École des Hautes Études Commerciales

Electricity Market Reforms: Institutional Developments, Investment Dynamics and Game Modeling

Pierre-Olivier Pineau

Presented in Partial Fulfilment of the Requirements
for the Degree of Doctor of Philosophy
at the École des Hautes Études Commerciales

Montréal, Québec, Canada

November 2000

Université de Montréal

Faculté des études supérieures

This thesis entitled :

ELECTRICITY MARKET REFORMS:
INSTITUTIONAL DEVELOPMENTS, INVESTMENT DYNAMICS AND GAME MODELING

Presented by

PIERRE-OLIVIER PINEAU

Has been evaluated by the following committee:

ALAIN LAPOINTE (PRESIDENT)
ALAIN HAURIE (EXTERNAL EXAMINER)
RICHARD LOULOU
MICHÈLE BRETON (CO-SUPERVISOR)
GEORGES ZACCOUR (CO-SUPERVISOR)

Thesis accepted on

Table of Contents

List of Tables

List of Figures

Remerciements (in French and Finnish)

Le doctorat est une épreuve de longue haleine. Pour tenir, il faut avoir été bien préparé avant son début. C'est pourquoi je remercie Michèle Breton d'abord, pour m'avoir engagé lors de mon baccalauréat. François Lepage, professeur au département de philosophie, pour m'avoir dirigé à la maîtrise. Et encore une fois Michèle Breton et Georges Zaccour pour leur co-direction pendant le doctorat. Je suis extrêmement redevable à Georges Zaccour pour son support indéfectible durant ces années de recherche. Il a été un directeur disponible, amical et exigeant.

Je remercie aussi tout particulièrement le *Systems Analysis Laboratory* de la *Helsinki University of Technology* et son directeur Raimo P. Hämäläinen. Le long séjour en terre Nordique m'aura non seulement fait découvrir les bienfaits des saunas et de la *Terva viina*, mais il aura été déterminant dans l'accomplissement de ce travail. Mes pensées vont spécialement à Tuomas Raivio et Pauli Murto pour leur amitié et les projets développés ensemble.

Kiitos myös kaikille Systeemianalyysin laboratorion henkilökunnalle. En koskaan unohda aikaa minkä vietin siellä, työtuntien aikana ja jälkeen. Minulla oli ilo ja kunnia tehdä siellä tutkimusta, niin sydänmellisessä, dynaamisessa ja vahvassa laboratoriossa. Odotan innolla että pääsen tulemaan uudestaan!

Plusieurs amis ont joué un rôle important dans mon entrain au travail: Gerald Karner, Miltiadis Daniil, Arzu Çöltekin, Timo Alakoski, lorsque j'étais en Finlande, mes amis étudiants de doctorat au HEC, lorsque j'étais au Québec, et Simon Pierre Sigué, peu importe où je me trouvais. Merci enfin à ma famille et à mes amis scouts, artistes et autres.

Résumé (in French)

À l'instar des secteurs des télécommunications et du transport aérien, les marchés de l'électricité de nombreux pays ont vu ces dernières années leurs règles de fonctionnement entièrement modifiées. Les états restant à l'écart de ce mouvement subissent par ailleurs de nombreuses pressions pour adopter les "nouvelles" règles, qui émanent d'un processus de déréglementation. Ces réformes ont le plus souvent pour effet de briser le monopole public en charge du secteur de l'électricité par le biais d'une ouverture à la concurrence et par un allégement des conditions d'opérations. Jusqu'à un certain point, la nouvelle structure qui est en voie d'être introduite à l'échelle planétaire ramène l'industrie électrique à un cadre proche de celui de ses débuts au XIX^e^ siècle. Ainsi, lors des premiers pas de l'industrie électrique, Edison et Westinghouse évoluaient dans un cadre réglementaire qui laissait libre court à la concurrence (voir Gilbert et Khan, 1996b pour un historique de l'industrie électrique américaine).

L'objet de cette thèse n'est pas d'établir si effectivement un retour en arrière est en train de s'effectuer, mais plutôt, dans un premier temps, de comprendre pourquoi des réformes sont entreprises. Nous étudierons donc les principales caractéristiques du secteur de l'électricité, puis nous verrons les éléments qui permettent un renouveau du cadre réglementaire. Les avenues possibles de changement seront analysées, tout comme plusieurs cas de réformes. En particulier, la transition qu'a connue la Finlande sera étudiée en profondeur, étant donné son originalité et le libéralisme avancé qu'elle a induit dans ses marchés de l'électricité. Dans un second temps, nous nous pencherons sur le problème des investissements et de la puissance de marché dans ce secteur. Alors même qu'une plus grande concurrence est espérée, les risques d'abus de pouvoir oligopolistique ne sont pas à exclure. En particulier au niveau des investissements et dans les périodes de pointes, le nombre restreint d'intervenants dans le marché pourrait mener à une situation socialement sous-optimale.

La thèse est divisée en cinq chapitres, qui forment deux parties complémentaires. La première partie, tel que mentionné plus haut, est davantage institutionnelle et analyse en

profondeur quelques cas empiriques de déréglementation. Elle regroupe les chapitres 1 et 2. La seconde partie (chapitres 3 à 5), plus analytique, développe un modèle issu de la théorie des jeux. Il permet d'examiner les problèmes possibles concernant les liens entre les investissements et la puissance de marché dont les producteurs peuvent bénéficier lorsque leur nombre est limité. Nous présentons de manière détaillée dans ce qui suit le contenu de chacun de ces chapitres.

Chapitre 1. Les réformes du secteur de l'électricité: motivation, possibilités et zones sensibles

Ce premier chapitre est consacré à une présentation des différents aspects qui touchent l'industrie de l'électricité et les réformes qui sont proposées. Dans une première section, la structure traditionnelle de ce secteur est présentée sous un angle économique. On y voit les caractéristiques des monopoles naturels ainsi que leurs modes de réglementation (contrôle de l'entrée et tarification). Les arguments poussant au démantèlement de cette structure sont ensuite détaillés tour à tour. Nous y retrouvons en particulier les avantages des marchés concurrentiels, l'évolution technologique et les nouvelles tendances mondiales. Les limites de ces arguments sont aussi discutées. Les différentes directions que peuvent prendre les réformes sont précisées dans la section suivante, ainsi que la teneur des textes législatifs américains et européens. La situation canadienne est abordée province par province. Pour donner un aperçu des réactions des grandes entreprises du secteur face à ces changements, une analyse des stratégies de cinq compagnies internationales est effectuée. Enfin, des critères permettant de juger du succès de ce mouvement de réforme sont revus, tout comme les principales approches analytiques utilisées pour étudier ce secteur.

Ce chapitre de la thèse a donné lieu à l'article "Déréglementation des marchés de l'électricité et enjeux sociaux et environnementaux: un état de la situation dans les pays nordiques", Pineau P.-O. (2000), publié dans la revue *Gestion*.

Chapitre 2. Analyse de réformes: le cas de la Finlande

Poussant plus loin l'étude d'un cas concret de déréglementation, ce chapitre présente et analyse en détail le marché de l'électricité en Finlande et les réformes qu'il a connues. Tout comme ses voisins scandinaves (Suède et Norvège), la Finlande possède un marché de l'électricité extrêmement libéral. Par contre, son évolution jusqu'à ce stade est restée très peu documentée, malgré son originalité. Un des points saillants de ce caractère distinct est la présence pendant de nombreuses années d'une concurrence au niveau de la transmission, un secteur unanimement reconnu comme ayant les attributs d'un monopole naturel. Le chapitre 2 explore ainsi toutes les particularités de ce marché.

L'article "A Perspective on the Restructuring of the Finnish Electricity Market", Pineau P.-O. et Hämäläinen R.P. (2000), publié dans la revue *Energy Policy*, en est tiré.

Chapitre 3. L'investissement dans un modèle statique: qu'advient-il de l'équilibre après la déréglementation ?

Les deux premiers chapitres brossent un portrait général de la situation dans le secteur de l'électricité tout en s'attardant au cas plus spécifique de la Finlande. Parmi les menaces identifiées dans cette présentation se trouve la possibilité d'un abus de pouvoir de marché dû à un nombre trop petit d'intervenants dans le secteur. Les caractéristiques d'un oligopole pourraient donc prévaloir, menaçant par le fait même certains des gains espérés par l'ouverture du marché à la concurrence.

Le chapitre 3 présente cette menace d'une manière beaucoup plus explicite en comparant les équilibres survenant dans un monopole, un oligopole et un marché concurrentiel à celui d'un marché réglementé. Le danger en terme d'investissements limités et de prix supérieurs est ainsi documenté à l'aide d'un modèle statique simple, comportant toutefois les principales caractéristiques du secteur.

Chapitre 4. Le problème dynamique de l'investissement

L'extension du modèle à un cadre dynamique s'avère néanmoins nécessaire pour pousser plus loin l'étude de l'équilibre oligopolistique, une situation que l'on ne peut écarter dans un marché déréglementé. C'est ce qui est entrepris dans le quatrième chapitre, où une présentation méthodologique de la théorie des jeux est d'abord réalisée. Les différents concepts de solution sont revus, ainsi que les structures d'information utilisées dans les jeux dynamiques. Des résultats s'appliquant à notre étude sur l'existence et l'unicité des équilibres sont présentés, juste avant de développer le modèle dynamique d'investissement qui nous intéresse.

Ce modèle, bâti sur trois périodes, est résolu pour trois structures d'information différentes: en boucle ouverte, en *feedback* et selon la structure d'information "S-adapted". Le choix de la structure d'information utilisée s'avère très important, parce qu'il peut grandement limiter les possibilités d'obtenir une solution. Par ailleurs, la structure d'information se doit de refléter les caractéristiques réelles de la situation dans laquelle les joueurs auront à prendre leurs décisions. Ainsi, si une solution est obtenue plus facilement pour un jeu en boucle ouverte, celle-ci n'est pas *subgame perfect*, ce qui peut être considéré comme une lacune. La solution en feedback possède cette caractéristique, mais elle est par contre plus difficile à obtenir, voire impossible dans certains cas.

Le chapitre montre que la structure d'information "S-adapted" possède des caractéristiques intéressantes, qui la font se rapprocher de la structure en feedback, tout en gardant la simplicité de calcul d'une solution en boucle ouverte. Son attrait provient de l'adaptation des stratégies obtenues à un événement aléatoire qui peut se réaliser à plusieurs reprises durant le jeu. Une application numérique illustre ce résultat et montre qu'une solution comparable à celle en feedback est obtenue.

Chapitre 5. Un jeu stochastique et dynamique du marché finlandais de l'électricité

Se basant sur les résultats du chapitre 4 et la pertinence de la structure d'information "S-adapted", un modèle de plusieurs périodes caractérisant le marché de l'électricité est développé, avec une croissance aléatoire de la demande. Deux types de demande sont incluses: celle de pointe et celle de base, pouvant être satisfaites par des joueurs ayant deux types de capacité de production, reflétant les structures de coût de production d'unités thermiques et hydrauliques/nucléaires. Les joueurs doivent décider des quantités à produire et de leur investissement à chaque période, leur choix ayant une influence directe sur les prix dans les deux marchés considérés (marchés de "base" et de "pointe"). C'est donc un jeu de type Cournot qui est joué.

Une solution est obtenue suite à l'application de techniques de résolution numérique programmées sur le logiciel GAMS. Différentes analyses sont menées pour étudier l'impact sur les prix et l'investissement de la structure de marché, du nombre de joueurs, du coût de l'investissement, du taux de dépréciation des investissements, de l'élasticité-prix et des probabilités de réalisation des différents niveaux de croissance de la demande.

Ce modèle permet d'étudier la dynamique d'investissement dans un marché oligopolistique et d'approfondir l'analyse de la puissance de marché dans un tel contexte. L'article tiré de ce chapitre, "A Stochastic Dynamic Game Model of the Finnish Electricity Market" (Pineau et Murto, 1999), a été soumis à une revue académique internationale.

La contribution de cette thèse se situe donc à deux niveaux distincts. Tout d'abord, une étude exhaustive est offerte sur les motivations de la déréglementation et les avenues qu'elle peut suivre. Cette réflexion est enrichie par la présentation de l'expérience déréglémentaire de plusieurs pays, et en particulier celle de la Finlande. Cette recherche documente ce secteur de l'industrie électrique en pleine mutation, qui ne réalise pas toujours la justification ni la portée des réformes qui sont mises en œuvre.

La seconde contribution majeure de la thèse réside dans l'application d'un modèle de la théorie des jeux à un cas concret d'investissement, dans un contexte dynamique et stochastique, sous une structure d'information moins connue: la structure d'information "S-Adapted". La compréhension et l'analyse de la nouvelle dynamique de marché et de son impact sur les investissements sont essentielles pour s'assurer que les réformes du secteur de l'électricité le transforment en un marché réellement concurrentiel.

Abstract

The reform trend of the 1990's in electricity markets recreates, to some extent, the institutional framework from which they developed one century ago. Although these reforms do not endeavor to completely remove regulation, the basic objectives of deregulation dwell on limiting central and governmental control over the industry in order to promote free competition at all possible levels. In the early days of the electricity industry, free entrepreneurs such as Edison and Westinghouse were facing a similar structure, and it is only progressively that more legislation came to shape the entire electricity industry (see Gilbert and Khan, 1996b, for a historical background of the U.S. electricity industry).

To assess whether the electricity industry is or is not moving back to a 19th century structure is not the goal of this thesis. We will rather try to understand on what grounds deregulation reforms stand and review how different countries and large utilities have reacted to this trend. The special nature of electricity (non-storable basic good, centrally produced) creates different obstacles in the restructuring of electricity markets, compared to other industries like the airline or telecommunication ones. For example, the dominant positions of some utilities, the production structure and the importance of electricity in modern life could transform these reforms in a threatening move for consumers. Another specific issue arising from deregulation, now that national energy policy goals no longer rule the behavior of utilities, is how investment will be coordinated in the new market.

A key element to keep in sight is the *competition level* targeted by these reforms. To which extent full competition can really occur in electricity markets remains an unanswered question. Indeed, the oligopolistic structure of the market could prevent such an outcome. An investigation of the investment dynamics in such a context seems therefore appropriate, and this will be an important theme of the thesis.

This work offers an analysis of deregulated electricity markets and studies the oligopolistic market dynamics that could prevail in the new structure. Two complementary approaches are used for these purposes. The first is institutional and presents a thorough illustration of

the economic arguments advanced to support market reforms and an industry view of the actual strategic actions undertaken by important utilities. Legislative changes will be reviewed for different countries with a discussion on the assessment procedures for these reforms. A detailed example of the reform process in the Finnish electricity market is presented. The investment issue will emerge as an interesting challenge to focus on, due to its importance for the market. The second approach is more analytical and develops on the market equilibria that could result from the new structure. A dynamic model of investment for the electricity market is built and applied to the Finnish market.

The first contribution of this thesis is therefore to establish more clearly on what principles all electricity reforms rely. As will be shown in chapters 1 and 2, this matter is not self-evident and these principles, when explicitly identified, are at least open to debate. A thorough review is made in these two first chapters of the economics of this sector, the policy changes and the industry adjustments.

The second main contribution, stemming from the second approach, is to use game-theory to study the dynamic investment problem in electricity markets. Chapter 3 presents the investment problem in economic terms in a simple static context. Game theoretical elements needed to move forward to a dynamic analysis are presented in chapter 4, with an important discussion on the relevance of three different information structures. One of these, the S-adapted information structure, will be used to show some interesting features, motivating its application to the case of Finland, one of the most advanced deregulated electricity market. Chapter 5 develops a 10-year, 5-period oligopolistic electricity market with many players, where production and investment choices have to be made under stochastic demand growth scenarios. This model offers a new contribution to the analysis of investment in deregulated electricity markets, where dynamic effects are seldom taken into account in game models.

Proposed methodology

In order to study these problems, two methodologies are adopted. The first is a case study methodology to review actual industrial reforms in the electricity sector. The second one is in line with recent developments in dynamic game theory and mathematical programming computational methods. Dynamic Nash-equilibria can be obtained for different information structures. We discuss to what extent they can be found and be useful. As well, we use a relatively new information structure: the S-adapted open loop information structure (Haurie, Zaccour, Smeers, 1990) which allows the inclusion of a stochastic element in the modeling process and improves on the shortcomings of the open-loop information structure.

