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Unilateral Market Power in Wholesale Electricity Markets - A Cournot Based Analysis

Economics

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Abstract

This thesis studies the unilateral market power in wholesale electricity markets, its reasons and its extent. The study is constructed on a Cournot competition model.

I first go through the Cournot duopoly competition and then present the Cournot competition for n firms. I show that the Cournot equilibrium always settles between the competitive and the monopoly equilibriums. I then construct an electricity market specific duopoly game considering different marginal costs for different (base and peak load) capacities. I play five games, each with a slightly different setting. I prove that firms' unilateral market power rises along with the marginal costs of electricity. When capacity gets more expensive firms have less incentives to offer it to the market and are therefore also more aware of their rival's preferred strategies. I prove my point by presenting some of the most relevant previous empirical studies from two chosen markets, the United Kingdom and California.

I study the British electricity market from its reform in 1990 until 2001. The empirical work shows that the market power abuse was maintained at a very low level in Britain's duopolistic market thanks to strict regulation. However evidence of collusive behavior towards the end of the decade is strong. Also evidence for regulation-responding behavior is found.

I also examine California's electricity market during its crisis in 1998-2000. Researchers have found that large part of the increase in electricity's wholesale prices was due to decreased hydroelectric energy input, increased natural gas price and increased demand. However strong evidence of capacity withholding exists and the hypothesis for market power abuse cannot be rejected. Certain studies also show prices to be very close to Cournot equilibrium.

Keywords Cournot model, market power, game theory, electricity market reform, California electricity crisis

Contents

1. Introduction

”It’s always been my dream to have a successful business. I’d like one day to open more stores, and maybe even expand into the provinces. But the conditions are very difficult to start a business. Taxes are very high and services are very limited. The electricity was out for eleven days last month, but I still had to pay for thirty days. And when I try to use a generator, the costs are so high that the customers stop coming. It’s very difficult.”

— A man from Kinshasa, Congo on the *Humans of New York* blog (visiting Congo) on August 21, 2014

Since the invention of the electromagnetic induction by Michael Faraday in 1831 and especially after the first electricity distribution systems introduced by Thomas Edison and Nikola Tesla in the 1880’s, electricity has played a vital role in the modern economy and the economic growth. Researchers are not unanimous about whether the relationship between electricity consumption and GDP growth is uni- or bidirectional, but about one thing they strongly agree: these two are inseparable (e.g. Payne, 2010; Chen, Kuo and Chen, 2007; Kraft and Kraft, 1978). One can easily agree; there are not too many things we could possibly do nowadays without electricity.

Soon after the electricity generation and consumption became more common, the electricity generation, transmission, distribution and supply became national or regulated local monopolies. It was no earlier than in the late 1980’s when Chile and Great Britain opened the game towards competition. Electricity markets across the globe have experienced reforms ever since. With efficiency improvement as their goal, both developed and developing countries have eagerly introduced competition on their electricity markets.

Nowadays strict monopolies are a minority and most of the World’s electricity markets are either fully or nearly liberalized to competition. Many countries (or in the case of the US, states) have also organized their electricity market as a wholesale competition: generation is fully liberalized and megawatts are traded through a centralized spot market that sets an hourly (or half-hourly) price for electricity. Market participants are also free to make forward contracts with each other. Electricity producers, traders, and retailers have open access to the bulk transmission and local distribution networks, yet both networks are seen as natural monopolies even today, just often separate and not necessarily national ones as before. Finally, final consumers are able to choose from who and which generation company's electricity they buy.

Now everything looks good at the first glance, but can a traditionally monopolistic market easily be transformed into an actually competitive one? Are the wholesale electricity prices really on their competitive level meaning the marginal cost? According to wide research in different continents, the simple answer to both questions is: no. The best known example must be California in 1998-2000 (e.g. Borenstein, Bushnell and Wolak, 2002; Joskow and Kahn, 2002), where market power exploitation, combined with exceptional conditions, lead to astronomical wholesale prices.

So the power generation indeed generates power. "Market power" simply means that the market price is above the marginal cost of the last unit of output introduced to the market. Market power is said to be unilateral whenever a firm can affect the market price with its own decisions, given the actions of its rivals. Research (e.g. Puller 2007) has shown that rather than participating in tacit collusion, electricity generators abuse the *unilateral market power* they have. Neither have the competition authorities found evidence of coordinated actions among generators to raise prices in violation of the antitrust or competition law (e.g. Wolak 2005). The exercise of unilateral market power is the main reason for a costly market failure, and it appears to be significantly higher in the electricity supply industry than in other network industries (e.g. Wolak, 2014).

There are several explanations to this, most of which are a direct consequence of three forces: finance, physics and geography. First, there's a necessity to balance the electricity supply and demand at every instant: electricity is hard and so far very expensive to store[1] and customers cannot be put to queue for electricity. The generation capacity is also constrained and, especially with the increasing amount of renewable energy, in risk of unexpected shocks.

Second, the electricity must be carried from the generator to the consumer. The electricity flows in the transmission network according to the laws of physics rather than laws of economics: the network has its finite transmission capacity and its geographical constraints. When being congested, generators located far from the demand are not able to compete with those closer to demand. Borenstein, Bushnell and Stoft (2000) show that limited transmission capacity can give a firm the incentive to constrain its output in order to congest transmission on its dominance area. Furthermore, Joskow and Tirole (2000) find that holding financial and/or physical transmission rights[2] enhances the market power of a generator at the importing node of the transmission line. And just like the generation unit, also the transmission line contains a risk to fail.

The third is probably the most obvious reason: the small number of firms. Electricity generation typically involves a significant up-front investment to construct a generation unit, leading to unwritten entry barriers. Bigger generation units also often lead to economies of scale with lower per-unit fixed and variable costs. In the developed countries the demand doesn't notably increase in the long run, and therefore switching from a monopoly regime into a competitive one doesn't invite for investment. In contrast, in the developing countries the demand is highly increasing in the long run, but the countries lack investment. Wolak (2014) notes that the generation capacity ownership also tends to be concentrated in small geographic areas

[1]According to Wolak (2014), constructing significant storage facilities typically requires notable up-front investments and more than 1 MWh of energy must be produced and consumed to store 1 MWh of energy.

[2] Financial rights mean a "firm price" for transmission offered to market participants to protect themselves from fluctuations due to changes in demand, supply and transmission capacity (failures). Physical rights give the holder the right to use congested network interfaces. (Joskow and Tirole, 2000)

within the wholesale markets, leading to "local monopolies", thanks to the transmission constraints.

The fourth reason for market power to flourish in the electricity markets is rather independent from physics and geography: the inelastic, peaking demand. Demand varies constantly, peeks intraday and by seasons and is subject to sudden shocks caused by already mentioned plant or line failures, weather changes and "even the halftime break in a major sporting event" (Holmberg and Newbery, 2010). The main reason for such a steep demand curve is that consumers lack real-time metering and knowledge of their electricity consumption and electricity prices. In other words, they have no incentive to balance their demand. Joskow and Tirole (2006) also note that on some markets consumers may not be able to adjust their consumption freely even if they wanted to[3]. To change this, investments are again needed.

When you add politics, independency / willingness to national self-sufficiency, spot and future markets, the power soup slowly begins to boil. Below I have constructed a figure representing my understanding of the cause-effect relationships behind the existence of market power in electricity markets.

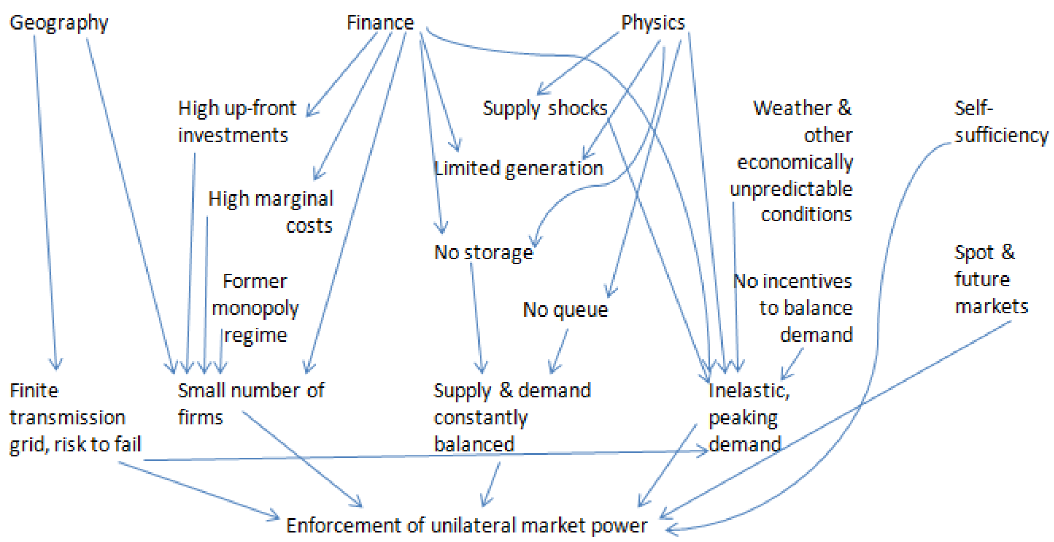


Figure 1: Forces behind the unilateral market power in electricity markets.

[3] Joskow and Tirole (2006) note that the system operator might physically be unable to cut off individual customer loads and is forced to ration on a zonal basis instead.

