# WELFARE ANALYSIS
# IN AN IMPERFECTLY COMPETITIVE ELECTRICITY MARKET
# WITH DISTRIBUTED RENEWABLE GENERATION

HÜSEYİN EMRE SAYICI

BOĞAZİÇİ UNIVERSITY

2020

# WELFARE ANALYSIS
# IN AN IMPERFECTLY COMPETITIVE ELECTRICITY MARKET
# WITH DISTRIBUTED RENEWABLE GENERATION

Thesis submitted to the

Institute for Graduate Studies in Social Sciences

in partial fulfillment of the requirements for the degree of

Master of Arts

in

Economics

by

Hüseyin Emre Sayıcı

Boğaziçi University

2020

DECLARATION OF ORIGINALITY

I, Hüseyin Emre Sayıcı, certify that

- I am the sole author of this thesis and that I have fully acknowledged and documented in my thesis all sources of ideas and words, including digital resources, which have been produced or published by another person or institution;
- this thesis contains no material that has been submitted or accepted for a degree or diploma in any other educational institutions;
- this is a true copy of the thesis approved by my advisor and thesis committee at Boğaziçi University, including final revisions required by them.

Signature.........................................

Date...30/09/2020...........................

## ABSTRACT

Welfare Analysis in an Imperfectly Competitive Electricity Market

With Distributed Renewable Generation

This thesis aims to analyze the optimal amount of renewable electricity generation in a dominant firm and a competitive fringe model. The dominant firm(s) produces non-renewable electricity and the fringe produces renewable electricity. The fringe aims to represent the distributed renewable energy generation. The optimality stems from the trade-off between more costly but clean renewable energy and less costly but environmentally polluting non-renewable energy. The model is solved under fixed and premium tariffs and for different number of oligopoly firms, allowing examining of the differences between these two Feed in Tariff (FiT) instruments and the effects of market power and marginal costs on equilibrium outcomes. Using data from Turkish electricity market, the model is simulated over a set of chosen parameters to see the how these effects play out under different circumstances. As for theoretical results, it is shown that in concentrated electricity markets the fixed tariff outperforms the premium tariff in terms of total welfare. On the other hand, the premium tariff leads to higher renewable generation; so when the sole concern is environmental pollution premium tariff may be preferred. This pro-environment effect is most evident when the dominant sector is a monopoly. As the number of oligopoly firms increases and the market becomes less concentrated, the outcomes under the two policy instruments become close to each other. When the model is calibrated using the current market concentration levels in the Turkish electricity market, the two instruments generate nearly the same outcomes.

# ÖZET

## Dağıtık Yenilenebilir Üretimli Eksik Rekabetçi Elektrik Piyasasında Refah Analizi

Bu tez, dominant firma ve kenar firmalar ("kenar") modelini kullanarak optimal miktarda yenilenebilir elektrik üretimini analiz etmeyi amaçlamaktadır. Bu modelde dominant firma(lar) yenilenemeyen elektrik, kenar ise yenilenebilir elektrik üretmektedir. Kenar, son on yılda Türkiye dahil bir çok ülkede yaygın olarak görülmeye başlayan dağıtılmış yenilenebilir enerji üretimini temsil etmektedir. Model sabit ücretli ve değişken prim tarifeleri altında ve dominant sektörde farklı sayıda oligopol şirketi için çözülerek, iki sübvansiyon enstrümanı arasındaki farklar ve piyasa gücü ile marjinal maliyetlerin denge sonuçlarına etkileri incelenmiştir. Türkiye elektrik sektörü verileri kullanılarak yapılan simülasyonlar aracılığıyla bu etkiler bir dizi farklı parameter konfigürasyonu için grafiksel olarak da gösterilmiştir. Elde edilen önemli bir teorik sonuç, yoğunlaşmış piyasalarda sabit ücretli tarifenin toplam refah açısından değişken prim tarifesinden daha iyi performans gösterdiğidir. Diğer taraftan, değişken prim tarifesi, çevresel amaçlara daha uygun olacak bir şekilde, daha yüksek yenilenebilir enerji üretimine yol açmaktadır. Daha yüksek yenilenebilir enerji üretimi en çok dominant sektörün tekel olduğu durumda belirgin olmaktadır. Dominant sektördeki oligopol şirketlerinin sayısı arttıkça, yani pazar daha rekabetli bir hale geldikçee, iki politika enstrümanı etkileri itibariyle birbirine yaklaşmaktadır. Model, Türkiye elektrik piyasasının mevcut rekabet seviyesine kalibre edildiğinde, iki enstrüman hemen hemen aynı denge sonuçlarını ortaya çıkarmaktadır.

ACKNOWLEDGMENTS

I am sincerely thankful and deeply indebted to Prof. Ünal Zenginobuz for his advising, as well as his patience, during the course of this study. I also thank my thesis committee members Assist. Prof. Tunç Durmaz and Prof. Begüm Özkaynak for their valuable contributions.

TABLE OF CONTENTS

LIST OF FIGURES

# CHAPTER 1

# INTRODUCTION

While the world is getting at the peak of the global warming crisis, clean energy technologies become more and more important every day from an environmental perspective. Moreover, from economic and political perspectives too, producing green energy instead of fossil-fueled production can be crucial even in the near future. Among the significant reasons offered by those perspectives for green energy investments are maintaining energy security, fostering innovation, decreasing fuel dependence (especially for resource poor countries), and even increasing energy efficiency. The reaching of these goals and realizations of associated production targets mostly depend on the implementation of smart regulation policies. To design such policies, policy-makers needs to be informed about economic aspects of regulations, and namely, the outcome that is going to be reached by the responses of rational agents in the market, while not getting too far from the specific realities of policy scope.

Electricity is very close to representing the ideal concept of good theorized in economics because of its homogeneous feature. The same amount of electrical power, regardless of by whom it is produced or how it is produced, provides the same utility to consumers. Although it can be classified as green or brown concerning the externality due to the nature of emission caused during the production phase, the homogeneity feature is a very important aspect of electricity markets. Another important feature of electricity is its non-durability. Storage and transmission of electricity are costly. Therefore, maintaining production levels close to demand will result in efficiency gains.

There are different ways to plan the new energy structure and the change towards it for any country, either allowing more significant market shares for the central large producers (a monopoly, or an oligopoly) to produce both green and brown energy or allowing and supporting greater shares for small scale distributed generation units that generally use clean energy or low-carbon production technologies. The combinations among these options yield scenarios having different macro and micro aspects. Regarding the technology and location-specific characteristics; the advantages and disadvantages of the options should be weighted. In this study, I will try to evaluate the optimality and the efficiency of direct support mechanisms for renewable distributed generation, first from a theoretical perspective and then applying it to the case of Turkish electricity markets. The application is not meant to offer an empirical analysis of the Turkish market, but to provide further insight regarding theoretical results obtained.

Main direct support instruments for renewable energy generation are fixed and premium feed-in-tariffs (FiT). Under the premium tariff, the firms that are subsidized get a premium over the market price, while under the fixed tariff they receive a fixed amount independent on the market price. Although variations and mixtures can be seen, these two instruments stand out as the main support mechanisms in applications, and a theoretical comparison of them to understand differences in the outcomes they generate is important. Another reason behind choosing this topic as a research question is the fact that these policies have been implemented in Turkey for the last fifteen years, and academic research is needed to serve as background for evaluating the performance of the current or past policies. Although this study does not focus directly on policy evaluation, it aims to contribute to the current discussions by providing a framework for applications in determining optimal policies. Moreover, by bringing into forefront the weight that decision-maker's put on the importance of environmental externalities, the analysis offered will show how such environmental valuation choices interact with the electricity sector parameters in determining optimal tariff levels in supporting renewable energy.

Although different dimensions of electricity market design, including the role of renewable production, are discussed in the literature, the optimal share of renewable distributed generation in the electricity market is studied less. The aim of this thesis is to propose a model to compare two different support instruments for renewable energy generation, namely the fixed tariff and premium tariff, and to determine the efficient level for the instrument that comes out as the preferred one. The main trade-off involved in determining the optimal tariff levels is the one between higher production costs for renewable technologies compared to the conventional 'brown' technologies, and the negative environmental externality of the conventional technologies. Other than these two mechanisms, there are also more market-dependent measures such as green certificates. Analysis of those are beyond the scope of this study, as, first, they are not prevalent in the related scope of policy suggestion of this thesis, namely Turkey; and, second, those more market dependent measures have been shown to be significantly vulnerable to market power issues and often lead to inefficient outcomes in supporting renewable generation (der Fehr and Ropenus 2017)

In the model that will be studied, the distributed generation involves a dominant sector with a large monopoly or a Cournot duopoly that produces nonrenewable electiricty, and a competitive fringe that produces renewable electricity. Oligopoly formulation allows studying the effect of increasing competition in the dominant sector. Using the dominant firm and the fringe model is not new in the energy economics literature. The Cournot model has been used by (Cardell, Hitt, and Hogan

1997), (Borenstein and Bushnell 2003), and a monopoly and a fringe model by (Ropenus and Jensen 2009), and (der Fehr and Ropenus 2017). We combine those models to study a question that, to our knowledge, has not been addressed, namely the optimal size of the renewable sector and the optimal levels of tariffs to support that.

The structure of the thesis is as follows. Chapter 2 first overviews briefly how electricity markets work, including an account of the restructuring electricity markets have been subjected to in the last thirty years, and goes on to review the related economics literature. Chapter 3 introduces the model studied and analyzes it under different assumptions. Chapter 4 provides a simulation of the model using data representing the Turkish electricity market. Chapter 5 provides a brief discussion of results and concludes.

# CHAPTER 2

# ELECTRICITY MARKETS: LITERATURE REVIEW

## 2.1 Restructuring the electricity markets

From its production to end-use, electric power has four stages: generation, transmission (including decreasing the voltage), distribution and retailing to end-users. Therefore, the four stages are subject to restructuring. Restructuring of electricity markets has occurred as privatization and deregulation of the existing structure, which was operated by either government-owned utilities or regulated natural monopolies before the deregulation. During the restructuring, new markets have been created to increase as well as to ease transactions. Those markets can be categorically classified into wholesale and retail markets in the first step. Wholesale trade of electricity may occur between generators as sellers and traders, responsible procurement firms, and large end-users like factories as buyers. Electric power is then sold to end-users in retail markets. Retail markets can also be restructured with either fix prices for small scale consumers and negotiated prices for large scale consumers, or with no regulated procurement firms at all. Restructuring the generation side means privatization of plants, deregulation of supply-side with the hope of competitive or contestable market outcomes. Restructuring of the transmission system is intended to prevent vertical integration, which leads to entry deterrence practices via raising transmission costs for competitiors.

Since the ’90s, many countries have deregulated their electricity sectors with a view to making more use of markets instruments. One of the first attempts towards liberalization of the electricity market was undertaken by the British government on April 1990 (Wolfram 1999). Sevral states in the US followed the UK in the deregulation path and adopted similar reforms. Prior to the reforms between 1995-2002, customers in the US were provided electricity by regulated monopolies that were subject to a cost-of-service type regulation. Those monopolies were responsible for all four stages of electricity provision (Borenstein and Bushnell 2015). Successful deregulation experiences in other similar infrastructure sectors, such as telecommunication, airlines, and railroads, encouraged governments to adopt similar policies in the electricity sector as well.

The deregulation process in the US focused on the restructuring of generation, transmission, and retail side while leaving the distribution to natural monopolies. Borenstein and Bushnell (2015) describe the deregulation of generation as moving from average cost pricing to marginal cost pricing. Reserve margins that are under utilized can increase the average costs under regulation, and factors that increase the marginal costs can increase competitive prices, such as increasing fuel costs if gas-fired power plants are inframarginal. They also argue that restructuring only in one of the four stages of electricity production is likely to be not sufficent to achieve better outcomes. For instance, liberated retail markets would be affected by high wholesale prices if the supply-side is not competitive, or transmission providers can extracts rents from competitive generators. In summary, the authors conclude that although deregulation increased generation efficiency, whether the fall in prices was due to the restructuring is not clear. The main motivation behind it was rent-shifting, which is according to them, is also the current motivation behind the change towards diidtributed generation (DG) intensive systems.

## 2.2 How electricity markets work

To have independent and competing generators, traders and retail sellers operating securely, there is considerable agreement that there should be market mechanisms for electricity trade at the wholesale and retail levels. For the wholesale trade of electricity, various mechanisms have been introduced in the UK, Europe, the US, and in other countries that followed their lead. Notable examples are a spot market (also called the pool) for electricity trade (day-ahead and intraday markets); bilateral agreements that frame general conditions for exchange after which the transactions occur at any size in any time; contracts that range from difference payments for the spot price realizations above or below the contracted price; forward contracts; and financial contracts. At the retail scale of electricity resale to end-users, consumers are classified as free and non-free consumers, according to their monthly consumption or peak consumption. While free consumers can choose their procurement agencies, non-free consumers buy electric power from regulated distributor companies that are responsible for the local area they invested in. Since the storage is costly and inefficient in large scales, demand and supply should match continuously. To ensure that, balance markets are also added to the system.