Closed form solutions are determined for simple cases, and a numerical model is built for a more elaborate model. The equilibrium can be found in this latter case via a complementary formulation or by an optimization-based algorithm (Smeers, 1997). Numerical implementation on GAMS, a computer language designed for economics mathematical programming problems, is included in the research methodology.

Within the new market dynamic studied, we observe that market power limits investment and that prices are significantly affected by this effect. Our study adds to the literature on energy research by applying a dynamic game approach to investment behavior in a deregulated context.

Chapter 1. Electricity reforms: grounds, implementation and issues[1]

1.1 Introduction

Numerous countries around the world have undertaken regulatory reforms of their electricity industry, with a growing literature to document it, e.g. Gilbert and Kahn (1996), Yajima (1997) or Zaccour (1998). This coverage has a very wide range, but only very few studies make the link between *implemented reforms* and their performance with regards to the *goals of deregulation*. On one side, a part of the literature promotes the liberalization of the electricity industry (e.g. Demsetz, 1968, Joskow, 1998, Navarro, 1996), and on the other side, research is conducted to study different market structures (e.g. for transmission, see Einhorn and Siddiqi, 1996, or Schweppe et al., 1988, for spot markets and pools, see Barker et al., 1997). Policy makers, presumably endorsing the arguments of the former literature, implement reforms inspired from studies made in the latter one. The question of knowing if these structures fulfill or can possibly fulfill reform expectations still remains to be answered. Some studies review impacts of ownership and market integration (see for example the surveys of Banks, 1996, Kwoka, 1996, Pollitt, 1997, and Walker and Lough, 1997), based on different criteria. However, they do not directly analyze the official grounds for reforms on which governments and international agencies stand and they do not extensively cover any specific case.

This chapter surveys the arguments put forward for deregulation in official documents, relates them to economic theory and describes how reforms can be implemented and assessed. An analysis of how major utilities have reacted to deregulation is also provided, in order to understand the new dynamics of the market. Changes in the investment behavior will be identified along the chapter, shedding light on the investment issues we deal with in the three last chapters.

---

[1] Parts of this chapter have been included in Pineau (2000).

First, we review the economic and regulatory context faced by the traditional vertically integrated utility. This presentation will help us understand the context in which reforms arise and their possible justification. We explore the argumentation supporting the reforms in the electricity sector, and then present the possible areas of reform. How to assess these reforms and to model the electricity sector are the last topics of this chapter.

1.2 Traditional economic structure of electric utilities

1.2.1 Characterization of natural monopoly

The characterization and definition of a natural monopoly became much more technical as economic theory developed. At the beginning of the century, Farrer (1902) proposed five properties for product or production process in such firms[2]:

- to be capital intensive (significant fixed cost or scale economy);
- to be viewed as a necessity (or essential to the community);
- to be nonstorable (yet subject to fluctuating demands);
- to be produced in particularly favored locations (yielding rents);
- to involve direct connections with customers.

Although all of these points are still relevant today, the prevailing definition given by later economists is more formal. Natural monopolies are now classified according to *weak* and *strong* properties (Berg and Tschirhart, 1988, Train 1991), and also with respect to the stability of cost function properties along production levels (Schmalensee, 1979).

In the case of a single product firm (which corresponds to the traditional electricity utility), a weak natural monopoly has decreasing average cost:

$$\frac{C(q^i)}{q^i} \leq \frac{C(q^j)}{q^j} \qquad (1.1)$$

where q^i and q^j are production levels such that $q^i \geq q^j$, and $C(\cdot\ )$ is the total cost function. Truth of equation 1.1 reveals the presence of scale economies.

[2] Taken from Berg and Tschirhart (1988), page 3.

The strong natural monopoly is not defined in relation to scale economies, but rather with the *subadditivity* of its cost function. A subadditive cost function satisfies the following property:

$$C(\sum_{i=1}^{m} q^i) \leq \sum_{i=1}^{m} C(q^i) \tag{1.2}$$

where m is the total number of production lots. It is possible, as shown in Baumol (1977), to have a subadditive cost function without decreasing average cost.

If the production cost function displays scale economies (or is subadditive for all possible production levels), it is then said that the natural monopoly is *permanent*. If on the other hand these properties are only valid in a restricted range of production levels, then the natural monopoly is *temporary*. In this case, for those levels where properties defining the natural monopoly are not true, many firms could produce the same outcome without any efficiency loss for the society.

However, as long as demand justifies a production level in the range defining the natural monopoly situation, a single firm can produce the required quantity for a smaller total cost. Therefore, an efficiency gain can be made compared to the multi-producers possibility.

Giving a firm the opportunity to be the sole supplier of a commodity or a service is handing it some market power. The firm could use this power to maximize its own interest, while decreasing the total welfare of the society. This threat calls for some regulation, to control the monopolist's behavior. Indeed, regulation has the goal of maintaining economic efficiency, but it also has some political goals. In fact, as stated by Schmalensee (1979), economic efficiency gives nobody direct gain nor pleasure. So even in choosing economic efficiency, a political choice is made in order to favor the whole society. Some wealth redistribution can also be achieved through regulation, as well as quality, safety and reliability standards. This explains why regulation can always be criticized, and that it is of the interest of some groups to remove regulation. In economics, the two main tools for regulation are control of entry and pricing.

1.2.2 Control of entry

In our sector of interest, when used, control of entry is made through national energy policy and laws. Authorizations are granted to a unique firm in each franchise territory. It is simply forbidden for other firms to start their own business activities in this sector. This allows the (natural) monopolist to produce at the most efficient cost and to set the adequate price to recover its fixed costs. The pricing issue is of great interest, because it has a particular importance and distinct features in the electricity sector. We extend more on pricing in the next section. Control of entry, which is one type of barrier to entry, can also have political importance, specially in strategic economic areas such as natural resources and energy. For more on these issues, see Geroski, Gilbert and Jacquemin (1990).

1.2.3 Pricing

Pricing is the second and main regulatory tool. Wealth redistribution goals can be achieved through it, but it also provides easy targets for critics. Indeed, when pricing is regulated, some customer categories can benefit from it, at the expense of other categories. *Cross subsidies* can take place and consumer groups paying more than the real cost of their consumption have grounds to complain. Many pricing possibilities are available. We discuss the most common of them in table 1.1.

Before developing on the pricing of electricity, we shortly describe the cost structure of electricity generation. Three main elements determine the total cost of consumption[3]:

- the energy used (measured in *watt-hour*, Wh);
- the maximal load, or power (in *watt*, W);
- the voltage (in *volt*, V).

The two last elements represent fixed costs (with respect to energy), because they induce a specific level of capacity for generation, transmission and distribution. Once this capacity is built, only maintenance needs to be done. Additional cost derives only from the amount of energy consumed, which varies in time. This variation implies that the total capacity will not be used at all times. The *load factor*, defined as the ratio of the average load to the maximal load, is a good indicator of the utilization of the production and transmission capacities. The higher the load factor, the more often total capacity is fully used. A lower load factor indicates that a large part of the capacity is idle most of the time, meaning that the investment is not productive. Being productive only in some particular moments creates a cost recovery problem as the periods during which consumers may be charged are limited. This problem, caused by varying electricity demand and the non-storability of electricity is known as the *peak load problem*.

The voltage at which the electricity is delivered is also of importance, because transmission is made at high voltage, although consumers use lower voltage[4]. Changing the voltage requires transformers, and thus linking a consumer directly to the transmission network would save the transformer cost.

With this background on the cost structure of electricity, issues in pricing can be more easily understood.

---

[3] See Mitchell, Manning and Acton (1978), page 9.

[4] Transmission can be made at voltage as high as 735 kV, but the residential end-user uses 110/220V.

Table 1.1 Main pricing options

Name	Description
AVERAGE COST PRICING	A uniform price is applied for all kWh of energy consumed, for all consumers. The level of price is based on total cost of the firm, plus a regulated return on investment.
MARGINAL COST PRICING	Consumers pay the marginal cost of their consumption.
REAL-TIME PRICING	Close to marginal cost pricing, real-time pricing does not have to be at marginal cost, but is instantaneously related to the time of use. It can include other costs.
TIME-OF-USE PRICING	It is a type of real-time price where price varies only between different periods. It is easier to implement because the price is not continuously changing.
RAMSEY PRICING	Also known as *second-best pricing*, this tariff acknowledges the differences in elasticity between consumer groups, leading to different prices for them. It has been developed with a revenue constraint covering all fixed costs.
NONLINEAR PRICING	Also known as *non-uniform pricing*, this tariff evolves with consumption, allowing for quantity rebates or premiums.
RELIABILITY PRICING	This tariff discriminates among reliability levels desired by consumers, with price increasing with reliability.

Each of the pricing options presented in table 1.1 has some interesting features, as well as drawbacks. Since a natural monopoly, when regulated, cannot directly follow a profit maximization objective, it needs to define other goals. As mentioned previously, these goals, implemented through regulation, are economic and political.

More precisely, the main economic goal is to produce at the cheapest cost. To set the pricing structure, however, other goals need to be defined. These other goals could be to recover all cost (fixed costs), to have a "fair" price for all consumers, to induce efficient consumption, to favor some industries, to reduce consumption at specific times, to promote energy saving, etc. Clearly, here some "political" choice enters into account. We now discuss each of the aforementioned pricing options with relation to these goals.

Average cost pricing

This may be the simplest tariff, which is really convenient for many consumers because they always pay the same price for each kWh of energy. It can also be conceived as fair, because no distinction is made between consumers. However, for some large consumers, this pricing could be problematic. Indeed, if they consume during low production cost periods, when the average price is above the real cost of consumption, they end up subsidizing consumers that use electricity during peak load periods.

Three major problems are related to average-cost pricing scheme:

- cross subsidies, as just explained;
- no peak-load reduction incentives;
- Averch-Johnson effect.

With no cost signal in price, fluctuating demand is not affected by the price, and the load factor is not improved by the tariff structure. Average cost pricing does not help to reduce the peak capacity, and this results in extra investment cost to maintain this peak capacity. Moreover, as the utility can take a specific return on its investment and include it in the average cost price, it has no incentive to improve investment, and can even invest inefficiently because of the guaranteed return. This is known as the Averch-Johnson effect and has been discussed in Averch and Johnson (1962), Kahn (1989) and Train (1991).

Marginal cost pricing

As a direct response to cross subsidies and poor peak-load reduction incentives, marginal cost pricing can be used. In electricity, Boiteux (1960) was the first to study this concept (see also Vickrey, 1971). Under this tariff, all consumers pay for the marginal cost they are responsible for, so it directly solves these two problems.

However, two important problems are linked to marginal cost pricing:

- feasibility and convenience;
- cost recovery and excess profit problem.

As marginal cost evolves continuously with total load demand, the electricity price is constantly changing. For a majority of consumers, this would hardly be acceptable, and probably not even feasible, due to the metering requirements. Fast improvement in metering and remote monitoring of consumption could nevertheless change this figure. Also, simplified versions of marginal cost pricing, such as time-of-use tariffs, could be used.

The second problem of marginal cost pricing is twofold. On one hand, large generation units used for base load have low marginal costs, but high investment cost. This is especially true for nuclear and hydro power plants. Use of (short-term) marginal cost pricing would then results in cost recovery problems, because in the base load period, the marginal cost would be below the average cost. On the other hand, during peak load, smaller generation units are put into operation. These units require a smaller initial investment, but have a higher marginal cost. In these periods, the marginal consumption causes a marginal cost to the system that is much higher than the average cost. The utility could then make enormous profit if the price was set to the marginal cost. This threat of high prices was a reason explaining the reluctance of regulators to use marginal cost pricing (e.g. Mitchell, Manning and Acton, 1979, or Monnier, 1983).

It is possible that the two effects could compensate for each other and that reasonable overall profit could be made. This matter, surprisingly unexplored in the energy economic literature, should be investigated further.

Real-time pricing

This pricing is similar to the marginal cost pricing, but could also include other costs. The marginal cost would thus be augmented by an extra part or percentage.

Time-of-use pricing

Again, this tariff is very close in its objective with the previous two. It is advantaged by its simplicity and lower metering requirements. Generally, only two levels are defined in this structure (day and night for example), which allows for easy adaptation from consumers.

Peak load reductions can thus be realized through this structure, and prices are closer to real costs than in the average cost pricing. However, it remains an average cost pricing principle, as it defines an average cost for each time period. When the time period tends to zero, then it becomes a real-time pricing.

Ramsey pricing

Ramsey (1927) developed this different price scheme, which explicitly takes into account a cost recovery constraint and considers different market segments. It is based on exactly the same principles as marginal cost pricing, which explains the name *second-best pricing* also used[5]. A different price is defined for each market segment, according to its price elasticity for electricity.

This approach has two main flaws:

- it creates open discrimination between consumers;
- and it uses problematic data.

By considering different segments and their elasticity, the Ramsey pricing is charging to the captive, inelastic, consumers a higher price than to the elastic consumers. In light of a social policy, this scheme is rather difficult to maintain.

Moreover, determining the price elasticity of consumers might be a difficult task. The estimation of demand elasticity, as will be reported in chapter 3, is not a simple task and does not lead to very robust results.

See also Baumol and Bradford (1970) for more theory on Ramsey pricing, and Train (1991) for a complete discussion.

Nonlinear pricing

This tariff structure is more often used for industrial customers. They pay for the maximal load capacity they need and for the energy used, according to a fee that varies with quantity and periods of time. Spulber (1993) and Brown and Sibley (1986) discuss this pricing in an

[5] As we will see later, marginal cost pricing is often considered as the "best pricing" because it induces maximal economic efficiency.

electricity context. Wilson (1992) makes a thorough presentation of this scheme, for the many sectors to which it could be applied.

Reliability pricing

Since consumers value electricity according to their usage of it (and profit they make out of it), and have different outage costs in case of supply failure, different reliability levels among them can be acceptable. By offering many reliability options in the tariff structure, a simple tool is offered to deal with the peak-load problem. Indeed, higher reliability options will be more expensive as they have to support generation units for peak-load production. Lower reliability options, accepting to receive less power at given periods, can save some capacity cost.

Under this family of pricing, one also has *interruptible rates* and *priority pricing*. They all share the common principles of allowing the supplier to serve only a fraction of the total demand and of discriminating between consumers for power allocation according to the agreed reliability need.

In this section, we have presented the economic structure and issues of the regulated natural monopoly. With this basic understanding of the previously prevailing situation in the electricity sector, we can now focus on the study of the deregulation movement.

1.3 Arguments and targets of electricity industry reforms

"It is not immediately clear, however, why reorganization of this industry is occurring now, what are the driving forces, and whether there will be an international convergence in its structure". This comment made by Richard J. Gilbert, Edward P. Kahn and David M. Newbery in Gilbert and Kahn (1996) shows that even for experts of the field, the explanation of electricity deregulation is not completely manifest. In this section, we wish to shed some light on these driving forces. The presentation of the main arguments for the reorganization of the electricity sector will help to understand the grounds and targets of this

trend, being legally enforced through important energy policy texts (examined in section 1.4).

1.3.1 Economic argument for competition

Standard microeconomics states that price should be equal to the marginal cost in order to maximize social welfare. Brown and Johnson (1969) prove this result for the electricity context. This principle becomes nevertheless difficult to implement, as seen in the discussion of the pricing options in section 1.2. Keeping this in mind, policy makers seeking to maximize social welfare should favor marginal cost pricing, or a tariff near it. There are two ways to approach this result:

- to constrain producers through regulation to sell at marginal cost (or at a reasonably close level);
- to rely on the premise that producers will make that choice on their own.

Traditionally, the "compulsory" option was chosen as only one producer was active, and the second option was therefore not feasible. Indeed, fixing the price to marginal cost is not the best mean for a monopoly to maximize its own benefit (see for example Varian, 1992). The presence of this single producer was justified by the natural monopoly features of the market. A regulator or an entity having some control over the monopoly was needed to guarantee that prices would not deviate from the social objective. But regulation is criticized by many. It can be costly and does not run perfectly well with ideas of free choices, a concept valued in many countries. A more theoretical argument lies within the *capture theory* (see e.g. Berg and Tschirhart, 1988, or Primaux and Nelson, 1980). This theory examines how some groups can "capture" the regulator to act in their own interest. In that case, the monopoly could behave according to a regulation only made to satisfy the interest of some specific groups.