The above introduction and figure show the complexity and broadness of the electricity market behind the unilateral market power research. Some parts of it (notably geographical and physical constraints and their consequences) cannot even be explained nor solved through economics. However, economics offers great tools to define the source of the market power more closely. After all, the market power settles somewhere in between the inelastic demand curve and the oligopolistic electricity production competition. Definition of this area is indispensable for any further actions to mitigate it.

The aim of this thesis is not to solve the market power dilemma on the electricity market, but rather to show from where the unilateral market power economically arises. This is done through theoretical research, construction of a theoretical game, and presentation of previous empirical findings. The research question is simply the following: Why and to what extent does market power arise in power markets?

The structure of this thesis is the following: first I will present my chosen theoretical framework or the Cournot competition model in chapter 2. I will then construct a Cournot-based, electricity market specific game in chapter 3. Chapter 4 presents some of the most significant empirical studies from the field of market power research supporting my theoretical findings. In chapter 5 I will conclude and give suggestions for future research.

2. Theoretical Framework

"We will make electricity so cheap that only the rich will burn candles."

— Thomas Edison

As mentioned in the introduction, there are several unique characteristics that differentiate the electricity markets from others. Before diving deeper into these characteristics, however, I want to point out two things essential to our research, which simultaneously are prerequisites for any market power research: 1) the market produces one single good with no product differentiation and 2) the market is oligopolistic, with two or more, yet few producers.

The three most popular game theoretical approaches to the market power in oligopolistic markets producing a single good are Bertrand model, Cournot model and Supply Function Equilibrium (SFE) model. All of them model non-repeated, or one period interaction of competing oligopolists. I will now present each of them shortly and explain why I chose the Cournot model beyond the others to play the role of the theoretical framework for this thesis.

In the Bertrand model firms take the demand as given and compete in price with the idea that "if my rival lower's his price, I lower my price". Naturally both output and price are chosen to maximize the profit. The Bertrand model is very suitable for tacit collusion and cartel behavior research, or even for analyzing unilateral market power on a market with very low marginal costs. However, this is not the case for the electricity markets, where marginal costs are often sharply increasing and the generation capacity limited.

Kreps and Scheinkman (1983, cited in Tirole 1988) also investigated a two-stage Bertrand game where firms first choose quantities simultaneously and once they're aware of each other's capacities, they choose their prices. Kreps and Scheinkman (1983) proved that when firms 1) face a concave demand function, 2) follow an efficient rationing rule (customers with the highest willingness to pay will be served first) and 3) have arbitrary investment costs, the two-stage Bertrand game gives the same results as a one-stage Cournot game. Therefore there's no need to include a deeper presentation of the Bertrand model to this point of this thesis.

Whereas in the Bertrand model firms compete directly in price, in the Cournot model they compete primarily in quantity. This means that smaller the number of the firms, more they have power in affecting the market price by increasing / decreasing their outputs. Now this is exactly what the unilateral market power is about: each firm's output decision affects the good's price. No wonder the Cournot model is one of the most used ones for modeling market power in the electricity markets and therefore I have also chosen it as the theoretical framework for this thesis, to be presented more closely in the following subchapters.

Next to the Cournot model, the Supply Function Equilibrium (SFE) is the other one of the most used tools to analyze market power in the electricity markets. Contrary to the Bertrand and Cournot models which originate from the 19th century, the SFE approach was originally presented only a bit over two decades ago, in 1989, by Paul Klemperer and Margaret Meyer. In the SFE model firms compete in both quantity and price, and instead of choosing an optimal output, they choose their optimal offer curve considering the different demand curves they face.

Out of all three models SFE is the most complex with a set of differential equations to solve and offers multiple equilibria instead of only one. Klemperer and Meyer (1989) further argue that all supply curve equilibria are bounded by the Cournot and Bertrand outcomes, so that when the demand is static, any equilibrium between Bertrand and Cournot is possible, Cournot outcome including most market power. Due to its complexity SFE is closer to reality and is therefore preferred for instance in ex-ante analyses predicting prices (Ventosa et al, 2005).

Willems, Rumiantseva and Weigt (2009) for their part find that Cournot and SFE offer equally adequate results on market power on the German electricity market. They further suggest using the Cournot model for short-term analysis for model's ability to accommodate additional market information, such as network constraints, and the SFE model for long-term analysis since it is less sensitive to the parameters selected. Some researchers prefer the SFE over Cournot (see e.g. Baldick, Grant and Kahn, 2004), and some of the empirical studies presented in chapter 4 have indeed used the SFE as their ground theory. However, as we are not constructing a simulation model in this thesis, it is sufficient for us to understand the fundamentals of the market power, and for that it is sufficient to understand the Cournot model. Therefore I have left a closer presentation of the SFE model for others.

It is also very common to evaluate the extent of market power through different concentration indices, such as the Herfindahl-Hirschman Index (HHI). However, on a market such as electricity with highly volatile, inelastic demand, significant short-run capacity constraints and extreme storage costs even firms with small market shares could still exercise significant market power (Borenstein, Bushnell and Wolak, 2002; Borenstein, Bushnell and Knittel, 1999). Wolak (2005) also notes that several wholesale electricity markets have been subject to severe market power problems even when they had HHIs that would not raise market power concerns on any other industry. Concentration measures incorporate no information about the (in)elasticity of demand, which plays a crucial role on the electricity markets. Therefore I have left a closer presentation of market concentration indices out of this thesis as well.

2.1 Cournot Model

I will now present the theoretical framework of this thesis, the Cournot model. The model was named after the French mathematician and philosopher Antoine Augustin Cournot (1801-1877) who presented his original duopoly model in his book *Researches on the Mathematical Principles of the Theory of Wealth* published already in 1838; interestingly, around the same time as the electromagnetic induction was invented.

One period Cournot model is the basic model of unilateral market power. A firm has unilateral market power when it can, with its own decisions, affect the market price. In the Cournot model, each firm does so by choosing their optimal output to maximize their own profit. While the basic Cournot model is a static, one period model, it doesn't mean that unilateral market power wouldn't last longer. However, the unilateral market power doesn't depend on whether firms face each other on the market repeatedly or not, and therefore there is now no need to build a dynamic model.

To use the Cournot model the market in question has to fulfill the following assumptions: 1) there is more than one firm and all firms produce a homogeneous product, meaning there's no product differentiation; 2) the number of firms is fixed; 3) firms act strategically and seek to maximize profit given their competitors' decisions. It is easy to see that a wholesale electricity market fulfills all of these criteria: there is no real product differentiation and due to high up-front investments the number of firms can be seen as fixed even in the long term. Profit maximization is somewhat natural for any market.

The model further assumes that 4) firms compete in quantities and choose them simultaneously; 5) firms do not cooperate, meaning there is no collusion; 6) firms have unilateral market power: each firm's output decision affects the good's price. The model will tell us prices, quantities and profits as functions of cost structures, the demand function and the number of firms.

The Cournot game must always end in Nash equilibrium. When each player is assumed to know the equilibrium strategies of the other players and no player can benefit by changing its strategy while the other players keep theirs unchanged, the set of strategy choices and the corresponding payoffs create a Nash equilibrium.

I will begin with a throughout presentation of a duopoly model as it is the easiest to model and understand. I will then shortly widen the Cournot model to an n firm case. Although most of the wholesale electricity markets consist of more than two generation firms, the duopoly model gives us all the necessary information in the easiest possible form. It also works as a basis for the electricity market specific model I have constructed in the next chapter. The following mathematical presentation is based on Tirole's (1988) book.

2.2 Cournot Duopoly

Let's consider a duopoly where two firms, i and j, choose their output quantities simultaneously. Firm i's profit function is the following:

$$\pi^i(q_i, q_j) = q_i P(q_i + q_j) - C_i(q_i)$$

where q_i and q_j are the quantities produced by each firm, $P(q_i + q_j)$ is the market price taking into account the total quantity produced and $C_i(q_i)$ is the cost function of the firm i. This function is said to have the exact Cournot form.

Further following Tirole's (1988) path, we assume the profit function π^i to be strictly concave and twice differentiable in q_i. This naturally means that the profit is maximized at the point where the first-order condition of the profit function π^i is equal to zero:

$$\pi_i^i(Q) = P(q_i + q_j) - C_i'(q_i) + q_i P'(q_i + q_j) = 0$$

As Tirole (1988) notes, the first two terms yield the profitability of an extra unit of output, which is equal to the difference between price and marginal cost. The third term for its part represents the effect that the extra unit of output has on the profitability of inframarginal ones. The extra units produced create a decrease in price P', which affects the q_i units already produced. This can be interpreted as the negative externality between the firms: when choosing its output, firm i takes into account the negative effect of the market price change on its own output q_i instead of the aggregate output $q_i + q_j$. This leads to an outcome where each firm tends to choose an output that exceeds the optimal aggregate output from the industry's point of view.

In short, the market price will be lower than the monopoly price and the aggregate profit will be lower than the monopoly profit.

Although the price is lower and the output higher than in a monopoly case, neither reaches the competitive level. Tirole (1988) also points out from the same equation that the Cournot equilibrium does not equalize marginal costs C_i' except in the case that firms are symmetric. From the welfare point of view the aggregate output is too low and furthermore the industry's cost of production is not minimized.