Although there are slight differences, the general structure under which electricity markets operate are similar, reflecting the common features of modern electrical systems. The most complicated of market mechanisms is the spot market (the pool) for wholesale electricity trade. In the UK it was first designed as a uniform auction mechanism, but was later changed to a discriminatory auction in 2001 to lower the prices. In discriminatory auctions, everyone pays their bids, however in uniform auctions, a day is split into periods, generally of half-hour, and the system marginal price is determined by an algorithm maximizing the total surplus. In other words, sellers and buyers state their supply and demand offers with size and price features and ranked in order. Which units will be dispatched is then determined by the demand, “system marginal price” is determined for a given period using the offer of a marginally operating unit. All operating units are paid the “SMP”.

## 2.3 Economics of distributed generation (DG)

Distributed generation is to produce electric power over the distribution lines, close to where it is consumed, rather than over transmission lines. High-voltage electricity is transmitted over long distances on transmission lines, from the generator plants to the substations close to the demand; while distribution lines transfer the low-voltage electricity from substations to the end-consumers. Distributed generation includes both renewables like solar photovoltaics, wind and micro-wind turbines, micro-hydro, and biomass/waste plants, and non-renewable low carbon production technologies such as combined heat and power plants (CHP). Distributed generation can be of two types regarding the purpose of the generator: either only to meet the demand of residential or commercial consumers of electricity or also to sell the surplus generation to the grid. Therefore, the distributed generation requires an active network system that can take the electric power generated by the prosumer (producer and consumer at the same time) to the grid, so double way lines are required for the prosumer locations. However, it decreases the infrastructure spendings on the transmission network, which is subject to aging and capacity constraints. (Allan et al. 2015)

Optimum share of DG units in the energy portfolio of a country or a region depends on the technology and location-specific characteristics and also the pros and cons of DG systems. Supporting DG investments means encouraging green energy at the same time. Although some DG systems are not renewables, they are at least low-carbon technologies. Even with non-renewable DG Technologies, such as cogeneration plants, increases in energy efficiency are obtained in providing for commercial and residential buildings, as well as for production facilities. Increasing the energy produced within a country or a state reduces energy and fuel dependency, and consequently leads to enhanced energy security. As explained above, increasing the share of DG minimizes transmission costs of electricity which is a very important factor in electricity costs, also decreases the infrastructure spending on transmission lines. Encouraging DG investments also foster domestic innovation while making the technology cheaper in the medium run. It also can increase social awareness about electricity consumption and the way that it is produced.

On the other hand, DG has some disadvantages too. Central production facilities have economies of scale advantages in the production process. DG units are generally not financially viable without subsidies. As explained, it also requires active networks, which increases infrastructure spendings on the distribution network. The most important one of these disadvantages is that it has high installation costs at the beginning, which typically translates as a burden on tax-payers' shoulders.

Apart from the environmental and economic arguments regarding the desirability of DG technologies, it has been argued that there are political economy factors, such as rent-shifting, behind the movement towards DG technologies. To give an example, people get extra savings by not paying the transmission and distribution costs reflected in the bill. Moreover, if the storage technologies get efficient enough, they can completely leave the grid and get free from these charges, making it a larger burden on the other consumers' share. (Borenstein and Bushnell 2015)

## 2.4 Renewable energy statistics

In 2018, the share of renewables in total electricity production was 26 percent, with 36.4 percent in Europe, and up to 58.5 percent in Latin America. Though each continent has varying shares, there is a general increase in renewable electricity generation worldwide. Share of renewable technologies have reached 97.9 percent in Norway and 82.3 percent in New Zealand, while it is around 32.4 percent in Turkey (yearbook.enerdata.net). That increase is mainly due to solar and wind installations, which have become relatively easier to finance because of falling costs. Note that these numbers include hydropower generation as well, and there has been a debate over whether the hydropower is renewable or not due to its possibly adverse environmental impact. Since it has been one of the main components of electricity generation in many countries for decades, counting hydropower as renewable generation would most likely to overestimation of renewable energy use.

In 2018, of the total electricity consumption in Turkey, 37.3 percent was from coal, 29.8 from natural gas, 19.8 from hydroelectric plants, 6.6 from wind, 2.6 from solar energy, and 2.5 from geothermal energy. By the end of the first half of 2019, of total electricity produced, 7.2 percent was from wind and 3 percent was from solar energy (enerji.gov.tr).

Figure 1 displays the general increase in renewable generation's share worldwide, with a greater increase observed in Europe. The information is taken from BP's dataset, and their definition of renewables does not include hydropower generation. In 2018, Turkey's renewable share over its total electricity production is around 12,5 percent which is consistent with the consumption statistics revealed by the Ministry of Energy.

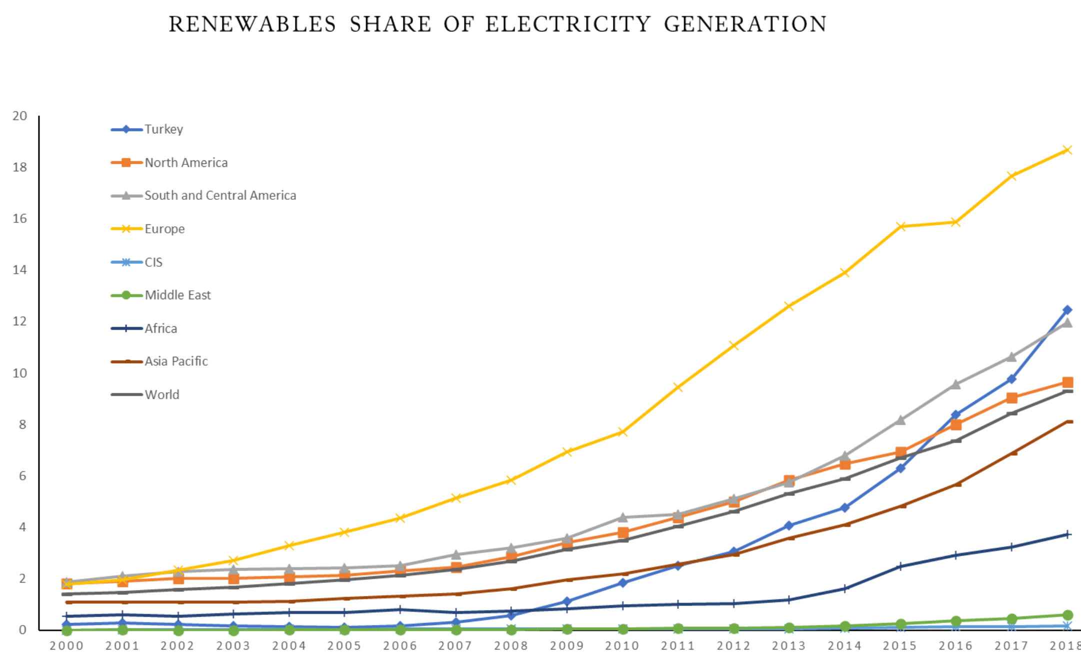


Figure 1. Renewables share of electricity generation worldwide

Source: BP Statistical Review 2019, a data set for 1965-2018

The same dataset published by BP also reveals that in 2018, the growth rate of solar generation in Turkey was 173 percent relative to the previous year, while wind generation had increased 10.7 percent, and renewable generation in total had increased 29.8 percent.

Figure 2 shows the current distribution of installation capacities of renewable generation sources in Turkey. Excluding reservoir and canal types hydropower generation plants, it is seen that solar and wind generation comprise the most of renewable generation, while the two are close in installed capacities.

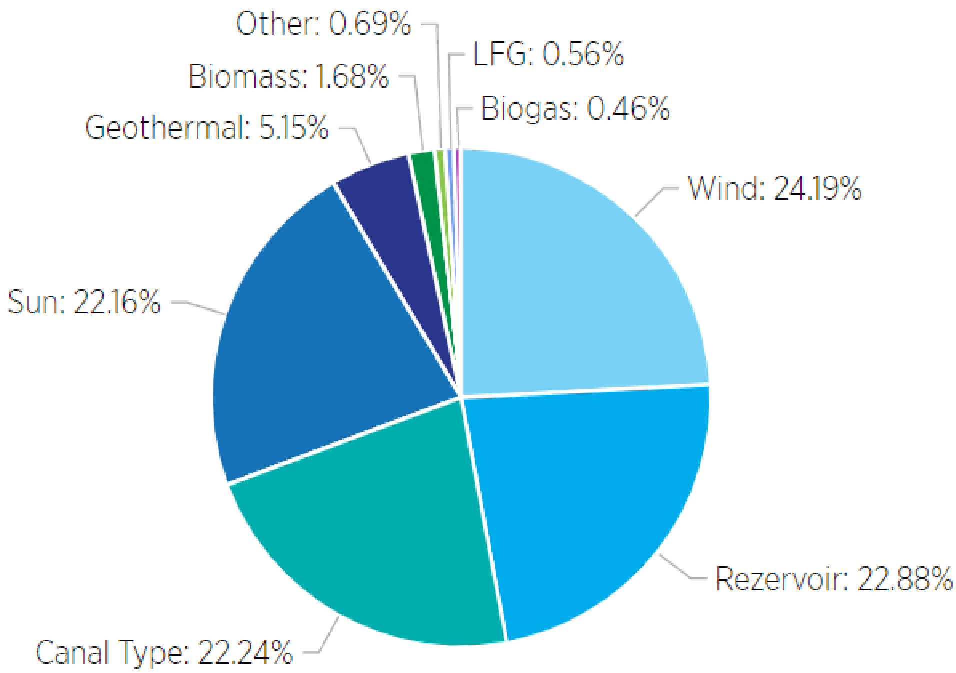


Figure 2. Renewable installation capacities in Turkey by March 2020 (including hydro)

Source: seffaflik.epias.com.tr

2.5 Modelling electricity markets and main discussions

Economists and policy-makers have sought for answers regarding transformation of electricity markets long before the onset of the deregulation process in Europe and the US, but the search for answers to questions such as the nature and scope of the associated efficiency gains was intensified in the wake of deregulation. One of the main issues is the likely emergence market power after deregulation, owing to the properties of production in different segments of the electricity sector.

2.5.1 Spot market design and the exercise of market power:

One of the early papers in the literature is an experimental study conducted by Hahn and Boening (1990), which compares single-price sealed bid auction and split-savings rule regarding how much the outcome diverges from the competitive equilibrium. In split-savings mechanism, bids and offers are sorted and the highest bid and the lowest offer are matched, and the price is their average. Single-price sealed-bid mechanism works like a uniform auction mechanism explained above in the day-ahead spot market section. Conducting experiments, each one with four buyers and sellers, repeated three times, 24 experiments in total, they find deviations from competitive equilibrium are more likely under split-savings rule than single-priced sealed bid auction, and split-savings rule is slightly more efficient although they both have above 90 percent efficiency. However, misrepresentation is less under the split-savings rule. Deviations get higher if one of the parties misrepresents more. (Hahn and Boening 1990)

Green and Newbery (1992) applied Klemperer and Meyer's (1989) supply function equilibrium model on British electricity markets, assuming that many bids for electricity loads can be thought to compose a continuous supply function. Theoretical results imply high markups on marginal costs leading to substantial deadweight losses. They simulate the effect of entry which reduces the prices. However, they criticize the deregulation policy of the British government at the time of privatization, which initially split the electricity generation into two companies only and promoted entry of new firms in the medium-run. They fit the theoretical model to the British spot electricity market using quarterly data on the quantity produced, demand, price and costs of generators. With a social welfare analysis they find that instead of splitting the system into two and adding new entrants to have an unregulated market, splitting generation into five companies and having a regulated quintopoly would have been more efficient in terms of social costs. In short, instead of expensive restructuring policies, better regulation of the system would have been preferable according to the authors.

Fehr and Harbord (1993) modeled the British wholesale electricity market as a first-price sealed-bid auction mechanism, which leads to the Nash equilibrium of prices well above the firms' marginal costs. They suggest and prove that if the market were designed as a second-bid auction mechanism, it would have led to marginal-cost pricing. They also show as an example that the two largest generators in the UK bid more than their marginal costs. Cost data is publicly available for the period in which the factories were government-owned. They have also criticized Green and Newbery (1992) claiming that bids of a company in the day-ahead market are not exhibiting the properties of a continuous supply function, rather there are jumps between the bids that reflect discontinuity. This, according to the authors, which makes supply function equilibrium modeling not appropriate for the UK electricity market.