For all these reasons, attempts to do without a regulator were formulated. As early as Demsetz (1968), the question "Why regulate utilities?" was asked. Demsetz offered an argument to remove regulation, consisting mainly in stating that a monopoly situation does not necessarily induce high prices. The reason for this is that franchise competition, inside the monopoly territory, could lead to the appropriate tariff. His argument can be viewed as a particular case of Bertrand (price) competition in oligopolistic markets, where the price equilibrium arises at marginal cost. It goes as follows. All firms competing for the franchise submit the price they would charge if chosen. The firm with the lowest price gets the exclusive right to supply the franchise. Thus, the auction process tends to result in marginal cost pricing, as in Bertrand competition.

Although interesting, this manner of introducing competition has not been pursued. The main reason for this is that as the natural monopoly nature of the electricity market was challenged, the idea of having a global competitive environment seemed more relevant. How natural monopoly is contested will be seen in the next section. But what is important to notice is that the perspective of marginal cost pricing naturally arising in a competitive setting led to a strong interest in attempting to remove the regulator. Indeed, this solution has the advantage of relieving the need for a regulator (avoiding its cost and the reluctance to accept its existence), while delivering the desired result. Thus, behind the official objective of liberalizing electricity markets, there is this economic argument of having a natural way to achieve marginal cost pricing, and efficiency (seen as the maximization of social welfare).

The efficiency created by marginal cost pricing, as a result of competition, is only one specific type of *efficiency*. Efficiency can be understood in many ways as Gunn (1997) shows. Newbery (1998) discusses a broader meaning of efficiency, when he reviews the state of the U.K. electricity market and reform process. In this broader sense, efficiency is not only the maximal welfare obtained in a static situation, but also the dynamic process of having constant adjustment to the lowest production costs. Competition is not only expected to bring prices to marginal cost, but should also result in a more efficient use of resources. This result is in fact part of the standard microeconomic theory and can be proven by showing that supply functions are obtained by following a cost minimization process. Costs of production are at their minimum under rational economic behavior of microeconomic agents in perfect competition[6].

---

[6] See for example Varian (1992), chapter 4-5.

To sum up, in the economic argument advocating competition, we have the goal of marginal cost pricing and minimum production cost. However, to accept this economical argument, the traditional natural monopoly situation used to describe the electricity industry has to vanish. If not, the society could be better off in term of total cost (efficiency in resource usage) in a regulated monopolistic situation with marginal cost pricing. To see how a natural monopoly may no longer be the relevant assumption in the electricity industry, we now present the *technological arguments*.

1.3.2 Technological arguments

Improvements in three areas of technology prepared the ground for deregulation: in *generation*, *transmission* and *information technology*.

Efficient small scale generation

Natural monopolies have been studied widely (see the references of section 1.2). Their main characteristic, as shown by Baumol (1977) is the subadditivity of their cost function. But in the context of electricity, it is sufficient to characterize a natural monopoly by economies of scale[7]. This property means that average production costs are decreasing, resulting in a cost advantage for large power plants over small ones.

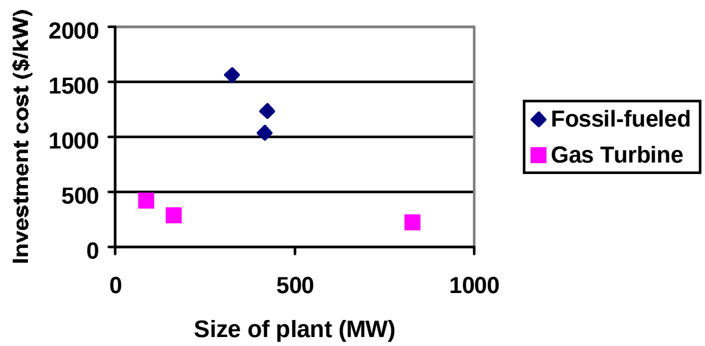
In the generation segment of the electricity industry, this characteristic was well exemplified by the usual huge scale of power plants. The installation cost per megawatt (MW) decreased continuously from the beginning of the century to the end of the 70s, as long as the size of the power plant was *increasing*[8]. But in the 80s, technological improvements resulted in efficiency gains such that small generation units, especially combined-cycle gas turbines (CCGT), could be economically sound. Prior to that, a capacity of 1000 MW was needed to reduce average fixed cost per MW to a competitive level. Currently, the same average cost can be attained with gas turbine power plants of only 100 MW. For example, the investment cost in CCGT is now between 300 and 600US$ per kilowatt (kW), against a range of 800-

---

[7] For firms producing only one commodity, Baumol (1977) has shown that scale economies are sufficient to prove that monopoly is the "least costly form of productive organization", so in the case of electricity we can ignore the subadditivity condition for the cost function.

1 400US$/kW for coal plants (Pfeifenberger et al., 1997). Figure 1.1 shows how relatively small gas turbine power plants can be installed at lower cost per kW of capacity compared to traditional fossil-fueled power plants[9].

Figure 1.1 Size and investment cost of new plants (1996)



This trend allows small producers, either new independent power producers (IPP) or large industrial consumers, to enter more easily into the generation market. In such a context, the cost argument of the natural monopoly is harder to maintain, and prospects for many players generating at low cost seem to be good enough to expect some competition. On such grounds, the regulator could be removed to let competition bring prices to their desired level (i.e. marginal cost).

However, to present a complete picture of the cost structure in the electricity sector, one should also mention the structure of marginal cost of production. With the initial investment cost, the marginal production cost represents the dominant economic factor in the choice of a generating technology. As a rough characterization of the structure of marginal costs, it can be said that the more expensive the production unit is (high investment cost), the cheaper it is to produce (low marginal costs). Figure 1.2 presents this relation[10].

---

[8] See for example Hunt and Shuttleworth (1996), page 2.

[9] Data are taken from Table 14 in the *Financial - Investor-Owned Electric Utilities* section of the Energy Information Administration web site (www.eia.doe.gov).

[10] Data are taken from Table 4 and 14 in the *Financial - Investor-Owned Electric Utilities* section of the Energy Information Administration web site (www.eia.doe.gov). Nuclear and hydro investment costs are estimated.

Figure 1.2 Investment and short term marginal production cost

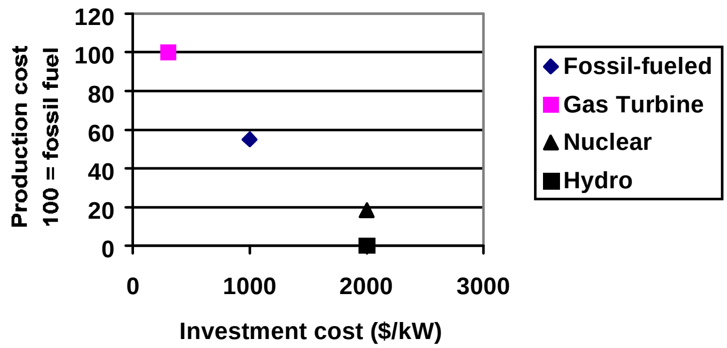


Figure 1.1 and 1.2 lead to the following comment. If new entries are only made with fossil fueled and gas units, then the industry short term marginal cost of production will rise. As a result, customer prices, although at marginal cost and in a competitive environment, could increase in the mid and long run. This possible scenario would be due to investment decisions favoring lower investment cost generation units. However, the fact remains that entry and production in the electricity industry are economically more open due to the new technologies.

High voltage transmission lines

Another technological argument supports freer electricity markets. This argument is related to new transmission possibilities. With the development of more efficient transmissions, exchange of electricity becomes more and more possible. For example the first line operating at a voltage higher than 700 kV was introduced in 1965 in Canada and eased the transport of electricity far away from the generating points. New connections of more than 400 kV between Norway and Germany are planned for the beginning of the millennium[11], and their technical possibility is an important element in the potential competition of producers from different countries. Now that long distance exchanges of power are more feasible, removing protection of sales territory could benefit consumers and increase efficiency in at least two ways. First, by taking advantage of non-coincidental peak loads, customers of different

[11] See the data given at www.nordel.org.

regions can have access to cheaper electricity at certain hours. Secondly, increased interconnections can reduce global capacity requirements while keeping reliability at a similar level, because available capacity becomes accessible from different regions.

Powerful information technology

Real time information sharing and update through internet and high level computing possibilities opened the way to new electricity transactions. These short-term and financial transactions were impossible to make before our "information age", largely because they require the processing of a huge amount of information in a short period. For example, buying and selling MWh should be done one hour ahead to have efficient short term markets, but the physical scheduling and dispatch of the system needs to be done according to the settled transactions. Only now when computers and software are available to do the job is this possible.

These three advances in technology, competitive smaller generation units and high voltage transmission lines seem to give a clear ground to reform electricity markets, from a regulated to a competitive market.

1.3.3 Other arguments

Linked to these two classes of arguments are some other ones we now present. They are not widely used and documented, probably because they are more difficult to prove with strong evidence. However, we mention them for the sake of completeness.

Privately owned businesses are more efficient

It is sometimes held that private companies are more efficient than public ones. If this is true, then selling public assets in the electricity sector to private interests could be beneficial. However, studies like the one conducted by Kwoka (1996) find very mitigated results for this idea.

Accountability of investment

When market shares are protected, the producer has the possibility of investing in new capacities in a sub-efficient manner. This can be explained by his advantageous situation, allowing him to recover all his costs from his customers, who cannot choose another supplier. This scenario can lead to non-responsible and costly investments.

Free entry in generation and competitive wholesale electricity markets induces more responsible investments, or at least the responsibility of the investment is clearly attributed to the investor. Consequently, society does not pay for erroneous capacity additions through higher tariffs.

However, in the transition period from a regulated to a deregulated market, some generation assets are becoming uneconomic to run, because the market price is lower than their running costs. The remaining unpaid part of their investment cost, which cannot be recovered, is called a *stranded* cost. Diverse solutions are chosen to pay this cost: either the government (main shareholder) takes full responsibility of it (European solution), or the cost is shared between shareholders and customers (American solution) through a temporary levy.

Price diversity

One source of complaints in the traditional monopolistic electricity industry is the price differences between different groups of customers (industrial, commercial, residential) and different geographic areas. Either the price level was said to be unfair because of *cross-subsidies* or some groups reacted to their inability to have access to the (lower) prices of the neighboring market.

With unregulated prices and open-access to all markets, these situations should end. Harmonization of prices should be possible with competition bringing prices to the real marginal cost of service for each customer and in each geographic region.

Worldwide globalization and liberalization trend

One important factor in favor of deregulation is the global liberalization trend, in all economic sectors and throughout the world. With the wider acceptance that the liberal organization of the market is better than other alternatives, it becomes harder to justify and maintain regulation in any market.

Furthermore, once many countries have adopted a specific economic system, it could be more damageable to remain isolated by not being included in trades with these external markets, because of different systems. Adopting the dominant industrial organizational structure might be better in such cases, only to insure access to foreign markets.

1.3.4 Limits of these arguments for deregulation

These six arguments given to explain the change in the electricity industry structure and regulation are the dominant ones. As for any argument, they have their own limits. We can mention the following ones:

- ***Market power***. It could limit competition and prevent marginal cost pricing to appear.
- ***Higher marginal cost***. Production units with lower initial investment cost (in capacity) usually have higher marginal costs. If only such investments are made, electricity prices could tend to rise.
- ***Reliability problems***. As no single entity is responsible for the whole electricity market reliability, reliability management could be harder to accomplish. Also, as profit becomes the first driver of the industry even before secure supply, a pressure on lower reliability standards could continuously be felt.
- ***Local price increase***. Areas with lower electricity prices will see a price increase as the market will average prices between areas.
- ***Environmental protection***. Free investment in generation can become more economically responsible, but environmental regulation should still guarantee that it is also environmentally responsible.
- ***National energy policies***. They will become impossible to sustain as electricity markets become internationally meshed.

Independently of these limits and of their real scope, the deregulation trend is growing. We now focus on what exactly can be achieved under these reforms and on their implementation in laws.

1.4 Restructuring possibilities and official texts

Once the arguments underlying the reform have been made explicit, it becomes important to have a clear view of what can be done. Before looking at actual new policies of different countries, we present the four dimensions along which policy makers can act.

1.4.1 The four restructuring dimensions

Liberalization of the generation segment is the main objective of electricity market reforms, with the hope that prices will tend to the marginal cost of production without any regulator, as we have seen with the previous arguments. This result maximizes total welfare and achieves economic efficiency (Gunn, 1997, Varian, 1992). However, liberalizing the generation sector is only one of the many possibilities that a reform can achieve, as table 1.2 shows. Many restructuring moves can be accomplished, and some of them are usually performed to ease the liberalization of the market, seen as the change towards a more competitive market.

Table 1.2 Restructuring possibilities

	Market structure Monopoly ⟷ Competition	
Vertical integration ↕	*Generation* *Coordination of sale* *System operation* *Transmission* *Distribution* *Retail supply*	Private ↕ **Ownership** Governmental
	⟷ **Horizontal integration**	

In the center of table 1.2 are the main levels of the electricity sector, where all physical and informational activities take place. Many possible reforms are feasible and are presented in numerous places (e.g. Yajima, 1997, OECD, 1997b). They correspond to different realizations of reforms carried out within the framework described in this table. It is not our purpose to go through all these possibilities again (any combination of market structure, ownership, horizontal and vertical integration being possible at each of the six levels of the industry), and enough is said by mentioning what the most common forms of actual reforms are.

For the physical activities occurring at the *generation*, *transmission* and *distribution* levels, competition is usually only discussed for the generation level, as natural monopoly features still characterize transmission and distribution. To introduce competition, horizontal disintegration of large utilities or changes in the law (to make entry legal) are used.

At the other three levels, *coordination of sales*, *system operation* and *retail supply*, where informational activities are carried out, competition usually occurs only in retail supply, and has been introduced in several countries (see next chapter). It is at this level that the energy part of the electricity service (distinct from the transport and distribution parts) is managed. Coordination of sales can be done through two means: over-the-counter bilateral contracts or spot markets. Spot markets pool production and sell it to buyers. This pooling can be mandatory (as in the British system) or parallel to direct bilateral contracts between sellers and buyers[12]. At that level, competition occurs only if different spots markets are active in the same region, which is usually not the case, as an official spot market is designated. Within the pool, many mechanisms can be used to fix the price. Different bidding and auctioning systems can be developed, but we again refer to other works for detailed description of these, because this kind of review is outside the scope of this work (see Hunt and Shuttleworth, 1996, Yajima, 1997). Finally, system operation is responsible for the physical dispatch of electricity from power plants to distribution systems, through transmission lines and transformers. System operation is mainly an informational business because it has to gather information about inflows and demand, respecting the constraints of the physical systems. No responsibility is assumed for generating electricity, and the physical transportation and distribution assets do not have to be under its ownership. Indeed, in the United States, the FERC is promoting a system with an Independent System Operator (ISO) managing the system, without owning any physical assets (transportation and distribution wires). Assets remain under utilities' ownership. System operation has still to be kept centralized and thus regulated.

1.4.2 The American situation

Going back in time, we can retrace the history of federal electricity reforms in the following table, illustrating the most important changes made by the *Federal Energy Regulatory Commission* (FERC), an independent regulatory agency within the Department of Energy.

---

[12] See section 1.5 for more on this.

Table 1.3 Major American legislative moves in the electricity legislation

Act or order[13]	Year	Description
PUBLIC UTILITY HOLDING COMPANY ACT (PUHA)	1935	Prevented enormous holding companies to control large shares of the electricity market.
PUBLIC UTILITY REGULATORY POLICIES ACT (PURPA)	1978	Increased the competition in the generation segment by requiring utilities to buy electricity from qualified non-utilities under certain rules and restrictions.
ENERGY POLICY ACT (EPAct)	1992	Relaxed the barriers to entry in generation and eased market exchanges between utilities and other generators.
ORDER 888	1996	Allowed third party access to the transmission network in order to prevent monopoly behavior by transmission companies.
ORDER 889 on OPEN ACCESS SAME-TIME INFORMATION SYSTEM AND STANDARDS OF CONDUCT (OASIS)	1996	Required an on-line information system to be built to give real time information to all market participants on the transmission capacities.