To observe the Cournot equilibrium price more closely, we can rewrite the first-order condition for profit maximization as followed:

$$L_i = \frac{\alpha_i}{\varepsilon}$$

which is defined as the Lerner index for firm i:

$$L_i \equiv \frac{P - C_i{}'}{P}$$

This is the famous Lerner index, also known as the price-cost margin. It is constructed from the following elements:

$$\alpha_i \equiv \frac{q_i}{Q}$$

which is the firm i's market share, where $Q \equiv q_i + q_j$ is the total output of the industry, and

$$\varepsilon \equiv -\frac{P'}{P}Q$$

which is the elasticity of demand. Thus the Lerner index is proportional to the firm's market share and inversely proportional to the elasticity of demand. This index measures the degree to which prices exceed marginal costs. Whenever the price P is higher than the marginal cost C_i', the index is positive, meaning that the firm possesses market power. In a competitive case price would equal the marginal cost and thus the index would give 0; closer the index is to 1 (=monopoly), more the firm has power. In the Cournot equilibrium the index is always positive and therefore the Cournot equilibrium is not socially efficient.

What have we learned so far? The Cournot equilibrium settles between the monopoly equilibrium and the competitive equilibrium: Cournot profit is lower than the monopoly profit but higher than from a competitive market (price is higher than marginal cost yet lower than the monopoly price) and therefore each firm can, with its own production decision, affect the market price. Also the cost of production is not minimized except in a symmetric firms' case. This altogether means that the Cournot equilibrium is not effective either from the industry's point of view or from the social point of view. Simultaneously, it enables the firms to obtain greater profits than from a fully competitive market and offers consumers greater profit than a monopoly.

Following Tirole's (1988) example, I note a few more technical details important for our further analysis. The second-order conditions with respect to q_i and q_j are the following:

$$\pi^i_{ii} = 2P'(q_i + q_j) - C''_i(q_i) + q_i P''(q_i + q_j)$$

and

$$\pi^i_{ij} = P'(q_i + q_j) + q_i P''(q_i + q_j)$$

Now we want the profit function to be concave ($\pi^i_{ii} < 0$) and the quantities produced by each firm to be strategic substitutes ($\pi^i_{ij} < 0$). Recall that $P' < 0$. For the latter one it then suffices the inverse demand function to be concave ($P'' \leq 0$). Beyond that, the profit function to be concave we need the firm's cost to be convex ($C''_i \geq 0$). These assumptions seem pretty obvious and are met for instance for linear demand ($P'' = 0$), which we will be using both in the following example and the model constructed in the next chapter.

As we can now assume the profit function π^i to be strictly concave and twice differentiable in q_i, we obtain a reaction curve R_i with the following definition:

$$q_i = R_i(q_j)$$

This implies that as firms choose their quantities simultaneously, each of them takes the output of their rival as given and bases their output decision (reaction) on that. The objective of each firm's output decision is to maximize profit given the quantity chosen by the other firm:

$$\pi_i^i\big(R_i(q_j), q_j\big) = 0$$

When the outputs are strategic substitutes (meaning zero product differentiation) such as electricity, firm i's profit is decreasing with the other firm's quantity and therefore the reaction curves are downward sloping. We'll look more closely on this once we've derived the Cournot equilibrium.

I hereby derive the results obtained by Tirole (1988). As he shows, the Cournot equilibrium can easily be derived in the case of linear demand and cost. Let's decide the demand function to be $D(p) = 1 - p$ (or more usefully, in the inverse form $P(Q) = 1 - Q$) and the cost function $C_i(q_i) = c_i q_i$.

By replacing the above definitions to the first order condition function, the quantity chosen by the i'th firm (or the reaction function) then becomes:

$$q_i = R_i\big(q_j\big) = \frac{1 - q_j - c_i}{2}$$

and by symmetry:

$$q_j = R_j(q_i) = \frac{1 - q_i - c_j}{2}$$

By replacing the q_j in the first function by its definition (the second function) we obtain the Cournot equilibrium:

$$q_i = \frac{1 - 2c_i + c_j}{3}$$

Again replacing the definitions of inverse demand and cost, this time to the original profit function, and with a little help from the q_i's definition, we finally get the Cournot duopoly equilibrium profit for the firm i:

$$\pi_i = (q_i)^2 = \frac{(1 - 2c_i + c_j)^2}{9}$$

It is understandable that the firm's output q_i decreases with its marginal cost c_i. This implies that an increase in firm i's marginal costs c_i decreases the firm's output, or (and now we get back to the reaction curves as promised) shifts the firm's reaction curve down. What is more interesting, is that the firm's output increases with its rival's marginal cost c_j. The explanation is rather simple: as the firm j faces higher marginal costs, it decreases its output q_j which leads to a larger demand faced by the firm i (recall that the total quantity demanded must be satisfied by these two firms alone as $Q = q_i + q_j$), encouraging it to produce more.

As Tirole (1988) notes, this outcome can be obtained for a more general demand and cost functions, as long as 1) the reaction curves are downward sloping (quantities are strategic substitutes), 2) there exists a unique Cournot equilibrium (the reaction curves cross only once) implying that the slope of R_j in the (q_i, q_j) space is smaller in absolute value than the slope of R_i[4]. This is visualized in the following figure. From the same figure we see that if the firm i's output decreases (the reaction curve shifts down), the rival firm j's output increases (moving upwards on firm j's reaction curve to find a new equilibrium).

[4] To find out more about this "stability condition" you may study the chapter 8 on Tirole's (1988) book.

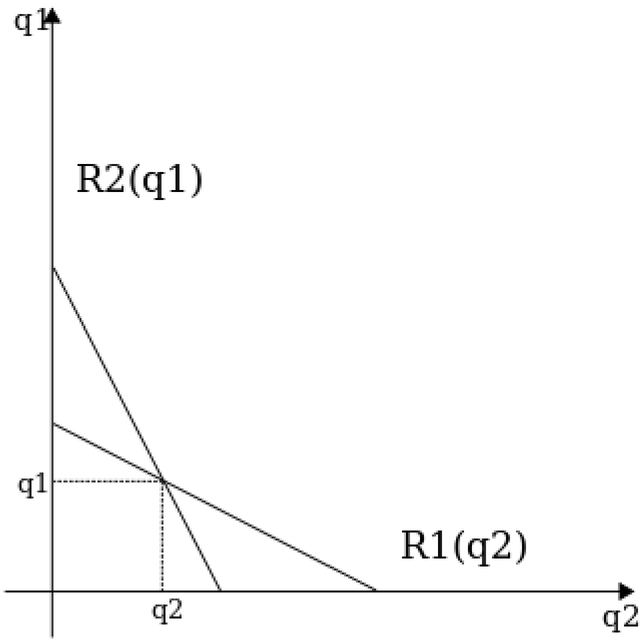


Figure 2: Reaction curves[5].

2.3 Cournot with n Firms

I will now shortly go through the Cournot equilibrium for more than two firms again following the steps of Tirole (1988). This is of course a more realistic case, and the outcome of the model when n approaches infinity further strengthens the reliability of the Cournot model.

Let the total number of firms now be n, forming again the total output Q:

$$Q \equiv \sum_{i=1}^{n} q_i$$

The first-order condition of the i'th firm's profit function now becomes:

$$\pi_i^i = P(Q) - C_i'(q_i) + q_i P'(Q) = 0$$

[5] Now $R1 = R_i$ and $R2 = R_j$. The figure retrieved from Wikipedia, http://en.wikipedia.org/wiki/Cournot_competition, on August 31st, 2014.

The Lerner index or the price-cost margin remains the same: firm's market share divided by the elasticity of demand. If we assume all firms to be identical, with linear demand $P(Q) = 1 - Q$ and linear cost $C_i(q_i) = cq_i$ for all i (with the condition of $c < 1$), the profit maximization equation becomes:

$$\pi = 1 - Q - c - q_i = 0$$

As the total quantity $Q = nq$, there are altogether $n + 1$ "q"s in the previous function, leading us to the equilibrium output per firm:

$$q = \frac{1 - c}{n + 1}$$

and further helping us to define the market price:

$$P(Q) = 1 - nq = c + \frac{1 - c}{n + 1}$$

After a few twists and turns we again obtain the profit per firm:

$$\pi = \frac{(1 - c)^2}{(n + 1)^2}$$

Both the market price and each firm's profit decrease with the number of firms n. Thereby it follows that the aggregate profit $n\pi$ also decreases with the number of firms. And now comes the beautiful part: when the number of firms approaches infinity ($n \to \infty$), the market price approaches the competitive market price or the marginal cost c. Thus, the Cournot equilibrium with a large number of firms is close to a competitive market. This makes sense: as there are many firms on the same market, each has very little power on the market price and therefore acts almost as a price taker.

2.4 Discussion

This basic Cournot model is pretty much identical to any school book presentation, and for a good reason: it is a great tool to understand the basics of unilateral market power on any oligopolistic market. It helps us to visualize why the market price on such markets is in between the competitive and the monopoly price, why everybody is better off than in their worst case scenario and vice versa. No wonder the Cournot model has maintained its popularity since almost two hundred years.

However, as nothing is perfect in this World, neither is the Cournot model. When observing it from the electricity market point of view, probably the biggest concern arises from the demand side assumptions. In the Cournot model the demand and the elasticity of demand are taken as given, whereas in reality the demand is very volatile and especially during its peaks very inelastic. These are obviously also the moments when the abuse of market power most easily takes place. However, a peaking demand curve is pretty impossible to model ex ante.

Other electricity market specific defects of the basic Cournot model have to do with marginal costs and capacity. First, marginal cost of electricity is rarely linear, but rather varies by the technology chosen and the size of the generation unit in question. It is often lower for base load and higher for peak load. Most of the generation technologies don't allow smooth and complete adjustment, but only the option to have the generation unit to be on or off. A generation unit is also always constrained by its maximum production capacity, which means that it cannot be adjusted to very high demand peaks. This means that the capacity is not elastic, and cannot be adjusted as easily as in the Cournot model.