Wolfram (1998) offers an empirical analysis of the UK's electricity market and finds that companies increase their price bids for supply in order to get paid more for their inframarginal capacities, and this effect is escalated for high marginal cost units. This can lead to an inefficient dispatch of plants, namely a more efficient plant may not be dispatched as frequently as it should be because of the high prices the company bids for it. Therefore, the discriminatory auctions need to be introduced to replace single-price mechanisms.

Firms can also use the available capacity declaration as a market power exercise, by declaring high marginal cost units available first in order for SMP to be determined highly. Also, under some spot market conditions, balancing dispatches when the demand is not met provides extra payments to firms for the additional capacity increases. Firms can strategically plan which units will be made available in that case. Wolak and Patrick (2001) discuss these details in their working paper and argues that looking only at the bidding activity for market power exercise can be misleading.

Fabra, Fehr, and Harbord (2006) compare uniform and discriminatory auctions in a duopoly case, first assuming that firms offer horizontal bids which are a single price for their entire capacity, facing inelastic demand known with certainty by firms (short-lived bids), which can be justified for small periods by fixed prices of a retail market in a day. It is reasonable because the consumers do not respond to the bids in the spot markets in the short-run, but respond in a longer-run when the spot market prices affect the retail prices. Then the authors extend the model to price-elasticity, long-lived bids, multiple bids, and oligopoly cases and results are robust. The two equilibria are compared in terms of average prices and productive efficiency. In the certainty case, uniform auctions result in higher average prices. Based on their theoretical results, they claim that the adoption of discriminatory auction instead of the uniform auction for spot market mechanism in England in 2001 is one of the important factors behind the wholesale price reductions observed from 2001 to 2002.

### 2.5.2 Contracts and the effect on market power

As mentioned above, electricity is traded in two stages: wholesale and retail. Since the relevant literature focuses on the competition between suppliers, the focal point is wholesale markets. Besides the spot market, suppliers can also sell their output through contracts of bilateral agreements, physical contracts, financial contracts, forward contracts, etc.. Therefore, contracts may have significant implications on modeling issues and decreasing effects on the exercise of market power.

Allaz and Vila (1993) models the market as a Cournot game and claims that the forward contracts are not only an issue of risk-hedging but also provide an opportunity to be the first mover through selling the future output and decreasing the future residual demand for the other firm. Therefore, turning the game into a Stackelberg version pushes the firms into a kind of prisoner's dilemma, when one of the firms is involved it is better of, but if the two are involved they are both worse off. Increasing the number of periods between the contract and the actual realization of trade makes the outcome more competitive, reaching competitive equilibrium in the limit. However, Borenstein et al. (1995) mention that since the forward markets are repeated every other hour, duopoly firms can cooperate over contracts and punish each other for deviations, leading to even higher prices and less output than before. Thus, by itself, contracts' effect is ambiguous; however, they claim that due to the arbitrage condition there should not be a significant effect of contracts over modeling issues. If the prices in one of the two instruments (spot market and contracts) are higher, buyers substitute with the other, finally neutralizing the difference. Thus, they can be assumed as perfect-substitutes for each other.

Newbery (1998) applied a contract extended version of the supply function equilibrium model and showed that the incumbents can increase their contract cover to deter entry if they have enough spare capacity, which in turn leads to price reductions in the spot market because of more competitive behavior of incumbents. Green (2003) also applied the supply function equilibrium model with the extension of contracts to England and Wales, finding that, due to risk-averse buyers, contract markets may even have higher prices due to hedging risk of uncertainty.

### 2.5.3 Empirical works on market power

Wolfram (1999) carries out an empirical analysis over British markets and finds that although the companies charge prices well-above marginal costs, they do not exploit the inelastic demand fully. Thus, the prices are below the oligopoly models' predictions. Suggested reasons are firms' behavior to escape regulatory action and the threat of entry. She finds that little support for the effects of contracts.

Borenstein and Bushnell (2003) model the California electricity markets as a static Cournot equilibrium and empirically assess the market power potential. They claim that using equilibrium models such as Cournot estimates the issue of market power more accurately and in more detail than using concentration indexes such as Herfindhal-Hirschman Index (HHI), which was the regulators' preferred method at that time. Using two state-owned plants' cost data, they simulate a Cournot game, concluding that in cases of high and inelastic demand periods there is a substantial potential for market power. They also find that above-average hydroelectric conditions and integrated regional transmission decrease the severity of market power.

Prices tripled in California in the Summer of 2000 over a short period of time. Borenstein et al. (2002) provide two reasons for the trend: rising input cost which would have increased the prices even the market was competitive, and retail market's inability to receive the price signals in the wholesale market which causes demand inelasticity in the short run.

### 2.5.4 Comparison of models: Bertrand, Cournot, and supply function equilibria

There are three categories of methods to model the electricity markets: equilibrium, optimization, and simulation models. Within the equilibrium models, there are three models mostly used: supply function equilibria (SFE), Cournot and auction models.

In the supply function equilibirum model, producers submit their quantities as a function of price, and the model produces a range of equilibria bounded by Cournot and Bertrand. It is more difficult to solve SFE models, especially with increasing complexities reflected in the model, and it does not specify a unique outcome. However, using the Cournot may result in the overestimation of market power. Whether the Bertrand or the Cournot is best to use is discussed in the literature. The Bertrand equilibrium is based on the assumption of pricing below others to capture the entire demand. Due to the capacity constraints and increasing marginal costs near to full-capacity use, it is not appropriate to use it in the electricity context. Thus, quantity setting models are more appropriate for modeling electricity market oligopolies instead of price setting. (Borenstein and Bushnell 2003)

Willems et al. (2009) use German electricity market data to compare Cournot and the SFE models. They find that although in the long-run SFE models are more robust, they are difficult to solve with the added complexities. Besides, the Cournot model can be calibrated to fit the data by adjusting the forward contracts' shares, leaving the firms with less residual demand. Using the Cournot with suggested calibrations does not lead to considerable losses in the analysis. While the import-dependency of a market increases and the concentration decreases, the two models' performances get close, due to the relatively increasing demand elasticity.

### 2.5.5 Supporting mechanisms for renewables

Policy-makers have several instruments at their disposal to cope with negative externalities of fossil-fuel-based energy production (brown energy), such as carbon taxes, mandates, direct subsidies, and quotas. These instruments, either to tax brown energy or to support green energy, can be categorized into two types: market-based, (pricing externalities) and non-market based (subsidies, technology mandates) policies. There are advocates for both policies. Supporters of market-based policies argue that subsidies are not efficient due to three reasons: first, it leads to underpricing of non-renewable energy and consequently to overconsumption; second, it does not displace brown energy efficiently, such as whether the natural gas or coal plants will be displaced out of subsidy policy; thirdly, the displacement may not result in the targeted local area. (Borenstein 2012)

The proponents of non-market based policies argue that market-based policies can be exploited by the incumbents and subject to a market power exercise, which will lead to insufficient levels of renewable generation in the system. For instance, designing a green-certificates market and requiring a minimum green energy quota on electricity consumption, the government can leave the pricing of green energy to the market with the hope that the market determines the true value of the externality. Fehr and Ropenus (2017) show that such a design allows the large incumbent companies to temporally involve in the renewable sector, to decrease the certificate prices by increasing their green energy production below entrants' marginal costs, and finally to deter entry in the long-run.

Butler and Neuhoff (2008) compare three mechanisms to promote wind installations by looking at the UK and Germany cases: feed-in tariff, quota, and auction. While the UK applied a tradable green certificate mechanism, Germany applied a feed-in tariff. They assess the claim that subsidizing green energy is more costly than market-driven mechanisms to promote it, and show that it is not true. Germany has been able to sustain cheaper prices for wind energy, to deploy more wind energy installations, and even to have a more competitive mechanism. They have surveyed project developers to measure the competition they feel, and claim that competition level in Germany is not below the UK.

The paper by Ropenus and Jensen (2009) deals with the relation of the vertical integration and fixed feed-in tariff. They use a non-renewable generating monopoly and a renewable generating fringe, with the extensions of two cases: comparison between vertical integration and unbundling, and the monopoly producing renewable too. In vertical integration, the monopoly exploits the fringe's profits, causing less provision of renewables. This effect is stronger if the monopoly can also produce renewable energy.

Feed-in tariff mechanisms can be integrated into the market mechanism as well, by outlining a premium tariff instead of a fixed one. Couture and Gagnon (2010) introduce and compare different types of FiT (feed-in tariff), as market dependent and independent versions. There can be caps that a premium added price can reach or floor prices to keep green energy generators revenue within a range. Rodriguez and Haas (2012) compare fixed and premium tariffs with calculations based on the Spanish electricity market between 2004-2009, in terms of profitability and the burden on consumers for each technology of renewable generation that was present in Spain during that time interval. They conclude that generally, the premium tariff is preferable due to its adaptation to the demand. Since fixed-feed in tariff is less risky for the investors, it can be preferred for non-mature technologies and small-scale projects such as house type solar installations.

As a case showing the handicaps of market-based support mechanisms, Newbery (2012) states that Britain was having difficulty in reaching the renewable targets, and sustaining energy security because the market mechanism lowers the carbon price and the nuclear power generation plants were suffering from it. He also suggests that available capacity subsidies should be preferred instead of output payments, to foster the innovation by encouraging the investments, to decrease the risks affecting future prices, and to establish more efficient location choices. He also evaluates the Energy White Paper (issued by Department of Energy and Climate Change in 2011), which is suggesting a FiT mechanism combined with CfD (Contracts-for-Difference), in which the generator sells its output at a market price but compensated for below CfD value and pays back the positive difference, whose reference value should be set technology-specific. The author concludes that two-sided CfD is appropriate for controllable installations such as nuclear but not for the intermittent generation like wind or solar, which needs a less risky instrument like a FiT to prevent inefficient estimation costs. FiTs can also be thought of as contracts that are decreasing the risk for generators.

Andor and Voss (2016) propose a partial equilibrium model to analyze capacity and generation subsidies' optimality, and they claim that capacity subsidies (such as investment tax excerpts) should be equal to spillover effects (external benefit of green energy investments), and generation subsidies (such as the FiT) should be equal to greenhouse gas reductions (externality of green energy generation).

#### 2.5.6 DG's effect on the price

Mulder et al. (2015) use a Cournot model extended with a structural market model of the Dutch electricity market, to measure the effect of fringe generation (wind and horticultural farmers' CHP generators) on the electricity prices. While the wind generation's effect on prices is stronger than CHP plants, both lower the prices slightly.

# CHAPTER 3

# THE MODEL

We use the framework presented by der Fehr and Ropenus (2017) with some alterations and extensions. We assume a linear demand for electricity $D(p) = A - Bp$, with and $A, B > 0$, which implies that electricity demand is not inelastic. We also assume that the demand and the supply are simultaneously equated. This assumption, although it is common in the economics discipline, is even more crucial for the electricity sector. Because of the difficulty of transmitting and storing electric power, regulatory institutions in countries with a well established electricity market, try their best to maintain equality of demand and supply on the electricity grid.

The basic model consists $n$ number of dominant firms that are generating non-renewable electricity denoted by ($Q_i^D$) and a competitive fringe of a price-taker firms generating renewable electricity denoted by ($Q^F$). Non-renewable electricity producing dominant firms are indexed by $i \in [1, n]$. The index $M$ will be used when there is one dominant firm, i.e. a monopoly. Cost of generating non-renewable electricity for dominant firms is $C_i^D = c_i^D Q_i^D$, where $c_i^D > 0$ reflects constant strictly positive unit cost. Cost of generating renewable electricity for the competitive fringe is $C^F = c^F Q^F + (1/2)d^F(Q^F)^2$, with $c^F > 0$ and $d^F > 0$ as parameters of this quadratic cost function. We assume $c^F \geq c_i^D$, which renders generating renewable electricity always more costly than generating non-renewable electricity. On the other hand generating non-renewable electricity has a negative externality on the environment reflected as $\gamma(Q^D)^2$ with $\gamma > 0$ where $Q^D = \sum_{i=1}^{n} Q_i^D$ denotes the total output of dominant firms. We let $c^D = \sum_{i=1}^{n} c_i^D$ denote the sum of the unit cost parameters in the dominant sector.

The analysis theoretically works in three stages: first the government sets the optimal tariff by maximizing the social welfare function, then the dominant firms (or the firm in the monopoly case) solve their profit maximization problems as Cournot players towards each other, and collectively as a Stackelberg leader towards the fringe, then the fringe solves its problem taking the market price as given. We solve the model backwards starting from the fringe's problem, and then the dominant firms' problems finding their best response functions $Q_i^{D^e}$ and then the social welfare maximization will be held in which the optimal amount of tariffs will be found in terms of the parameters $A, B, c_i^D, c^F, d^F, \gamma$.