The federal legislation mainly concerns generation and inter-state exchanges of electricity. Within each state, a specific regulation still dictates how the market should be organized, in terms of *coordination of sales, distribution* and *retail supply*. Some states have already reached a higher level of deregulation, others are in the reviewing process.

Three categories of states can be defined regarding their level of liberalization in the electricity sector. The following table summarizes the main information on this[14].

---

[13] The texts of PURPA, orders 888 and 889 are available on the *Electric* section of the FERC web site (http://www.ferc.fed.us/).

[14] Data are taken from *The Changing Structure of the Electric Power Industry: Selected Issues, 1998* (DOE/EIA-0562(98)) and from the web page *Status of State Electric Industry Restructuring Activity as of September 1, 1999*, on the EIA web site (www.eia.doe.gov), under *electricity* and *restructuring*.

Table 1.4. Electricity reform advances by states

Level	**States** **(date of beginning of retail competition)**	**Description of the situation**
Advanced -Restructuring Legislation Enacted (21 states)	Arizona (1999), Arkansas (2002), California (1998), Connecticut (2000), Delaware (1999), Illinois (1999), Maine (2000), Maryland (2000), Massachusetts (1998), Montana (2000), Nevada (2000), New Hampshire (1999), New Jersey (1999), New Mexico (2001), Ohio (2001), Oklahoma (2002), Oregon (-), Pennsylvania (1999), Rhode Island (1998), Texas (1998) and Virginia (-)	These states either have retail competition or have a date scheduled in the law for retail competition. A state-specific stranded cost solution is proposed.
In progress - Comprehensive Regulatory Order Issued (3 states)	Michigan, New York, and Vermont	Retail competition is planned but still not enforced by the law.
Initial -Legislative Investigation Ongoing (27 states)	Alabama, Alaska, Colorado, District of Columbia, Florida, Georgia, Hawaii, Idaho, Indiana, Iowa, Kansas, Kentucky, Louisiana, Minnesota, Mississippi, Missouri, Nebraska, North Carolina, North Dakota, South Carolina, South Dakota, Tennessee, Utah, Washington, West Virginia, Wisconsin, and Wyoming	No schedule exists for retail competition. Regulated monopoly at the distribution and supply levels still prevails.

The dates for retail competition given in the preceding table are rather official dates than dates of effective retail competition. In some cases, this date reflects a first step towards retail competition or is the date of enforcement of the law. It is seldom the case that complete retail competition becomes effective from the official date. In Rhode Island, for instance, the standard offer of the utility had a price per kWh so low that no competitor could enter the retail market, even if retail competition was legally possible since 1998. In other cases, some technical problems delayed the real implementation of retail competition (California).

Although each state is currently regulating its own retail market, a proposal has been made to legislate retail competition at a federal level. This proposal, known as the *Comprehensive Electricity Competition Act*[15], aims at giving uniform rules to all states and thus achieve the maximum efficiency competition could yield. We give now a brief account of this bill that still needs to be enacted by the senate and the congress.

The 1998 American *Comprehensive Electricity Competition Act* (CECA)

In July 1998, a bill aiming for "more competitive electric power industry, and other purposes"[16] was proposed to the Senate and the House of Representatives of the United States of America to be enacted. Although a *supporting analysis* (U.S. Department of Energy, 1998b) was accompanying the bill, to "quantify the economic and environmental benefits of retail competition in electric markets"[17], a general presentation of incentives behind the reform process cannot be found in such document. This document presents only the expected savings American electricity consumers would make according to the model used for the analysis. This model assumes perfect competition in the retail electricity market and aims at accurately describing the real market after the implementation of the CECA.

To have a more general overview of the American reform process in electricity markets, one can rely on documents published by the *Energy Information Administration* (EIA), such as EIA (1996) or (undated). However, these documents, although prepared within the U.S. Department of Energy, "should not be construed as advocating or reflecting any policy position of the Department Energy or any other organization"[18]. Once this legal proviso has been made, information from this source can however highlight the American reform's motivation. Three underlying factors are identified in EIA (1996):

- the changing "regulatory climate" on monopolies;
- price differences between states;

[15] This bill, developed by the Clinton Administration, is available on the U.S. Department of Energy site http://home.doe.gov/policy/ceca.htm (15/09/1999).
[16] This is the first sentence of the U.S. Department of Energy's bill U.S. Department of Energy (1998a), downloadable from its web site (www.doe.gov).
[17] U.S. Department of Energy (1998b), page 1.
[18] EIA (1996), page i.

- technological advances.

We present here the first and second ones, leaving the third for section 1.2.3, as this argument is valid in all countries.

The first factor is not presented in details in any EIA document. This "changed climate" pushing for competition is based on the "[belief] that consumers will benefit more from an industry whose members must compete for customers than from an industry composed of regulated monopolies"[19]. This belief probably arose from the "advantages of competition over regulated monopolies" stressed by economists. We developed this economic argument in section 1.3.1, making explicit a position that is very often stated as a dogma to justify lesser regulation.

The electricity price differences between American States[20] is the second appealing factor for deregulation. It led to lobbies of consumers for free choice in electricity supply. As long as supply under free choice is physically feasible, this argument is straightforward because consumers in areas having high prices want to have access to low prices. Only customers in low price areas should fear competition, because it will make prices converge to a single value[21], between the two extremes.

The American policy is then driven by these three elements, belief in the virtues of competition, price differences and technological advances. As reflected by the recently proposed CECA and by previous regulatory reforms affecting wholesale markets[22], the main objective of this policy is clearly to strengthen competition in all electricity markets.

---

[19] All quotations of this paragraph come from EIA (1996), page 35.

[20] From 2.9 cents/kWh in Kentucky to 8.9 in Rhode Island for industrial consumers (EIA, 1996).

[21] Some regional differences will still exist when considering transmission price, constraints and losses, but they should not be as large as in the regulated case.

[22] The most known of these reforms are the Public Utility Regulatory Policies Act (PURPA) of 1978, the Energy Policy Act (EPACT) of 1992 and the Federal Energy Regulatory Commission (FERC)'s Order 888 and 889.

1.4.3 The European Union situation

In Europe, a two-level legislation also exists, but with the difference that the federal level is at a much earlier stage, and the situation between Member States is more varied than in America.

It is the *Directive 96/92/EC of the European Parliament and of the Council concerning common rules for the internal market in electricity* that started the legislative changes in the European electricity market[23]. As for all new policies, this directive came after a green paper[24], which accounted for the energy debate, and a white paper[25], which gave the main energy policy positions of the EU.

The white paper for the EU energy policy (EU, 1995) describes the lines of actions and agenda each member state should follow. It also contains a general introduction justifying this policy.

As long as it possible to summarize the main elements of this white paper, we can mention that the justification, under the title "general framework", is characterized by four major elements (paragraph 22):

- globalization of markets;
- increasing environmental concerns;
- technology developments;
- community institutional responsibilities.

Three objectives then arise for the energy sector (paragraph 46): (i) overall competitiveness, (ii) security of energy supply and (iii) environmental protection. Once some of these points are tempered by stating that "a choice has to be made on the relative weight to be given to these respective policy objective" (paragraph 47), a main result stems out of this white paper. Although no details are offered on how "weights" have been chosen, the result in the case of electricity markets was "to liberalize the internal market" in each country (paragraph

[23] This directive was published the 19/12/1996 and became effective the 19/02/1997. For more information, see the European Union web site http://europa.eu.int/en/comm/dg17/legislat.htm
[24] *For a European Union Energy Policy*, COM(94)659
[25] *An Energy Policy for the European Union*, COM(95)682

52). This will be implemented by progressively freeing the customers from their single supplier and adapting the structure accordingly, at a different pace for each member country.

Focusing mainly on the first objective, the directive 96/92/EC sets the requirements that electricity markets of each Member State should meet in 29 articles. The following table summarizes these requirements, concerning mainly the generation, the transmission and the distribution sectors.

Table 1.5 European electricity market requirements (Directive 96/92/EC)

Sector	**Requirement**
GENERATION	Capacity addition should be open to anyone, as long as fulfillment of all *objective*, *transparent* and *non-discriminatory* criteria given by the Member State are satisfied. Two procedures can be chosen by the Member State: • the **authorization** procedure. The criteria should be public and concern safety and security of the electricity system installation and associated equipment, protection of the environment, land use and siting, use of public ground, energy efficiency, the nature of primary sources, characteristics particular to the applicant such as technical, economic and financial capabilities and public service obligations. • the **tendering** procedure. A competent authority of the Member State establishes a list of required capacity addition and submits it for tenders. The choice among applicants should be based on similar criteria as above.
TRANSMISSION	The Transmission System Operator (TSO) is responsible for the dispatch of generators on its territory and for the maintenance and improvement of the system. Access to the system can be based on two procedures: • **Negotiated or Regulated Third Party Access** procedure. Buyers and sellers can deal directly with each other and then make the transmission with respect to the available capacity. • **Single buyer** procedure. All producers have to sell to the single buyer which is the only seller to consumers. It manages all transmission and makes all its (non-discriminatory) pricing public.
DISTRIBUTION	Regulation in distribution may still apply on prices and on the obligation to serve in specific areas, if the Member State sees a necessity.

These requirements have to be progressively fulfilled by liberalizing (or "opening") the electricity markets step by step. The calendar for gradually opening the market is given in the next table. However, it must be reminded that these data show the minimal market opening requirements, and that some Member States are already further (the United Kingdom and Nordic countries have indeed fully liberalized their electricity market).

Table 1.6 Progressive implementation of the Directive 96/92/EC

Date	**Minimum market share open to competition**	**Corresponding threshold (size of consumers, annual consumption)**
19 February 1999	26.48%	40 GWh
19 February 2000	28%	20 GWh
19 February 2003	33%	9 GWh

Although the market may be open "on paper", it can take some time before real competition occurs and before consumers start to feel a difference in market conditions. For instance, the dominant position of one producer can limit real competition (as in France), because other generators may not have the possibility to supply more effectively, at least prior to the transition period.

Furthermore, some specific rules concerning other aspects of electricity markets can limit the establishment of real competition. Therefore, in order to examine the progress of the reform process, two "harmonization" reports were produced in 1998 and 1999[26]. These reports discuss the existing challenges faced by the harmonization of market conditions in the different Member States. They are not stating any new rules, but point out some directions that further "re-regulation" may follow. These challenges are:

- ***Treatment of electricity produced from renewable sources***. To insure compliance with the third white paper objective (environmental protection) and

[26] These reports, entitled *Report* (and *Second Report*) *to the Council and the European parliament on harmonisation requirements* are not precisely dated and have respectively the reference number COM(1998)167 and SEC 1999/470. They were both available on the web site http://europa.eu.int/en/comm/dg17/elechome.htm the 14/09/1999.

to prevent different rules to develop in different Member States, similar rules should be used to promote renewable sources in electricity production. Among the support schemes for renewable sources are **purchase obligations**, **tax exemptions**, **support per kWh produced**, and **investment support**.

- ***Cross-border tariff***. Actual tariffs for crossing borders annihilate most of the time the competitive advantage a producer might have compared to another one on the other side of a border. Without a fair cross-border tariff, and a similar transmission fee, competition is unlikely to take place between different areas. Solutions can be found with the **transparency of available transmission capacities**, some **good allocation and tariff schemes** for this capacity, the development of regulated **priority rights** on transmission lines and the development and maintenance of transmission lines.
- ***European regulation of electricity network***. The coordination of all national Transmission System Operators might require a higher coordination level. Either all national TSO can agree on the adequate rules for this coordination or a new European regulator will be created to achieve this goal.
- ***Common environmental standards, standards for nuclear decommissioning and taxation***. Different environmental rules in electricity production can create different cost conditions between countries, and thus create unfair advantages for some countries. As for nuclear decommissioning and taxation, different national systems induce different cost conditions between Member States. A special attention needs to be paid to this issue to allow a single European electricity market to form.

The European documents we have outlined here list the general institutional objectives and challenges the EU has at the moment. They are basically similar to the ones faced by other countries, but the perspective shown have hopefully helped to better grasp how they appear in the European context.

1.4.4 Reform of the Finnish Electricity Market

The Organization for Economic Co-operation and Development (OECD) reviews all competition policies of its members in OECD (1997a). As our main illustrative case is Finland, we now present the justification given for the Finnish regulatory reform. It consists mainly in two parts (OECD, 1997a, page 39):

- change in the energy and competition policies;
- international developments.

These developments are particularly strong in Norway and Sweden, and the goal is to move toward a complete integration of these three electricity markets. Again, the main objective was to introduce competition in order to have uniform market conditions between these countries. In a Finnish government document (Ministry of Trade and Industry, 1997a), it is said that the reform is "intended to ensure an efficient and competitive electricity supply industry" (page 45), and its content aims at removing all obstacle to competition.

More on the Finnish situation is presented in chapter 2.

1.4.5 The Canadian situation

The Canadian situation resembles in some respects the American one, because each of the ten Canadian provinces has its distinct legislation over the electricity sector. Probably decentralization is even more complete because no regulatory agency exists at the federal level in this field, except for all nuclear issues and some environmental ones.

This makes it impossible to give a general portray of the Canadian regulatory situation without mentioning all provinces. The following tables offer a quick depiction of the main features of each of the ten electricity regulation state of affairs. We proceed from the east to the west coast.

Newfoundland

With a production of 41 TWh (almost all from hydro sources) and a large governmentally owned utility supplying a dominant private distributor, Newfoundland has a typical Canadian province electricity market structure.

Table 1.7 Electricity sector in Newfoundland

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION HIGH ------------- LOW	MARKET TYPE MONOP.--------COMP.	OWNERSHIP GVT. ---------PRIVATE
Generation	│	*__________________	*__________________	__*________________
Coor. of sales	│	*__________________	*__________________	__*________________
Sys. Oper.	│	*__________________	*__________________	__*________________
Transmission	│	*__________________	*__________________	__*________________
Distribution	│	___*_______________	*__________________	_____________*_____
Retail supply	│	___*_______________	*__________________	_____________*_____

Prince Edward Island

The smallest electricity market (0.021 TWh of thermal production) is completely private, but very integrated. At the distribution level, two firms have their own franchise territory.

Table 1.8 Electricity sector in Prince Edward Island

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION HIGH ------------- LOW	MARKET TYPE MONOP.--------COMP.	OWNERSHIP GVT. ---------PRIVATE
Generation	│	*__________________	*__________________	__________________*
Coor. of sales	│	*__________________	*__________________	__________________*
Sys. Oper.	│	*__________________	*__________________	__________________*
Transmission	│	*__________________	*__________________	__________________*
Distribution	│	___*_______________	*__________________	__________________*
Retail supply	│	___*_______________	*__________________	__________________*

Nova Scotia

The 1992 privatization did not change anything else in the structure of this market. 10 TWh of thermal power are produced each year.

Table 1.9 Electricity sector in Nova Scotia

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION HIGH ------------- LOW	MARKET TYPE MONOP.--------COMP.	OWNERSHIP GVT. ---------PRIVATE
Generation	│	*__________________	*__________________	__________________*
Coor. of sales	│	*__________________	*__________________	__________________*
Sys. Oper.	│	*__________________	*__________________	__________________*
Transmission	│	*__________________	*__________________	__________________*
Distribution	│	*__________________	*__________________	__________________*
Retail supply	│	*__________________	*__________________	__________________*

New Brunswick

A perfectly traditional structure describes the New Brunswick electricity market, with no plan of reforms. The annual 16 TWh production comes half from thermal sources, and the remaining comes in equal shares from hydro and nuclear units.

Table 1.10 Electricity sector in New Brunswick

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION	MARKET TYPE	OWNERSHIP
		HIGH ------------- LOW	MONOP.--------COMP.	GVT. ---------PRIVATE
Generation		*	*	*
Coor. of sales	|	*	*	*
Sys. Oper.	|	*	*	*
Transmission	|	*	*	*
Distribution	|	*	*	*
Retail supply	|	*	*	*

Québec

In 1996, the provincial government defined a new energy policy for the province, to insure sustainable development in economic and environmental sectors. The main driver of these changes was however the need for Hydro-Québec (HQ, the vertically integrated monopolistic utility) to be able to compete in the U.S. market by offering reciprocity in legislation. In theory, Québec saw its wholesale market opened to competition, and access to transmission lines was freed. In practice, the dominant position and cost advantage of HQ prevented any new entrant to reduce its market share and nothing really changed. HQ has an almost 100% hydro system, with large reservoirs. It produces annually 165 TWh at low cost (see section 1.5.2 for more on HQ). An independent regulator, the *Régie de l'énergie*, monitors transmission and distribution prices.