Finally, as any model, also the Cournot model is based on strong assumptions: not only the demand and its elasticity, but also the rival's strategy is taken as given. The capacity decisions are made simultaneously, and what happened in the previous period has no effect on the decisions in this period. This sounds to be pretty far from the reality, where rivals' decisions are rather impossible to predict without collusive behavior and where history always plays a certain role, in this case both in technology (if we had a generation unit running in last period, it might be as costly to keep it running for zero profit as it would be to turn it off) and in human behavior. Borenstein and Bushnell (1999) agree with this and note that it is possible for firms to learn over time to compete less aggressively with one another. According to them, the repeated interaction gives firms more power to punish non-cooperative rivals and therefore leads to less aggressive competition. Needless to say, this would further increase prices and lead to lost consumer welfare.

Furthermore, the Cournot model being static cannot address issues such as entry or exit, nor the issue of sales that take place through forward or futures contracts. The first one isn’t such a problem on the electricity markets due to low (and slow) level of entry. However the future market of electricity is an interesting topic that has raised contrary opinions among researchers about whether it is good or bad for market power mitigation (see e.g. Wolak, 2014; Allez and Vila, 1993; Ausubel and Deneckere, 1987 and Gul, 1987). This is an important subtopic we are not able to tackle with the chosen model.

In the next chapter I have constructed a more electricity market specific, simple game theoretical model based on the Cournot duopoly theory, in which I try to tackle as many of the defects discussed above as possible.

3. Duopoly Power Game

"Electricity is really just organized lighting."

— George Carlin

Electricity generation typically involves significant up-front investments to construct a generation unit. These fixed costs together with variable costs differ between energy sources and production technologies, usually associating lower variable costs with higher fixed costs and vice versa (Wolak 2014). Therefore different generation technologies have very different marginal costs. As Holmberg and Newbery (2010) state, the production cost of a plant is primarily determined by fuel costs and its efficiency, nuclear and hydro-power having the lowest marginal costs. Understandably plants with peak capacity are the most expensive ones: for instance open-cycle gas turbines burning natural gas or oil have low fixed, yet high variable costs (Holmberg and Newbery, 2010).

I have here constructed a very simple, electricity market specific duopoly model. Assume now that we have two kinds of generators: base load and peak load ones. Coal is used for base load generation thanks to its low marginal costs, $MC_C = 1$. Peak load generation is done either using natural gas with $MC_N = 2$, or even more expensive diesel oil, with $MC_D = 2{,}5$. Each firm will always apply the cheapest technology available first. All technologies allow the generation unit to be running either on full or zero capacity, meaning both our capacity and marginal costs are nonlinear. Furthermore, the capacity is not only nonlinear, but also constrained: the total capacity of the market is four generation units, $Q = 4q$, and there is no chance to construct more of them (due to high up-front investments meaning fixed costs which, for simplicity, I have left out of this analysis).

Now all the above assumptions are very strong, yet quite realistic for the electricity market. What is not quite realistic is the linear demand curve. However, it would not be useful to model a realistic demand curve of electricity that is dependent of so many economically unpredictable variables (such as weather) and often very inelastic. Therefore I have followed Cournot's example and assumed a linear demand $D(p) = 6 - p$ or in the inverse form $P(Q) = 6 - Q$.

Now I have constructed five different settings of a similar game, each to be presented in the following subchapters. The assumptions (above) and the basic idea is the same in every setting: there are two electricity generation firms on the market, each of which has two generation units (resulting in market's total capacity $Q = 4q$ as defined above). Now the only thing that changes is the marginal cost of the capacity, or the generation technology and its distribution between the two firms. Each firm can choose to run either 0, 1 or 2 of its generation units. Following the one-period Cournot game firms choose their outputs simultaneously and make their decisions based on the demand curve and the assumed strategy of their rivals. It further follows that as the marginal costs and their division change, the Nash equilibrium (or equilibria) changes.

On each of the following subchapters I have constructed a graphical presentation of the market (note that the demand curve and maximum capacity remain the same in all three models), as well as a payoff matrix to see all the possible profits for both firms in all possible outcomes, and of course to easily point out the Nash equilibria.

3.1 Identical Firms, Pure Base Load

In this first setting I assume the whole capacity $Q = 4q$ is generated through coal, which has low marginal costs $MC_C = 1$. As we can see from the graph on the left hand side, no such a thing as competitive market equilibrium exists on this market (demand D and marginal cost MC don't cross): the demand or the willingness to pay is so high that the duopolies will make profit with each unit of output even if they decide to run all of them. Now both firms i and j have two identical generation units each, and each with low marginal costs. On the right hand payoff matrix I present the possible outcomes of each individual strategy.

i, j	0	1	2
0	0, 0	0, 4	0, 6
1	4, 0	3, 3	2, 4
2	6, 0	4, 2	2, 2

Figure 3

Now it is easy to see that there are three Nash equilibria in this game: when (i, j) choose to run either (2,1), (1,2) or (2,2) generation units (profits are (4,2), (2,4) and (2,2) equivalently), the price p setting to either 2 or 3.

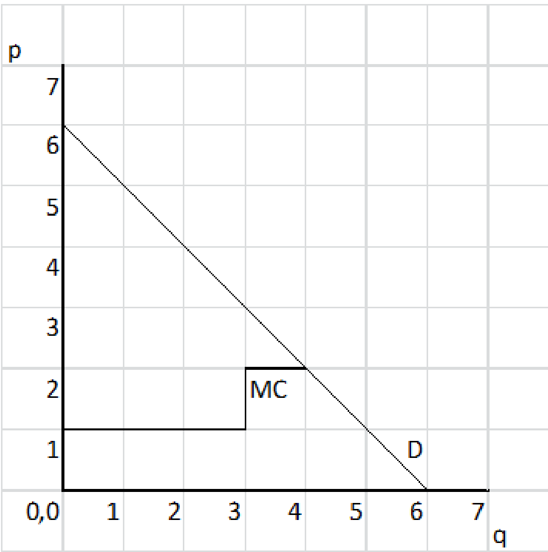
Although we cannot obtain the competitive market equilibrium with our assumptions in this setting (not that it would be our goal either, but for comparison), the Nash equilibria obtained here are also the closest possible to it: either all or the majority of the capacity will be in use. Note that both firms would obtain equal profits higher to the full capacity strategy if both ran only one generation unit. This is the joint monopoly or the tacit collusion outcome. However we can see this is not a Nash equilibrium and therefore not a valid outcome for this game.

3.2 Non-identical Firms, Base and Peak Load

Now I have modified the previous setting a little bit. Firm i still has two base load units, so for that part, his situation remains unchanged. Firm j, for his part, now has one base load unit and one peak load unit, the latter running with natural gas in 3.2.1 and with diesel oil in 3.2.2.

3.2.1 Cheaper Peak Load

The graphical presentation of the market as well as the payoff matrix may be seen below.



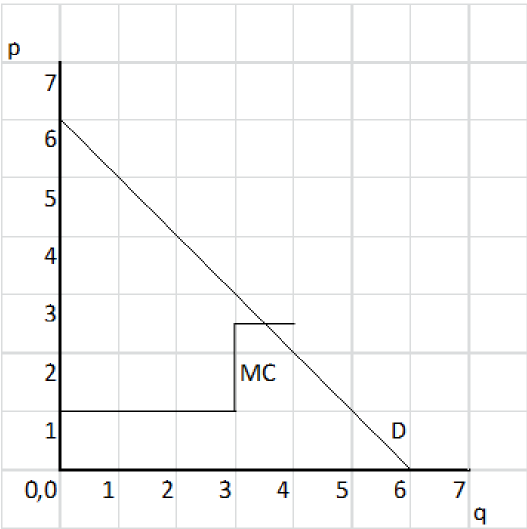
i, j	0	1	2
0	0, 0	0, 4	0, 5
1	4, 0	3, 3	2, 3
2	6, 0	4, 2	2, 1

Figure 4

Now the competitive market equilibrium could be achieved with the same outcome as in the previous model, this time being a real competitive market equilibrium with marginal cost and demand functions crossing at $p = 2$. However, as the matrix shows us, this is not the Nash equilibrium. Furthermore, there are now two Nash equilibria (compared to three in the previous game) in this game: when (i, j) choose to run either (2,1) or (1,2) units, giving payoffs of (4,2) and (2,3) equivalently. Either way, three generation units will be running for market price $p = 3$.

3.2.2 More Expensive Peak Load

Now let's see what happens when the marginal cost of the peak load unit rises fro 2 to 2,5.



i, j	0	1	2
0	0, 0	0, 4	0, 4,5
1	4, 0	3, 3	2, 2,5
2	6, 0	4, 2	2, 0,5

Figure 5

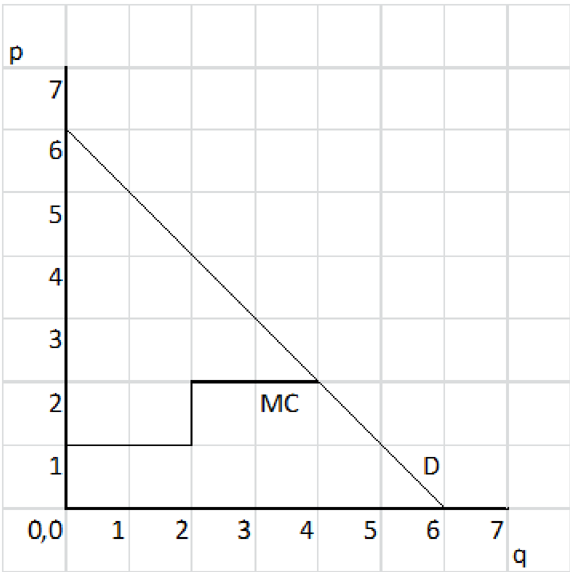
Now it is clear that there's no point to run all four units, as the fourth one would result in negative marginal revenue. Furthermore, the only Nash equilibrium of this game is obtained when (i, j) choose to run (2,1) units, giving payoff of (4,2) equivalently. Just like with the cheaper peak load unit, three generation units will be running in equilibrium for market price $p = 3$.