The model is solved for heterogeneous costs for $N$ number of dominant firms, and then the specific case of the Cournot duopoly and the fringe equilibrium is outlined. However, we will first present the solutions for the monopoly and the fringe case, because it has most of the insights we can extract from the $n$ dominant firms and multiple fringe firms case, and it is easier to interpret. When we present the solutions for n dominant firms we will use the linear demand function as $D = \frac{a-p}{b}$ instead of $D = A - Bp$.

For each $n$ in the case of oligopoly, we will look at two sub-cases of feed-in-tariff (FiT): fixed feed-in-tariff and premium-feed-in tariff, where in the fixed FiT case, the firms in the fringe are paid $T \geq 0$ per unit of electricity they sell, and in the premium tariff case they are paid a premium $\tau \geq 0$ on top of the price: $p + \tau$. Let $\overline{\tau}$ denote the critical value for the premium tariff to lead positive fringe outcome.

3.1 Non-renewable electricity producing monopoly and renewable competitive fringe with fixed feed-in-tariff

In the first case, the competitive fringe that produces renewable energy is paid a fixed tariff $T \geq 0$. Fixed tariff as a support mechanism is prevalent in the countries like Germany and Turkey to incentivize renewable energy investments.

Price taker firm in the competitive fringe maximizes profit:

$$\pi^F = TQ^F - C^F(Q^F) \tag{1}$$

The first order condition with respect to quantity produced results in:

$$Q^F = \frac{T - c^F}{d^F} \tag{2}$$

Equation (2) gives the critical value for the fringe production. For $T \leq c^F$ the effective tariff is zero. Since the fringe output is only dependent on the tariff value, it is independent of the monopoly decision.

Profit maximization problem of the conventional monopoly (producing non-renewable electricity only)

$$\pi_M^D = pQ_M^D - C_M^D(Q_M^D) \tag{3}$$

$$= p(D(p) - Q^F(T)) - C_M^D(D(p) - Q^F(T)) \tag{4}$$

The first order condition with respect to the price to be set by the monopoly results in:

$$(D(p) - Q^F(T)) + p(D' - Q^{F'}(T)) - C_M^{D'}(D' - Q^{F'}(T))) = 0$$

Letting $\varepsilon_{DF} = \frac{-p^{'}(D^{'} - Q^{F^{'}}(T))}{(D(p) - Q^{F}(T)}$ stand for the price elasticity of the residual demand for the monopoly the first order condition above can be rearranged as:

$$p(1 - \frac{1}{\varepsilon_{DF}}) = c_M^D \tag{5}$$

We recall from (2) above that the fringe does not supply unless $T$ is above $c^F$, in which case the whole demand is met by the monopoly firm and the effective fixed tariff would be equal to zero. Substituting $Q^F$ and $(Q^F)'$ into $\varepsilon_{DF}$ we get

$$\varepsilon_{DF} = \frac{pB}{(A - pB - \frac{T - c^F}{d^F})} \tag{6}$$

for the elasticity of residual demand. Plugging the elasticity of residual demand into (5), we find:

$$\begin{aligned} c_M^D =& p(1 - \frac{A - Bp - \frac{T - c^F}{d^F}}{Bp}) \\ p =& \frac{c_M^D + \frac{A}{B} - \frac{T - c^F}{Bd^F}}{2} \end{aligned}$$

Monopoly output is then easy to calculate by plugging the above price equation into the demand function and extracting the fringe output:

$$\begin{aligned} D =& \frac{A}{2} - \frac{Bc_M^D}{2} + \frac{T - c^F}{2d^F} \\ Q^F =& \frac{T - c^F}{d^F} \\ Q_M^D =& \frac{A}{2} - \frac{Bc_M^D}{2} - \frac{T - c^F}{2d^F} \end{aligned}$$

It is seen that total demand is increasing and monopoly output is decreasing in $T$. It is expected due to the decrease in price as fixed tariff increases.

Social welfare function is composed of total profits (producer surplus), consumer surplus, socialized cost of the tariff (which is exogenous to the electricity consumer's decision therefore not affecting the demand directly), and the environmental externality of non-renewable electricity production.

$$SWF = TQ^F - C^F(Q^F) + pQ_M^D - C_M^D(Q_M^D) + \frac{(Q_M^D + Q^F)^2}{2B} - (T-p)Q^F - \gamma(Q_M^D)^2$$

Maximizing SWF with respect to $T$ will give the optimal amount of fixed tariff $T$ in terms of the parameters.

Case 1: Below the critical value $T = c^F$ the effective fixed tariff will be zero, therefore the monopoly will cover the whole market. The social welfare reached by only monopoly production should be taken as a threshold for the social welfare reached by the optimal tariff:

$$SWF_1 = p(Q_M^D) - C_M^D(Q_M^D) + \frac{(Q_M^D)^2}{2B} - \gamma(Q_M^D)^2$$

Case 2: $T > c^F$ and the fringe output is positive:

$$SWF_2 = TQ^F - C^F(Q^F) + pQ_M^D - C_M^D(Q_M^D) + \frac{(Q_M^D + Q^F)^2}{2B} - (T-p)Q^F - \gamma(Q_M^D)^2$$

Maximizing SWF with respect to $T$, we find the optimal tariff as:

$$T^* = \frac{c^F + 3Bc_M^D d^F + Ad^F + 2\gamma(ABd^{F^2} - c_M^D d^{F^2} B^2 + c^F Bd^F)}{1 + 4d^F B + 2\gamma B}$$

$T$ increases as $c^F$ increases, which means a higher tariff is needed to mitigate the negative externality while producing renewable is getting more costly, however it may reach to a point where the fringe output is more costly than the negative externality of the non-renewable generation. That is, if $SWF_1 > SWF_2$, then the optimal fixed tariff is zero.

3.2 Non-renewable electricity producing monopoly and renewable competitive fringe with premium feed-in-tariff

In this case, the renewable competitive fringe is paid a premium over the price: $p + \tau$, with $\tau >= 0$. Premium tariff mechanism is not as much market-based as green certificates, and not as direct as fixed tariff. In this support scheme, there is an opportunity for the incumbent (dominant) firm to effect the net price of renewable energy generation, and to mitigate the effects of its entry.

Price taker firm in the competitive fringe maximizes profit:

$$\pi^F = (p + \tau)Q^F - C^F(Q^F) \tag{7}$$

The first order condition with respect to quantity produced results in:

$$p + \tau = c^F + d^F Q^F \tag{8}$$

$$Q^F = \frac{p + \tau - c^F}{d^F} \tag{9}$$

Profit maximization problem of the non-renewable electricity producing monopoly:

$$\pi_M^D = p(D(p) - Q^F(p+\tau)) - C_M^D(D(p) - Q^F(p+\tau)) \tag{10}$$

The first order condition with respect to $p$ results in:

$$(D(p) - Q^F(p+\tau)) + p(D^{'} - Q^{F^{'}}(p+\tau)) - C_M^{D^{'}}(D^{'} - Q^{F^{'}}(p+\tau)) = 0 \tag{11}$$

Solving (11) further and plugging the elasticity of residual demand in it we find:

$$p(1 - \frac{1}{\varepsilon_{DF}}) = c_M^D \tag{12}$$

Plugging the price elasticity of the residual demand $\varepsilon_{DF} = \frac{p(-B-(1/d_R)}{-(A-Bp-(p+\tau-c_R/d_R)}$ in (12) we find:

$$\begin{aligned} p =& \frac{c_M^D}{2} + \frac{A}{2(B+\frac{1}{d^F})} - \frac{\tau - c^F}{2(Bd^F+1)} && (13) \\ \frac{dp}{d\tau} =& \frac{-1}{2(B+\frac{1}{d^F})} && (14) \end{aligned}$$

The critical value for the premium tariff to lead to the positive fringe output can be computed as follows:

$$\begin{aligned} \tau \leq& c^F - p \\ \tau \leq& c^F - \frac{c_M^D}{2} - \frac{A}{2(B+\frac{1}{d^F})} + \frac{\tau - c^F}{2(Bd^F+1)} \\ \overline{\tau} =& c^F - \frac{c_M^D B d^F + c_M^D + A d^F}{2Bd^F+1} \end{aligned}$$

Thus, if $\tau$ is below $\overline{\tau}$, the monopoly finds it optimal to deter the fringe's entry. On the other hand, above this critical value, monopoly finds it optimal not to deter the fringe's entry. Then, as the premium paid to the fringe increases, monopoly price decreases.

We can easily compute the total demand from the price equation:

$$D(p) = \frac{A(Bd^F + 2)}{2(Bd^F + 1)} - \frac{Bc_M^D}{2} + \frac{B(\tau - c^F)}{d^F} \tag{15}$$

Equilibrium output to be produced by the fringe and the monopoly are then found by plugging (13) into (9) and then extracting the fringe output from total demand:

$$Q^F = \frac{A}{2(Bd^F + 1)} + \frac{c_M^D}{2d^F} + \frac{(2Bd^F + 1)(\tau - c^F)}{2d^F(Bd^F + 1)} \tag{16}$$

$$Q_M^D = \frac{A}{2} - \frac{(Bd^F + 1)c_M^D}{2d^F} - \frac{(\tau - c^F)}{2d^F} \tag{17}$$

Total demand and the fringe output are increasing and the price and monopoly output are decreasing in $\tau$. Thus as $\tau$ increases, the consumer surplus, the fringe profit, and the socialized cost of tariff increase while monopoly profit and the external cost on environment decrease.

Case 1: As long as $\tau \leq \overline{\tau}$ then there is only monopoly output, thus the SWF is:

$$SWF_1 = p(Q_M^D) - C_M^D(Q_M^D) + \frac{(Q_M^D)^2}{2B} - \gamma {Q_M^D}^2$$

Case 2: If $\tau > c^F - \overline{\tau}$, then the fringe output is positive:

$$SWF_2 = (p+\tau)Q^F - C^F(Q^F) + p(Q_M^D) - C_M^D(Q_M^D) + \frac{(Q_M^D + Q^F)^2}{2B} - (\tau)Q^F - \gamma {Q_M^D}^2$$

Maximizing the social welfare function with respect to $\tau$, optimal amount of premium is found as

$$\tau^* = \frac{(2\gamma(Bd^F + 1) - d^F)(Ad^F - c_M^D(Bd^F + 1) + c^F)}{2\gamma(Bd^F + 1) - d^F + 4Bd^F + 2} \tag{18}$$

It should again be checked for the corner solution whether $SWF_2 < SWF_1$ or not. In that case then the optimal premium tariff is zero because the cost of tariff is higher than the negative externality caused by monopoly.

### 3.3 $N$ firm Cournot oligopoly and renewable competitive fringe with fixed feed-in-tariff

In this section we briefly present the solution of optimal fixed FiT under $n$ firm Cournot oligopoly that produce non-renewable electricity, and the competitive fringe selling the electricity it produced at the fixed tariff $T$, which is independent of the market price. Oligopoly firms are indexed by $i$. The sum of oligopoly output is $Q^D$ and the sum of the marginal costs of the dominant firms in the oligopoly is $c^D$ (i.e., $Q^D = \sum_{i=1}^{n} Q_i^D$ and $c^D = \sum_{i=1}^{n} c_i^D$).

The first order condition (with respect to $Q^F$) for maximizing the profit

$$\pi^F = TQ^F - C^F(Q^F)$$

of the competitive fringe, leads to

$$T = c^F + d^F Q^F \tag{19}$$

$$Q^F = \frac{T - c^F}{d^F} \tag{20}$$

The critical value for fixed tariff is again $T = c^F$, below which there is no fringe output.

Profit function of one of the symmetric duopoly firms is

$$\pi_i^D = pQ_i^D - C_i^D(Q_i^D)$$

The usual steps in solving for the Cournot equilibrium, with $Q = Q^D + Q^F$ standing for total electricity output in the market, are

$$0 = a - bQ_i^D - bQ^D - bQ^F - c_i^D \tag{21}$$

$$0 = an - bQ^D - bnQ^D - c^D - bnQ_F \tag{22}$$

$$Q^D = \frac{an}{b(1+n)} - \frac{n(T - c^F)}{(1+n)d^F} - \frac{c^D}{b(1+n)} \tag{23}$$

$$Q = \frac{an}{b(1+n)} - \frac{c^D}{b(1+n)} + \frac{(T - c^F)}{(1+n)d^F}$$

Using the equation for best response function of a dominant firm $i$ (21), $Q_i^D$ in the equilibrium can easily be calculated as:

$$Q_i^D = \frac{a + c^D - (1+n)(c_i^D)}{b(1+n)} - \frac{(T - c^F)}{d^F(1+n)} \tag{24}$$

Plugging from expressions above into the price equation results in:

$$p = a - b(Q^D + Q^F) \tag{25}$$

$$p = \frac{ad^F + c^D d^F - b(T - c^F)}{d^F(1+n)} \tag{26}$$

Total demand and the fringe output are increasing, and price and monopoly output are decreasing in the fixed tariff.