Table 1.11 Electricity sector in Québec

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION	MARKET TYPE	OWNERSHIP
		HIGH ------------- LOW	MONOP.--------COMP.	GVT. ---------PRIVATE
Generation	│	___*________	___*________	___*________
Coor. of sales	│	*___________	*___________	*___________
Sys. Oper.	│	*___________	*___________	*___________
Transmission	│	*___________	*___________	*___________
Distribution	│	___*________	*___________	*___________
Retail supply	│	___*________	*___________	*___________

Ontario

The second biggest producing province after Québec, Ontario Hydro produces its annual 146 TWh equally from nuclear, thermal and hydro power. A report in 1996 started some discussion about the privatization of the unique generator, Ontario Hydro, but nothing was done until late 1999. Distribution and supply is highly horizontally disintegrated in Ontario, with more than 300 municipal distributors, a distinct feature in Canada.

Table 1.12 Electricity sector in Ontario

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION	MARKET TYPE	OWNERSHIP
		HIGH ------------- LOW	MONOP.--------COMP.	GVT. ---------PRIVATE
Generation	│	*___________	*___________	*___________
Coor. of sales	│	*___________	*___________	*___________
Sys. Oper.	│	*___________	*___________	*___________
Transmission	│	*___________	*___________	*___________
Distribution	│	___________*	*___________	*___________
Retail supply	│	___________*	*___________	*___________

Manitoba

Production in Manitoba comes all from hydro power (33 TWh per year). The market is structured in a very traditional way, with only a distinct distributor in Winnipeg (the province's capital).

Table 1.13 Electricity sector in Manitoba

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION HIGH ------------- LOW	MARKET TYPE MONOP.--------COMP.	OWNERSHIP GVT. ---------PRIVATE
Generation	│	*	*	*
Coor. of sales	│	*	*	*
Sys. Oper.	│	*	*	*
Transmission	│	*	*	*
Distribution	│	___*	*	*
Retail supply	│	___*	*	*

Saskatchewan

With a single state company producing, transmitting and distributing the 16 TWh yearly production (from thermal sources), nothing much needs to be said of the Saskatchewan situation.

Table 1.14 Electricity sector in Saskatchewan

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION HIGH ------------- LOW	MARKET TYPE MONOP.--------COMP.	OWNERSHIP GVT. ---------PRIVATE
Generation	│	*	*	*
Coor. of sales	│	*	*	*
Sys. Oper.	│	*	*	*
Transmission	│	*	*	*
Distribution	│	*	*	*
Retail supply	│	*	*	*

Alberta

Conversely, the market in Alberta the most active and deregulated. In 1996, a profound reform introduced competition in generation, with the creation of a competitive mandatory pool. This market of 53 TWh/year (all thermal) is the most deregulated in Canada.

Table 1.15 Electricity sector in Alberta

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION	MARKET TYPE	OWNERSHIP
		HIGH ------------- LOW	MONOP.--------COMP.	GVT. ---------PRIVATE
Generation	|	________*________	________________*	____________*____
Coor. of sales	|	*________________	*________________	____*____________
Sys. Oper.	|	*________________	*________________	____*____________
Transmission	|	*________________	*________________	____________*____
Distribution	|	________*________	*________________	____________*____
Retail supply	|	________*________	*________________	____________*____

British Columbia

The market structure in British Columbia is very traditional and the provincial utility, BC Hydro, has many similarities with HQ. Only its scale of operation differs: it amounts to one third of the HQ size (66 TWh). In parallel to BC Hydro, a small integrated utility operates in one location.

Table 1.16 Electricity sector in British Columbia

LEVEL	VERTI. INTEG.	HORIZONTAL INTEGRATION	MARKET TYPE	OWNERSHIP
		HIGH ------------- LOW	MONOP.--------COMP.	GVT. ---------PRIVATE
Generation	|	*________________	*________________	*________________
Coor. of sales	|	*________________	*________________	*________________
Sys. Oper.	|	*________________	*________________	*________________
Transmission	|	*________________	*________________	*________________
Distribution	|	*________________	*________________	*________________
Retail supply	|	*________________	*________________	*________________

This overview of reforms in different regions of the world gives the pulse of the market dynamics and changes: a move toward competition, with the substitution of business plans for national energy policies. The next section describes how the new markets generally operate at a practical level and how some important firms react to the new market rules.

1.5 Implementation of deregulation

Laws seldom describe accurately the behavior of individuals in a market and also leave room to different interpretations. They set boundaries on what can be done and try to induce certain results, but they usually leave some degree of freedom to the players. In this section we focus on the new behaviors and players that have appeared in the new structure, and on how players have reacted to the new rules.

1.5.1 Market coordination adjustments

As we have seen in the previous section, new legislation does not immediately lead to practical changes. A law does not reflect the actual position of each player, neither it necessarily induces people to explore all the possible avenues. Also, it surely does not describe exactly what the people actually do. In this section we describe new market behaviors that develop within the new legislative context.

Coordination of sales: Power pools, power exchanges and electricity spot markets

Competition at the generation level and coordination of sales can either take place through (private) bilateral contracts, or in a (generally public) spot market. Demand for transparency and for easy short term transactions resulted in the development of many power exchanges and electricity spot markets. In this section, we review these new types of power pools.

Power pools existed prior to deregulation to allow different utilities to save by sharing some available capacity. Transaction were either based on long term contracts or reliability criteria, and parties in these transaction were only producers. With deregulation, power pools developed in new ways, focusing more on short term transactions and with more diverse participants, including producers, brokers and consumers. Basically, two types of power pools have developed:

- ***Mandatory power pools*** where all participants have to meet to sell and buy their electricity in a given area. A reference market price is defined through a formula, based on supply, demand, and other criteria (capacity announced available, location, etc.). The pool makes the dispatch.
- ***Power exchanges***, which are voluntary spot markets to deal electricity contracts and financial products. The market price defined in these power exchanges is solely based on supply and demand, through bids and auctions. When the power exchange gains enough credibility, its price usually becomes a reference price for

the area. The dispatch is made by the transmission grid, which operates in collaboration but independently from the spot market.

In both systems, bilateral contracts between producers and consumers can be made, but in mandatory pools these contracts need to be made within the pool system. They are made independently from the power exchange when one exists (except maybe for the reference price).

Table 1.17 Main power pools over the world and starting date

MANDATORY POWER POOLS	POWER EXCHANGES
Electricity Pool of England and Wales **-** 1990	***Cammesa*** (Argentina) **-** 1992
Power Pool of Alberta (Alberta, Canada) **-**1996	***Nordpool*** (Norway, Sweden, Finland) **-** 1993
New Zealand Electricity Market (NZEM) **-** 1996	***Spanish Power Exchange*** **-** 1998
National Electricity Market Management Company (Australia) **-**1998	***California Power Exchange*** (California, U.S.A.) **-** 1998
	Amsterdam Power Exchange (Netherlands) **-** 1999

Financial tools to manage all risks

The development of spot markets to trade electricity increases the price volatility of electricity. To hedge against the inherent risks of spot markets and to develop the transactional tools to satisfy the needs of all participants, *financial instruments* are becoming increasingly used in the electricity markets.

The main product of these financial instruments is the *future*, an option on a future quantity at a given price.

Development of marketing and customer services

Although electricity seems at a first glance to be a homogeneous *product*, competition will increase the differentiation by focusing on the *services* it offers. Here are the main marketing axis on which electricity can be differentiated:

- ***Customer service***, including billing, energy and business information.

- ***Environmental value***, meaning the extent to which the electricity paid for is produced with "green" sources.
- ***Reliability***, including the quality of current and the likeliness of outage.

Sioshansi (1990) also gives a good account on these issues.

New consumer behavior

The previous new behaviors mentioned were on the production side of the market. On the customer's side, awareness of new options should increase energy shopping and expectations on service. One of the new types of behavior that is observed in some countries and could expand is the creation of customer coalitions. It creates bigger buying entities that are able to negotiate better energy deals and also to implement some energy management tools in the coalition (see Hämäläinen, Mäntysaari, Ruusunen and Pineau, 2000, for a concrete example of such cooperative behavior).

1.5.2 Corporate adjustments

In this section we depict five representative energy firms to analyze and compare how these corporations have adapted and reacted to deregulation. All information is taken from their 1998 annual report and corporate web site.

These five firms are all leaders in their market, albeit at different scale. The *Southern Company* is the largest investor-owned utility in the United States. *Hydro-Québec* is probably the world leader in hydro-electricity, whereas *Électricité de France* is the world leader in nuclear production. *Fortum*, a small Finnish energy company, is interesting because of its structure and its experience in completely deregulated energy markets. *Enron*, the world biggest energy marketer, is shaking many energy business traditions by taking advantage of new possibilities arising from deregulation.

Our analysis of these five firms gives a business point of view of deregulation. We first propose a brief presentation of each company and then discuss their market strategy.

Southern Co. (U.S.A.)

Well implemented in Georgia, Alabama and Mississippi, Southern Co. is the mother company of many vertically integrated local utilities. As in these states electricity rates are low (at about 6 cents per kWh), no opening of the retail market is planned and the subsidiaries of Southern Co. will probably enjoy their monopoly situation for a few more years.

However, as shown in table 1.8, Southern Co. is quite active in the world energy markets by developing business activities in different parts of the world. Its strategy, as formulated in its 1998 Overview document (Southern Co., 1999), can be summarized in the following points:

- Invest in generation and distribution to maintain its position.
- Expand revenues from the actual consumer base by adding related energy services.
- Keep its electricity operations integrated in the Southeast region, where it has its main activities.
- Acquire new capacities locally and internationally.
- Expand capabilities in natural gas.

Of its strategic intentions, the one concerning natural gas is probably the most crucial as integrated energy service will be the key factor to take full advantage of deregulation. As we will see, other companies are also acting towards this end.

Table 1.18 Company profile

Name (Country)	**Southern Co.** (U.S.A.)	**Hydro-Québec** (Canada)	**Électricité de France** (France)	**Fortum** (Finland)	**Enron** (U.S.A.)
Main source of data	Overview 1998	Annual report 1998	Annual report 1998	Annual report 1998	Annual report 1998
Total assets (US$)	$36.2 billion	$39 billion[27]	$112 billion[28]	$11.94 billion[29]	$29.35 billion
Installed capacity	31 161 MW	31 400 MW	102 000 MW	8 700 MW	14 350 MW
Sales (of electricity)					
US$	$12.74 billion	$5.99 billion	$30.18 billion	$1.57 billion	$13.94 billion
kWh	163.9 TWh	161.4 TWh	460 TWh	44.5 TWh	402.37 TWh (marketed)
Businesses (subsidiary or partial ownership)					
Generation	✔ (Many subsidiaries)	✔	✔	✔	✔
Transmission	✔ (Many subsidiaries)	✔ (Transénergie)	✔		✔
Distribution	✔ (Many subsidiaries)	✔	✔	✔ (Many subsidiaries)	
Retail supply	✔ (Many subsidiaries)	✔	✔	✔ (Many subsidiaries)	✔
Wholesale marketing	✔ (Many subsidiaries)	✔ (Marketing d'énergie)			✔
Energy services	✔ (Southern Company Energy Solution)	✔ (Many subsidiaries)	✔	✔	✔ (Enron Energy Services)
Gas	✔	✔ (Noverco)		✔	✔

[27] At the exchange rate CAN$ 1 = US$ 0.68
[28] At the exchange rate French Franc 1 = US$ 0.1631
[29] At the exchange rate Finnish Mark 1 = US$ 0.1797

Name (Country)	**Southern Co.** (U.S.A.)	**Hydro-Québec** (Canada)	**Électricité de France** (France)	**Fortum** (Finland)	**Enron** (U.S.A.)
International presence	Southern Energy	HQ International	EDF International	Fortum	Enron Europe / Enron International
Generation (MW)	*Argentina* (551), *Germany* (818), *China* (634), *Philippines* (1167), *Brazil* (182), *Chile* (358), *England* (82), *Bahamas* (80), *Trinidad and Tobago* (459) **Total: 4 431 MW**	*Costa Rica* (10), *Panama* (300), *USA* (174), *Senegal* (37) **Total: 521 MW**	*Switzerland* (2000), *Sweden* (590), *Poland* (1000), *Spain* (335), *Portugal* (600), Italy (1291), *Austria* (1141), *Morocco* (50), *Guinea* (97), *Ivory Coast* (1529), *China* (3720), *Mexico* (495), *Brazil* (907), *Argentina* (660) **Total: 14 415 MW**	*Estonia, Ireland, Holland, Great Britain, Sweden, Germany, Hungary, Thailand* **Total: about 300 MW**	*Great Britain* (2665),*Germany* (125), *Turkey* (478), *Guatemala* (234),*Panama* (335), *Dominican Republic* (185), *Brazil* (450), *India* (826), *Thailand* (50), *Hainan Island* (154), *Philippines* (226) **Total: 5 628 MW**
Transmission and distribution	*Germany*, *England*, *Brazil*, *Bahamas*, *Chile*	*Peru*, *Costa Rica*, *Australia*	*Switzerland*, *Sweden*, *England*, *Austria*, *Hungary*, *Morocco*, *Guinea*, *Ivory Coast*, *South Africa*, *Brazil*, *Argentina*		*Brazil*
Energy consulting		*Asia*, *Africa*, *Middle East*, *Caribbean Islands*, *Europe* and *Central America*.	*Europe*, *Africa*, *Asia* and *Latin America*		

Hydro-Québec (Canada)

This governmentally owned utility has a particularly favorable position in the American Northeast energy market. With an installed capacity of 31 400 MW (out of which more than 90% is hydro), low production costs (below $0.04 per kWh) and some sites still available for hydro power generation, Hydro-Québec is in a position of taking advantage of openings in electricity markets. Its strategy is therefore based on ambitious goals, and is composed of the four following points:

- Development of the production capacity (mainly hydro) but also of production diversity (for reliability and market adaptation).
- Development of the transmission network, to ease electricity exports.
- Increase its business in multi-energy services and products.
- Enlarge its traditional market area (province of Québec), to other provinces and states.

Table 1.8 also reveals an active international strategy, with some acquisitions in developing countries and also many consulting activities.

Électricité de France (France)

The only completely vertically integrated utility remaining in Europe, EdF, is very slowly adjusting itself to the new European Union market regulation, in its own territory, France. However, outside its borders, EdF is very active in acquiring generation, transmission and distribution assets wherever a market opening creates an opportunity.

The nuclear based-utility (more than 80% of its electricity generated) is already taking advantage of market deregulation in Europe by exporting more and buying foreign assets, but could be in a difficult position if its internal market was rapidly deregulated. Indeed, nuclear production needs a secure market base to recover the sunk costs, and cheap electricity from gas turbines could, in some locations, be a serious threat to EdF supply. In order to adapt to the irrevocable trend, EdF has nevertheless set up this strategy (see EdF 1998 Annual report):

- Focusing on customers, in all respects. This seeks to create a strong relationship between the utility and its consumer base, in order to retain them when they will be able to choose between suppliers.
- Commit itself by long-term investment in all levels of the traditional electricity business: generation, transmission, distribution and supply in Europe, Latin America and Asia.

Fortum (Finland)

Fortum is a recently created multi-energy company. In 1998, the two governmentally owned energy companies of Finland, Neste (oil and gas) and Ivo (heat and power), merged together to form this single entity. Its experience in Nordic countries, with their history of energy deregulation and market opening at all customer sizes, makes of Fortum an interesting case. The skills of Fortum in the Nordic power pool, linked to its knowledge of competitive retail supply and energy services complementary to electricity (heat, gas, oil), give to Fortum good chances to survive in the future European "energy market battlefield".

Fortum's strategy mainly consists of these two ingredients:

- Strengthening its position as a complete energy company (oil, gas, electricity and heat), from production to refining, distribution and marketing.
- Developing businesses in the Nordic countries, Northern Europe and selected countries over the world.

Enron (U.S.A.)

