DET ØKONOMISKE RÅD
SEKRETARIATET

Imperfect Competition in the Nordic Electricity Markets

Mikkel T. Kromann

Working Paper 2001:3

The Secretariat publishes a series of Working Papers, which primarily contains detailed information on the analysis of selected subjects of the reports by the Chairmanship. The Secretariat is responsible for the series of Working Papers.

Peder Andersen
Head of Secretariat

ISSN 0907-2977 (Working Paper - Danish Economic Council)
List of previous Working Papers: see last page.

To order, contact:

The Danish Economic Council
Secretariat
Adelgade 13, 5.
1304 København K

Phone: +45 33 13 51 28
Fax: +45 33 32 90 29
E-mail: dors@dors.dk
Home page: www.dors.dk

Symbols:
• Not applicable/data not available
Due to rounding, the figures in tables may not add up to the totals.

Imperfect Competition in the Nordic Electricity Markets

Mikkel T. Kromann

Working Paper 2001:3

Abstract:
Imperfect competition in a liberalized Nordic electricity market is simulated in a partial equilibrium model with elaborated demand and supply systems, the latter also including bi-production of district heating. It is found that Cournot competition can facilitate surprisingly large excess profits, even when a competitive fringe is allowed. The results indicate that a widely used concentration measure, the Hirshman-Herfindahl index, is a poor guide for revealing market power in electricity markets. This is in accordance with the findings of other recent research.

Keywords: Cournot competition, fringe supply, power markets, district heating, Hirschman-Herfindahl Index (HHI).

JEL: D4, L9, Q4

Table of contents

1 Introduction

Imperfect competition in the recently deregulated energy markets has emerged as an interesting issue for economists. Deregulation has been motivated by the belief that costs in a liberalized market would be lower than the costs minimized by the regulating authorities. However, deregulation also means that power producers set prices and quantities to maximize profits. As entry into the energy market is often constrained by large sunk costs, worries that imperfect competition could raise prices substantially above costs may be justified. Besides comparing price to marginal cost, an evaluation of the deregulation thus also needs to consider prices under the previous regulation regime.

Economic theory is not conclusive about imperfect competition with a small number of participants in a multiple period framework. On the one hand, contestability and war of attrition theories suggest that free entry will ensure that prices settle around average cost. On the other hand, tacit collusion between few competitors, predation, reputation, or limit-pricing that creates barriers to entry can facilitate above-cost prices. An overview of these topics is presented by Tirole (1988).

An often used reference point for imperfect competition with prices above costs is the price-quantity pair associated with Cournot competition. This paper describes a numerical model that provides estimates for prices in the Nordic power market under assumption of Cournot competition with an exogenously specified number of identical competitors. As the assumption of identicalness is strong, the model also provides an opportunity for sensitivity analysis with a fringe of small price-taking competitors that are too small to have an influence on the market price on their own. We do not model any tacit collusion, and assume that imperfect competition stems from barriers to entry.

Our model has an elaborate demand system and includes the production of district heating, which poses significant constraints in the Nordic energy mar-

1) This working paper is a part of the Secretariat of the Danish Economic Council's participation in the Danish Strategic Environmental Research Programme, whose financial support is gratefully acknowledged. The author wishes to thank Jens Hauch and Jan V. Hansen, who contributed with comments, discussion, and suggestions. Helpful comments from Peter Fristrup also improved this paper.

kets. However, it does not include spatial ownership structures, limitations on transmission capacity, and daily and seasonal variation in demand, although we will discuss these factors in passing.

We find that the potential for excess profits is surprisingly large when compared to a traditional measure of market concentration, namely the Hirschman-Herfindahl Index (HHI) as used by for example U. S. Department of Justice and U. S. Federal Trade Commission (1992). More work in this area is needed to reveal whether horizontal concentration is a severe problem in the Nordic electricity markets. Such work might also suggest measures that can counter the perverse effects of horizontal concentration in the Nordic markets or specify guidelines for effective merger regulation.

In section 2 we present a perfect competition model of the Nordic energy markets. For pedagogical purposes we extend this model to monopoly and Cournot competition in section 3 before we present our full-size Cournot competition with fringe supply model. The simulation results can be found in section 4, followed by a general discussion and conclusion in section 5.

2 Perfect Competition

The original model is a partial equilibrium model by Hauch (2000) describing supply and demand for energy and other goods and services in Denmark, Finland, Norway and Sweden. The model is calibrated on data for 1995 and is an annual model. Thus, it does not account for seasonal or daily variation in demand and supply.

Electricity is traded, and households optimize their utility and producers their profit. The model is a hybrid model: A “bottom-up” system describes production of electricity and district heating, while a “top-down” system of production and utility functions describes supply of other goods and demand. The bottom-up modelling allows a detailed description of energy production, which is our main point of interest, while the top-down system is a widely used method for modelling economic aggregates.

2.1 Supply of Electricity and District Heating

The stepwise marginal cost structure which is most suitable for this form of production is modelled with a bottom-up system. The production of electricity and district heating can be divided into to four broad technology types:

- **Condensing** technologies produce $\eta < 1$ energy units of electricity for each energy unit of fuel input. η is labelled the energy coefficient. The energy loss (due to excess heat) cannot be utilized for district heating purposes. Condensing technologies use oil, coal and gas as fuel inputs. It is convenient also to model nuclear, hydro and wind power as condensing technologies, as the equations describing these technologies are identical to those of genuine condensing technologies.
- **Backpressure** technologies can utilize the excess heat from electricity production to produce district heating. The η's associated with backpressure technologies account for the sum of electric and district heating energy produced from one energy unit of fuel input. Cm is used to designate the electricity-heat ratio. Backpressure technologies are found in both small and large scale and use oil, coal, gas and bio fuels.
- **Extraction-condensing** technologies run in either condensing or backpressure mode. Extraction-condensing technologies are only used on the large scale and use oil, coal and gas as fuel inputs.
- **Pure district heating** technologies do not produce electricity. It is assumed that only bio fuels are used for this technology. The η-values associated with district heating are interpreted as total energy output for each energy unit of fuel input.

District heating must be powered by small scale technologies when the areas supplied are too sparsely populated to support a large scale plant. Strictly speaking there are two separate markets for district heating, but it is more convenient to make the model sensitive to scale and geography by forcing some minimum share $0 \leq \theta \leq 1$ of district heating to be powered by small scale technologies.[2] θ corresponds to the observed ratio between large and small scale district heating.

2) Small scale technologies can also supply densely populated areas.

Whereas district heating must be delivered locally, electricity can be traded internationally. Hauch (2000) models an international transmission system with capacity limits and transportation costs. Assuming that the transmission system is operated under perfect competition (equivalent to perfect regulation) electricity is transmitted between the countries if the difference between prices is greater than the transmission cost. This causes the national demand curves (exports included) for electricity to become kinked.

For this reason we here assume no transportation costs and capacity limits for international transmission, as the model will otherwise become too complicated.[3] Transmission systems can also be used strategically by congesting a transmission line, see for example Cardell, Hitt and Hogan (1997) and Borenstein, Bushnell and Knittel (1999). Our model's underlying data is too sparse to describe strategic interaction through transmission. Furthermore as the scope is a rough estimate of potential market power, the inclusion of costly and limited transmission without strategic interaction cannot justify the extra complication which this would cause. For further evaluation of the Nordic market for electricity, this is an obvious topic to investigate.

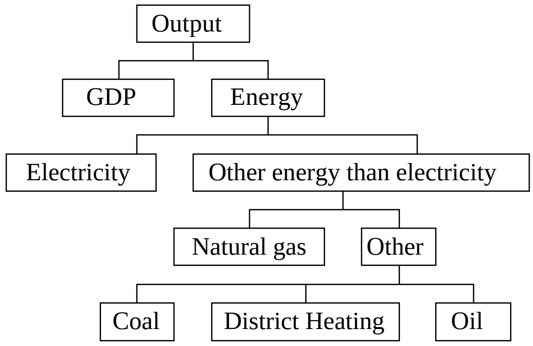
2.2 The System for Other Supply and Demand

Five sectors (the heavy, light, chemical and food/wood industries and the service sector) produce goods for consumption using electricity and district heating. Fuel inputs are supplied by world market at exogenous prices. An aggregate of "other inputs than energy" represents the value added from other commodities. This aggregate covers 97 percent of the inputs used, and this is why the model claims only to be a partial equilibrium model. The industrial input nest structure is shown in figure 1.

The outputs of the five sectors are used for household consumption, which also includes transportation, electricity and heating. The price of transportation is proportional to the oil price, so transportation can also be said to be supplied inelastically by the rest of the world. Heating is a nested utility function including electric and district heating, oil, gas and coal. All commodi-

3) Because of the stepwise cost structure the demand curve gets kinked as a result of the introduction of fringe supply which will be discussed later. In section 3.4 we show that it is necessary to check each kink seperately as they may represent opportunities for extra profit.

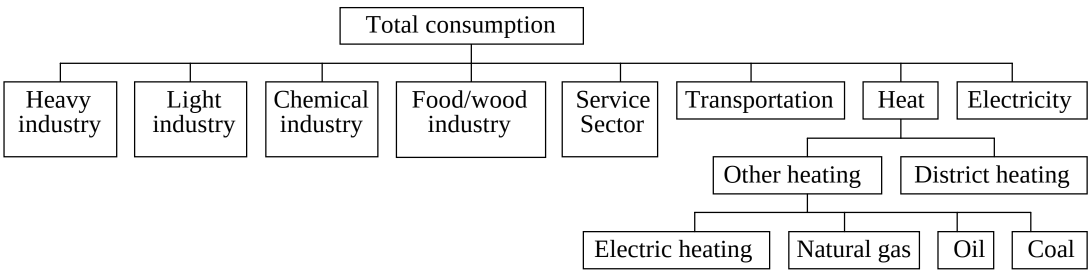
Figure 1 Industrial input nest structure



ties are priced separately for all four countries in order to allow, for example, different levels of taxation. The nesting of the household utility function is shown in figure 2.