Case 1: $T \leq c^F$, there is no fringe output and the oligopoly covers the all demand. In this case total social welfare is given by

$$SWF_1 = (\sum_{i=1}^{n} pQ_i^D - c_i^D Q_i^D) + \frac{b(Q^D)^2}{2} - \gamma(Q^D)^2$$

Case 2: $T > c_R$, i.e. the fringe output is positive, which leads to total social welfare given by

$$SWF_2 = (\sum_{i=1}^{n} pQ_i^D - c_i^D Q_i^D) + \pi^F + \frac{b(Q^D + Q^F)^2}{2} - (T - p)Q^F - \gamma(Q^D)^2$$

Maximizing $SWF_2$ with respect to $T$ gives the optimal level of fixed FiT as

$$T^* = \frac{ad^F + (2+n)(c^D)d^F + bc^F + \gamma(\frac{2n^2ad^F - 2n(c^D)d^F}{b} + 2n^2c^F)}{n^2d^F + 2nd^F + b + d^F + 2n^2\gamma}$$

If $SWF_2 > SWF_1$, $T^*$ is the optimal (interior) solution, otherwise the optimal fixed tariff is zero.

## 3.4 $N$ Firm Cournot oligopoly and renewable competitive fringe with premium feed-in-tariff

Note that in this case the price at which the fringe sells renewable electricity is $p + \tau$, and thus depends on the market price set by the domiant firms. Therefore the critical value for the fringe output to be positive will depend on the sum of premium and the price set by the dominant firms acting as Stackelberg leaders.

The profit function of the fringe:

$$\pi^F = (p + \tau)Q^F - C^F(Q^F)$$

The first order condition with respect to $Q^F$ results in:

$$(p + \tau) = c^F + d^F Q^F \tag{27}$$

$$Q^F = \frac{(p + \tau) - c^F}{d^F} \tag{28}$$

The fringe output is dependent on the price, and thus the production decisions of Cournot players will effect the fringe's decision, and Cournot players will consider this in their profit maximization:

$$p = a - b(Q^D + Q^F) \tag{29}$$

$$Q^F = \frac{a - b(Q^D + Q^F) + \tau - c^F}{d^F} \tag{30}$$

$$Q^F = \frac{\tau - c^F + a - bQ^D}{b + d^F} \tag{31}$$

It follows that $\frac{dQ^F}{dQ_i^D} = \frac{-b}{b + d^F}$. Profit function of one of the symmetric Cournot firms:

$$\pi_i^D = pQ_i^D - C_i^D(Q_i^D)$$

$$\pi_i^D = Q_i^D(a - b(Q_i^D + Q_-^D i^e + Q^F)) - C_i(Q_i^D)$$

$$= aQ_i^D - bQ_i^{D^2} - bQ_i^D Q_-^D i^e - bQ_i^D Q^F - c_i^D Q_i^D$$

Taking its derivative with respect to $Q_i^D$;

$$0 = a - bQ_i^D - bQ^D - bQ^F - bQ_i^D \frac{dQ^F}{dQ_i^D} - c_i^D \tag{32}$$
$$= a - bQ^D - bQ^F - bQ_i^D - bQ_i^D \frac{-b}{b + d^F} - c_i^D \tag{33}$$

Summing the equation 33 over all $i = 1, ..., n$, and plugging the equation 31 in it we find total output $Q^D = \sum_{i=1}^n Q_i^D$ by the dominant oligopoly firms as

$$Q^D = \frac{an}{(1+n)b} - \frac{c^D(b + d^F)}{(1+n)bd^F} - \frac{(n(\tau - c^F)}{(1+n)d^F}$$

Inserting this in (31) we can compute $Q^F$, and, together with the computed total equilibrium output level by the dominant oligopoly, we can compute $Q_i^D$:

$$Q^F = \frac{ad^F + c^D(b + d^F) + ((1+n)d^F + bn)(\tau - c^F)}{(1+n)d^F(b + d^F)}$$
$$Q_i^D = \frac{ad^F - b(\tau - c^F) + c^D(b + d^F) - (1+n)(b + d^F)c_i^D}{(1+n)bd^F}$$

Using the equilibrium output levels computed the above, we can easily arrive at the following:

$$p = a - b(Q^D + Q^F) \tag{34}$$
$$p = \frac{ad^F - b(\tau - c^F) + c^D(b + d^F)}{(1+n)(b + d^F)} \tag{35}$$
$$\frac{dp}{d\tau} = -\frac{b}{(1+n)(b + d^F)} \tag{36}$$
$$\frac{dD}{d\tau} = \frac{1}{(1+n)(b + d^F)} \tag{37}$$

Plugging (35) in (28) we find the critical value for the premium, above which the fringe output is positive, as

$$\overline{\tau} = c^F - \frac{ad^F + (b + d^F)c^D}{(bn + nd^F + d^F)}$$

Total social welfare is calculated in the same way as in subsections above:

Case 1: $\tau \leq \overline{\tau}$, there is no fringe output:

$$SWF_1 = pQ^D - (\sum_{i=1}^{n} Q_i^D c_i^D) + \frac{b(Q^D)^2}{2} - \gamma(Q^D)^2$$

Case 2: $\tau > \overline{\tau}$, fringe output is positive

$$SWF_2 = (\sum_{i=1}^{n} pQ_i^D - c_i^D Q_i^D) + \pi^F + \frac{b(Q^D + Q^F)^2}{2} - (\tau)Q^F - \gamma(Q^D)^2$$

Maximizing $SWF_2$ with respect to $\tau$, optimal level of $\tau$ is found as:

$$\tau^* = \frac{-and^{F^2} + c^D(b + d^F)d^F - nbc^F d^F}{2\gamma n^2(b + d^F) - nbd^F + (1 + n)d^F((1 + n)d^F + bn)} + \frac{\gamma(2n^2ad^F(b + d^F) - 2nc^D(b + d^F)^2 + 2bn^2c^F(b + d^F))}{b(2\gamma n^2(b + d^F) - nbd^F + (1 + n)d^F((1 + n)d^F + bn))}$$

If $SWF_2 > SWF_1$, $\tau^*$ is the optimal (interior) solution, otherwise the optimal premium tariff is zero.

# CHAPTER 4

# A PARAMETRIC EXAMPLE AND SIMULATIONS: THE CASE OF TURKEY

In this chapter we compare the fixed feed-in-tariff and premium feed-in-tariff are compared under various versions of the model studied: (i) the monopoly and the fringe, and (ii) cournot oligopoly as the dominant group and the fringe. The two instruments are evaluated in terms of renewable electricity output levels they give rise to, as well as overall efficiency as measured by total social welfare.

We note that government chooses a $\gamma$, the parameter indicating the magnitude of the social cost of environmental damage due to nonrenewable electricity generation felt by the society. The optimal tariff is computed taking into account the demand for electricity and the equilibrium reactions of the firms to the tariff announced by the government.

The parameters that are used in this simulation are as following: $c_M^D = 0.2$, $c^F = 0.7$, $d^F = 1$, $c_i^D = 0.2$, $A = 1$, $B = 1$. The value of $\gamma$ varies in the range: $[0.0, 3.0]$ to show the effects of the different levels of valuation for the environment under the two policies. The comparisons between the two policies (fixed and the premium tariffs) are held by comparing the prices, renewable and non-renewable energy quantities, total demand, total welfares; while keeping the decision maker's valuation of the environment same.

In the fourth section of this chapter, some relevant descriptive statistics of the Turkish electricity market will be presented, together with the story of how Turkish electricity market have developed. Then, the case of 18 non-renewable electricity producing Cournot firms and the renewable competitive fringe, that coincides with the current concentration level of Turkish electricity markets will be examined to find which tariff mechanism should be preferred.

4.1 Fixed and premium tariffs, monopoly and the fringe

Figure 3 shows how the price, optimal fixed tariff, and quantities at the equilibrium change in response to a change in $\gamma$.

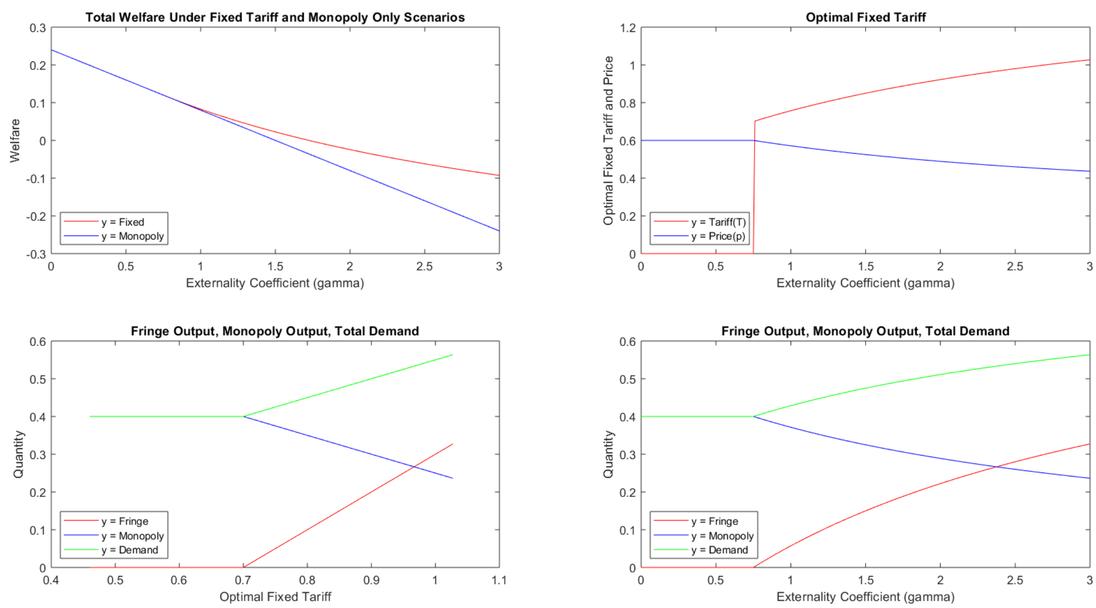


Figure 3. Fixed tariff, the monopoly and the fringe

Figure 4 shows how the price, optimal premium tariff, and quantities at the equilibrium change in response to a change in $\gamma$.

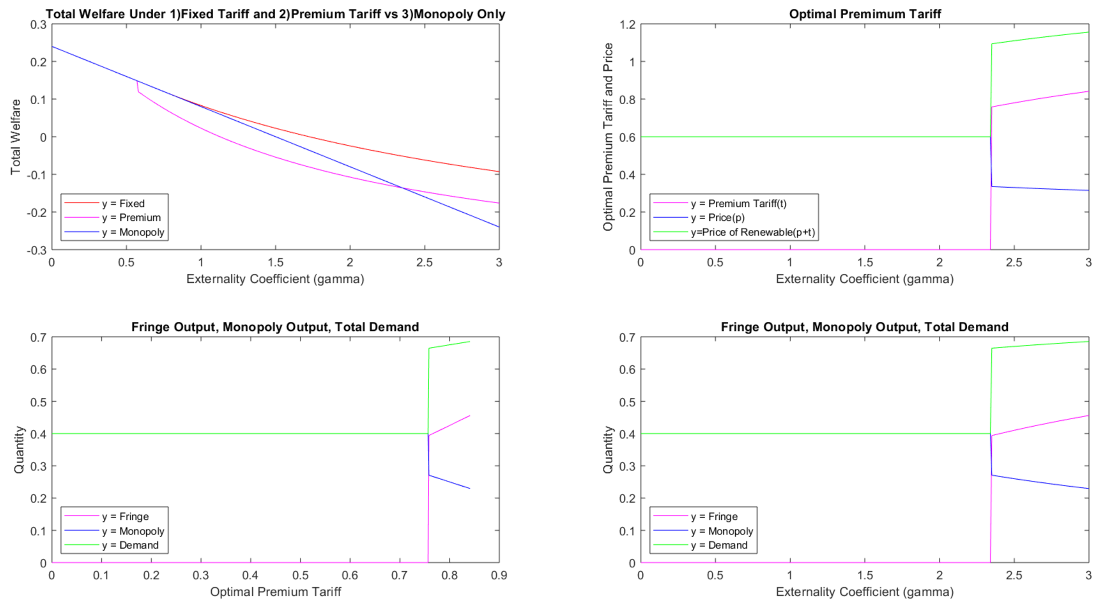


Figure 4. Premium tariff, the monopoly and the fringe

When the fixed tariff and the premium tariff are compared, it is seen that under the premium tariff until a specific gamma value above $\tau_2$ (between 2-2.5), output of the fringe is zero since with allowing renewable electricity production by the fringe in this case leads to less social welfare than that will obtain under a monopoly producing nonrenewable electricity. The explanation for this is the market power of the monopolistic firm. Since it can effect the price of renewable electricity when the fringe is paid $p + \tau$, it cuts its price more than it would do in the case of the fixed tariff. Since the consumers face the market price because the tariff mechanism is exogenous, the total demand of electricity increases more than it does under the fixed tariff case while the fringe output is positive. For this reason, there is a higher rebound effect for the premium tariff, and it leads to higher socialized costs of renewable electricity generation. Therefore, there is an overconsumption of the renewable generation.