Enron was traditionally more involved in the natural gas market. But electricity deregulation created market opportunities that Enron made its duty to take advantage of. The main activity of Enron in the electricity market is therefore not to generate, to transmit nor to distribute electricity, but to act as a power broker in the market and to arrange financial deals with customers at more competitive conditions. As a result, Enron is not really involved in any physical activity (with regards to the electricity business), but rather in transactional/informational activities, mainly based on financial tools. Its aggressiveness in energy markets and skills to take advantage of new opportunities make Enron a major player in the electricity wholesale business.

These two components, as expected, are the core of Enron's strategy:

- Taking advantage of all opportunities created by deregulation. The gas expertise of Enron is in this respect an important factor, because gas is strongly related to electricity markets, as a substitute and in generation.
- Being the largest power marketer and offering complete financial services in the energy sector.

Analysis

Although all five firms are developing a presence in foreign markets, the most insistent in this respect is Enron. Traditional utilities are focusing more on the development of physical activities, although the real challenge of deregulation is the new structure of market coordination, at the information level, not the physical one. Information is now widely and instantaneously available, making profitable transactions easier to arrange. This is how Enron is making its money.

The second noticeable element in the strategy of these firms is the key role of natural gas. Its availability is important not only to be able to offer integrated energy deals to the consumers, but also to generate electricity on demand within a short period of notice, using small scale gas-turbine technology. The importance of natural gas explains why we see a strong convergence between gas and electricity utilities.

Vertical integration also seems to be a favorable and efficient structure for utilities. Indeed, all four utilities studied (except the power marketer Enron) had a vertically integrated structure before deregulation, never complained about it, and wished to keep it in the deregulated market. It is only when forced by regulation that they break down their integration. For instance, Fortum had to discard its transmission activities to a new organization (although Fortum has some shares in this new entity, *Fingrid*, the different businesses are now completely independent). Hydro-Québec also had to create a separate business unit for its transmission activities. In this case, the separation is not as strong, because the new organization is simply a subsidiary of Hydro-Québec. Vertical integration is then an interesting strategic feature: Enron is buying some generation capacities and is entering the retail market. Distribution and retail activities are indeed good sectors for generators, since individual customers are the most profitable.

An other conclusion stemming from our comparison is that privatization is not required for deregulation, and is even not an important factor. Three out of the five players we described were publicly owned firms (Hydro-Québec, EdF and Fortum). They are important and active players in deregulated electricity markets and at least for two of them, ownership changes are not discussed, even partially (talks to privatize Fortum are ongoing in Finland). Quite incongruously, even Enron -the aggressive private company- says that "Privatization alone does not create cheaper, more efficient energy or cost-effective, competitive assets. Private ownership of assets in tandem with market liberalization often provides the environment that creates more efficient enterprises and provides opportunities for cost savings and innovation of new products and services" (Enron, 1999).

If privatization is not a key element for utilities in the new context, international operations seem to be a must. All companies are prospecting and developing foreign markets to be active in different geographical zones. Being exposed to other markets, taking advantage of one's competitive advantages and acquiring new skills are the main reasons for these international activities. Of course, the threat of having competitors developing a strong position before them in these markets is also a crucial factor. Many small companies will be too weak to compete with larger ones as the markets becomes more open. Acquisitions and mergers, as in the aviation, car or aluminum industries, will probably shape the market more like a oligopoly than a competitive market.

In short, five elements derive from the analysis of the strategy of these companies:

- The electricity market is trending from a physical business to an ***informational*** one.
- ***Natural gas*** is increasingly becoming a strategic factor for electricity players, in generation and energy supply deals.
- ***Vertically integrated*** firms are still the most profitable.
- ***Privatization is not necessary*** for successful deregulation.

- The real competitive pressure comes from ***international competition***, but mergers and acquisitions could reduce this pressure after the transition period.

1.6 Assessment of deregulation

In order to make the right choice among the different regulatory reform possibilities, an assessment of their expected outcome can be useful. Different criteria can be imagined, and different methodologies can be used to obtain this assessment. We first introduce some possible criteria and then give three possible standpoints to evaluate industrial organizations: transaction cost theory, econometrics and model simulations.

1.6.1 Assessment criteria

If the implementation of electricity reforms comes with complex challenges, as those identified in the EU harmonization reports (section 1.4.3), evaluating the outcome of the reforms might even be more difficult. Choosing the criteria to appraise the new industrial structure can be a controversial task. Here we simply mention six non-exhaustive dimensions along which a judgment can be made to estimate the success of a reform.

Electricity prices

The main goal of deregulation is probably to lower the price of electricity. Analysis of historical price curves could give interesting information on such a topic. Newbery (1998) studies the U.K. situation from this perspective.

Reliability

Concerns towards reliability are also very important, because of the central role of electricity in modern society. Among other papers, EIA (1995) accounts on how reliability challenges can be managed in a deregulated electricity world.

Investment

Related to the reliability and price dimensions is investment. Indeed, if investment is not sufficient, then capacity scarcity will increase price levels and decrease reliability levels.

It is therefore very important to study how uncoordinated investment will evolve in a deregulated environment and to assess the possibility of too few capacity additions. Fluctuating prices, by increasing the risks on good returns, is another factor acting against investment (along with the positive effect on profit of scarce capacity for the incumbents).

Environment

Centralized electricity production gives the benefit of having a clear player responsible for the pollution linked to electricity generation. With many players involved in smaller scale generating units, monitoring and regulating environmental impacts need new mechanisms.

The effect of deregulation on the environment depends on the success of the implementation of these new mechanisms.

Employment

A known way of increasing utilities' efficiency is to reduce human resources costs. Profits for the firm usually increase as a consequence, but the cost for the society should also be taken into account. Only then can one conclude on the overall effect of this downsizing.

If it is the society who pays for the layoffs (through welfare and/or reeducation), then this external cost should be included in the transition cost from a regulated to a deregulated industry.

Social equity

Having a profit-driven electricity market should obviously lead utilities to make profits. As utilities are no longer regulated, the use of these profits will not necessarily go for the welfare of the whole society, but most likely to shareholders.

Deregulation could result in a higher total social welfare, but if it benefits only to the shareholders, the major part of the society could be a global loser after deregulation. Social inequalities could increase, and this could be a negative impact.

As seen in Newbery (1998), the outcome of having the benefits of deregulation concentrated in the hands of shareholders is not unlikely. The issue should at least be openly discussed and assessed in deregulation talks.

1.6.2 Transaction cost theory

The theory of the firm of Coase (1937) states that firms stop developing new skills whenever it becomes cheaper to buy them from another firm. These other firms supply the required service more efficiently because it is their core business. Included in the cost of buying from outside is the *transaction* cost of dealing with another player. Williamson (1979) explores how these transaction costs can explain industrial organization. In the electricity sector, such an analysis has been made by Joskow and Schmalensee (1983) to assess the possible advantages of a deregulated industry over a monopolistic one. The main investigated elements are how transaction costs between all the different players in an open electricity sector could be compared to those in an integrated monopoly. In an integrated monopoly, production and all related activities are performed internally (production scheduling, dispatch, transmission management, load balance, etc.). Clearly, this avoids all contractual agreements between different, independent organizations, resulting from the unbundling of the monopoly. New firms have to pay for the required contracts used to coordinate themselves in the market. Williamson identified three constituting elements in the cost of such contracts:

- the frequency;
- the uncertainty and complexity;
- the presence of specific investment.

It is hard to predict precisely how costly these transaction costs will be for the electricity industry. However, Joskow and Schmalensee (1983) maintain that in this sector, where a certain long term involvement is needed, contractual agreements between different players may be more costly than the disadvantages of having a single player. They however temper this conclusion by saying that experience and evidence are too small to reach any decisive conclusion.

As the transaction costs point of view is difficult to use in practice, we will not use it here. However, it provides an interesting view on an issue not often discussed in other works on deregulation, which is the coordination cost. Paradoxically, the same Joskow in Joskow (1998) completely ignores this approach in his contrasting enthusiastic account on the reasons to reform the power sector.

1.6.3 The econometric approach

In this approach, one starts from empirical data taken from different market structures and constructs an explanatory model for variables of interest. As the total welfare is not easily observable (mainly because of the problematic nature of consumer surplus), more tangible variables need to be studied in this assessment of the differences between different markets. The more common variables are *production cost* and *price level*. If a specific feature of the market can be linked with low prices or production cost, then evidence has been found that this feature should be considered in market reforms.

Kwoka (1996) and Pollitt (1997) both survey many empirical studies on these two variables for different market situations. These situations correspond to different market structures of the electricity industry, and give at least an indication of the results foreseeable if on reform is implemented. We will review their results in the next chapter (section 2.3.2), after the presentation of some real reforms.

1.6.4 The simulation-modeling approach

Another way to assess the relevance of a reform is to simulate different market structures with a mathematical model and analyze how the variables of interest (usually production cost or price) behave in each possibility. This methodology has been used by the U.S. Department of Energy (1998a) to furnish data supporting the CECA, presented in section 1.4.2. Academic research also contributed to this approach (see Bolle, 1992, Green, 1996, or von der Fehr and Harbord, 1993). It will also be reviewed in the following chapter, and chapter 5 develops a model to study production and investment dynamic in an oligopolistic market.

The basic principle of this approach is to build an analytical model integrating the main characteristics of the situation of interest and then to study the solution obtained. In our case, the level of investment and of competition are of interest and usually assessed through a comparison of market price and marginal cost. Competitive market models then serve to illustrate what happens in the case of pure competition. Oligopolistic models are useful to give more realistic depictions of market options (since pure competition is only an ideal target).

1.7 Modeling approaches

1.7.1 Electricity modeling area

Many different models can be used to simulate the market and explore different characteristics of some market structures. Modeling in the electricity research field is not limited, however, to this specific structural problem. In this section we review the main electricity sub-sectors where modeling makes a significant contribution.

First, there are two large sub-sectors that we will not cover:

- engineering issues in generation, operation, transmission and control;
- demand forecasting and production cost benchmarking.

The first sub-sector deals with all the technical models of power systems essential to carry out all generation, transmission, transformation and distribution activities. A first introduction to these models can be found in El-Hawary and Christensen (1979) and in Wood and Wollenberg (1996).

The second sub-sector not covered here includes all models used in the econometric approach. They characterize demand and cost components and try to assess their influence using regression or other statistical tools. Pachauri (1975) and Kwoka (1996), among many others, give a description of these models.

In the following, we present the different modeling approaches in

- fixed cost allocation;

- transmission pricing;
- competition in power pools.

1.7.2 Fixed cost allocation

The problem of fixed cost allocation is of importance since, as we have seen in the first part of this chapter, fixed cost recovery was a problem in pricing. First, some pricing options did not guarantee full recovery of fixed cost (such as short term marginal cost pricing). Second, when there is recovery with the pricing scheme used, it either creates some cross-subsidies (average cost pricing) or takes advantage of the inelastic demand of some consumers (Ramsey pricing).

Three modeling approaches can be identified to allocate a share of fixed cost to each customer or group of customers:

- fully distributed costs;
- axiomatic approach;
- cooperative game theory.

In the first approach, fully distributed costs and cross-subsidies are not taken into account. It consists simply of a set of accounting principles used to guide how to split fixed cost between users. These principles can be a proportional share of cost based on total energy used, peak demand, generated revenues, induced costs, etc[30]. More than 30 models of allocations can be found in the literature (Primeaux and Nelson, 1980). Each of these models is arbitrary, so justifying the "good" one seems to be rather difficult within this framework.

In the axiomatic approach, the problem is taken from a completely different perspective. Instead of having to justify a model, a characterization is given for the properties a good fixed cost allocation scheme should have. The problem to solve now is to find a possible allocation within this characterization. Miran, Samet and Tauman (1983) use this approach.

Finally, the last modeling possibility is to use cooperative game theory. The goal here is to find a price without cross-subsidies. The process starts with a precise definition of what is a

[30] See Brown and Sibley (1986), page 44.

cross-subsidy. There is a cross-subsidy if a player can gain something by quitting the coalition he belongs to. In the electricity terminology, we could say that there is cross-subsidy if a consumer could obtain a better price by not being part of his actual consumer group. More formally, a situation without cross-subsidy is characterized by[31]:

$$\sum_{i \in S} p_i \geq C(S) \tag{1.3}$$

where p_i is the total price paid by each member *i* of the coalition *S*. *C(S)* is the total cost of serving *S*. To our knowledge, only few applications of this methodology have been developed. We can mention Sharkey (1982) in the electricity sector.

1.7.3 Transmission pricing

Electricity transmission pricing is an area where many dynamic research and modeling efforts are carried out. Problems linked with simplistic transmission pricing, as used now in the industry, are the same as in electricity pricing, but on two different scales. First, the scale of the cost recovery problem is increased, because fixed costs compared to marginal costs are much greater in transmission than in generation. This is so because the marginal cost of transmission is near zero, when there is no constraint. However, and this is the second point, pricing problems and cross-subsidies seem not to be of major concern for all electricity players because the total cost of transmission is not really significant compared to the energy cost.

Nevertheless, the area of research in transmission pricing seems very active, especially the stream of research following the spot pricing scheme initiated by Bohn, Caramanis and Schweppe (1984). This group of authors has developed a marginal cost transmission pricing model that takes into account:

- transmission losses;
- maximal capacities;
- energy balance;
- Kirchoffs' laws.

[31] Brown and Sibley (1986), page 52.

The model derives transmission costs equal to the cost of losses plus the difference of marginal production cost between nodes, when the line between two nodes is congested. Their model is a single period optimization model, integrating many real world physical features. Hogan (1993) and Kahn and Baldick (1994) improve this setting by adding reactive power features to the model. It allows for a more realistic description of the real network.

If transmission pricing does not seem to be a major issue for many players in the industry and is not often discussed in policy texts, market power, on the other hand, is of major importance. And it seems that transmission limits can play an important role in the development of market power, if strategic players can really take advantage of their position in the network. A first work by Doyle and Maher (1992) compares different scenarios where many generators compete throughout a network. In a simple deterministic setting, an illustration of market power in an electrical network is shown. Cardell, Hitt and Hogan (1997) and Hogan (1997) present a more complex model for the same purpose. In these two last papers, Cournot players with a competitive fringe play a game in a network, where different demands need to be satisfied at different nodes, and where transmission cost are paid through transmission rights, owned by the players. In addition to the traditional strategic behavior in supplying electricity, players owning transmission rights can influence transmission and market prices by choosing to create congestion on specific lines. This is a new type of market power specific to electricity. The example developed in these two papers remains a small-scale example, but illustrates the threat this new type of strategic behavior could put on electricity markets.

These models of transmission pricing and of transmission market power are still in a development stage. They are offering interesting avenues for transmission pricing, but the problem they solve still seems to be unappealing to really have an impact on actual transmission policy.

1.7.4 Competition in power pools

Deregulation reforms, as we have seen in this chapter, mainly aim at introducing competition in generation, through a spot market where all generators can pool their production and sell it to customers.

Modeling the competition in these power pools is an important task to assess how well competition can work and offer the desired results. Later in the following chapter (section 2.3.3), results from the simulation-modeling approach will be given to illustrate the type of conclusion these studies are obtaining. For now, we simply present a general overview of the setting of these models. Table 1.19 summarizes these elements.

Table 1.19 Overview of spot market game models

	Demand	**Cost**	**Supply**	**Price**	**Stochastic elements**	**Number of periods**
Herriott (1985)	Fixed	Not specified	-	Solution of the game	None	1
Bolle (1992)	Linear	Linear	Solution of the game	-	Demand parameters	1
Green et Newberry (1992)	Real data	Linear and quadratic (estimated)	Solution of the game	-	None	1
Von der Fehr et Harbord (1993)	Random variable (price independent)	Constant	-	Solution of the game	Demand	1
Exelby et Lucas (1993)	Fixed	Constant	Solution of the game	-	None	1
Green (1997)	Cubic fonction of time (estimated)	Quadratic	Solution of the game	-	None	1

1.8 Conclusion

We have seen in this chapter how natural monopolies are characterized, and the economic structure of the electricity sector. The main regulatory tools formerly used are control of entry and pricing. Reforms have changed this with the explicit goal of introducing competition[32], as seen in the policy texts. The target of deregulation is to improve efficiency by creating a market structure where price should naturally reach marginal production cost, and where costs are driven to their minimal level.

The market implementation and new industrial strategies seen in section 1.4 illustrated how the reforms have affected the market. More aggressive behavior and highly strategic investments are to be expected from the actual players, denoting a radical change in the way investment is planned. Chapter 3, 4 and 5 deal with this issue.