3.3 Identical Firms, Base and Peak Load

Let's again combine the previous settings in a new way. Just like in 3.1 we now have two identical firms. However this time both firms have one base load unit and one peak load unit each. Following the structure in 3.2, in the first game the peak load units run with cheaper natural gas and in the second setting with more expensive diesel oil.

3.3.1 Cheaper Peak Load

Once both firms have one generation unit running with natural gas, the graph and the payoff matrix get the following forms:



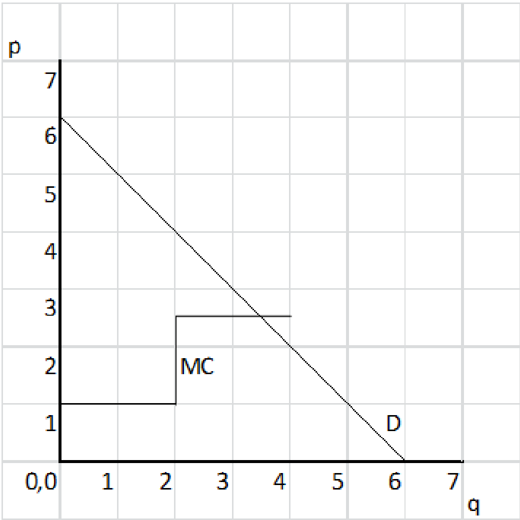
i,j	0	1	2
0	0, 0	0, 4	0, 5
1	4, 0	3, 3	2, 3
2	5, 0	3, 2	1, 1

Figure 6

This time we again have three Nash equilibria: when (i, j) choose to run either (1,1), (2,1) or (1,2) generation units, with equivalent profits of (3,3), (3,2) and (2,3). The price now settles to either 3 or 4.

3.3.2 More Expensive Peak Load

The following figure and payoff matrix show the equivalent results for more expensive peak load.



i, j	0	1	2
0	0, 0	0, 4	0, 4,5
1	4, 0	3, 3	2, 2,5
2	4,5, 0	2,5, 2	0,5, 0,5

Figure 7

Now this gets interesting: in this game the only Nash equilibrium is the strategy of both firms running only one single unit, giving profits of (3,3). This is equal to tacit collusion or joint monopoly equilibrium. I will discuss this finding along with the previous ones in the next subchapter.

3.4 Discussion

This game could be further developed in several different settings. However, the games played above give us all the information we needed. The most important thing observed here is the effect of marginal costs on firms' profits. Compare for instance the first and last games, or 3.1 and 3.3.2. In the first one the Nash equilibrium is obtained by any strategy (excluding the strategies where either one would fully refrain from the competition) except the one with least output (1,1) and highest equal profits of (3,3). In contrast, in the last game played this strategy of one unit of output each yielding profits of (3,3) is the *only* Nash equilibrium.

Simply put: more expensive the generation gets, fewer incentives the firms have to use it, more market power they have and closer to joint monopoly profits they get. As the generation units get more expensive, it is easier for firms to know each other's strategies without collusive behavior; the same strategy of one unit each with profits (3,3) could have been obtained already in the first game, but not being Nash equilibrium it was not sustainable and therefore not a realistic outcome of that game. In the last game however both can be sure of the other one offering only one unit of output to the market. Similar results can be found when comparing 3.2.1 with 3.2.2. Furthermore, similar results would be obtained even with the cheaper peak load capacity if the demand was even slightly lower.

All the games played above support the theory presented in chapter 2 stating that the Cournot equilibrium settles in between the competitive and the monopoly one. When looking at the payoff matrices, you may note that more expensive the capacity gets, higher the market price of electricity arises: with pure base load it settles between 2 and 3, with one peak load unit to 3, and with one peak load unit each between 3 and 4 or in the case of the more expensive peak load, directly to 4. This means that with higher marginal costs further from the competitive equilibrium and closer to the monopoly equilibrium we move. This sounds reasonable: as long as we have cheap capacity, it literally pays off to answer to high demand. Less payoff per extra unit of output we get, less interested we are to fulfill the high demand, knowing the amount of market power we have. As the duopolies have their market power, they have every reason to use it for their own benefit.

In the classical Cournot model the raise in rival's marginal costs raises the firm's profit through raising the demand it faces. Although our setting is a bit different with the constrained capacity and non-linear marginal costs, the outcome holds: for instance in both 3.1 and 3.3.1 (when firms are identical) the average payoff from the Nash equilibria is 2,67 for each firm. On contrary, as soon as firm j has higher marginal costs than i, as is the case in 3.2.1, firm j's average payoff from the Nash equilibria falls to 2,5 and i's arises to 3. This makes a lot of sense.

Just like the Cournot model, this game points out the existence of market power and the causes enforcing it. How much of market power there actually is in every game is based on strong assumptions of the demand curve. Once the demand is known and other parameters (for instance weather, raw material costs and energy imports) are controlled, the only remaining variable to define is the capacity decisions: how much of the withholding of capacity is done for maintenance and how much for "maintenance"?

4. Empirical Evidence

“Enthusiasm is the electricity of life.”

— Gordon Parks

In this empirical part I have handpicked some of the most relevant cases and studies on market power in electricity markets in the United Kingdom during 1990-2001 and California during 1998-2000. Note that not nearly all of the studies are run through a strict Cournot model. Instead, I have constructed a discussion between different approaches. However, once variables such as policy implications and weather are controlled, most of the studies find at least partial evidence in favor of unilateral market power and Cournot pricing on both markets.

4.1 Early Case: UK

The United Kingdom (UK) was the second country worldwide to open its electricity market for competition, right after Chile. It has therefore been under close observation of market power researchers. Although the British electricity market hasn’t experienced any notorious crisis after its reform (unlike California, to be discussed in the following subchapter), several researchers have still found loopholes (and their abuse) in the strictly regulated power market. It is also a great example of an electricity market where the concentration indices haven’t worked at all for successful price prediction. I have here collected some of the most relevant research articles observing roughly the first decade of Britain’s reformed electricity market.

Prior to 1990, a single government organization called the Central Electricity Generation Board (CEGB) was the only owner of all the generation plants and the countrywide transmission system. The CEGB’s only customers were the 12 government-owned Area Boards which distributed electricity to all end-use customers within their local districts in England and Wales. In April 1990 the Area Boards were converted into private Regional Electricity Companies.

CEGB for its part experienced bigger transformation: transmission was separated to its own company and the generation was divided between three firms, of which National Power and Power-Gen originally possessed around 80 % of the market, a share that dropped to 55 % by 1996 and to 25 % by 2001 (Bunn and Martoccia, 2005; Wolak and Patrick, 2001; Wolfram, 1999). Meanwhile the two largest generation firms steadily reduced their generation capacity, many smaller existing power producers increased their capacities and several independent power producers entered the market. The net effect of the deletions and additions to capacity in this market was a decrease in the total generation capacity serving the market despite growing electricity consumption over this same period (Wolak and Patrick, 2001). More interestingly, the strong decline in market concentration didn't decrease the electricity wholesale price.

For the first decade after the market reform, all wholesale electricity in Britain was traded through a central pool. The transmission network company was responsible of the pool administration. The pool operated as a spot market for electricity for the first 11 years after the market restructuring, giving a half-hourly price for the electricity traded. It also matched supply and demand in real time, maintained the network frequency, voltage and stability, managed network constraints and administered financial settlements between buyers and sellers (Wolfram 1999). In addition to the large generators and independent power producers, also Scottish and French generation companies sold electricity to the pool. From 2001 upon the pool was replaced by New Electricity Trading Arrangements (NETA), voluntary bilateral trading.

The studies cited below apply different theories and methods and use slightly different data sets. Therefore the exact results include some variation. However about the big picture they largely agree: as the concentration of the British electricity market decreased, the market power abuse increased. From the beginning of the reform until 1996 there is slight evidence of unilateral market power exercise, which was however kept modest thanks to strict regulation. From 1996 until 2000 the behavior of the firms had rather collusive characteristics: the market concentration kept falling but the prices remained steady. Early in 2001 the electricity prices as well as the price-cost margin fell significantly although the market structure didn't notably change. This suggests that tacit collusion may have broken down once it was known that the pool would soon be history.

Prior to the market reform, Green and Newbery (1992) predicted high levels of market power exercise by the duopolists. Later on Wolfram (1999) makes a detailed analysis of the early years of the reformed market and shows that generators exercised less market power from 1992 to 1994 than predicted by Green and Newbery (1992). As data she uses over 25 000 observations on prices obtained from the National Grid Company and half-hourly quantities from six months every year from 1992 to 1994, as well as marginal costs of generators from the same time period, including fuel price and weather information from secondary sources. Although the observed price levels fell far short from what the profit-maximizing oligopoly models had predicted, she indeed finds clearly positive price-cost margins for every time period studied, telling about the existence of market power. She finds evidence both for regulation-responding behavior and entry deterrence.