For a government that only cares about the amount of social welfare generated in the economy, the premium tariff needs more valuation for the environment to be implemented compared to the fixed tariff. That can be seen from the fact that it generates less welfare than without the premium scenario (namely the monopoly domination) till a very high level of $\gamma$ ($\gamma = 2.35$) compared to the fixed tariff ($\gamma = 0.75$), for the selected parameters. The premium tariff, although it leads to less social welfare than the fixed tariff, leads to higher renewable electricity generation which can be preferred if a faster development of renewable electricity facilities is desired.

As the number of dominant firms increase, their dominance decreases. This is expected to decrease their ability to effect the prices, meaning that the residual demand each firm covers shrinks. Thus, the total conventional output increases, because of the decrease in the price and the increase in the demand as the number of firms increase. However, these effects should be compared in each scenario for more certain findings. Below, the Cournot cases of 2, 3 and 18 firms are analyzed.

4.2 Fixed and premium tariffs, Cournot duopoly and the fringe

Figure 5 shows how the price, optimal fixed tariff, and quantities at the equilibrium change in response to a change in $\gamma$.

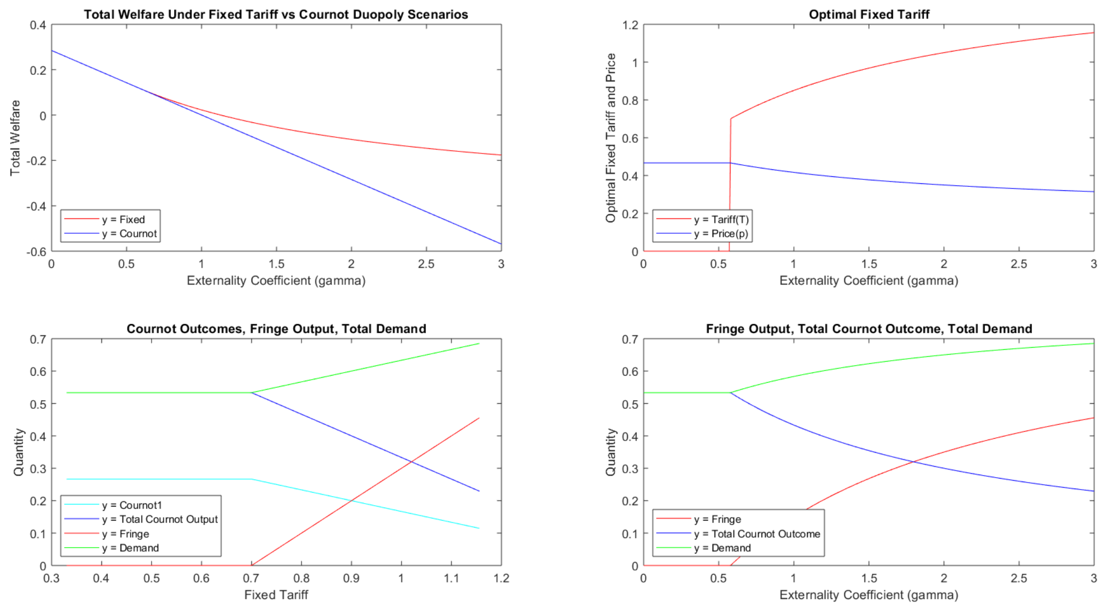


Figure 5. Fixed tariff, the Cournot duopoly and the fringe

Figure 6 shows how the price, optimal premium tariff, and quantities at the equilibrium change in response to a change in $\gamma$.

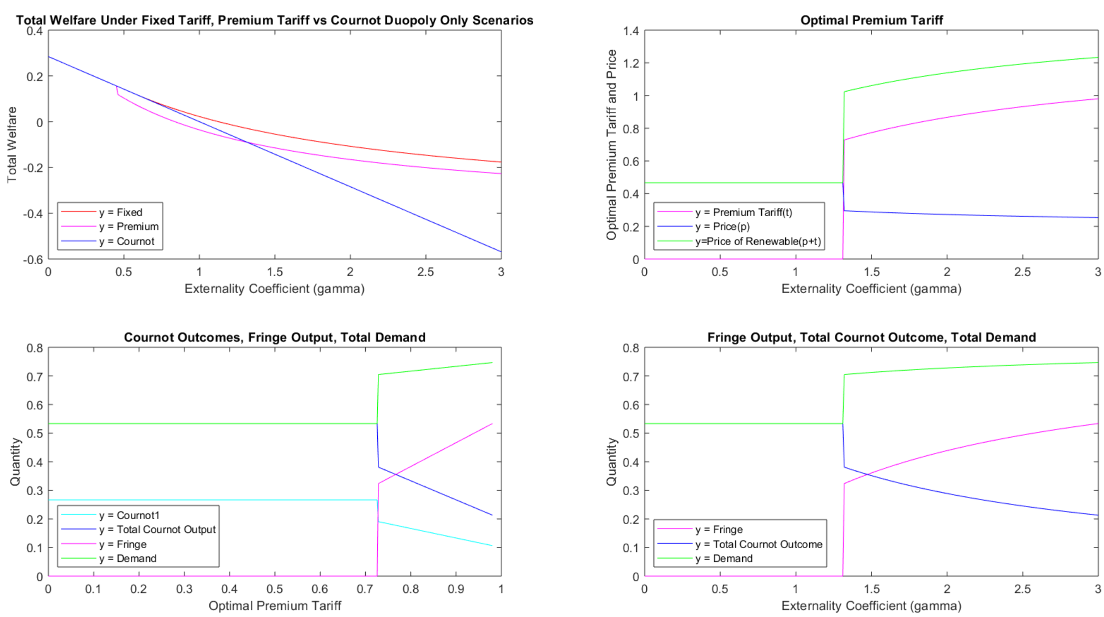


Figure 6. Premium tariff, the Cournot duopoly and the fringe

The same comments can be made for the Cournot duopoly model regarding the quantities and prices. For instance, lower prices of electricity in the premium tariff model, because of the Stackelberg leaders' move to cut their prices when faced the fringe entry, first to deter its entry, and then to increase their profits by increasing the residual demand they cover, and to make the fringe gets a lower price plus premium. This leads to a higher demand of electricity, which results in a rebound effect (although it is again covered by the increase in the renewable generation). However, since the market power of the incumbent firms is less relative to the monopoly case, they effect the price of renewable electricity at a less severe level. The decrease in the market price, and the increase in the demand are lower compared to the monopoly and the fringe scenario. Therefore we can conclude that as the number of incumbent firms increases, the difference in the social welfares of with and without fringe scenarios reached by the fixed and the premium tariff decreases and the two system approximate each other at the optimal level of tariffs.

The premium tariff still needs more valuation for the environment to be implemented compared to the fixed tariff. However, the gap between them has tightened relative to the monopoly and the fringe case. That can be seen from the minimum $\gamma$ values that generates positive fringe output: $\gamma = 1.31$ for the premium and $\gamma = 0.58$ for the fixed tariff.

In conclusion, it can be claimed that, for a competitive electricity market, premium tariff does not significantly underperform than the fixed tariff in a static duopoly and the fringe equilibrium. Moreover, premium tariff is expected to adjust to the changes in the market more rapidly than even a carefully adjusted fixed tariff, since it changes with the market price.

4.3 Fixed and premium tariffs, 3-firm Cournot oligopoly and the fringe

Figure 7 shows how the price, optimal fixed tariff, and quantities at the equilibrium change in response to a change in $\gamma$.

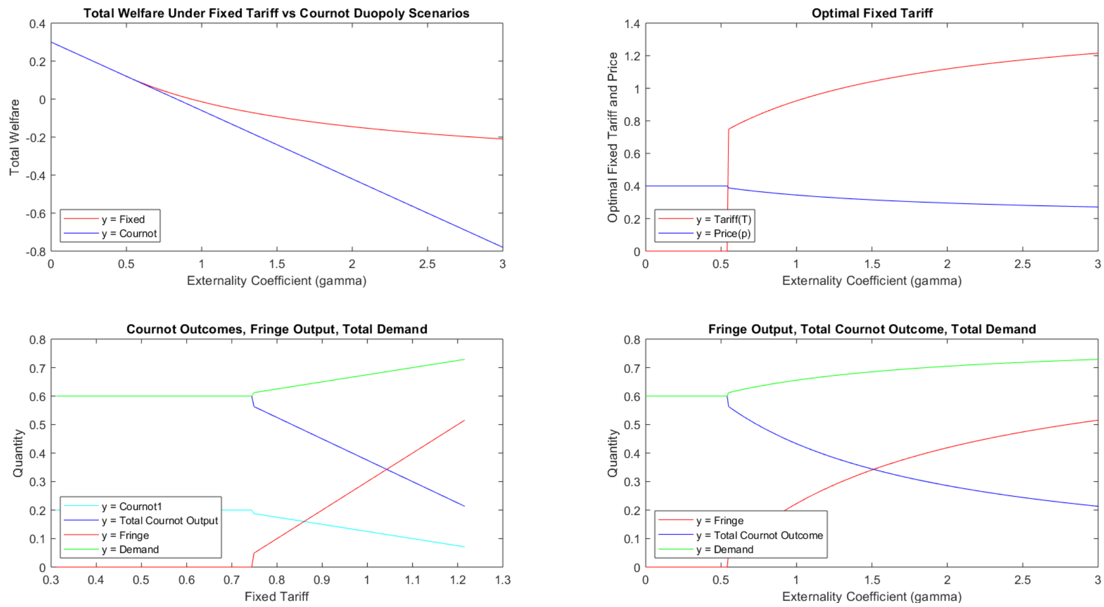


Figure 7. Fixed tariff, 3 firms Cournot oligopoly and the fringe

Figure 8 shows how the price, optimal premium tariff, and quantities at the equilibrium change in response to a change in $\gamma$. As it is expected, as number of dominant firms increased to 3 from 2, in other words as the concentration level decreased, the difference between social welfares reached by fixed and premium tariffs decreased and the two policies now resemble each other more. Still there is more fringe output under the premium tariff, and a higher lower bound of $\gamma$ is needed to lead positive fringe outputs compared to fixed tariff, however the differences in these measures have decreased as well.

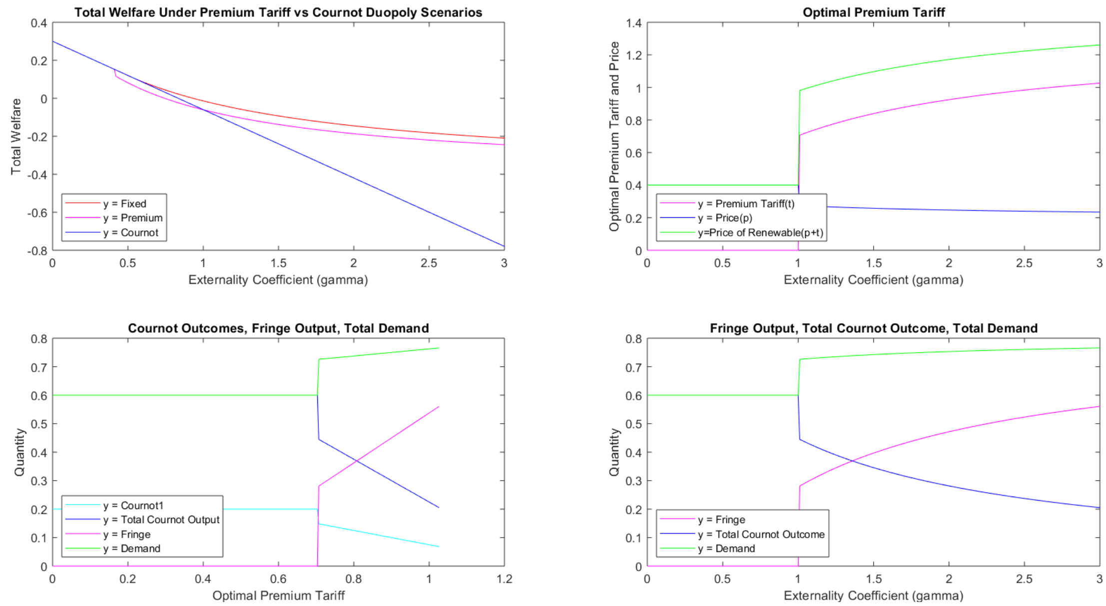


Figure 8. Premium tariff, 3 firms Cournot oligopoly and the fringe

4.4 History of the Turkish electricity market and the current situation

The Electricity Market Act numbered 4628 (EMA), enacted in 2001, started the liberalization of the Turkish electricity market. During the initial phases of this process, until 2009, market operations were buffered in case of shortages or surpluses, with balancing mechanisms controlled by the Turkish Electric Transmission Corporation (aka TEİAŞ in Turkish). In 2009, settlement mechanism for each hour, and a day-ahead planning mechanism were introduced, taking its final form in 2001 as a day-ahead market. In 2013 the Turkish Energy Exchange (aka EPİAŞ in Turkish) was opened and it was given the responsibility of organizing the settlement between sellers, buyers, and the day-ahead market mechanisms. In 2015, the intraday market is opened under control of EPİAŞ. Now there are three markets in the wholesale electricity trade sector: day-ahead market, intraday market, and balancing power market, the first two being operated by EPİAŞ and the last one by TEİAŞ.