As all utility and production functions are well-behaved (the functions used are Stone-Geary, CES and Leontieff) the aggregate utility function is also well-behaved. Then the aggregate demand function for electricity is also continuous, twice differentiable and decreasing in electricity price.

Figure 2 Household demand nest structure



2.3 Specification of Imperfect Competition

Because of Kreps and Scheinkman (1983), Cournot competition is often thought as an investment game in which none of the producers have any initial capacity and where they all simultaneously decide on some investment on the basis on the known demand and the number of other players in the game. The investment is a credible quantity commitment (it might take some time to get the investment ready for production) and the players can thereafter go into price competition. We assume some barriers to entry and thus allow only an exogenously determined number of firms to participate in the investment game.

Klemperer and Meyer (1989) introduce the Supply Function Equilibrium (SFE), which describes oligopoly price and quantity choice under uncertainty. The SFE concept applies well to the electricity hour-by-hour auctions used in many liberalized electricity markets. Electricity producers submit bid schedules to supply a market under uncertainty, and the bids submitted can be used as credible quantity commitments. This opens the possibility of Cournot competition, as the worst case outcome of the auctions when uncertainty is very low. At higher uncertainty the price converges towards the Bertrand equilibrium price.

Newbery and Green (1992), von der Fehr (1993), Wolfram (1999) and others have contributed on this topic for the electricity markets. They point out that a considerable share of the infra-marginal electricity supply is baseload with low marginal costs, whereas the marginal technologies have significantly higher marginal costs.[4] Thus, the possibility of earning large profits on the infra-marginal baseload units in peakload hours is likely to increase the producers' bids for marginal units.

Borenstein, Bushnell and Knittel (1999) criticize the SFE model because it has difficulties with including a competitive fringe, bilateral contracts, starting costs, plants running idle for standby dispatchment and other short term phenomena. As they find these characteristics more important in the Californian electricity market than the SFE models' resemblance to electricity auctions and market uncertainty, they depart from the SFE concept and model the worst-case: Cournot-Nash competition with non-identical producers and a fringe supply, where the producers are allowed to declare capacity "under maintenance" in order to diminish output and raise the price.

The data underlying our model does not lend itself naturally to the SFE approach. Neither is it applicable to the short-term phenomena described by Borenstein, Bushnell and Knittel. It does however allow us to include a

4) Generally, these plants have the advantage that their starting and stopping costs are considerably lower than baseload plants, thereby making them well-suited for producing only in peakload hours.

competitive fringe with limited production capacities.[5] This eases the questionable assumption of identical producers. Also, our strategically acting oligopolists can take capacity out of production or omit investments.

The market for district heating is a natural monopoly because of the large costs and capital intensity in the distribution, and it thus obviously lend itself to some kind of regulation. We apply a fixed price/quantity regulation that, besides simplifying the model, prevents the electricity market strategic interaction.[6] The prices and quantities chosen are those that would prevail under perfect competition.

To ensure the existence, uniqueness and optimallity of an equilibrium in our model it is also necessary to deprive the fringe of the possibility of extraction-condensing production (see appendix E). This raises the problem of capacity composition with respect to technologies between the fringe and the oligopolists. We argue that fringe producers should be assigned only small scale technologies, as owners exercising market power are likely to own large scale plants and not bother with small scale technologies.

Were there no restriction on fringe technology choice, the simple solution would have been to assume that fringe and oligopolists had identical compositions of technologies. However, the requirement for no strategic interaction through district heating markets leaves us with no desirable alternative other than assigning all backpressure technologies to the fringe and supplementing these with condensing capacity until the desired fringe market share[7] is reached.

The amount of district heating that the fringe and the oligopolists are forced to supply must then be calculated on the basis of production decisions under perfect competition, and the decentralized district heating requirements must be adjusted to reflect the altered capacities. Even though the market concen-

5) Thus, the fringe suppliers cannot invest in new capacity.

6) With the possibility of strategic interaction a fringe supplier could be forced out of the market if the district heating price fell below the production costs. Such interaction seems not very likely when the market is regulated.

7) The capacities assigned to the fringe in the two fringe scenarios are calculated so that the fringe under perfect competition supplies 40 and 20 percent of the electricity market respectively.

tration is the same under different compositions of capacity between fringe and oligopolists, their cost structurea are still different.

2.4 The Nordic Markets for Power in 2005

Hauch (2000) simulates 25 annual periods where the agents have myopic expectations. This is done by solving the model for each year while investing in and depreciating electricity and district heating production capacities (measured as possible yearly fuel input) and updating real income.

As mentioned above, there is no obvious way to model a multi-period investment game, so instead we model only one period with Cournot competition as our imperfect competition specification. As liberalization is assumed to happen in 2000 we use 2005 as the base year, as typical planning and building of a power plant takes 5 years. Our base year data are the 1995 data extrapolated 10 years ahead by depreciating capacities linearly according to lifetime and updating the real income with historical growth rates. We reject the Hotelling hypothesis and assume no real energy price increases, which is in line with historical data for a long time period.

In table 1 we show the production capacities (investments included) for district heating and electricity projected to 2005 under the assumption of perfect competition. Because of Danish regulation, 20 percent of all power consumed must be produced by environment-friendly technologies in 2010. We assume that this figure is 15 per cent in 2005, and that the technology is wind power. Thus 5GWh of wind power is added exogenously to the already installed capacity in 2005 before new investments.

Other investments are 11GWh of Danish backpressure, and in both Sweden and Finland 10GWh of extraction capacity is invested. As the fringe cannot invest, the Danish backpressure capacity is also added exogenously. In the table the demand for electricity and district heating resulting from a perfect competition simulation with these capacities is also shown.

As the model is annual it does not take peak loads (either daily or seasonal) into account. Instead, demand is the total electricity use per year. To account for the demand fluctuations, the utilization time of the installed capacity has been adjusted. Backpressure technologies in particular have a lower utiliza-

Table 1 Nordic markets for electricity and district heating, projection for 2005 under the assumption of perfect competition

	Denmark	Finland	Norway	Sweden
	--------- GWh production per year ----------			
Condensing capacity	0.4	11.3		12.6
Nuclear capacity		17.0		45.6
Hydro/wind capacity	5.5	11.8	108.9	60.0
Backpressure capacity	14.6	16.4	0.3	12.8
Extraction capacity	15.0	13.3		20.9
Total electricity capacity	35.5	69.8	109.3	151.8
Total electricity demand	33.5	55.4	82.2	117.7
Backpressure heating	24.8	50.9		21.7
Extraction heating	21.1	13.1		20.8
Pure distrinct heating		26.0		60.6
Total district heating capacity	45.9	90.1		103.0
Total district heating demand	44.8	81.1		63.8

Source: Hauch (2000) and own calculations

tion time as the demand for district heating has significant seasonal fluctuations.

2.5 Producers' Problem under Perfect Competition

We have four countries and we assume that all producers have an equal share of the capacities for all technologies.[8] For each technology k and country i: Let $H^b_{k,i}$ and $H^p_{k,i}$ denote the heat output from backpressure and pure district heating production respectively. Also, let $E^b_{k,i}$ and $E^c_{k,i}$ denote the electricity output from backpressure and condensing production. Let $F^b_{k,i}$, $F^c_{k,i}$ and $F^p_{k,i}$ denote the fuel use, and $K^{inv}_{k,i}$ denote any added capacity, while $K^{ini}_{k,i}$ is the ex-

8) Note that though the capacities are also separated by countries, there is no national distinction in ownership: the producers own an international portfolio of production capacity.

isting capacity. For some technologies an upper capacity limit, $K_{k,i}^{max}$, exists.[9] P_i^H and P^E denote the prices of produced heat and electricity, and $P_{k,i}^F$ is the price of technology-specific fuel. The price of capacity is $P_{k,i}^K$, which is exogenously set to the capital cost of one fuel unit input at the given interest rate. E, H_i^l and H_i^s are the total amount of electricity produced, and large- and small-scale district heating supplied in equilibrium respectively. Finally, let d_k be a binary parameter assigned the vaule 0 or 1 for large- or small-scale district heating technologies.

For convenience, these calculations assume that each technology can produce in condensing, backpressure and pure district heating mode. No technology can in fact do so, but when the appropriate η's are set to zero, cost minimization will rule out the impossible production modes. The producers' profit maximization problem is:

$$\max \Pi\left(F_{k,i}^b, F_{k,i}^c, F_{k,i}^p, K_{k,i}^{inv}\right) = \sum_{k,i} P_i^H\left(H_{k,i}^b + H_{k,i}^p\right)$$
$$+\sum_{k,i} P_E\left(E_{k,i}^b + E_{k,i}^c\right) - \sum_{k,i} P_{k,i}^F\left(F_{k,i}^b + F_{k,i}^c + F_{k,i}^p\right) - \sum_{k,i} P_{k,i}^K K_{k,i}^{inv} \quad (1)$$

subject to the conditions for all technologies and countries, k and i, that

$$E_{k,i}^b = \frac{Cm_{k,i}}{1+Cm_{k,i}}\eta_{k,i}^b F_{k,i}^b \quad (2)$$
$$E_{k,i}^c = \eta_{k,i}^c F_{k,i}^c \quad (3)$$
$$H_{k,i}^p = \eta_{k,i}^p F_{k,i}^p \quad (4)$$
$$Cm_{k,i} = \frac{E_{k,i}^b}{H_{k,i}^b} \quad (5)$$

9) This applies for example to some unused Norwegian hydropower potential.