Supporting Wolfram's (1999) findings, Wolak and Patrick (2001) study the first four years of the restructured electricity market. They use half-hourly market-clearing prices and quantities, and the half-hourly bids submitted from the British electricity market. Their interest is to know whether the new market structure has been able to eliminate significant profit-making opportunities for generators. They find that the prices had mostly been maintained close to competitive levels; however the two largest producers had been able to temporarily obtain spot prices much higher than the average cost of supply through withholding of capacity for short time periods on a daily basis.

Wolak and Patrick (2001) further note that this market power activity leads to prices in excess of marginal and even average costs only for time periods as short as two or three half-hour load periods within one day. They also find that the days in which the high-priced half-hour load periods occurred tended to follow one another in the same week. As a result of this action, the profits of National Power and Power-Gen didn't decline in direct proportion to their decreased annual electricity output and market share. Their findings directly support the use of the Cournot model for high demand periods.

In contrast to Wolak's and Patrick's (2001) findings, Green (2004) believes the opposite. He tests whether the British generators were withholding capacity in order to raise prices above competitive levels. He states not to find any evidence of market power abuse and even suggest that a Bertrand competition would be more suitable more market power research on electricity markets than the Cournot one.

I dare to disagree. Although the information sources Green (2004) uses seem accurate (he uses information on load factors[6] before and after restructuring published by CEGB and Monopolies and Mergers Commission, as well as hourly load-duration curves provided by the National Grid Company), the time unit chosen (a full year) seems little accurate to me. I do agree with his statement that the evidence for large-scale capacity withholding is weak, yet it is the same as Wolak and Patrick (2001) formerly made. However the market power existence is as fast moving phenomena as electricity itself, and therefore such a general approach seems little valid and even less comparable with Wolak's and Patrick's (2001) half-hourly findings.

All researchers agreed that, no matter whether market power was formerly abused or not, the continuous fall in market concentration should translate into declined electricity prices. However this was not the case.

Sweeting (2007, 2001b) studies the second half of the decade by testing the static Nash equilibrium assumption, or our beloved Cournot theorem. Using residual demand functions for each player, he finds a significant change in behavior in late 1996. He states that prior to this the generator behavior was consistent with the static Nash equilibrium assumption, taking into account that most of the output (70 %) was

[6] If the generation unit is up and running every moment of the year, its load factor is 100 % (Green, 2004).

covered by financial contracts which hedged prices from rising excessively high. After 1996, instead of the static Nash equilibrium assumption, the firm behavior and prices were closer to a repeated game tacit collusion. What makes this interesting is that an obligation to keep prices low expired in April 1996 and as part of it, the divestiture of capacity completed in July 1996. This further supports Wolfram's (1999) findings about regulation-responding behavior.

The graph below represents the monthly average price-cost margins based on prices paid by generators. According to the graph generators exercised less market power during the low demand summer months and more market power in every month in 1998-1999 than in 1995-1996.

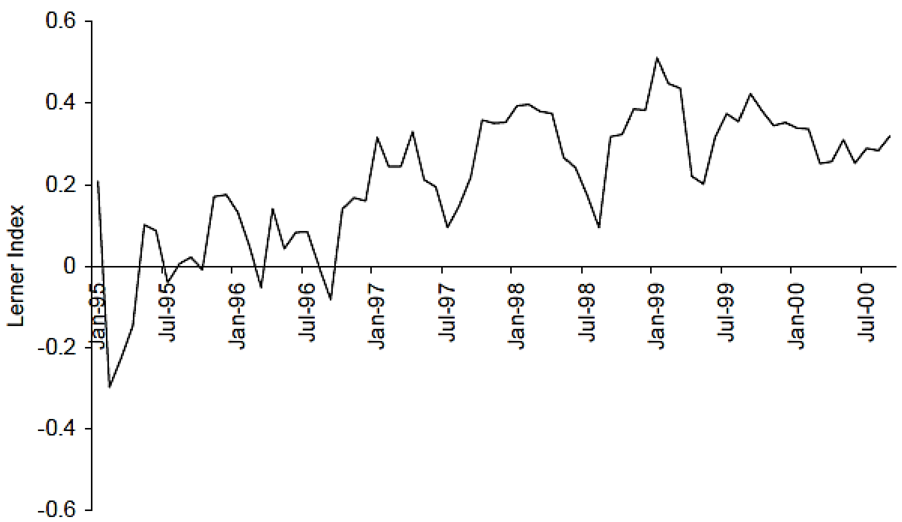


Figure 8: Monthly average price-cost margins in the UK electricity market 1995-2000 (Sweeting, 2007).

Bunn and Martoccia (2005) study the changes in electricity prices from the whole decade constructing a microsimulation model of agent bidding behavior. The electricity prices in Britain did not fall at all during the 1990s despite the massive changes in the market structure. However the prices did fall by some 25% in 2000-2001, although no remarkable market structure or market share changes occurred (Bunn and Martoccia, 2005). Their research supports the above referred findings of Wolfram (1998) and Sweeting (2007, 2001a) about the National Power's regulation-constrained exercise of unilateral market power in the early years. Bunn and Martoccia (2005) further suggest that as the market concentration declined, the unilateral market power gradually turned into coordinated, tacit collusion in the later years.

4.2 Extraordinary Case: California

Inspired by early-movers such as the UK, California reformed its electricity market in 1998. Prior to deregulation, Borenstein and Bushnell (1999) used the Cournot model to examine different scenarios, assumptions and issues concerning the organization of the Californian electricity market. They calculated the Cournot equilibria at several demand levels for six selected hours in four different months to include seasonal variations in available hydro energy, gas prices and relative regional demand levels. As a comparison, they also calculated the price that would have resulted if all firms acted as competitive price takers.

This is what they found: "Absent significant divestiture of assets by incumbent producers, the restructured California electricity generation market could have a few large producers each of which would potentially find it profitable to restrict output to raise price. […] The simulation recognizes that large firms might have an incentive to restrict output to raise price." And this is exactly what occurred.

California's electricity market, and especially the crisis it experienced at the change of the millennium, must be the most known worldwide. California began to open its federal electricity market during the second half of the 1990's and the market was formally opened in April 1998. Towards the end of the decade the price of natural gas increased, a heatwave hit the area causing the demand for electricity to peak and drought to the Pacific Northwest states, further causing decrease in imports of electricity to the California state. Needless to say, the conditions were perfect for unilateral market power to raise its head (and high).

At the same time the fact that the generation and wholesale prices were liberalized and the retail prices capped led electricity wholesale prices to exceed retail prices. This made the wholesalers unwilling to pay their bills, making the generators unwilling to provide them energy. The whole mess ended up as broad, consequent blackouts that affected tens of thousands of people and finally the bankruptcy of Pacific Gas and Electric Company, one of the state's largest energy companies.

The following graph represents the hourly wholesale prices of electricity in California from April 1998 until November 2000. According to Joskow (2001), wholesale electricity prices in California increased by 500% between the second half of 1999 and the second half of 2000. As the conditions enhancing the unilateral market power were directly price-increasing as well, several studies have been made about the extent of the market power's role in the wholesale price formation.

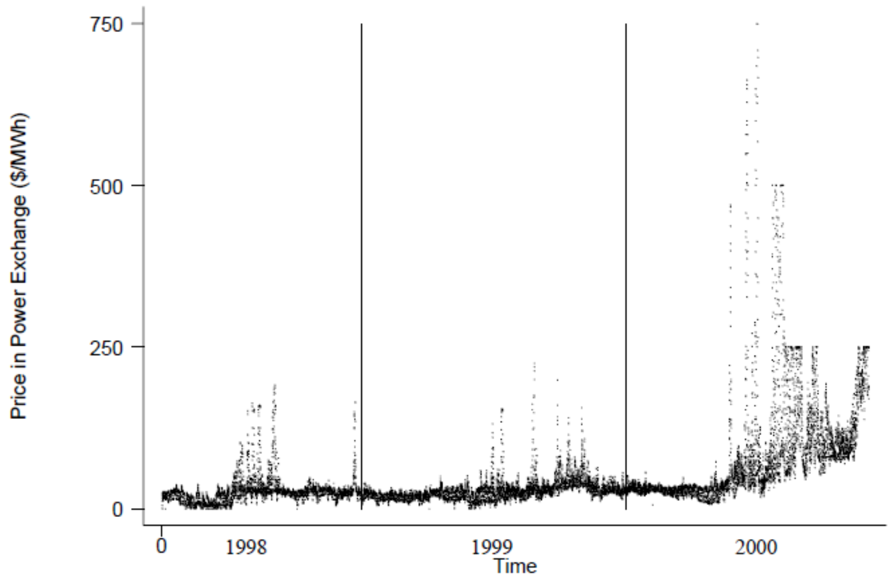


Figure 9: The hourly wholesale prices of electricity in California from April 1998 until November 2000 (Puller, 2007).

The following figure from Joskow (2001) displays the difference in reported outages between 1999 and 2000 for October and November. The proportional shares of intended and scheduled outages got arguments and counter-arguments from generators and California government (Joskow 2001). Whatever the proportions are, it is clear from the figure that the quantity of generation capacity being out of use was excessively huge at the end of 2000 compared to the same period previous year. Joskow (2001) further notes that from November 2000 until May 2001, as much as 35% of total capacity of the generating capacity in California was not in service and was unavailable to supply electricity during this period, which is approximately twice the typical historical forced and planned outage rate.