To assess the success of these reforms, we reviewed three different methodologies: the transaction cost analysis, the econometric approach and the simulation-modeling one. As the first seemed difficult to use and implement, focus was and will be given on the two other approaches.

Different reform possibilities were described and an overview of some modeling issues in the electricity sector was given.

In the following chapter, we direct our attention again to reforms from different countries, with a specific focus on the Finnish case. This will provide a throughout illustration of an implemented reform, and will clearly show the new market dynamic taking over this sector, with its impact on investment behavior.

---

[32] Nevertheless, we have to acknowledge that other targets are also sometimes stated (to give more choice to customers, to improve customer service and reliability, etc.), but appear to be of marginal importance in the reform process.

Chapter 2. Implemented reforms: focus on the Finnish case[33]

2.1 International overview of electricity reforms

We now present a synthesis of the main features of some of the most relevant international examples of electricity market reforms. This will more precisely set the global context in which production and investments are now made. We then examine the Finnish electricity industry and reform process in details, motivated by two reasons. First the structure of the Finnish electricity industry has been unique and, in some occasions, at odd with most countries' electricity structure. Its portrait is in itself clearly appealing when considering industry structure possibilities. Second, electricity reforms in Nordic countries, with England and New Zealand, are often referred to as classical examples. But although Finland is a Nordic country, a larger focus has been given to the Norwegian and Swedish cases (e.g. Hjalmarsson, 1996, Amundsen and Bergman, 1998, or Midttun and Summerton, 1998). Since some significant features distinguish the Finnish market, its extensive presentation could help to understand the unifying movement observed in the Nordic electricity markets.

Many countries have already gone through electricity market reforms. We begin this section by reviewing some of their key features and results (Table 2.1).

---

[33] An adapted version of this chapter has been published in *Energy Policy* under the title "A Perspective on the Restructuring of the Finnish Electricity Market" (Pineau and Hämäläinen, 2000).

Table 2.1 Market structure in 1999 for some pioneer countries

Important features		California	Great Britain	Chile	New Zealand	Norway	Finland
		Countries					
Vertical disintegration *p* = with privatization			• *p*	• *p*	•	•	•
Horizontal disintegration *p* = with privatization			• *p*	• *p*	•		
Competition in generation		•	•	•	•	•	•
Spot market *m* = mandatory pool		•	• *m*	*m*	• *m*	•	•
Transmission assets	System operation	Independent	NGC	ELDC	Transpower	Statnett	Fingrid
	Owner	Utilities		Transelec			
Type of organization	System operation	Nonprofit organization	Privatly owned by distributors	Gvt. Agency	State firm	State firm	Utilities, state, investors
	Owner	Private		Private			
Competition in transmission				•			• (withdrawal)
Competition in distribution							
Competition in retail supply		•	•		•	•	•
Main references		Bushnell & Oren (1997)	Newbery & Green (1996)	Rudnick & Raineri (1997), Spiller & Martorell (1996), Yajima (1997)	Read (1997)	Bråten (1997)	Ministry of Tade and Industry (1997a)

Table 2.1 shows that in almost all cases, the reforms contained some vertical disintegration, to separate generation from transmission. Indeed, in all states except California and Chile, where an Independent System Operator (ISO) was created, transmission assets and system operation have been separated from generation, to avoid any privilege in transmission. In California, system operation is carried by the ISO even if the property of the transmission lines remains with the previous owners (utilities). It is also worth mentioning that in Chile, investment in transmission is open to anyone and that some competition does take place in that sector between the major transmission company, Transelec, and other smaller ones (Rudnick and Raineri, 1997). System operation in Chili is planned by the Economic Load Dispatch Center (ELDC), which is an entity ruled by the National Energy Commission (CNE). In Finland, as seen below, competition in transmission has been ended. Spot markets

were also created with all reforms, except in Chili were competition takes only place through contracts (Yajima, 1997). But as in England and Wales, a mandatory pool allows the ELDC to calculate a system marginal cost, which serve as a basis for the market price. When a spot market is active, the spot price directly gives a public reference price.

Detailed description of all reforms can be found in many references (some are given in table 2.1), except for the Finnish case that has been covered in relatively few papers. The only two known by the author are Ministry of Trade and Industry (1997a) and Rännäri (1995), which have not been widely accessible. To try correcting this situation and to have one example at hand to analyze electricity reforms, we chose to present more extensively the Finnish electricity market reform.

2.2 The Finnish reform process

2.2.1 Pre-reformed Finnish electricity industry

The Finnish electricity industry is unique due to its historical development, and this has induced uncommon reforms. Indeed, at the beginning of the century, Finland was far from being an industrialized country, and the GNP per capita was clearly below the one of western European or other Nordic countries[34]. All the electricity technology had to be imported and wood was still the major energy source. From that original state, a modern and diversified electricity industry arose, as efficient as the one of countries initially much more developed. For a complete account of the historical development of the Finnish electricity industry, we refer to Myllyntaus (1991). Here we review the more recent regulatory changes that took place in 1995 with the Electricity Market Act (EMA).

Generation and coordination of sales levels

In Finland, generation has always been a multi-player business. Even with a state-owned company (*Imatran Voima Oy*, or IVO, now called Fortum) that dominates generation with

[34] With 100 being the GNP per capita level of Finland in 1910, U.K. was over 200, Belgium and Germany around 170 and Sweden and Norway at 130 (Myllyntaus, 1991, page 10).

more than 30% of the total production capacity (it has approximately 5 000 MW[35]), other smaller utilities were already important before deregulation with a capacity of nearly 4 000 MW. Distribution companies (2 000 MW), as well as industries (2 400 MW) were also producing.

Wholesale market was theoretically open, but in practice dominated by IVO and limited by the long-term contracts and the difficult access to the grid. Nevertheless, industries and distributors were allowed to produce and to sell, thus limiting the monopoly power of IVO. Small private pools operated to dispatch in an efficient merit order, under the leadership of IVO and other producers. To ensure high level reliability of the system, a discipline of cooperation and self-regulation was maintained between the different parties. It means that no regulatory board such as the *North American Electricity Reliability Council* (NERC) ever existed.

Another specificity of the Finnish electricity industry is the diversity of the production technologies in use. Nuclear (27%), hydro (17%) and all types of thermal units are exploited, with as much as 32% of electricity coming from Combined Heat and Power production (CHP)[36], making Finland a leader in this technology. Remaining electricity comes from other thermal units and imports. As early as 1989, no construction permit was needed for power stations of capacity less than 250 MW. Nuclear power and hydropower productions are nevertheless subject to specific laws for environmental concerns. Foreign trades of electricity also need a license.

Transmission and operation control levels

A very uncommon feature of the Finnish electricity industry compared to the worldwide situation was, at that time, the presence of competition in the transmission network. Indeed, two companies, IVO and *Pohjolan Voima* (PVO) owned and operated most of the transmission lines, with some parallel links in certain locations. From 1992 to 1997,

---

[35] All capacity shares are taken from Ministry of Trade and Industry (1997b).

[36] These percentages come from FINERGY (1997).

subsidiary companies of IVO and PVO, respectively IVS and *Teollisuuden Voimansiirto* (TVS), had to manage their transmission activities.

TVS' objective was to minimize the cost of a consortium of generators who wanted to avoid the use of IVO's network. Hence, no real open access to third party was available from this network, which was also limited in length. IVS network was open to third parties and the transmission pricing system used is described in table 2.2[37].

Table 2.2 Transmission pricing structure of IVS

	Duration	Component	Variants
Long-term contracts (S-2000 pricing)	5-10 years	• Fixed fees (FIM / input-output points / month). • Power fees (FIM / MW / month). • Distance relative fees (FIM / MWkm / month).	• If transmission goes through a densely populated area. • If contracts were of a shorter length.
Spot transactions	temporary	• Fixed and variable components.	

All spot transactions were subordinate to the long-term contracts, so that they only took place if no conflict arose. The level of fees was fixed such that the forecast average cost plus an adequate profit was realized by IVS. Some limits on these fees were nevertheless naturally introduced by the fear of some entry in transmission. Indeed, construction of new lines was open to anyone, and IVS had the obligation in such a case to link them with the existing network.

This pricing practice limited spot transactions and was not giving an efficiency signal to the sender of electricity, because no short-term indication was given on the losses and constraints of a particular transmission.

At the operating level, these elements have to be said about IVS behavior:

- Losses of transmission were compensated by IVS' electricity purchases according to anticipated use of the network. This was made at IVS' own risk.
- Cooperation with other networks was done whenever it could avoid losses.
- When lines were constrained, or near full capacity, no long-term contracts were made. Only some spot agreement could be agreed on.

---

[37] Source: Ministry of Trade and Industry (1997b).

- In peak periods, out-of-merit power was bought (by IVS) at the destination node if congestion in a line prevented respect of all transmission contracts.

This transmission pricing practice precludes full efficiency for the following reasons. First, IVO was the main user of its own grid but was not applying its transmission pricing scheme for its production. The global efficiency efforts in transmission pricing were consequently smoothed out. Indeed, the economic signals contained in the transmission price were not apparent in the price of energy sold. Furthermore, these signals could only be of limited scope because they did not reflect the continuously (or at least hourly) changes in the network. Marginal losses and constraints caused by a particular transaction could not be taken into account.

Distribution and retail supply levels

About 100 distribution companies[38] owned mainly by municipalities were operating in their local (and exclusive) territory. Between their network and the high-voltage transmission network, some regional networks are in operation, linking the national grid to the distribution networks. Table 2.3 shows the number of different owners and the voltage of the three types of networks before 1997.

Table 2.3 Number of owners and voltage level of the different networks[39]

Level	Number of players	Voltage
Distribution network	113	0,4-20 kV
Regional network	10	30-110 kV
Transmission lines	2	110 kV and over

Construction of lines was already open to anyone, but acceptance from the Ministry of Trade and Industry (Electricity Market Authority after 1995) was required for lines exceeding 110 kV. In their territory, distribution companies could build lines without special permission, as required for projects on other territories. Pricing principles of the distribution and regional networks did not change after 1995. They will be discussed later.

[38] Between 1987 and 1997, this number was reduced by more than one third, from 157 to about 100 (Ministry of Trade and Industry, 1997b).

[39] Source: Electricity Market Authority (1997).

Distribution companies held a monopoly over their territory, such that retail customers were captive. From 1988 to 1995, the Office of Free Competition (OFC) monitored their pricing, on a "reasonable profitability" basis.

Regulator role

Under the system we described in the previous sections, only one organization acted as a regulator, the Ministry of Trade and Industry. OFC's role is only to react to complaints and to monitor "free competition". The following points can summarize the Ministry's main tasks, in the electricity sector:

- Delivering licenses for nuclear production.
- Delivering licenses for transmission lines of and over 110 kV.
- Giving judgment in case of complaint on transmission prices in the three networks and abuse of monopoly power in distribution.
- Monitoring imports.

These are limited fields of action, compared to the traditional role of a usual regulatory agency. In most countries, regulators usually have some control over new production capacities, prices and levels of profits for companies involved in generation, transmission and distribution. The monitoring of the Ministry was mainly reactive and relied on cooperation of the players. Indeed, no explicit and detailed rules to follow are written.

2.2.2 Opening of the Finnish electricity market

As seen in chapter 1, it was mainly pressures from the worldwide market integration and the European energy policy (see also EU, 1995), combined with the desire to fully participate in the Norwegian/Swedish electricity market, that led to some reforms in the Finnish electricity market.

The common market place for Sweden and Norway, and its major coordinating tool, is the Nord Pool, which started in 1996. Finland and Denmark are active in this pool, but not as full participants because their domestic market is still considered too different to stand on an equal foot with the Swedish and Norwegian ones in the Nord Pool. For example, some border fees are still imposed on exchanges. We now retrace the moves made by Finland to integrate this international electricity market place, the first one of its kind.

The Electricity Market Act

Adopted during the summer of 1995, the Electricity Market Act (EMA) had the following objective. Increase efficiency and competition in generation and transmission in order to be ready for an opening of the Finnish electricity market to international competition (mainly from other Nordic countries) and to conform to the EU policy energy directives[40].

The EMA led to the following results:

- **Creation of the Electricity Market Authority - 1995**. It is "an independent expert body subordinate to the Ministry of Trade and Industry"[41] supervising transmission pricing and delivering licenses for transmission operations.
- **Gradual opening of network**. In 1995 open access was given to lines over 500 kW, and to all lines at the beginning of 1997 (see Creation of Fingrid below).
- **Creation of EL-EX - 1995**. This formal and independent power exchange organization eases trade of electricity by offering standard spot contracts. Basic contracts are of one hour, and they can be grouped to form blocks of various lengths.
- **Unbundling of tariffs - 1996**. Tariffs shown to customers have to separate as much as possible the different components of the delivery of electricity, namely energy, transmission and measurement.
- **Unbundling of book keeping - 1996**. Companies involved in both generation and distribution have to keep separate accounts for each activity.
- **Reform of taxation - 1997**. The new tax focuses on consumption instead of production, in harmony with the situation in other Nordic countries.
- **Creation of Fingrid - 1997**. This independent company was then created to operate the transmission network in a neutral mode. More details are given below.
- **Complete opening of the market - 1997**. From the beginning of 1997, all customers had the possibility to choose their supplier. However, in practice, a costly metering system (5 000 to 10 000 FIM[42]) was needed, and only large consumers could really select this option. Since fall 1998, such a meter is no

[40] See Ministry of Trade and Industry (1997b) and Fingrid (1997).
[41] Electricity Market Authority (1997)
[42] Five Finnish Marks (FIM) are approximately equivalent to one US dollar.

longer necessary. A "load profile" billing system is used, in which the residential customers are classified in different load profiles close to their real load pattern, and charged according to this profile.

The EMA improved the market structure to bring it closer to the principles of free market and to the practice of the other Nordic countries. Before describing in more detail changes and actual practices at different levels of the industry, we present two sectors where the EMA had remarkably low impact. The first one is the nuclear sector and the second one trade.

Conversely to other deregulation cases, significant and non-decreasing use of nuclear power remained in generation after the EMA. Nuclear power is indeed fading in many countries (United States, Canada and United Kingdom) because of some difficulties to integrate such production units in the free market[43]. It is noteworthy that in Finland nuclear power remained sustainable. This situation can be explained by a successful choice of reactor technology, efficient management and adequate regulation on safety and licensing (Hjalmarsson, 1996). We can also mention that nuclear power in Finland was developed in a context of low regulation, so that the financial plans for investment in this technology were not deeply affected by market restructuring.

The EMA also had a very limited influence on trade, where all previous types of trading mechanism remained in use. These types of trade are:

- **Bilateral contracts**. A seller and a buyer make a private agreement for the supply of electricity. This mainly covers base load needs, and is generally done on a mid- or long-term basis. Most trades are still made under this kind of contract.
- **Official spot markets**. The Finnish spot market, initially named EL-EX, was created at the time of the EMA. It is now part of the Nord Pool and covers approximately 10 to 15% of the traded electricity[44].
- **Private pool**. For immediate and small adjustments of supply, private pools constituted by different competitors are used. They collaborate in this continuous exchange pool to minimize their own dispatch cost. In March 1998, three private pools were operating in Finland.

[43] An explanation of this could be linked to the particular cost structure of nuclear power and to the investment risk involved. See Kidd (1998) for more on this topic.
[44] See Nordel (1998) for information on the volume traded in the Finnish spot market in 1997.

As it can be seen, we have presented the trading places in a decreasing time horizon of contracts. In the first one, agreements could be made for years, in the last one, for minutes.

As bilateral contracts still cover the majority of power exchanges, less intense competition is taking place in the spot market. This situation will change with the progressive end of the contracts. At that time (1999-2000), buying in the spot market may become more interesting for bulk customers than having a fixed contract with one producer, and all new contracts will be linked to the spot price.

Change in the transmission segment

It is the transmission sector which was the most affected by the EMA. This is so because transmission has to be impartial and fully open to give all players the same opportunities to transport outputs of trades. Independence was realized by merging the two existing grids in one national network, and by changing the ownership structure. The result was the creation of Fingrid, a private company operating, maintaining and developing the high-voltage transmission lines.

We first describe here the main characteristics of Fingrid and its central role, then we review the transmission pricing used, and finally we discuss the investment issue in the grid.