$$F^b_{k,i} + F^c_{k,i} + F^p_{k,i} - K^{ini}_{k,i} - K^{inv}_{k,i} \leq 0 \tag{6}$$

$$\theta H_i \leq H^s_i \Leftrightarrow \sum_k (\theta_i - d_k) \left(\frac{1}{1 + Cm_{k,i}} \eta^b_{k,i} F^b_{k,i} + \eta^p_{k,i} F^p_{k,i} \right) \leq 0 \tag{7}$$

$$K^{ini}_{k,i} + K^{inv}_{k,i} - K^{max}_{k,i} \leq 0 \tag{8}$$

The problem is constrained by the energy efficiency in the three technology types (equations 2, 3, 4), the electricity-heat ratio (equation 5) and the capacity limits (equation 6). Equation 7 is the decentralized district heating condition, and equation 8 represents potential limits imposed on total capacity. Substituting equations 2 to 5 into equation 1 the problem can be solved with respect to fuel and capital inputs (henceforth we refer to the three types of fuel input and added capacity for all technologies and countries as the input vector) as a Kuhn-Tucker, problem because the derivatives of the profit function and the constraints with respect to the input vector are continuous. This yields the following (for all k technologies and i countries) four first-order conditions and seven complementary equations:

$$\frac{\eta^b_{k,i}}{1 + Cm_{k,i}} \left(P^H_i + Cm_{k,i} P_E - (\theta_i - d_k) \lambda^{dec}_i \right) - P^F_{k,i} - \lambda^{cap}_{k,i} \leq 0 \tag{9}$$

$$\eta^c_{k,i} P_E - P^F_{k,i} - \lambda^{cap}_{k,i} \leq 0 \tag{10}$$

$$\eta^p_{k,i} P^H_i - P^F_{k,i} - \lambda^{cap}_{k,i} - \eta^p_{k,i} (\theta_i - d_k) \lambda^{dec}_i \leq 0 \tag{11}$$

$$\lambda^{cap}_{k,i} - \lambda^{max}_{k,i} - P^K_{k,i} \leq 0 \tag{12}$$

$$\lambda^{cap}_{k,i} = 0 \quad \vee \quad \text{Equation 6 with strict equality} \tag{13}$$

$$\lambda^{dec}_{i} = 0 \quad \vee \quad \text{Equation 7 with strict equality} \tag{14}$$

$$\lambda^{max}_{k,i} = 0 \quad \vee \quad \text{Equation 8 with strict equality} \tag{15}$$

$$F^b_{k,i} = 0 \quad \vee \quad \text{Equation 9 with strict equality} \tag{16}$$

$$F^c_{k,i} = 0 \quad \vee \quad \text{Equation 10 with strict equality} \tag{17}$$

$$F^p_{k,i} = 0 \quad \vee \quad \text{Equation 11 with strict equality} \tag{18}$$

$$K^{inv}_{k,i} = 0 \quad \vee \quad \text{Equation 12 with strict equality} \tag{19}$$

There are three slack variables. $\lambda_{k,i}^{cap}$ is the shadow value of any added capacity. If this value is equal to the capacity cost, investment is made. Thus the shadow value for new capacity in some technologies can only be larger in the case that the technology has a capacity limit.[10] Here, $\lambda_{k,i}^{max}$ is the shadow value of expanding this capacity limit. In this sense $\lambda_{k,i}^{cap}$ is a gross shadow value with respect to investment cost, whereas $\lambda_{k,i}^{max}$ is a net shadow value which is always zero when there are no capacity limits.

Finally, $\lambda_{k,i}^{dec}$ is the shadow value of the decentralized district heating production constraint. For the reader's convenience, the equations of the perfect competition model are gathered in appendix A. A thorough explanation of the supply system can be found in Hauch (2000).

2.6 Simulation with Perfect Competition

When studying imperfect competition it is desirable to compare the results to the situation under public regulation. Though prices under imperfect competition are higher than under perfect regulation, regulation is seldom perfect. As our main simulations will relate prices under imperfect competition to perfect competition prices, it is useful to compare the actual prices under regulation to those of simulated perfect competition.

Detailed studies about regulation and the associated inefficiency have been undertaken by others, for example Olsen (1998). To keep our study simple we compare the actual 1995 prices of electricity to simulated perfect competition prices. Liberalization has, however, not been introduced at the same time in the various Nordic countries. Norway was the first to liberalize early in the 1990s, followed by Sweden and Finland, whereas the Danish deregulation has taken place only recently.

It is not possible for the model to handle country-specific liberalization at different points in time. Instead, we report three counterfactual scenarios where liberalization takes place in 1995, 2000 or 2005 respectively. Table 2 shows indices for potential efficiency gain. The index is calculated as the difference between actual 1995 average electricity price and the simulated perfect competition price in the relevant year relative to the actual 1995 price.

10) Otherwise investment would be carried out until the increased production caused the power prices to fall to the point where the investments break even.

Table 2 Index for potential efficiency gain due to trade and reduced capital intensity

	Denmark	Finland	Norway	Sweden
1995	0.561	0.379	-0.016	0.523
2000	0.209	-0.118	-0.830	0.141
2005	0.012	-0.396	-1.285	-0.073

Note: The index is calculated as the difference between actual 1995 average electricity prices and the simulated perfect competition prices in the relevant year relative to the actual 1995 prices. In these simulations there is no 5-year lag in the investments. The relevant comparison with respect to imperfect competition simulations later in the paper is thus 2005.

The indices presented are found by depreciating capacities and updating national income according to the historical income growth figure, and then simulating perfect competition.

These scenarios must be interpreted very carefully, as the markets are not in a long-run equilibrium. Generally a large index value means that the average payment is well above long-run marginal cost, while a small value indicates a very efficient power sector.

There are some negative values in the table. This does not indicate that producers become less efficient with liberalization. Rather, it indicates that the common Nordic market electricity price is higher than the actual 1995 prices which, unlike the common market price, are country specific. For example, the Norwegian consumers will pay more for electricity compared to actual 1995 prices, but will also earn substantially larger profits from their power producers. We present no welfare comparisons, however, as our partial equilibrium model does not offer adequate measures for this.

In the table it can also be seen that early liberalizations tend to result in lower prices than later ones. This is caused by overcapacity, which postpones investments. Electricity price will then be equal to the short-run marginal costs, i.e. around the fuel input prices. However, as capacity depreciation causes supply to shrink, and demand rises because of larger income, investments take place when the price has risen enough to cover their capital costs.

One of the perils of the Danish regulation in particular, was that capital intensity was not decided by the market interest rate. Rather, a non-profit principle applied, and this led to over-accumulation of capital. It is noteworthy that the

Danish capacity in 1995 was so large that 10 years of depreciation and income growth was needed to bring the liberalized market price to the same level as the prices under regulation. Similarly, the Swedish power sector also seems to have had some overcapacity. The problem has not been so urgent in Finland.

3 Imperfect Competition

For pedagogical purposes we now present three serial extensions for imperfect competition. We start by modelling a power market monopolist. We then extend this to Cournot oligopoly, and hereafter we add a fringe. For the first two extensions we retain Hauch's modelling of the decentralized district heating condition.[11] For the reasons listed in section 2.3 this condition is altered in the last extension.

3.1 Monopolist Supply

A monopolist energy producer is a price-taker on all markets but the markets for electricity. The problem is to maximize profits by choosing fuel and capital inputs knowing that the output choices will affect the price of electricity ($P_E(E)$ is a continuously decreasing and differentiable function). The solution to the problem (which is still as in equation 1) is the Kuhn-Tucker necessary conditions, which are stated in appendix B. The monopoly model is very similar to the perfect competition model presented above. Only a single difference calls for attention. Noting that the quantity of electricity supplied is

$$E = \sum_{k,i} \left(\frac{\eta^b_{k,i} Cm_{k,i}}{1 + Cm_{k,i}} F^b_{k,i} + \eta^c_{k,i} F^c_{k,i} \right)$$

11) We do not, however, use these models for simulations, as they break our assumption that no strategic interaction must affect the district heating market. In these two models, producers might shut down backpressure capacity in order to raise electricity price. This would also have smaller district heating output and rising prices as side effects.

we find that when the producers do not take prices as given, the production decisions for backpressure and condensing are

$$\frac{Cm_{k,i}\,\eta^b_{k,i}}{1+Cm_{k,i}}P_E(E)+\frac{\partial E}{\partial F^b_{k,i}}P'_E(E)\,E$$
$$-P^F_{k,i}-\lambda^{cap}_{k,i}+\frac{\eta^b_{k,i}}{1+Cm_{k,i}}\left(P^H_i-(d_k-\theta)\,\lambda^{dec}_i\right)\leq 0 \tag{20}$$

$$\eta_{ck}i\,P_E(E)+\frac{\partial E}{\partial F^c_{k,i}}P'_E(E)\sum_{k,i}E-P^F_{k,i}-\lambda^{cap}_{k,i}\leq 0 \tag{21}$$

If the monopolist uses one extra unit of fuel input in a technology, the extra electricity on the market is precisely the fuel efficiency of this technology:

$$\frac{\partial E}{\partial F^b_{k,i}}=\frac{\eta^b_{k,i}Cm_{k,i}}{1+Cm_{k,i}}\qquad\text{and}\qquad\frac{\partial E}{\partial F^c_{k,i}}=\eta^c_{k,i}$$

Now we can rewrite equations 20 and 21 as:

$$\frac{\eta^b_{k,i}Cm_{k,i}}{1+Cm_{k,i}}P_E(E)+\frac{\eta^b_{k,i}Cm_{k,i}}{1+Cm_{k,i}}P'_E(E)\,E$$
$$+\frac{\eta^b_{k,i}}{1+Cm_{k,i}}P^H_i-P^F_{k,i}-\lambda^{cap}_{k,i}-\frac{\eta^b_{k,i}}{1+Cm_{k,i}}(d_k-\theta_i)\,\lambda^{dec}_{k,i}\leq 0 \tag{22}$$

$$\eta^c_{k,i}P_E(E)+\eta^c_{k,i}P'_E(E)\,E-P^F_{k,i}-\lambda^{cap}_{k,i}\leq 0 \tag{23}$$

This is analogous to the generic monopolistic output choice problem (presented here with constant marginal costs and our model's efficiency coefficient, to make comparison with our model easy): $\max\pi=\eta QP(\eta Q)-Qc$

with the first order condition $\eta P + \eta P'(\eta Q)\,\eta Q = c$. Let Q represent fuel input and ηQ electricity output, and it is easy to see that the solution to the energy producer's problem resembles the well-known equality between marginal cost and marginal revenue.

