETER beta(i) inv dem slope

/n1 0.002388

n2 0.002091

n3 0.001520

n4 0.002978

n5 0.009115

n6 0.008324

n7 0.004568

n8 0.014414

n9 0.003497/

Table PTDF(k,i) PTDF matrix (reference bus n1:TRAKYA)

*(See Table 6.1.1)

Parameter T(k) line limits / 11 3000, 12 3000, 13 1000, 14 1000, 15 1000, 16 6000, 17 3000, 18
1000, 19 7000, 110 1000, 111 1000, 112 1000, 113 2000, 114 1000/ ;

*No line limits case

*T(k)=10*T(k);

Positive Variables

x(f,h,i) generation
s(f,i) sales
DCapacity(f,h,i) dual for upper limit on generation output
DLineLimNeg(k) dual for line limit negative direction
DLineLimPos(k) dual for line limit positive direction

Variables

y(i) power hub to node i
w(i) dual for MarkClear(i)
DSalesEqGen(f) dual for sales equal generation

Equations

sGrad(f,i) gradient for sales by f h at i
xGrad(f,h,i) gradient for generation by f at i
yGrad(i) gradient for y at i
Capacity(f,h,i) upper limit on generation output
SalesEqGen(f) sales equal generation
LineLimNeg(k) line limit negative direction
LineLimPos(k) line limit positive direction
MarkClear(i) market clearing at node i ;

*NASH-COURNOT (LINEAR DEMAND-MCP MODEL)

sGrad(f,i).. $-(\alpha(i) - \beta(i)\text{sum}(g, s(g,i))) + \beta(i)*s(f,i) + w(i) + \text{DSalesEqGen}(f) =g= 0 ;$

*PERFECT COMPETITION (LINEAR DEMAND-MCP MODEL)

sGrad(f,i).. $-(\alpha(i) - \beta(i)*\text{sum}(g, s(g,i))) + w(i) + \text{DSalesEqGen}(f) =g= 0 ;$

xGrad(f,h,i)\$jg(i).. $C(f,h,i) - w(i) - \text{DSalesEqGen}(f) + \text{DCapacity}(f,h,i) =g= 0 ;$

yGrad(i).. $-w(i) + \text{sum}(k, \text{PTDF}(k,i) * [\text{DLineLimPos}(k) - \text{DLineLimNeg}(k)]) =g= 0 ;$

Capacity(f,h,i)\$jg(i).. $-x(f,h,i) =g= -\text{XK}(f,h,i) ;$

SalesEqGen(f).. $\text{sum}(i, s(f,i)) - \text{sum}((jg,h), x(f,h,jg)) =e= 0 ;$

```

LineLimNeg(k)..  sum(i, PTDF(k,i)*y(i) ) =g= -T(k) ;

LineLimPos(k)..  -sum(i, PTDF(k,i)*y(i) ) =g= -T(k) ;

Markclear(i)..  sum(f, s(f,i) ) - (sum((f,h), x(f,h,i)) )$jg(i)  - y(i) =e= 0 ;

Model  HobbsMCP  /  sGrad.s,  xGrad.x,  yGrad.y,  Capacity.DCapacity,  SalesEqGen.DSalesEqGen,
LineLimNeg.DLineLimNeg, LineLimPos.DLineLimPos, MarkClear.w / ;

***MCP MODEL
Solve HobbsMCP using mcp ;

Parameters      TotalSales(i)  total sales at node i
                 Price(i)      Electricity prices at node i
                 Profit(f)     Profit of firm f
                 RevTrans      Transmission operator's revenue
                 ConsSurp      Consumer's surplus
                 TotSurp       Total surplus
                 Generation(f) Total generation by f
                 Flow(k)       Power flow on line k;

TotalSales(i) = sum(f, s.l(f,i)) ;
Price(i) = alpha(i) - beta(i)*sum(f, s.l(f,i)) ;
Profit(f)=sum(i, s.l(f,i)*[Price(i)-w.l(i)])- sum((jg,h), x.l(f,h,jg)*[C(f,h,jg)-w.l(jg)] ) ;
RevTrans=sum(i, w.l(i)*y.l(i));

TotSurp = sum(i, (alpha(i) - 0.5*beta(i)*sum(f, s.l(f,i)))*sum(f, s.l(f,i))) - sum((f,h,jg),
C(f,h,jg)* x.l(f,h,jg) );

ConsSurp = TotSurp - sum(f, profit(f))- RevTrans;

Generation(f)=sum((jg,h), x.l(f,h,jg));

Flow(k)=sum(i, PTDF(k,i)*y.l(i));

Display  Price, w.l, DLineLimNeg.l, DLineLimPos.l, Profit, RevTrans, ConsSurp, TotSurp;
Display  TotalSales, s.l, Generation, Flow;

```