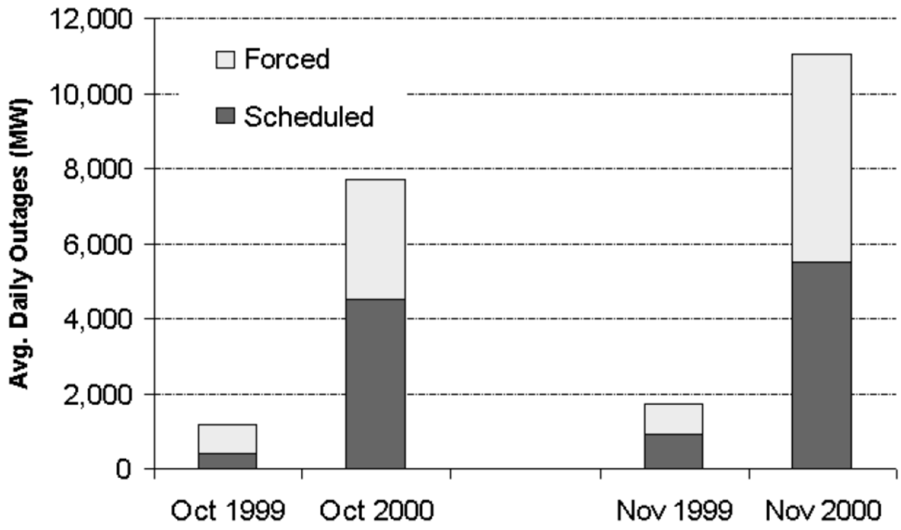


Figure 10: The difference in reported outages between 1999 and 2000 for October and November (Joskow, 2001).

Joskow and Kahn (2002) construct a simulation model of competitive benchmark wholesale prices for electricity in California during the summer of 2000. Their research differs from several others by its data: instead of using confidential data available only to the California Independent System Operator (CAISO) or to the California Power Exchange (PX), Joskow and Kahn (2002) use public data provided by Environmental

Protection Agency, Continuous Emissions Monitoring System and Western Systems Coordinating Council. They control the increased electricity demand and natural gas prices, and the decreased imports of electricity from other states, as well as the impact of changes in the prices of nitrogen oxides (NOx) emissions permits on estimated competitive benchmark prices for electricity. They further compare these prices to the actual, occurred prices. Their research states that whereas all the mentioned variables explain the high wholesale prices to a certain extent, the higher NOx permit prices and their interaction with reduced imports have a particularly large impact on competitive benchmark prices. From the remaining fraction of the price exceeding marginal costs they indeed find strong evidence of market power abuse, not surprisingly in the form of withholding capacity.

Borenstein, Bushnell and Wolak (2002) follow the methodology developed by Wolfram (1999) cited in the previous subchapter and simulate a perfectly competitive market from 1998-2000 and compare those prices to actual prices. They decompose wholesale electricity payments into production costs, inframarginal competitive rents, and payments resulting from the exercise of market power. They use data on the unconstrained PX[7] day-ahead electricity prices from June 1998 to October 2000. They find near-competitive pricing during the lower-demand months of the first two years and in contrast heavy departures from competitive pricing during the high-demand summer months. Furthermore, in summer 2000, wholesale electricity expenditures were $8.98 billion up from $2.04 billion in summer 1999. They state that even a perfectly competitive California electricity market would have seen wholesale electricity expenditures triple between the summers of 1998 and 2000, but agree with other researchers on the unarguable existence of market power: "We find that 21 percent of this (price) increase was due to production costs, 20 percent to competitive rents, and 59 percent to market power" (Borenstein, Bushnell and Wolak, 2002).

Borenstein's Bushnell's and Wolak's (2002) research also supports my previous theoretical findings that market power is most commonly exercised during peak

[7] The PX ran a day-ahead and day-of market for electrical energy utilizing a double-auction format Borenstein, Bushnell and Wolak (2002).

demand periods. The intertemporal variation in the ability to exercise market power is something characteristic for an unstorable good such as electricity. Furthermore, "the problem is exacerbated in electricity because demand is very inelastic in the short run, and supply becomes very inelastic as production approaches the system-generation capacity" (Borenstein, Bushnell and Wolak, 2002).

Wolak (2003) finds results similar to Borenstein, Bushnell and Wolak (2002) when observing market power on a firm level. He uses the actual bids submitted to the CAISO's real-time energy market to measure the unilateral incentives of California's five largest electricity generation companies[8] to exercise market power in the state's wholesale market during the summers of 1998 to 2000. Wolak (2003) uses the inverse of hourly *ex post* residual demand elasticity faced by each of the five biggest firms to measure the extent to which each of them is able to raise the hourly real-time energy price above its marginal cost. He finds significantly higher values for this measure of unilateral market in 2000 relative to the corresponding firm-level values in the previous years.

Although all the researchers sited above (along with pretty much everyone aware of the California electricity crisis) agree on the existence of some form of market power during the crisis, Puller (2007) sharply notes that there is less understanding of the type of oligopoly pricing that led to the exercise of market power. He remarks that different oligopoly pricing models could have existed in California during that time, not only unilateral market power but also tacit collusion. The inelastic residual demand faced by individual firms provides the ability to unilaterally raise prices, whereas the daily repetition of the bidding game between a small set of firms combined with very accurate information about rivals' costs (largely available on the Internet at the time) would have facilitated tacit collusion. Puller (2007) therefore tests whether firm-level production behavior was more consistent with unilateral market power or tacit

[8] AES-Williams, Reliant, Duke, Southern Energy and Dynegy, which together accounted for about 50 % of the market. (Puller 2007)

collusion. Furthermore, he analyzes the extent to which higher prices resulted from less competitive pricing behavior rather than less elastic demand or higher costs[9].

Puller (2007) analyzes the competitive behavior of the five largest firms, who together counted for about 50 % of the in-state production capacity in California during the crisis. He uses hourly firm-level data on output and marginal cost of production and estimates the hourly residual demand function faced by the five large firms using the known supply of the rest of the generators, as well as PX day-ahead energy price (80-90% of all transactions occurred in the PX during the time from April 1998 to November 2000). He gets similar results to Joskow (2001): each of the five large generating firms withheld output when price exceeded marginal cost. Puller (2007) further compares the actual wholesale prices to competitive pricing (perfect competition, the intersection of marginal cost and residual demand) and joint monopoly (or perfect tacit collusion, giving same results as an actual monopoly; the intersection of marginal revenue and marginal cost) pricing. Note that this is exactly what we did in the theoretical chapters 2 and 3 of this thesis. And so are Puller's (2007) results: "I find that actual prices are between the two benchmarks."

As such prices can arise from different oligopoly strategies, Puller (2007) further constructs a methodology to test whether the actual prices were closer to efficient tacit collusion or static non-cooperative behavior, meaning the Cournot competition. For this purpose he estimates both the dynamic and the static first-order conditions. The dynamic model easily rejects efficient tacit collusion by two or more of the firms. In other words, firms were pricing far below the joint monopoly prices, as the figure below shows[10].

[9] Price-cost margins can vary due to both supply and demand side factors: demand can become more or less elastic and firms can engage in a more or less competitive oligopoly pricing game. Therefore the rise in price-cost margins during the crisis could have resulted from firms behaving similarly on a less elastic demand function or firms behaving less competitively. (Puller 2007)

[10] Puller (2007) experiments with two functional forms, constant elasticity and quadratic, to estimate sensitivity. The joint monopoly price is very sensitive to the shape of residual demand at very high prices and therefore different functional forms give different results.

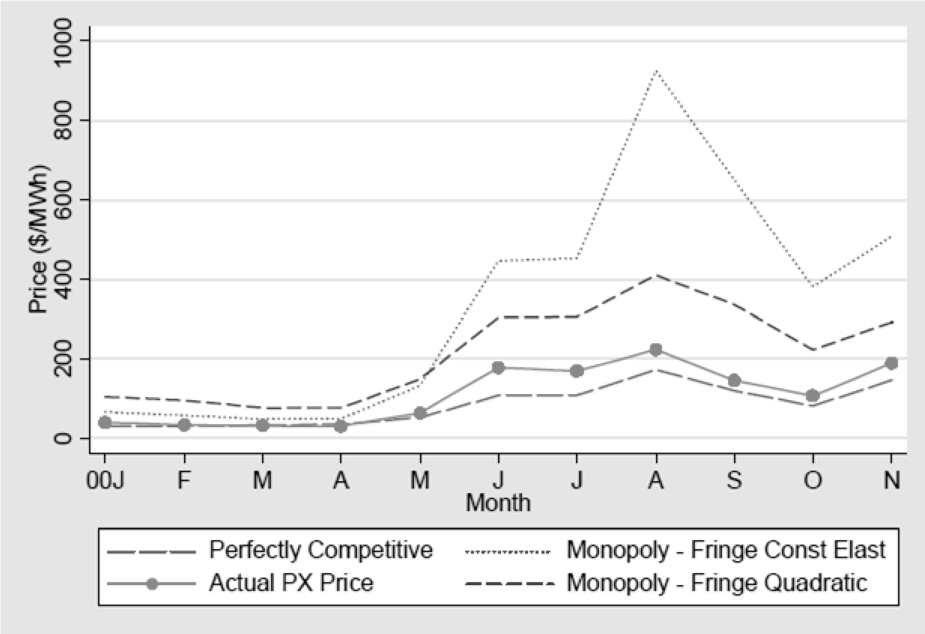


Figure 11: Competitive, actual and monopoly prices of electricity in California in 2000 (Puller, 2007).