3.2 Cournot Competition

Consider now N large and identical producers of power. Each has an equal share (that is $\frac{1}{N}$) of production, fuel use, capacity and the imposed capacity requirements. The supply of electricity by one oligopolist is then:

$$\sum_{k,i}\left(\frac{Cm_{k,i}\eta^b_{k,i}}{1+Cm_{k,i}}F^b_{k,i} + \eta^c_{k,i}F^c_{k,i}\right) = \frac{E}{N} \tag{24}$$

As the producers are identical, the fuel efficiency relations, heat-electricity ratios, the two capacity constraints and the two district heating constraints are unaltered compared to the monopoly situation, as they are simply multiplied by $\frac{1}{N}$ on both the right and left hand sides of the equations. These equations can be reviewed in appendix C, together with the rest of the solution to the Cournot oligopolist's problem.

However, the production decisions for backpressure and condensing technologies are a little less straightforward. The corresponding first-order conditions from the Kuhn-Tucker solution are still as stated in equations 20 and 21, but we note that the summarized expressions represent the electricity production of one Cournot oligopolist.

The identical oligopolists have the same first order conditions, and if all of these are satisfied then none of them have any incentive to alter their output decision. The marginal change in total electricity supply due to one of the producers using slightly more fuel input in one technology is then still the fuel efficiency of this technology:

$$\frac{\partial E}{\partial F^b_{k,i}} = \frac{\eta^b_{k,i}Cm_{k,i}}{1+Cm_{k,i}} \qquad \text{and} \qquad \frac{\partial E}{\partial F^c_{k,i}} = \eta^c_{k,i} \tag{25}$$

Substituting this and equation 24 into equations 20 and 21 yields

$$\frac{\eta_{k,i}^{b}}{1+Cm_{k,i}}\left(P_i^H + Cm_{k,i}\left[P_E(E) + P_E'(E)\frac{E}{N}\right]\right)$$
$$-P_{k,i}^F - \lambda_{k,i}^{cap} - \frac{\eta_{k,i}^{b}}{1+Cm_{k,i}}\left((d_k - \theta_i)\lambda_i^{dec} - \lambda_i^{dih}\right) \leq 0 \tag{26}$$

$$\eta_{k,i}^{c}\left(P_E(E) + P_E'(E)\frac{E}{N}\right) - P_{k,i}^F - \lambda_{k,i}^{cap} \leq 0 \tag{27}$$

These equations are also similar to those of the standard identical Cournot oligopolist's quantity competition (here still with constant marginal costs), $P + P'Q/N = c$. The more competing firms there are, the closer the price gets to marginal cost.

3.3 Cournot Competition with Fringe Supply

As mentioned in section 2.3, a fixed quantity regulation is needed to avoid strategic interaction through the market for district heating. Both the fringe and the oligopolists are obliged to supply a negotiated amount of district heating. The fringe cannot supply centrally produced district heating, and thus does not need a decentralized district heating condition. The oligopolists produce both types of district heating and retain their decentralized district heating condition. Both types of producers get a condition of the type

$$\overline{H}_i - H_i \leq 0 \tag{28}$$

and cost minimization ensures that the condition binds with equality (as decentralized district heating is more costly). The constraint has the associated shadow value λ_i^{dih}. If the fringe is given backpressure or district heating capacity, the oligopolist's share of decentralized district heating, θ, must be adjusted accordingly. We will not present the fringe suppliers' problem here, as it is very similar to the problem of the producer under perfect competition. Instead its solution is stated in appendix D.

The total supply of electricity is now

$$E = N \sum_{k,i} \left(\frac{Cm_{k,i} \eta^b_{k,i}}{1 + Cm_{k,i}} F^b_{k,i} + \eta^c_{k,i} F^c_{k,i} \right) + E^{fri}_{k,i}$$

where E^{fri} denotes the total electricity production of the fringe suppliers. The introduction of fringe supply alters the Cournot model only slightly. The changes are to be found in the production decision conditions for electricity, which are shown below:

$$\left[\frac{\eta^b_{k,i} Cm_{k,i}}{1 + Cm_{k,i}} P_E(E) + \frac{\partial E}{\partial F^b_{k,i}} P'_E(E) \frac{E - E^{fri}}{N} \right]$$
$$+ \frac{\eta^b_{k,i}}{1 + Cm_{k,i}} \left(P^H_i + \lambda^{dih}_i + (d_k - \theta_i) \lambda^{dec}_{k,i} \right) - P^F_{k,i} - \lambda^{cap}_{k,i} \leq 0 \qquad (29)$$

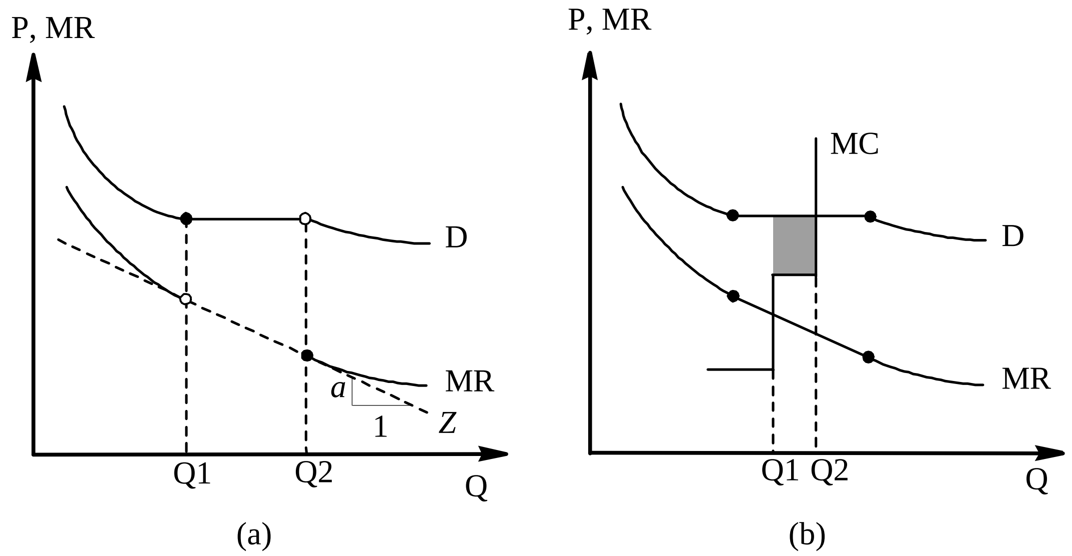
$$\left[\eta^c_{k,i} P_E(E) + P'_E(E) \frac{\partial E}{\partial F^c_{k,i}} \frac{E - E^{fri}}{N} \right] - P^F_{k,i} - \lambda^{cap}_{k,i} \leq 0 \qquad (30)$$

The stepwise cost structure of the fringe suppliers, which always supply at marginal cost, makes the demand curve perceived by the Cournot competitors kinked with horizontal sections as shown in figure 3a below.

When the price is lowered below the marginal cost of the fringe's marginal technology, its capacity is taken out of production, leaving more demand for the large suppliers. At flat segments of the perceived demand curve we choose to say that a fringe technology is forced out of the market. This corresponds to the following conditions:

$$\frac{\partial E}{\partial F^b_{k,i}} = \begin{cases} \frac{\eta^b_{k,i} Cm_{k,i}}{1+Cm_{k,i}} & \text{when not forcing out the fringe} \\ 0 & \text{when forcing out the fringe} \end{cases}$$
$$\frac{\partial E}{\partial F^c_{k,i}} = \begin{cases} \eta^c_{k,i} & \text{when not forcing out the fringe} \\ 0 & \text{when forcing out the fringe} \end{cases} \qquad (31)$$

Figure 3 Structure of the oligopolists' residual demand and their costs



The oligopolists' marginal revenue is equal to the market price P when they take over the demand supplied by the fringe technology that is forced out of the market. This is so because the total demand is unchanged (the fringe supply is substituted on a one-to-one basis by the oligopolistic supply). However, the oligopolists sell a larger quantity, and this affects their marginal revenue, because when the price decreases after a fringe technology is forced out, their profits are affected more because of the larger total quantity they sell.

From equations 29 and 30 it can be seen that the oligopolist's marginal revenue (square bracket terms) is also a function of his own production $\frac{E-E^{fri}}{N}$. As this increases while the fringe is forced out, the marginal revenue is lower at $Q2$ than $Q1$, because $P'(E) < 0$. In the figure the line Z has the slope a. It can be seen from the two equations that a is proportional to $P'(E)$, which is constant while the fringe is forced out because total demand is unchanged.

We have assumed that when price equals marginal cost of the fringe's marginal technology, the fringe decreases their output whenever the large suppliers increase production. It seems natural that it is the fringe suppliers that exit the market, as the oligopolists earn profits while the fringe suppliers sell at marginal cost.

3.4 Existence, Uniqueness and Optimality of Equilibrium

Until the inclusion of the fringe supply our different maximization problems have fulfilled the conditions that make them solvable by the Kuhn-Tucker necessary conditions: the profit function has continuous derivatives with respect to the input vector. This is not so with fringe supply included.