Looking at the day-ahead and intraday markets, most of the transactions are realized in the day-ahead market. Only those who could not buy or sell in the day-ahead market make offers in the intraday market. The intraday market works as a normal spot market, which clears through a discriminatory auction of hourly periods in which suppliers wait for the bids in each period, and then sell the bulk power at the best price they get. However, the operation of the day-ahead market is more complicated, with a market barter price (aka PTF in Turkish) set according to the intersection of supply and demand offers as an hourly market price. Producers, traders, and buyers enter their bids to sell or buy a specific amount from a specific price into the system, and an algorithm sets an hourly price by maximizing the total welfare of all buyers and sellers in that period. Those sellers whose bids exceed the PTF can have an option not to sell from that price; however, if their bids are close to the PTF and compensating them for their loss is found feasible by the algorithm, then they can also be compensated. Those who bid to sell at a cheaper price than PTF get a surplus. The same logic applies to buyers. Besides these markets, sellers and buyers of wholesale electricity can make long-term bilateral agreements which prevents price uncertainties.

The price-setting mechanism in the retail electricity market is more complicated, differing for consumer types: ”free” and ”non-free” consumers. To be a free consumer one’s energy consumption needs to exceed the free consumption limit, currently 1,400 kWh annually. In that case, he/she can buy from any seller in his/her region, or beyond. Otherwise, the price he/she will buy from is regulated by the Energy Market Regulatory Authority (aka EPDK in Turkish). The regulated price includes distribution fees (also compensating for transmission fees and the losses and leaks), charge for energy production, distribution firms’ profit, and taxes. Therefore, a non-free consumer pays the producer's fees, transmission fees, distributor's share, and taxes (VAT, municipality's share, official television's share, a fee to Ministry of Energy for R&D costs) all reflected in the bill. Free consumers can choose any seller distributing to their region. Figure 9 below shows the change in the free-consumers' consumption volume for the year 2019-2020.

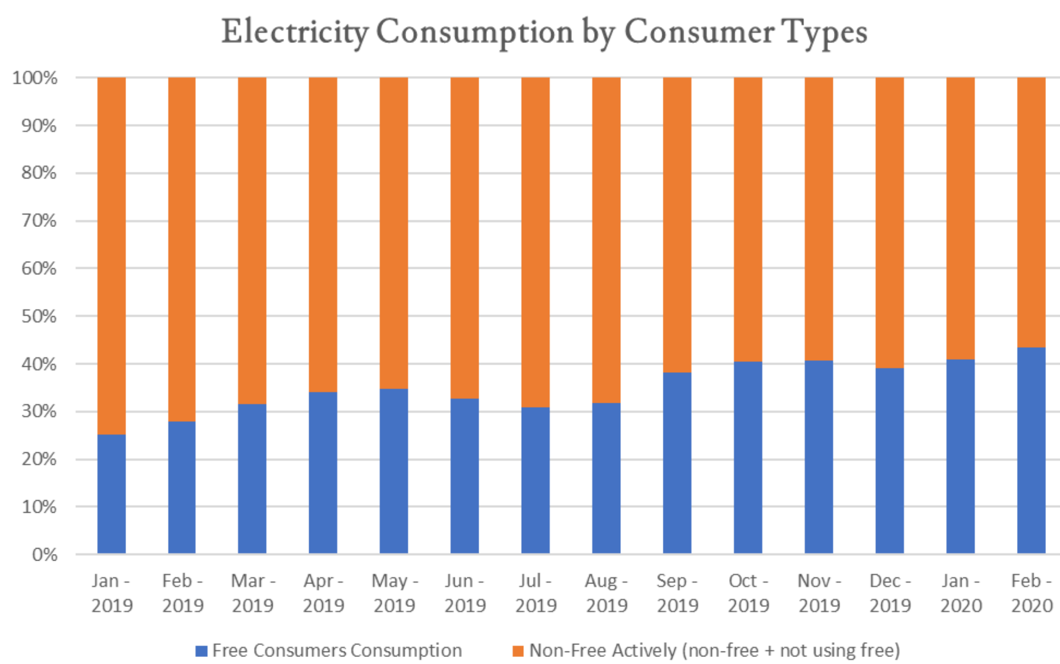


Figure 9. Electricity consumption by consumer types

Source: seffaflik.epias.com.tr

Figure 9 shows that there is an increasing trend in free consumers' share of total consumption, mainly because of the increasing number of free consumers. That is due to two reasons: firstly the free consumption limit has been decreasing steadily over the last several years: it was 2,000 kWh annually in 2018, 1,600 kWh in 2019, and it is 1,400 kWh currently in 2020. By doing that, the policymakers intend to increase competition in the retail sector. Secondly, more people among those who had already qualified have become interested in moving to free-consumption by time. This fact can be inferred from Figure 10 below. As in Figure 9, the consumer category labeled as non-free actively includes the non-free consumers by their annual consumption below the limit, and can-be free consumers but not choosing to do so.

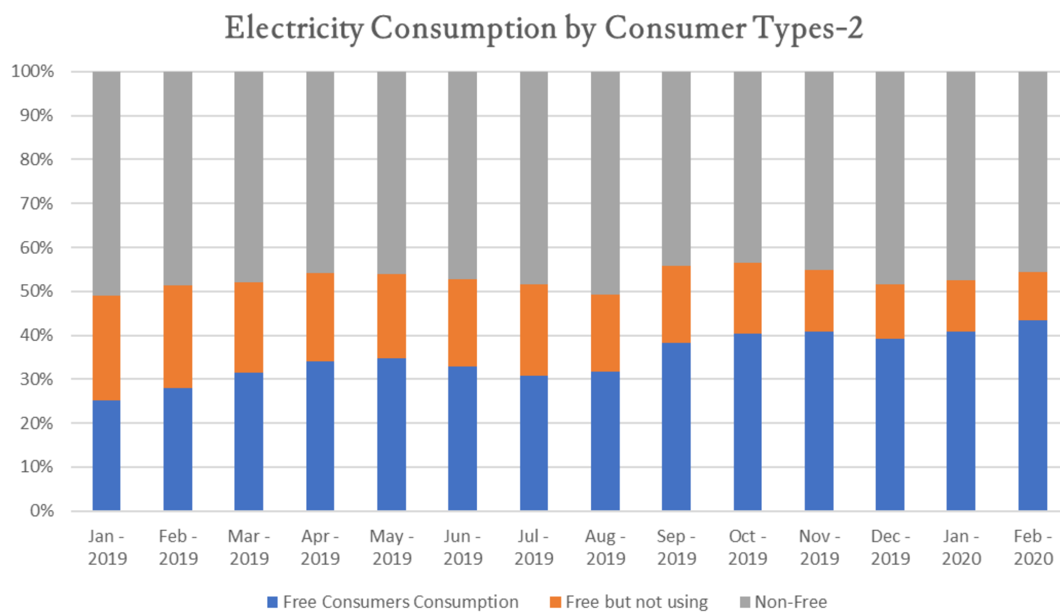


Figure 10. Electricity consumption by consumer types-2

Source: seffaflik.epias.com.tr

With the recent improvements in renewable energy technologies, and the help of the incentive policies, another option to sell to the system is generated and it is through the responsible distribution firm. Small enough renewable energy generators, called distributed generators (DG), that are on the distribution lines sell to the distributor firm at a price set or subsidized by policy-makers. Namely, they sell to the grid through the local distribution firms that they buy energy from if their generation exceeds their own needs. Details of the distributed generation technologies will be explained in the next section. However, to estimate the approximate amount of DG production in the Turkish electricity market, the license to generate electricity can be used as a proxy. To promote renewable distributed generation deployments, the government issued an exemption from the license payments for generators below a specific limit, which is 5 MW currently. Besides, there is a recently added requirement for the exemption which is the generation and the consumption of electricity should be in the same location. Therefore, measuring the unlicensed production provides an accurate proxy for overall DG production in Turkey.

Figure 11 shows that most of the investments in solar energy are unlicensed. Since solar energy comprises almost all of the unlicensed investments, taking solar energy as a proxy for the distributed generation in Turkey would be reasonable. Remaining important statistics for Turkish electricity markets, especially the amounts of production, both renewable and non-renewable, will be presented in the next sections.

| Source | Installed Capacity(Licence - MWh) | Installed Capacity(Unlicen - MWh) | Total(MWh) |
|---|---|---|---|
| Wind | 6,549.86 | 51.97 | 6,601.83 |
| Rezervoir | 6,242.78 | 0.00 | 6,242.78 |
| Canal Type | 6,046.20 | 22.22 | 6,068.42 |
| Sun | 174.75 | 5,872.71 | 6,047.46 |
| Geothermal | 1,404.39 | 0.00 | 1,404.39 |
| Biomass | 424.87 | 32.96 | 457.83 |
| Other | 0.00 | 187.30 | 187.30 |
| LFG | 153.20 | 0.00 | 153.20 |
| Biogas | 100.93 | 25.69 | 126.62 |
| Total | 21,096.97 | 6,192.84 | 27,289.82 |

Figure 11. Installed capacities of renewable energy in Turkey by March 2020

Source: seffaflik.epias.com.tr

Herfindahl-Hirschman Index (HHI), which is a commonly accepted measure of market concentration (calculated by squaring the market share of each firm competing in a market and then summing the resulting numbers). HHI index varies between 1 to 10,000, and industries with HHI number below 1,000 are generally considered as competitive. Although HHI measure fails to consider the complexities of a specific sector, it can be taken as a starting point in assessing the market power in a given sector. Figure 12 below shows that there is a decreasing trend in the Turkish electricity market concentration level.

| | HHI Index | | | | | |
|---|---|---|---|---|---|---|
| | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 |
| Generation | 1416 | 1123 | 673 | 696 | 575 | 550 |
| Installation Capacity | 1132 | 996 | 873 | 789 | 682 | 599 |

Figure 12. HHI index for Turkish electricity market

Source: Electricity Market Development Report 2019

4.5 Fixed and premium tariffs, 18 firms Cournot oligopoly and the fringe case

In a market consisting of $n$ firms, where each firm's share of output is indicated as $s_i$, the HHI is measured as $\sum_{i=1}^{n} s_i^2$. From Figure 12 the current HHI value for the Turkish electricity market is approximately 550). It can be shown that this value corresponds to a Cournot oligopoly of 18 firms with homogeneous costs. Positing our model as a stylized version of the Turkish electricity market, in the simulations below the number of firms in the Cournot oligopoly of our model will be taken as 18, and an assessment of the relative merit of using fixed vs premium feed-in-tariff intrument for supporting renewable energy will be provided.

Using the parameter values indicated before and $n = 18$ as the number of firms in the dominant Cournot oligopoly of our model, Figure 13 shows how the price, optimal fixed tariff, and quantities at the equilibrium change in response to a change in $\gamma$.