The following figure for its part represents the simple average of five largest firms' price-cost margins each hour[11]. If the firm is producing at full capacity, its margin is set to zero. The figure shows that price-cost margins vary considerably over the whole period and are higher during the third and fourth quarters of each year, when total demand for electricity is high. These results are in line with Borenstein, Bushnell and Wolak (2002) who find the largest differences between price and marginal cost during the summer months and above all in 2000.

[11] Puller (2007) notes the following: "*I emphasize that these margins are not scarcity rents because these are differences between price and marginal cost when firms have excess capacity. (…) The margins are not interpreted as measures of profitability because firms incur other on-going costs such as the cost of starting up a generator. Rather, these positive margins are measures of non-price-taking behavior because the units I analyze have already incurred the startup costs yet fail to utilize capacity when price is above marginal cost.*"

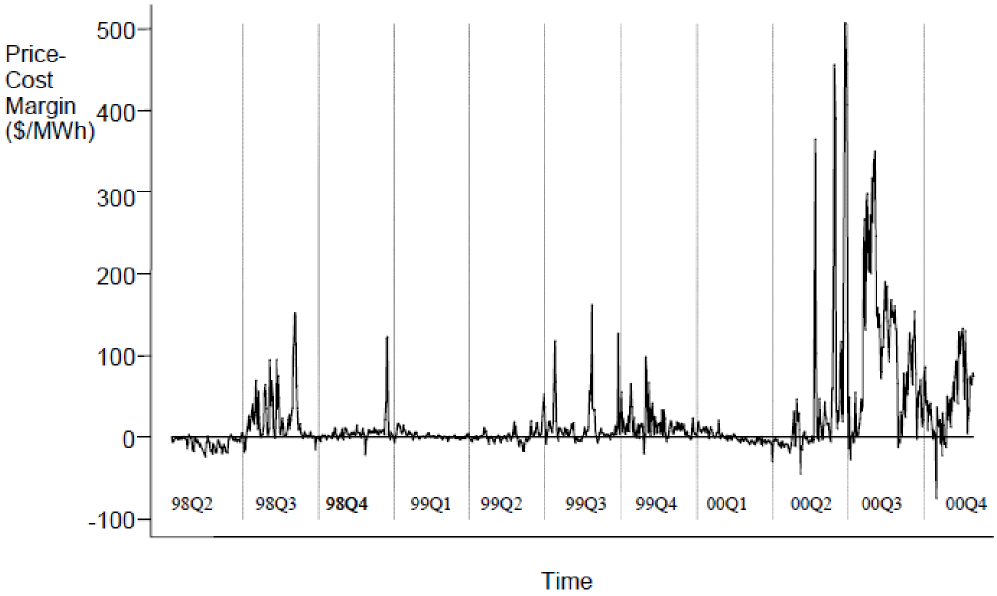


Figure 12: Average price-cost margins of five largest generation firms in California 1998-2000 (Puller, 2007).

Puller (2007) finds that pricing was approximately Cournot for 3-4[12] of the 5 firms during most of the 1998-2000 period. Even when allowing firms to have individual conduct parameters, the hypothesis of Cournot pricing remains (Puller, 2007). Puller (2007) says this to suggest that the large variation both in prices (Figure 9) and price-cost margins (Figure 12) was driven by changes in the size of residual demand faced by the five large firms with incentives to exercise market power, rather than by changes in the oligopoly pricing game. As a defect of his broad study, he notes that the empirical model is not capable to test for inefficient tacit collusion nor any other form of

[12] Puller (2007): "*When I allow for heterogeneous conduct parameters from June-November 2000, I fail to reject Cournot pricing for AES, Duke and Reliant. However, Southern and Dynegy's conduct parameters, $\hat{\vartheta}$ = 1.46 and 2.39 respectively, are statistically higher than unity. I cannot rule out the possibility that these two firms are engaging in some form of tacit collusion between firms with asymmetric cost structures as discussed earlier. However, there are strong reasons to believe that Dynegy's conduct parameter is biased upwards because I do not have data on the output from its peaking units.*"

dynamic pricing that would sustain prices between the Cournot and efficient collusive prices.

To sum up, it is easy to agree with Wolak (2010): the exercise of unilateral market power is not a long-term problem. As the retail electricity prices in California were liberalized and began to rise in June 2001, wholesale prices began to fall. By the end of August 2001 wholesale prices had fallen 90% from December 2000, to the level preceding the crisis (Joskow, 2001). However, enormous amounts of economic harm had already occurred in a relatively short time period.

4.3 Discussion

Although the British electricity market was practically a duopoly at the beginning of its reformed history, it was well regulated and therefore the wholesale electricity prices didn't notably rise at any point. On the other hand, even after notable fall in market concentration the prices remained unchanged, giving researchers reasons and data to believe that tacit collusion took place.

In contrast in California, the electricity crisis experienced was extensive for several reasons favoring unilateral market power abuse: due to the weather conditions the import level of hydroelectric energy was lower and the demand higher. Simultaneously natural gas experienced a price increase. Researchers are unanimous about the existence of market power exercise, but of the extent there are competing results. The capacity withholding in California during highest demand periods was extensive, which supports the Cournot competition. For instance Puller (2007) finds that, all other variables controlled, the actual prices were very close to the Cournot equilibrium.

On neither market was the market power a constant phenomenon, but instead took place during certain hours of the day and certain months of the year characterized by even less elastic demand than the others.

Joskow (2001) concludes the idea well: “Since there is virtually no real demand elasticity yet in these markets, and during peak periods most demand is satisfied with purchases in the spot markets, it is evident that as demand grows and supply gets very tight, generators realize that a small amount of capacity withholding, even with moderate levels of concentration, can lead to large price increases.”

5. Conclusion

"I've found out so much about electricity that I've reached the point where I understand nothing and can explain nothing."

— Pieter van Musschenbroek

This thesis represents the basic Cournot competition model to understand market power in oligopoly markets. I also construct a simple game of two electricity generation firms with different capacity settings, showing how the firms benefit from increased capacity costs in the form of increased market power. I further represent two interesting electricity markets, the one in Britain and the other in California, and relevant empirical research on them to show how electricity oligopolies function in practice. Especially in California strong evidence supporting the Cournot competition can be found.

As many researchers have noted, electricity market is a very fruitful one to study (especially ex post) due to high level of accurate information about prices, costs and demand. Likewise, many policy makers have noticed the importance of such research. To mitigate market power we must first understand it. I believe it is useful to use several different tools and theories to analyze the existence of market power: I don't see Bertrand, Cournot and SFE as rivals, but rather each other's supporters. Together with the market simulations and other market measures these tools provide us with a complete pack to tackle the market power issues. Furthermore, their extensive application is essential prior to any significate policy changes. If there's one thing we can learn from the California's crisis, it is patience: electricity markets contain so much power that no reform should be made prior profound market research and adequate regulation.

Several researchers cited in this thesis have published their own views on most efficient tools for this. I would like to point out two things worth focusing on: regulation and demand side motivation. Too often is "liberalization" or "deregulation" misleadingly used as a synonym for the market reform. Introduction of competition to the former monopoly regime doesn't automatically make a market competitive. Knowing the physical, geographical and financial constraints of the electricity markets, I dare to doubt whether perfectly competitive markets can ever be obtained. Therefore adequate regulation is needed. How to do this in such a way that existing and new firms still have enough incentives to operate in the market? Undoubtedly perfect regulation is as difficult to obtain as perfect competition.

The other point, demand side motivation, is perhaps easier to mathematically model. No matter the theory applied, the researchers are unanimous about the fact that the inelastic demand is a key player in giving space for market power to be exercised. Less elastic the demand is, stronger the market power gets. Some unpublished research (see e.g. Kahn and Wolak, 2013; Wolak, 2006) have found empirical evidence that customers can respond to short-term wholesale price signals if they have the metering technology or even the knowledge to do so. Wolak's (2006) experiment supports this hypothesis holds whether the customers are industrial, commercial or private and, in the case of private consumers, the raised elasticity does not significantly depend on their income level.

A great thing about the demand side motivation for more elastic demand is that it is independent from geography and physics, as the figure presented in the introduction shows. However it is largely dependent on financial resources. Furthermore, firms must be the market participant with best resources to develop real-time meters forward. Unfortunately they also have the least incentives to do so.

In short, just like the electricity plays a role in governments' development goals and individuals' lives so are governments and individuals needed to play a role in the electricity markets.

Further research topics are numerous. As the electricity markets as a whole are a bit more than 120 years old and as their reformed journey began only a few decades ago, the topic is still fresh with a long future to come. Furthermore the new emission regulations, population growth and the current worldwide economic situation raise even more questions to solve.

How big is the effect of the demand curve on the market power? Would the Cournot model still be successful in its predictions if the demand was more elastic? What are policy makers' interests to mitigate market power? How will the increasing amount of electricity generation by individual households (such as solar panels) affect the extent of market power? How does the share of renewable energy affect the market power? These are only some of the numerous possible topics for future research.

A lot has been learned from the reforms in UK, California and elsewhere, and a lot remains to be learned. Every market is different, every reform is different and therefore the outcome of every market reform is different. Therefore it is not possible to "copy-paste" any reform to any other market, no matter how perfect the outcomes obtained. Yet to make successful policies and even successful research, it is necessary to be aware of the surrounding world with its markets and researches. The aim of this thesis was to present one old and golden tool to understand the market power in oligopolistic electricity markets. I hope you have enjoyed as much as I did.

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