As we saw above, the marginal revenue is no longer continuous because it jumps to the price of electricity when a fringe technology is forced out. However, if we replace expression 31 with expression 25 our maximization problem would again qualify to be solved with the Kuhn-Tucker method, because this condition ensures that the MR curve becomes continous, as it will follow line Z in figure 3a between Q1 and Q2.

We could not, however, be sure that the solution found actually maximizes the oligopolists' profits. An example of this situation is shown in figure 3b. $Q1$ is the $MR = MC$ solution to this problem, but increasing supply to $Q2$ would not decrease the price, and thereby profits would increase by the amount represented by the shaded area.

Fortunately, the true profit maximizing input vector can still be found. In appendix E we show that only a small number of possible input vectors can maximize profits. The characteristics of these input vectors are restricted to the following three categories:

- The input vector associated with the $MR = MC$ solution from the Kuhn-Tucker necessary conditions for the Cournot model with fringe, where expression 25 replaces expression 31.
- The input vectors associated with just forcing out any one of the fringe technologies with a cost minimized output. The vectors are found by setting the price of electricity equal to the cost for each (k, i) of the fringe's technologies, while ensuring that there is no fringe production with this technology:

  $$P^E = \frac{P^F_{k,i}}{\eta^c_{k,i}}$$

  The fixed price both sets the quantity demanded and the quantity supplied by the fringe suppliers. The oligopolists then clear the market by supplying the quantity needed.

- The input vectors associated with exactly using up the capacity of each (k, i) of the oligopolist technologies with a cost minimized output. This is specified with the condition (remembering that pure district heating technologies do not affect the electricity market)

$$F^b_{k,i} + F^c_{k,i} = K^{ini}_{k,i} + K^{inv}_{k,i}$$

In this case the clearing of the electricity market takes place by adjusting the price until demand meets supply.

Cost minimization for the oligopolists in these two latter cases (which in effect state that a specific output must be produced) yields input decisions very similar to those of previously described models, except that the electricity price does not appear. Instead, an internal shadow price acts to choose the cheapest technologies for the production. The full model of Cournot competition with fringe supply can be found in appendix D.

3.5 The Approximated Slope of Demand

The production decision of the large suppliers relies on their marginal revenues as they are price setters. Marginal revenue depends on the slope of the demand curve $P'(Q)$, the price and the quantity supplied by the single producer. Only the slope of the demand is not known directly in the model. To calculate this analytically is difficult for our demand system, which is a deeply nested structure of utility and production functions.

Instead we have simulated the slope of the demand curve with a Taylor approximation. We calculate the slope of the demand curve for a number of price and quantity pairs by adding a tiny fraction to the electricity price and then measuring the demand decrease. The parameters for our Taylor approximation are then found through an OLS regression on the generated data set.

The model is solved using the approximation as the large suppliers' perceived $P'(Q)$. However, the approximation will inevitably be incorrect, so we solve the model several times, each time measuring the correct $P'(Q)$ as described above and correcting the approximated $P'(Q)$ accordingly. In this way the difference between the approximation of $P'(Q)$ and the measured $P'(Q)$ can be brought below $\frac{1}{1000}$ by solving the model and correcting as few as 3 consecutive times.

Our solution to this problem is inspired by Hoffmann (1999). He estimates and recalculates the elasticity of demand, whereas this model only estimates and recalculates the slope of the inverse demand curve. Because of the lack of a closed form expression for the true general equilibrium optimal markup, the Marshallian approximation of the optimal markup is, despite the approximation error, still used by many modellers.

4 Simulation Results

To compensate for the difficulties created by specifying imperfect competition, both with respect to the theoretical and empirical questions, we provide markups for eight scenarios with different combinations of fringe size and number of Cournot oligopolists. Table 3 shows the markups measured by the Lerner Index (markup over price) before taxes. In those scenarios including fringe supply, the fringe has been given all backpressure capacity. The fringe electricity production capacity has then been adjusted to either 40 or 20 percent of the market supply in a perfect competition simulation by adding condensing capacity.

Table 3 Lerner Index and Hirschman-Herfindahl Index (HHI) for the simulations

	Lerner Index			**HHI**		
Fringe size	40%	20%	0%	40%	20%	0%
$N = 25$	14.4%	18.9%	20.5%	144	256	400
$N = 10$	30.2%	40.1%	43.2%	360	640	1000
$N = 3$	78.8%	94.5%	•	1200	2133	3333

Source: Own calculations

Note: The Lerner Index is measured as the difference between price under imperfect competition and the price under perfect competition relative to the price under imperfect competition. The size of the fringe capacity is adjusted so that the fringe has a 40 or 20 per cent market share under perfect competition.

For each of the combinations of number of competitors and fringe share size, the table also has a calculation of the Hirschman-Herfindahl Index (HHI)[12], which is widely used to give easy overview of the concentration in an industry.

The U.S. Federal Trade Commission and the Department of Justice (1992) "divides the spectrum of market concentration as measured by the HHI into three regions that can be broadly characterized as unconcentrated (HHI below 1000), moderately concentrated (HHI between 1000 and 1800), and highly concentrated (HHI above 1800)." In an "unconcentrated market" the markup in our simulations apparently makes up 43 per cent of the price. This finding replicates the results of Borenstein, Bushnell and Knittel (1999), who investigate the Californian electricity market.

Table 4 shows the increase in market prices (taxes included) for Denmark for two sectors compared to a perfect competition outcome. As can be seen, the price increases are not as drastic as the markups found would suggest. This is because electricity is heavily excise taxed.

Table 4 Percentage price increase in two Danish sectors compared to perfect competition

	Light industry			**Households**		
Fringe size	40%	20%	0%	40%	20%	0%
$N = 25$	6.9	9.6	10.6	2.3	3.1	3.4
$N = 10$	18.8	27.4	31.2	6.1	8.9	10.2
$N = 3$	52.1	98.7	•	16.9	32.1	•

Source: Own calculations

As a sensitivity test, another setup has the electricity-other energy nest elasticities (see figure 1) tripled. It can be seen from table 5 that this has only a modest effect.

We noted in section 3.3 that it is problematic to distribute the capacity between the fringe and the oligopolists without leaving room for strategic inter-

12) The index is calculated as the sum of squares of all market shares measured in per cent.

Table 5 Sensitivty analysis: Lerner index with trippled elasticities

	Lerner Index		
Fringe size	40%	20%	0%
$N = 25$	10,2%	13,6%	14,8%
$N = 10$	20,4%	30,1%	33,5%
$N = 3$	62,9%	87,8%	•

Source: Own calculations

action through the district heating market. We have presented a model where the markets for centralized and decentralized production of district heating are separated and where the fringe possesses all the backpressure technologies. However, we have also simulated a scenario where the fringe has no district heating production at all. The markups found here differ from those in table 3 by no more than two percentage point. Other scenarios where we have assumed the strategic interaction away show similar results.[13]

5 Discussion

Our findings suggest that large producers in the Nordic market for electricity might be able to gain considerable market power and that this could be used to raise the electricity price substantially above marginal cost, even though the concentration in the market by a traditional measure, the Hirschman-Herfindahl Index (HHI), is only low or modest. This is in accordance with other research. Evenso, in comparison with the previous regime of regulation the markups due to severe market power are not very different from the markups due to inefficiency in the regulation. However, some important qualifications apply to our findings.

First, we use the Cournot-Nash model of quantity competition in a one-shot investment game. The Supply Function Equilibrium (SFE) applied to electricity markets by others suggest that the auctions often used in electricity markets have a worst case outcome equivalent to the Cournot equilibrium. Where the SFE has been applied, the markups have been large in peak load periods, whereas the price comes close to marginal cost outside these pe-

13) The scenarios are available upon request.

riods. Thus our results can be interpreted as worst case scenarios for the Nordic electricity market. Extending the investment game to more periods would probably tend to increase the investments as the quantity commitment in the Cournot game becomes less binding. This strengthens the case for liberalization.

Second, our model requires that the large firms are identical. A market with only identical firms is not realistic, so we also include a price-taking fringe. We find that a competitive fringe increases the market output and lowers the markups. We have carried out sensitivity tests indicating that the composition of technologies assigned to the fringe does not alter the markup decisions of the oligopolists very much.

Third, we have included a district heating market in our model. It shows, however, that this does not affect the markups very much, as the oligopolists have other capacity with roughly the same costs relative to the market price to take out of production.

Some aspects that our model and its underlying data cannot investigate are seasonal and daily variation and regional and international transmission constraints. Other research has found that these factors can be important for the presence of imperfect competition. Transmission capacity can be congested with the strategic purpose of raising the price in selected regions with only a small fringe capacity. And even with plenty of transmission capacity, start-up costs (which our model does not include) of other plants may be too large to trigger increased output. The Nordic markets are characterized by a large amount of hydro power capacity. As hydro power has small start-up costs, it is potentially an important factor for lowering prices in short peak load periods as long as the capacity is not owned by oligopolists.

The limitations of our model show the need for further research with models that have more fine-grained time periods. There is also a need for better spatial dimension to investigate the transmission capacity limits. Even though we find potential for strong market power, there is no need to conclude that the process of deregulation should be reversed. On the contrary, the better understanding of the electricity markets from recent research seems promising for finding measures that can limit the market power and bring the price close to the cost.

References

Borenstein, S., J. Bushnell and C. Knittel (1999): Market Power in Electricity Markets: Beyond Concentration Measures. *The Energy Journal,* 20 (4), pp. 66–88.

Cardell, J., C. Hitt and W. Hogan (1997): Market Power and Strategic Interaction in Electricity Networks. *Resource and Energy Economics,* 19, pp. 109–137.

Green, R. and D. Newbery (1992): Competition in the British Electricity Spot Market. *Journal of Political Economy,* 100 (5), pp. 929–953.

von der Fehr, N.-H. M. and D. Harbord, (1993): Spot Market Competition in the UK Electricity Industry. *Economic Journal,* 103 (418), pp. 531–546.