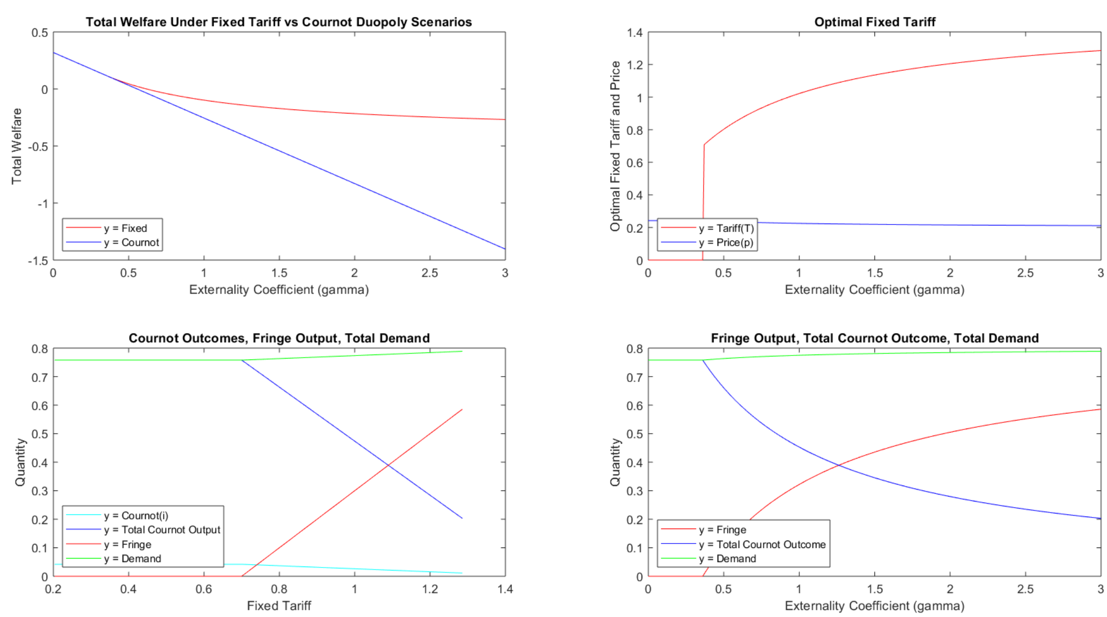


Figure 13. Fixed tariff, 18 firms Cournot oligopoly and the fringe

Under the same assumptions Figure 14 shows how the price, optimal premium tariff, and quantities at the equilibrium change in response to a change in $\gamma$.

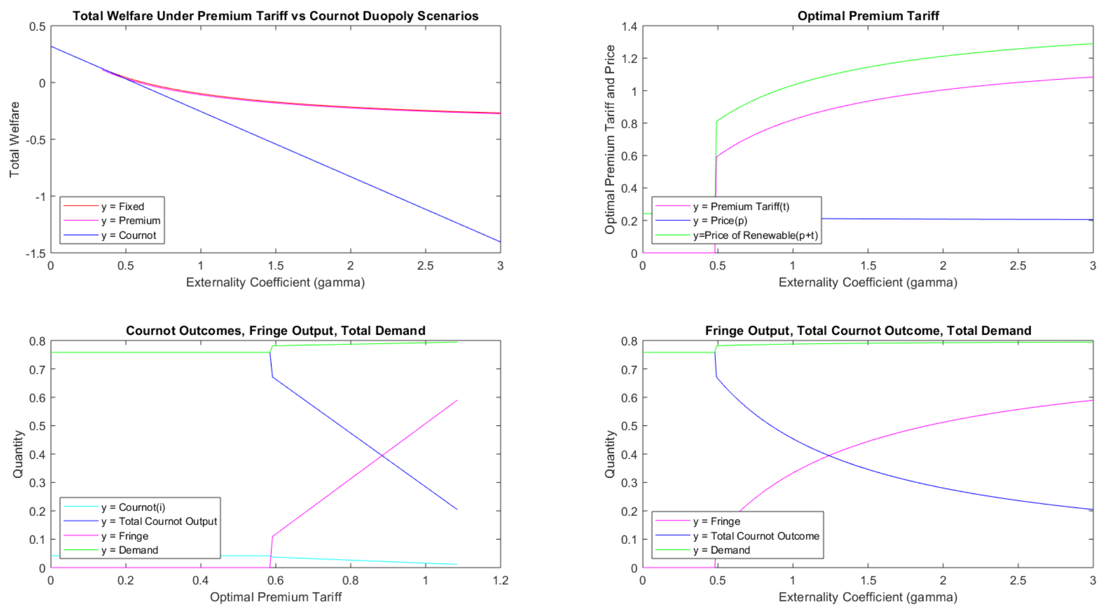


Figure 14. Premium tariff, 18 firms Cournot oligopoly and the fringe

Figures 13 and 14 show that the two feed-in-tariff support instruments lead to nearly same equilibrium outcomes, which is in line with the theoretical results we have shown. Social welfare generated by the premium tariff is just below the welfare generated by the fixed tariff. The total demand and the renewable fringe output generated by the premium tariff are just above their counterparts generated by the fixed tariff. For the chosen parameter set under this case it can be concluded that, implementing either one of the tools (fixed or premium FiT) does not lead to a significant difference in terms of prices, quantities, and welfare.

# CHAPTER 5

# CONCLUSIONS

In the last half-century, electricity markets have experienced two great transformations: deregulation of the generation structure and transition to the renewable generation. Share of the renewable electricity production worldwide has increased to 9.32 percent in 2018 (Figure 1). The restructuring phase of deregulation, similar to the one that occurred in the UK and the US during eighties, has begun to take place in the Turkish electricity market in the last twenty years. Since the process is quite recent compared to those countries, the vast academic literature on the deregulation of the electricity markets can be helpful in the ongoing transformation process. One of the important questions regarding this transformation is the share of renewable electricity generation, both central and distributed, its efficient level, and the optimal policy structure to lead and sustain this generation level.

There is a trade-off between the cost of the transition to an electricity generation portfolio with more renewable generation capacities and the cost of environmental externality caused by non-renewable generation. The latter component of the trade-off is more crucial in terms of leading to irreversible effects on the environment, society, and consequently the economy, while the cost of increasing the renewable generation's share is predictable and short-term. These costs include new infrastructure spendings needed to facilitate distributed renewable generation, higher costs of generating renewable electricity, and the cost of uncertainty and inability of determining the production time, which makes the continuous adjustment between supply and demand more difficult. Representing all of these costs in one model can make the analysis unnecessarily complicated. This research used quadratic and higher costs of generating renewable electricity compared to non-renewable electricity to represent this trade-off. This approach is defended conceptually (see Borenstein, 2012) and used in various academic studies on electricity markets (e.g., see der Fehr and Ropenus, 2017).

This research, in line with der Fehr and Ropenus (2017), uses the dominant firm and the fringe model, and its modest contribution is studying the welfare properties of fixed versus premium feed-in-tariff instruments that are used to support renewable electricity production. This allows us to comment on the differences in the outputs, prices and total social welfare under each of these policies at their optimal levels. Further empirical research can provide more accurate values for the parameters of the model and allow for more precise assessments. Since we did not have an accurate estimate for the cost electricity generation in Turkey (either for nonrenewable or for renewable generation), the simulations carried out in Chapter 4 using the market concentration index for Turkish electricity market is only meant to be suggestive. Accessing to the cost data can facilitate the application as a further project.

To summarize, the dominant sector with a monopoly and the fringe case shows that the fixed and the premium tariff lead to significantly different outcomes. Under the premium tariff, since the monopoly can effect the fringe's price, $(p + \tau)$, it cuts its price more than it does under the fixed tariff. This leads to the rebound effect: although it does not cause higher external costs by increasing the non-renewable output, there is an overproduction of renewable electricity under premium tariff. For environmental reasons this may be claimed as desirable; however in terms of welfare calculations, it leads to welfare losses (Figure 4). Premium tariff needs higher $\gamma$ values (higher concern for environmental damage) to be feasible in total social welfare terms, implying that for a government that does not value the environment much fixed tariff will be the chosen instrument. These features of the premium tariff is especially present if the market is concentrated, namely the monopoly and the fringe case. As the number of firms increase, the market power of the dominant firms becomes weakened. Therefore, the rebound effect they cause decrease, and the two policies resemble each other more as the market becomes less concentrated.

Under the assumption that the HHI = 550 reflects the true state of concentration in Turkish electricity generation market (see Figure 12), the indicative simulations run for a Cournot oligopoly of 18 firms as constituting the nonrenewable electricity generation segment, confirm the result obtained on the relative efficiency of the two feed-in-tariff instruments sudied, namely that when there is. enough competition in the nonrenewable sector it does not matter which of the two instruemnts gets used to promote distributed renewable electricity generation by companies in a competitive fringe. However, assessing the right fixed tariff value can be difficult for the decision makers. Moreover, it may not adapt to the changes in the market as fast as the premium tariff, even if the fixed tariff is set by using dynamic indexes. This question should be examined in a further research, such as whether a sliding premium or a fixed tariff adjusted using a dynamic index (such as a price index) performs better. Figure 12 shows that HHI was 1416 in 2014, above the competitive market definition. With the information set at hand and the help of this research, it can be said that the transition to a premium tariff for regulating the renewable electricity investments in the Turkish electricity market can be a better idea now, compared to before when the HHI was higher.

## REFERENCES


Allan, G., Eromenko, I., Gilmartin, M., Kockar, I., & McGregor, P. (2015). The economics of distributed energy generation: a literature review. *Renewable and Sustainable Energy Reviews, 42*, 543-546.

Allaz, B., & Vila, J.-L. (1993). Cournot competition, forward markets and efficiency. *Journal of Economic Theory, 59*(1), 1-16.

Borenstein, S. (2012). The private and public economics of renewable electricity generation. *Journal of Economic Perspectives, 26*(1), 67-92.

Borenstein, S., & Bushnell, J. (2003). An empirical analysis of the potential for market power in California's electricity industry. *The Journal of Industrial Economics, 47*(3), 285-323.

Borenstein, S., & Bushnell, J. (2015). The US electricity industry after 20 years of restructuring. *Annual Review of Economics, 7*(1), 437-463.

Borenstein, S., Bushnell, J. B., & Wolak, F. A. (2002). Measuring market inefficiencies in California's restructured wholesale electricity market. *The American Economic Review, 92*(5), 1376-1405.

Borenstein, S., Bushnell, J., Kahn, E., & Stoft, S. (1995). Market power in California electricity markets. *Utilities Policy, 5*(3), 219-236.

BP. (2019). BP statistical review of world energy 2019. Retrieved from https://www.bp.com/en/global/corporate/energy-economics

Butler, L., & Neuhoff, K. (2008). Comparison of feed-in tariff, quota and auction mechanisms to support wind power development. *Renewable Energy, 33*(8), 1854-1867.

Cardell, J. B., Hitt, C. C., & Hogan, W. W. (1997). Market power and strategic interaction in electricity networks. *Resource and Energy Economics, 19*(1), 109-137.

Couture, T., & Gagnon, Y. (2010). An analysis of feed-in tariff remuneration models: implications for renewable energy investment. *Energy Policy, 38*(2), 955-965.

der Fehr, N. M., & Ropenus, S. (2017). Renewable energy policy instruments and market power. *The Scandinavian Journal of Economics, 119*(2), 312-345.

EMRA. (2019). Electricity market development report 2019. Retrieved from https://www.epdk.gov.tr/

Fabra, N., Fehr, N.-H., & Harbord, D. (2006). Designing electricity auctions. *The RAND Journal of Economics, 37*(1), 23-46.

Green, R. (2003). The electricity contract market in England and Wales. *The Journal of Industrial Economics, 47*(1), 107-124.

Green, R. J., & Newbery, D. M. (1992). Competition in the British electricity spot market. *Journal of Political Economy, 100*(5), 929-953.

Hahn, R. W., & Boening, M. V. V. (1990). An experimental examination of spot markets for electricity. *The Economic Journal, 100*(403), 1073-1094.

Klemperer, P. D., & Meyer, M. A. (1989). Supply function equilibria in oligopoly under uncertainty. *Econometrica, 57*(6), 1243-1277.

Mulder, M., Petrikaitė, V., & Scholtens, B. (2015). Distributed energy generation techniques and the competitive fringe effect in electricity markets. *Resource and Energy Economics, 42*, 125-140.

Newbery, D. M. (1998). Competition, contracts, and entry in the electricity spot market. *The RAND Journal of Economics, 29*(4), 726-749.

Ropenus, S., & Jensen, S. G. (2009). Support schemes and vertical integration—Who skims the cream? *Energy Policy, 37*(3), 1104-1115.

Schallenberg-Rodriguez, J., & Haas, R. (2012). Fixed feed-in tariff versus premium: a review of the current Spanish system. *Renewable and Sustainable Energy Reviews, 16*(1), 293-305.

Willems, B., Rumiantseva, I., & Weigt, H. (2009). Cournot versus supply functions: What does the data tell us? *Energy Economics, 31*(1), 38-47.

Wolak, F. A., & Patrick, R. H. (2001). The impact of market rules and market structure on the price determination process in the England and Wales electricity market (Working Paper No. 8248; Working Paper Series). National Bureau of Economic Research.

Wolfram, C. D. (1998). Strategic bidding in a multiunit auction: an empirical analysis of bids to supply electricity in England and Wales. *The RAND Journal of Economics, 29*(4), 703-725.

Wolfram, C. D. (1999). Measuring duopoly power in the British electricity spot market. *American Economic Review, 89*(4), 805-826.