Hauch, J. (2000): *Environmental Regulation and Nordic Energy Markets.* Ph.D. Thesis, Institute of Economics, University of Copenhagen, Copenhagen.

Hoffmann, A. (1999): *Imperfect Competition in Computable General Equilibrium Models—A Primer.* Working Paper no. 1/99, Danish Ministry of Business and Industry, Copenhagen.

Kreps, D. and J. Scheinkman (1983): Quantity Commitment and Bertrand Competition Yields Cournot Outcome. *Bell Journal of Economics,* 14, pp. 326–337.

Olsen, O. J. (1998): *The Consequences of Different Institutional Settings for the Creation of a Common Electricity Market in Northern Europe.* Paper presented at the Nordic Energy and Society Conference in Oslo, Oct. 1–2. 1998.

Tirole, J. (1988): *The Theory of Industrial Organization.* MIT Press, Cambridge, Massachusetts.

U.S. Department of Justice and U.S. Federal Trade Commission (1992): *Horizontal Merger Guidelines.* Washington D.C., http://www.usdoj.gov/atr/public/guidelines/merger.txt

Wolfram, C. (1999): Measuring Duopoly Power in the British Electricity Spot Market. *The American Economic Reveiw,* 89 (4), pp. 805–826.

A Perfect Competition Model with Solution

Below is shown the full supply system for perfect competition. Some equations run over (k, i) or i:

$$E = \sum_{k,i} E^b_{k,i} + E^c_{k,i} \tag{1}$$

$$H = \sum_{k,i} H^b_{k,i} + H^p_{k,i} \tag{2}$$

$$E^b_{k,i} = \frac{Cm_{k,i}}{1 + Cm_{k,i}} \eta^b_{k,i} F^b_{k,i} \tag{3}$$

$$E^c_{k,i} = \eta^c_{k,i} F^c_{k,i} \tag{4}$$

$$H^p_{k,i} = \eta^p_{k,i} F^p_{k,i} \tag{5}$$

$$Cm_{k,i} = \frac{E^b_{k,i}}{H^b_{k,i}} \tag{6}$$

$$F^b_{k,i} + F^c_{k,i} + F^p_{k,i} - K^{ini}_{k,i} - K^{inv}_{k,i} \leq 0 \tag{7}$$

$$\theta(H^s_i + H^l_i) \geq H^s_i \Leftrightarrow \sum_{k,i} [\theta_i - d_k] \left(\frac{\eta^b_{k,i} F^b_{k,i}}{1 + Cm_{k,i}} + \eta^b_{k,i} F^p_{k,i} \right) \leq 0 \tag{8}$$

$$K^{ini}_{k,i} + K^{inv}_{k,i} - K^{max}_{k,i} \leq 0 \tag{9}$$

$$\frac{\eta^b_{k,i}}{1 + Cm_{k,i}} \left(P^H_i + Cm_{k,i} P_E - (d_k - \theta_i) \lambda^{dec}_i \right) - P^F_{k,i} - \lambda^{cap}_{k,i} \leq 0 \tag{10}$$

$$\eta^c_{k,i} P_E - P^F_{k,i} - \lambda^{cap}_{k,i} \leq 0 \tag{11}$$

$$\eta^p_{k,i} P^H_i - P^F_{k,i} - \lambda^{cap}_{k,i} + \eta^p_{k,i} (d_k - \theta_i) \lambda^{dec}_i \leq 0 \tag{12}$$

$$\lambda^{cap}_{k,i} - \lambda^{max}_{k,i} - P^K_{k,i} \leq 0 \tag{13}$$

$$\lambda_{k,i}^{cap} = 0 \quad \vee \quad \text{Equation 7 with strict equality} \tag{14}$$

$$\lambda_{i}^{dec} = 0 \quad \vee \quad \text{Equation 8 with strict equality} \tag{15}$$

$$\lambda_{k,i}^{max} = 0 \quad \vee \quad \text{Equation 9 with strict equality} \tag{16}$$

$$F_{k,i}^{b} = 0 \quad \vee \quad \text{Equation 10 with strict equality} \tag{17}$$

$$F_{k,i}^{c} = 0 \quad \vee \quad \text{Equation 11 with strict equality} \tag{18}$$

$$F_{k,i}^{p} = 0 \quad \vee \quad \text{Equation 12 with strict equality} \tag{19}$$

$$K_{k,i}^{inv} = 0 \quad \vee \quad \text{Equation 13 with strict equality} \tag{20}$$

B Monopolist Model

Below is shown the full supply system for monopoly. Some equations run over (k, i) or i:

$$E = \sum_{k,i} E^b_{k,i} + E^c_{k,i} \tag{1}$$

$$H = \sum_{k,i} H^b_{k,i} + H^p_{k,i} \tag{2}$$

$$E^b_{k,i} = \frac{Cm_{k,i}}{1 + Cm_{k,i}} \eta^b_{k,i} F^b_{k,i} \tag{3}$$

$$E^c_{k,i} = \eta^c_{k,i} F^c_{k,i} \tag{4}$$

$$H^p_{k,i} = \eta^p_{k,i} F^p_{k,i} \tag{5}$$

$$Cm_{k,i} = \frac{E^b_{k,i}}{H^b_{k,i}} \tag{6}$$

$$F^b_{k,i} + F^c_{k,i} + F^p_{k,i} - K^{ini}_{k,i} - K^{inv}_{k,i} \leq 0 \tag{7}$$

$$\theta(H^s_i + H^l_i) \geq H^s_i \Leftrightarrow \sum_{k,i} [\theta_i - d_k] \left(\frac{\eta^b_{k,i} F^b_{k,i}}{1 + Cm_{k,i}} + \eta^b_{k,i} F^p_{k,i} \right) \leq 0 \tag{8}$$

$$K^{ini}_{k,i} + K^{inv}_{k,i} - K^{max}_{k,i} \leq 0 \tag{9}$$

$$\begin{aligned} &\frac{\eta^b_{k,i} Cm_{k,i}}{1 + Cm_{k,i}} P_E(E) + \frac{\eta^b_{k,i} Cm_{k,i}}{1 + Cm_{k,i}} P'_E(E) E \\ &+ \frac{\eta^b_{k,i}}{1 + Cm_{k,i}} P^H_i - P^F_{k,i} - \lambda^{cap}_{k,i} - \frac{\eta^b_{k,i}}{1 + Cm_{k,i}} (d_k - \theta_i) \lambda^{dec}_{k,i} \leq 0 \end{aligned} \tag{10}$$

$$\eta^c_{k,i} P_E(E) + \eta^c_{k,i} P'_E(E) E - P^F_{k,i} - \lambda^{cap}_{k,i} \leq 0 \tag{11}$$

$$\eta^p_{k,i} P^H_i - P^F_{k,i} - \lambda^{cap}_{k,i} + \eta^p_{k,i} (d_k - \theta_i) \lambda^{dec}_i \leq 0 \tag{12}$$

$$\lambda^{cap}_{k,i} - \lambda^{max}_{k,i} - P^K_{k,i} \leq 0 \tag{13}$$

$$\lambda_{k,i}^{cap} = 0 \quad \vee \quad \text{Equation 7 with strict equality} \tag{14}$$

$$\lambda_{i}^{dec} = 0 \quad \vee \quad \text{Equation 8 with strict equality} \tag{15}$$

$$\lambda_{k,i}^{max} = 0 \quad \vee \quad \text{Equation 9 with strict equality} \tag{16}$$

$$F_{k,i}^{b} = 0 \quad \vee \quad \text{Equation 10 with strict equality} \tag{17}$$

$$F_{k,i}^{c} = 0 \quad \vee \quad \text{Equation 11 with strict equality} \tag{18}$$

$$F_{k,i}^{p} = 0 \quad \vee \quad \text{Equation 12 with strict equality} \tag{19}$$

$$K_{k,i}^{inv} = 0 \quad \vee \quad \text{Equation 13 with strict equality} \tag{20}$$

C Cournot Oligopoly Model

Below is shown the full supply system for Cournot oligopoly. Some equations run over (k, i) or i:

$$E = N \sum_{k,i} \frac{1}{N} E^b_{k,i} + \frac{1}{N} E^c_{k,i} \quad (1)$$

$$H = N \sum_{k,i} \frac{1}{N} H^b_{k,i} + \frac{1}{N} H^p_{k,i} \quad (2)$$

$$\frac{1}{N} E^b_{k,i} = \frac{Cm_{k,i}}{1 + Cm_{k,i}} \eta^b_{k,i} \frac{1}{N} F^b_{k,i} \quad (3)$$

$$\frac{1}{N} E^c_{k,i} = \eta^c_{k,i} \frac{1}{N} F^c_{k,i} \quad (4)$$

$$\frac{1}{N} H^p_{k,i} = \eta^p_{k,i} \frac{1}{N} F^p_{k,i} \quad (5)$$

$$Cm_{k,i} = \frac{\frac{1}{N} E^b_{k,i}}{\frac{1}{N} H^b_{k,i}} \quad (6)$$

$$\frac{1}{N} \left(F^b_{k,i} + F^c_{k,i} + F^p_{k,i} K^{ini}_{k,i} - K^{inv}_{k,i} \right) \leq 0 \quad (7)$$

$$\theta \frac{1}{N} (H^s_i + H^l_i) \geq \frac{1}{N} H^s_i \Leftrightarrow \sum_{k,i} [\theta_i - d_k] \left(\frac{\eta^b_{k,i} F^b_{k,i}}{1 + Cm_{k,i}} + \eta^b_{k,i} F^p_{k,i} \right) \leq 0 \quad (8)$$

$$\frac{1}{N} \left(K^{ini}_{k,i} + K^{inv}_{k,i} - K^{max}_{k,i} \right) \leq 0 \quad (9)$$

$$\frac{\eta^b_{k,i} Cm_{k,i}}{1 + Cm_{k,i}} P_E(E) + \frac{\eta^b_{k,i} Cm_{k,i}}{1 + Cm_{k,i}} P'_E(E) E$$
$$+ \frac{\eta^b_{k,i}}{1 + Cm_{k,i}} P^H_i - P^F_{k,i} - \lambda^{cap}_{k,i} - \frac{\eta^b_{k,i}}{1 + Cm_{k,i}} (d_k - \theta_i) \lambda^{dec}_{k,i} \leq 0 \quad (10)$$

$$\eta^c_{k,i} P_E(E) + \eta^c_{k,i} P'_E(E) E - P^F_{k,i} - \lambda^{cap}_{k,i} \leq 0 \quad (11)$$

$$\eta^p_{k,i} P^H_i - P^F_{k,i} - \lambda^{cap}_{k,i} + \eta^p_{k,i} (d_k - \theta_i) \lambda^{dec}_i \leq 0 \quad (12)$$

$$\lambda^{cap}_{k,i} - \lambda^{max}_{k,i} - P^K_{k,i} \leq 0 \quad (13)$$

$$\lambda_{k,i}^{cap} = 0 \quad \vee \quad \text{Equation 7 with strict equality} \tag{14}$$

$$\lambda_{i}^{dec} = 0 \quad \vee \quad \text{Equation 8 with strict equality} \tag{15}$$

$$\lambda_{k,i}^{max} = 0 \quad \vee \quad \text{Equation 9 with strict equality} \tag{16}$$

$$F_{k,i}^{b} = 0 \quad \vee \quad \text{Equation 10 with strict equality} \tag{17}$$

$$F_{k,i}^{c} = 0 \quad \vee \quad \text{Equation 11 with strict equality} \tag{18}$$

$$F_{k,i}^{p} = 0 \quad \vee \quad \text{Equation 12 with strict equality} \tag{19}$$

$$K_{k,i}^{inv} = 0 \quad \vee \quad \text{Equation 13 with strict equality} \tag{20}$$

D Cournot Oligopoly with Fringe

Below is shown the full supply system for Cournot oligopoly with fringe. Some equations run over (k, i) or i:

$$E = E^{cou} + E^{fri} \tag{1}$$

$$E^{cou} = \sum_{k,i} E^{b}_{k,i} + E^{c}_{k,i} \tag{2}$$

$$H = \sum_{k,i} H^{b}_{k,i} + H^{p}_{k,i} + H^{fri}_{k,i} \tag{3}$$

$$E^{b}_{k,i} = \frac{Cm_{k,i}}{1 + Cm_{k,i}} \eta^{b}_{k,i} F^{b}_{k,i} \tag{4}$$

$$E^{c}_{k,i} = \eta^{c}_{k,i} F^{c}_{k,i} \tag{5}$$

$$H^{p}_{k,i} = \eta^{p}_{k,i} F^{p}_{k,i} \tag{6}$$

$$Cm_{k,i} = \frac{E^{b}_{k,i}}{H^{b}_{k,i}} \tag{7}$$

$$F^{b}_{k,i} + F^{c}_{k,i} + F^{p}_{k,i} - K^{ini}_{k,i} - K^{inv}_{k,i} \leq 0 \tag{8}$$

$$\sum_{k,i} [\theta_i - d_k] \left(\frac{\eta^{b}_{k,i} F^{b}_{k,i}}{1 + Cm_{k,i}} + \eta^{b}_{k,i} F^{p}_{k,i} \right) \leq 0 \tag{9}$$

$$K^{ini}_{k,i} + K^{inv}_{k,i} - K^{max}_{k,i} \leq 0 \tag{10}$$

$$-\overline{H_i} + \sum_{k} \left(\frac{Cm_{k,i}}{Cm_{k,i} + 1} \eta^{b}_{k,i} F^{b}_{k,i} + \eta^{p}_{k,i} F^{p}_{k,i} \right) \leq 0 \tag{11}$$

$$\frac{\eta^{b}_{k,i} Cm_{k,i}}{1 + Cm_{k,i}} P_E(E) + \frac{\eta^{b}_{k,i} Cm_{k,i}}{1 + Cm_{k,i}} P'_E(E) E$$
$$+ \frac{\eta^{b}_{k,i}}{1 + Cm_{k,i}} P^{H}_{i} - P^{F}_{k,i} - \lambda^{cap}_{k,i} - \frac{\eta^{b}_{k,i}}{1 + Cm_{k,i}} \left((d_k - \theta_i) \lambda^{dec}_{k,i} - \lambda^{dih}_{i} \right) \leq 0 \tag{12}$$

$$\eta^{c}_{k,i} P_E(E) + \eta^{c}_{k,i} P'_E(E) E - P^{F}_{k,i} - \lambda^{cap}_{k,i} \leq 0 \tag{13}$$

$$\eta^{p}_{k,i} \left(P^{H}_{i} - \lambda^{dih}_{i} \right) - P^{F}_{k,i} - \lambda^{cap}_{k,i} + \eta^{p}_{k,i} (d_k - \theta_i) \lambda^{dec}_{i} \leq 0 \tag{14}$$

$$\lambda^{cap}_{k,i} - \lambda^{max}_{k,i} - P^{K}_{k,i} \leq 0 \tag{15}$$

$$\lambda_{k,i}^{cap} = 0 \quad \vee \quad \text{Equation 8 with strict equality} \tag{16}$$

$$\lambda_{i}^{dec} = 0 \quad \vee \quad \text{Equation 9 with strict equality} \tag{17}$$

$$\lambda_{k,i}^{max} = 0 \quad \vee \quad \text{Equation 10 with strict equality} \tag{18}$$

$$\lambda_{i}^{dih} = 0 \quad \vee \quad \text{Equation 11 with strict equality} \tag{19}$$

$$F_{k,i}^{b} = 0 \quad \vee \quad \text{Equation 12 with strict equality} \tag{20}$$

$$F_{k,i}^{c} = 0 \quad \vee \quad \text{Equation 13 with strict equality} \tag{21}$$

$$F_{k,i}^{p} = 0 \quad \vee \quad \text{Equation 14 with strict equality} \tag{22}$$

$$K_{k,i}^{inv} = 0 \quad \vee \quad \text{Equation 15 with strict equality} \tag{23}$$

$$E^{fri} = \sum_{k,i} E_{k,i}^{b,fri} + E_{k,i}^{c,fri} \tag{24}$$

$$E_{k,i}^{b,fri} = \frac{Cm_{k,i}}{1 + Cm_{k,i}} \eta_{k,i}^{b} F_{k,i}^{b,fri} \tag{25}$$

$$E_{k,i}^{c,fri} = \eta_{k,i}^{c} F_{k,i}^{c,fri} \tag{26}$$

$$Cm_{k,i} = \frac{E_{k,i}^{b,fri}}{H_{k,i}^{b,fri}} \tag{27}$$

$$F_{k,i}^{b,fri} + F_{k,i}^{c,fri} - K_{k,i}^{fri} \leq 0 \tag{28}$$

$$\sum_{k,i} H_{k,i}^{b,fri} = \overline{H}_{i}^{fri} \tag{29}$$

$$\eta_{k,i}^{c,fri} - P_{k,i}^{F} - \lambda_{k,i}^{fri} \leq 0 \tag{30}$$

$$\frac{\eta_{k,i}^{b}}{1 + Cm_{k,i}} \left(P_{i}^{H} + Cm_{k,i} P_{E}\right) - P_{k,i}^{F} - \lambda_{k,i}^{fri} - \lambda_{i}^{fdih} \leq 0 \tag{31}$$

$$\lambda_{k,i}^{fri} = 0 \quad \vee \quad \text{Equation 28 with strict equality} \tag{32}$$

$$\lambda_{i}^{fdih} = 0 \quad \vee \quad \text{Equation 29 with strict equality} \tag{33}$$

$$F_{k,i}^{b,fri} = 0 \quad \vee \quad \text{Equation 31 with strict equality} \tag{34}$$

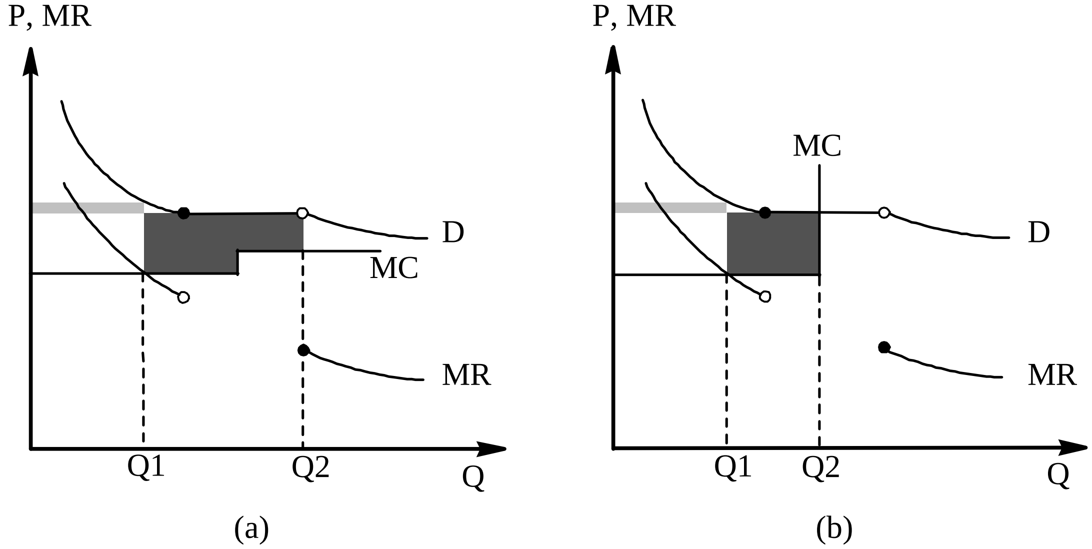
$$F_{k,i}^{c,fri} = 0 \quad \vee \quad \text{Equation 30 with strict equality} \tag{35}$$

E Proof of Existence, Uniqueness and Optimality of Equilibrium

By lowering prices by a fraction, the large suppliers might be able to force out the marginal technology of the fringe. As the large suppliers' output is priced above its marginal cost, such a strategy might be profitable if the fringe technology forced out has a large capacity and a marginal cost only a little lower than the ordinary Cournot equilibrium price reached by the large suppliers. Such a situation is illustrated in figure 4a, where the light shaded area is the profit gain associated with the $MR = MC$ solution, and the dark shaded area is the profit gain associated with forcing out the fringe.

It might also happen (figure 4b) that the large suppliers do not have the sufficient efficient capacity (with marginal costs lower than market price) to meet the demand if all the capacity of the marginal fringe technology is forced out of the market. In this case the large suppliers would prefer to let the fringe produce with some part of their marginal technology, rather than supplying the excess demand with marginal losses (their remaining capacity has costs higher than the market price).

Figure 4 Ambiguous cost structure



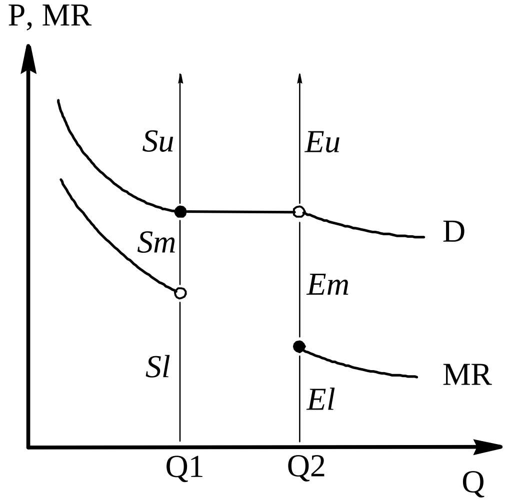
Apparently there are situations where the $MR = MC$ equilibrium found by our solution to the Cournot competitors' problem may not maximize profits.

This happens only when the fringe can be forced wholly or partly out of the market. Fortunately we can show that these situations, which we call ambiguity between perceived demand and cost structure, restrict themselves to one of these two sufficient conditions:

- when the price is equal to the cost of the fringe's marginal technology, but where the fringe production in this technology is zero.
- when the large suppliers produce at the capacity limit of some technology.

To show that this claim is correct we need to consider the large suppliers' marginal cost when they start to force out a marginal fringe technology and when they have just forced it out. Figure 5 gives a useful classification of all possible cost structures related to a given fringe technology that may or may not be forced out to increase profits.

Figure 5 All possible cost structures



Our classification has six distinct types, as the three remaining logical combinations of intersections are not feasible because MC is nondecreasing:

1. An MC curve that intersects *Su* and *Eu*. Figure 6a shows that MC is above the price for the whole of the horizontal section, so forcing

out the fringe technology will always decrease the profit. Also, no fringe technologies to the right of $Q1$ can be profitable to force out. However, there might be a fringe technology with higher marginal cost (another flat piece on the perceived demand curve which is not shown in the figure) that could be forced out of the market. The cost structure associated hereby could be any of types 1 to 6.

2. An MC curve that intersects Sm and Em. Figure 4a presented above shows this situation. The light shaded area is the profit associated with the $MR = MC$ solution (quantity $Q1$), while the dark shaded area is the profit associated with just forcing the fringe's technology out of the market (quantity $Q2$). Whether it is profitable to leave the former solution in favor of the latter depends on the precise structure of cost and demand.

3. An MC curve that intersects Sm and Eu. Figure 4b presented above shows this situation. The light shaded area is the profit associated with the $MR = MC$ solution (quantity $Q1$), while the dark shaded area is the profit associated with using all of the capacity with marginal costs lower than those of the fringe's marginal technology (quantity $Q2$). Whether it is profitable to leave the former solution in favor of the latter depends on the precise structure of cost and demand.

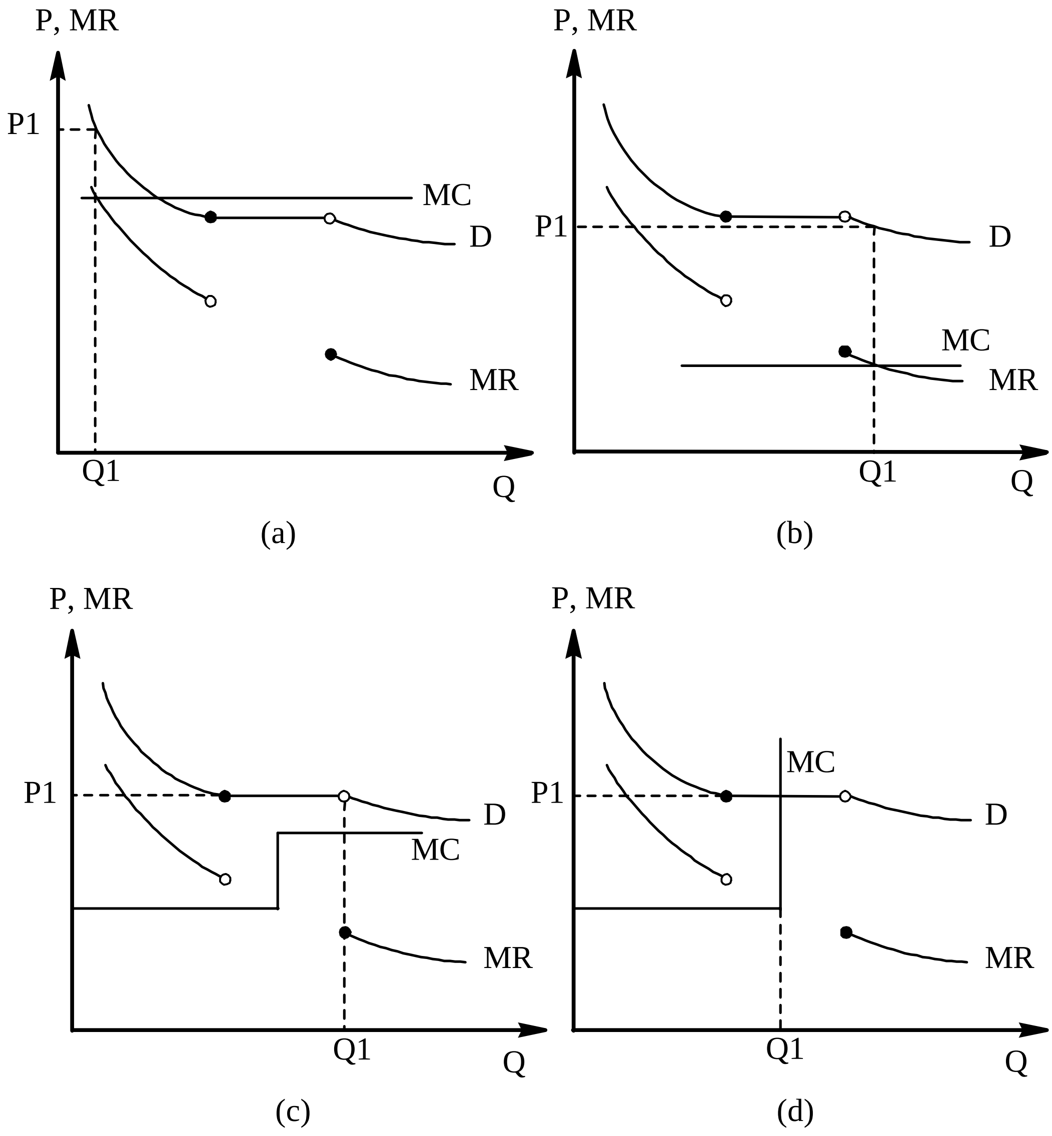
4. An MC curve that intersects Sl and El. As can be seen in figure 6b $MR > MC$ for all quantities left of $Q1$. Thus it is always profitable to move rightward towards this point. It may be profitable to move even further rightward if there is an even cheaper fringe technology that may be forced out. The cost structure relating to this particular fringe technology would then be of type 1, 2 or 3.

5. An MC curve that intersects Sl and Em. Figure 6c depicts this situation, and it is obvious that it will always be more profitable to choose the quantity $Q1$ than choosing any other quantity.

6. An MC curve that intersects Sl and Eu. Likewise in figure 6d $Q1$ is more profitable than any other quantity.

From this we see that ambiguity is associated with just forcing the fringe technology out of market (type 1) and capacity limits of large suppliers' technologies (type 2). In the remaining 4 possible cost structures there can be no ambiguity, and this confirms our claim.

Figure 6 Unambiguous cost structures



Note that this proof assumes that the oligopolists' and fringes cost structures do not change while a fringe technology is being forced out. This is the reason that the fringe and the oligopolists are assumed to supply separate district heating markets. If they supplied the same markets, forcing out a fringe backpressure technology might change the cost minimization problem of the oligopolist (because a larger district heating quantity requirement has to be met), thus altering the resulting marginal cost curve.

For the same reason, the fringe cannot posses extraction technologies. Forcing out some fringe backpressure technology would then be likely to change the heat/electricity ratio of some of the fringe's extraction technologies. This would alter the amount of electricity supplied inframarginally by the fringe, and the oligopolists' perceived demand curve would thereby be shifted inwards or outwards, depending on whether the fringe produced more or less electricity. By only allowing the fringe condensing and backpressure technologies there is no inframarginal change in the fringe supply. Only the production in marginal fringe technology is changed, as the inframarginal technologies are used to their capacity limit.