Fingrid

Fingrid is the operator of the national transmission network of Finland, which "carries" all electricity at a voltage equal or higher than 110 kV. The company owns 13 600 km of lines, representing almost all the transmission lines of Finland as well as the cross-border lines. It began operating in September 1997 after the merger of the transmission assets of IVO and PVO, and is now owned at an equal level of 25% by IVO and PVO, the state (12%) and by institutional investors (38%), who have no other interest in the electricity business. This type of ownership is distinct from the one encountered in other countries[45].

Fingrid plays a central role in the free operation of the market for two reasons. The first is that an open access to transmission lines is crucial for competition to take place. Indeed, if one player only controls the network, he has the power to limit electricity transactions and can then prevent competition from taking place, if ever this is to his advantage. The second reason is more related to the development of the market in Nordic countries. The official electricity trading place of Norway and Sweden, Nord Pool, is owned equally by Statnett and Svenska Kraftnat, the national grid companies of these countries. In order to integrate Finland in this common free market, Fingrid also has to have an equal participation in Nord Pool. The goal is to integrate transactions taking place EL-EX to those of Nord Pool. A first move in this direction was done when Fingrid bought EL-EX in February 1998, preparing the combination of the two pools. Now Finland constitutes a distinct price-zone for the Nordic spot price of electricity defined in the Nord Pool, and EL-EX does not exist on its own anymore.

Coordination of electricity transactions and transmissions can be done efficiently by this co-ownership of the pool and the grid. Neutrality in the network is possible if no player has a dominant participation and if transmission prices are non-discriminatory. We further investigate this last point in the next section.

The transmission pricing system

Fingrid introduced in November 1998 a simpler transmission tariff, replacing the previous "point-tariff" principle used since 1997 (see appendix). This tariff gives access to the whole transmission network, independently of the destination. The four components of the fee, all in FIM/kWh, are (Fingrid 1998):

- **Marketplace charge**. (Fixed charge) All users connected to the grid pay this charge, independent of their usage of the grid. The charge is based on their consumption "behind" the connection point. The rationale for this charge is to pay for the possibility of using the grid for trade.
- **Use of grid charge**. (Variable charge) Two time periods are defined for this variable charge, winter weekdays and other days.
- **Loss charge**. (Variable charge) To compensate for transmission losses, all input and output to the grid have to pay a fee for losses. On winter weekdays, this charge is higher for output from the grid, but otherwise it is similar for all users.

---

[45] See Table 2.1.

- **System service charge**. (Fixed charge) In order to cover operation costs and system balance, this charge applies to all consumption behind the connection point.

Each owner of a connection point pays this fee to Fingrid. Transmission cost, profits and future investment needs are included in the fee. Some other fees are paid for regional and distribution network services. The Electricity Market Authority, mandated to react in case of excess pricing from the network operator, monitors the pricing level and discriminating effects. He applies rules of "reasonable" pricing for "reasonable" profit to the owners.

As one can see, this pricing structure is similar to the previous one (see table 2.3), except that it is no longer distance-dependent. The main criticism is then the same: tariffs are fixed. No signal of the current effect on the network (and thus the actual marginal cost) is given to the transmissions, preventing the full efficiency in the network. But one can also say that customers appreciate the simplicity of the tariff structure and that as far as no capacity limits are present all economic trades can take place. Thus, the possible gains in efficiency from a better tariff structure may not outweigh the efficiency created by simplicity.

Long term development of the network

One of Fingrid's duty is to maintain and develop the network. Investment then has to be directed for that purpose. The situation in Finland is one of excess transmission capacity, and a yearly investment of FIM 250 million is made to maintain this situation. Free access to cross-border transmission lines is also one of Fingrid's goal, in order to allow for international transactions and competition.

Reliability criteria and development of the market place are the main objectives of investment decisions. Developing the market place is understood by Fingrid as a requirement to always offer capacity for trade. If no capacity is available in the short run (bottleneck), then Fingrid will buy electricity at a point of the network in order to allow the initial trade to take place, as agreed by the two parties. If such a situation extends into the long run, then Fingrid undertakes some capacity additions.

The regional and local distribution segment

The lower voltage networks operate in exclusive territories, and apply a pricing principle close to the one of Fingrid. They are also subject to the decisions of the Electricity Market Authority who watches for reasonable price and profit.

The distribution segment is now just a wire business, because retail competition is completely open to any seller. Takeovers of distribution companies by generation ones occurred, because up to the fall of 1998, distributors were the exclusive sellers of electricity. The retail market knowledge and information on customers they possess, such as local load pattern, is indeed the pinpoint of success and profitability for sellers. That explains the appetite of generators for these businesses. The acquisition of distributors by generators is not, in 1998, subject to any law nor to the approval of the Electricity Market Authority. However, such vertical integration could moderate competition or even to some extend annihilate it, because of possible collusion. This is of course against deregulation's spirit. This issue is actually discussed by the parliament of Finland, and new legislation could limit the participation of sellers in the ownership of distributors.

The role of the regulatory agency in the energy market

The only "regulator" in Finland is the Electricity Market Authority, but its role resembles more the one of an arbitrator. This agency is subordinate to the Ministry of Trade and Industry, but acts independently. The ministry names the director of this agency. Mandatory tasks consist in delivering transmission licenses to network operators (national, regional and local) and monitoring transmission pricing practices of the 120 firms involved in network operation. A staff of less than 10 persons does this work. The agency gets its financing from the government, licensing fees and annual fee paid by each network operator, linked to its volume of activity.

As we have already mentioned, no explicit pricing rules are used to judge the adequacy of the transmission price proposed by a firm. The price should simply be at a "reasonable" level.

No other area of the electricity market is regulated except nuclear, which is still controlled. New generation projects need only to get an environmental authorization. Trading is free, and the only constrained components of the price paid by customers are the transmission and distribution components, that have to be "reasonable" and respect the general lines of the OFC and the Electricity Market Authority.

2.2.3 Future moves

The next steps in the Finnish deregulation process are the following:

- **End of cross-border fee**. Exchanges with Norway and Sweden will be fully free when no tax is imposed on transmission across the border.
- **Integration with the European electricity market**.

2.3 Analysis of electricity regulatory reforms

2.3.1 Analysis of the Finnish case

At least three features in the "regulated" Finnish electricity industry are unique to it:

- the high diversity in generation, in terms of technologies and number of producers, has led to significant competition;
- the transmission field was not a monopoly;
- no regulatory agency was active, because reasonable and cooperative behavior could be expected.

We can see that the argumentation developed in chapter 1 to justify deregulation does not perfectly apply to the Finnish case. Indeed, there was already no monopoly preventing competition from taking place and no dedicated bureau was regulating the market. However, the EMA allowed for a significant improvement of competition in the industry, mainly by making changes at the transmission level. Unifying the network reduced the inefficiencies of the two previous ones, and introducing open access eliminated the strategic positions some players had due to their ownership of transmission assets. More competition resulted from the reform, as aimed.

However, if the competition level has improved, does it mean that marginal cost pricing and efficient markets will directly follow? We develop here three points that could offer some counter indication of this for the Finnish market.

Transmission pricing practice

If the actual transmission pricing is neutral, in the sense that it is the same for all users, it is nevertheless not always a perfect promoter of competition, because the transmission price does not reflect the real economic value of each transmission. For example, all users pay the same loss charge for their transactions, although each transactions has a different impact on real losses (and could even avoid losses). Thus, some inefficiency is introduced into the market.

A scientific literature is considering the subject of an efficient transmission pricing system (see Chao and Peck, 1996 and 1997, Hogan, 1992, and Hogan et al. 1996). The main idea of these works is to sell transmission rights at the economic value of the marginal transmission. In these frameworks, these rights represent the income of the grid. But such a system implies that non-congested lines are not resulting in any revenue, because the marginal cost of transmission is then zero (if we neglect losses). The grid owner, in order to have revenue and make profit, would then have interest to have congested lines. Few incentives for capacity expansion would result of such a system, and even if motivation were there, revenues induced by the transmission rights would probably not cover the investment costs. A parallel system of charge would be necessary for maintenance and development of the network.

These last important problems and the complexities involved in other types of pricing offer some grounds for Fingrid's practices. However, by ignoring marginal cost of transmission, the actual pricing cannot achieve complete economic efficiency.

Market power

In order to be competitive, the market should be free of large, dominant players. Having a large number of players is usually necessary for this. When too few are present, an oligopoly assumption can prevail to describe the market. In Finland, as we have seen previously, a small number of important players rules the market to a certain extent. Market power in the Finnish industry will be illustrated in chapter 5 in a dynamic oligopoly model. In this study, market prices are shown to be above marginal cost in situations where only a few important market players are active.

Another concern is the vertical integration of distributors with producers. Since distributors still control a large share of the retail market, such mergers could reduce competition.

In a deregulated market, if not enough players are present, then competition does not really take place and the implicit goal of marginal cost prices is not achieved. This is probably by far the biggest concern one can have about electricity market reforms, and calls for careful attention by market authorities.

New regulatory office

Paradoxically, even if deregulation is meant to remove regulation and unnecessary bureaucracy, the creation of a new regulatory office is usually unavoidable. Indeed, in Finland, where no special bureau ever existed to monitor the electricity industry, one was created in 1995 with the EMA. This regulatory agency was created to prevent abuse and to ensure a "reasonable" level of pricing, a behavior that was mostly natural in the former Finnish regulated market.

In his attempt to illustrate the positive aspects of the UK electricity reform, Newbery (1998) concludes by saying "that the price of an efficient and competitive electricity industry is eternal vigilance by the competitive authorities". The goal of having natural low electricity prices by competitive pressure seems then to be difficult to reach. The cost of this eternal vigilance should not be neglected, even if a reliable estimate would surely be difficult to obtain. However, it should also be kept in mind that this regulatory cost will always be marginal compared to the overall turnover of the industry.

The Finnish example showed how a reform can improve the level of competition, without reaching complete efficiency. A legitimate question would then be the following. Which kind of possible reform illustrated in table 1.2 could bring the market the nearest to the maximal efficiency? As a start toward answering this question, we will now review results from the two assessing methods we have introduced.

2.3.2 Results from the econometric approach

Many empirical studies have focused on the impact of different structures on cost behavior and price levels. Kwoka (1996) reviews conclusions on performance found in many of these studies with respect to private property, vertical integration and supply competition. He analyzes himself these issues for the U.S. market. Pollitt (1997) reports findings of similar studies. Here we list their conclusions in table 2.4. This overview allows one to see the kind of signal the assessment of different market structures gives.

Table 2.4 Conclusions of surveys

Kwoka (1996)	Pollitt (1997)
1. On average, public distribution firms have lower cost and prices than private ones. However, private generating firms are found to have lower costs. 2. There are significant economies to be generated from vertical integration between generation and distribution. Private firms are more prone to realize these savings. 3. In supply, competition results in lower prices for consumers.	1. Privatization creates productivity gains. 2. Privatization reduces incentive to invest. 3. Restructuring and privatization induce an important cost assumed by the government. 4. Deregulation has a mixed environmental impact 5. Regulatory framework has an important impact on the outcome of privatization. 6. Restructuring has a redistributional effect that favors shareholders, at the cost of government and consumers.

From the conclusions stated in table 2.4, it can be said that empirical findings do not give a strong signal in favor of privatization and a mixed signal for restructuring. General recommendations are hard to reach because inference from these conclusions cannot be done so directly. However, vertical integration, competition in supply, public ownership in distribution and private in generation seem to be good avenues to lower costs and prices. The difficulty is to succeed to obtain all at the same time, without creating large utilities necessitating constant monitoring.

Another review of deregulated electricity markets (Walker and Lough, 1997) associates electricity price reduction to different factors independent of electricity reforms. The main factor identified is the general price reduction of primary energy sources (coal, oil and gas) used in generation. The decrease in electricity prices could then at least partially be explained by this factor, offsetting the credits attributed to electricity market reforms.

Regarding the main goal of reform, introduction of competition, it can be said that the observations reviewed here do not directly contradict its implementation. But once implemented, will competition always be effective? This would be true if market power had no impact. Different studies have interesting results on this issue. We review some of them in the following section.

2.3.3 Results from the simulation-modeling approach

Instead of looking backward to assess what happened, as in the econometric approach, another strategy is to try to foresee how the market would behave if different structures were prevailing. This is what the simulation-modeling approach does, by building models characterizing new features of the market to give insights on the possible outcomes.

One of the most recent uses of this method can be found in the supporting analysis of the American CECA (U.S. Department of Energy, 1998). The CECA is a bill aiming to create a federal regulatory framework favoring retail competition in the American electricity sector. A perfect competition model of the electricity market is built, with links to other energy models, to assess the advantages of perfect competition and other features of the CECA over a status quo scenario. Since this model has been published as a *supporting analysis* for more competition, it is not surprising that the perfect competition scenario gives significantly better results than the status quo. Price decreases are obtained in all states and environmental issues face better prospects under the proposal.

However, it could be the case that all conditions required to create a perfectly competitive market in electricity, as modeled, will not be met. In such circumstances, simulation of oligopolistic markets could be of interest to study how market power can influence the market price. In an industry long dominated by monopolies and still benefiting from some scale economies (at least in production cost, see figure 1.2), a limited number of firms will probably characterize the market. The oligopolistic hypothesis is then not completely irrelevant. Many papers have dealt with the issue of market power in electricity markets. Among others are Bolle (1992), von des Fehr and Harbour (1993), Newbery (1995), Green (1996), Brennan and Melanie (1998). All these models use actual electricity market settings and a representative number of players. They all conclude that marginal cost pricing cannot be reached with the observed number of players, because of the low level of competition. Consequently, market efficiency is never reached.

The straightforward solution to this problem is to increase the number of players (electricity producers), by splitting existing firms or encouraging the entry of new ones. The former option seems to be difficult to apply in a context where international competition is growing and favors larger firms[46]. Newcomers will certainly enter the market, because entry in the electricity business is easier as we have previously seen (technological argument). But will enough entry occur, without cartel formation or collusion? This question remains open. It is known, however, that sunk costs are a significant barrier to entry, and some recent studies suggest also that they favor cartel formation (Schmitt and Weder, 1998). Even if they are decreasing, initial capital costs in electricity generation, largely sunk, are still important. Thus, counting on a large number of new entries might not be very realistic.

2.4 Conclusion on electricity reforms

We reviewed in this chapter some important international cases and described in detail the Finnish reform process. Some elements having the potential to limit competition have also been stressed. Assessment of different market structures, by the econometric and simulation-modeling approaches, shows that competition can result in lower costs and prices. However, market power could prevent all the expected reductions to happen, as many studies also showed.

Besides the double intrinsic relevance of this chapter (document the Finnish reform and learn from its originality), we have been able to highlight some critical points for competitive market behavior and adequate investment. Neutrality of the transmission and the distribution sector, coupled with an open spot-market are important moves to introduce competition. However, concentration of firms at the generation level can threaten the level of competition and negatively impact investment.

---

[46] Indeed, for a defined market, many firms are needed to create competition. But as markets become more and more international, mergers of smaller firms are necessary if they want to be competitive in the forthcoming international electricity market. This results in two opposite forces: (1) splitting generating firms to improve competition in the local electricity market and (2) merging them to improve their future position in the international market (see Koster, 1998, for an illustration of this paradox in the Dutch context).

Firms could indeed have two major incentives to limit their investment in new capacity. First, market competition makes investment riskier (and therefore more expensive): the open market removes the exclusive access to the consumers and therefore ends the cost recovery guarantee. Second, scarcity of supply increases prices, which in turn affects positively the profits of utilities. With the business oriented management of utilities, instead of the previous "public service" type of management, market power will surely be used.

The next three chapters explore more formally, with economic and game theoretic tools, the investment game that could be played in electricity markets.

2.5 Appendix: The transmission pricing system (1997 - November 1998)

The transmission pricing system used by Fingrid from 1997 to November 1998 follows a "point-tariff" principle. A fixed fee per MW/h is calculated for each access point of the network and has to be paid for any load put in the network, independently of the destination of the electricity (fee is then not distance dependent, contrarily to the previous IVS's tariff, see table 2.2). This fixed fee is public and is changed at regular time periods (yearly). The fee at each access point is calculated according to the following components:

- **Loss charge**. This volume-dependent fee reflects an estimate of the cost of the loss caused by an injection of power at one point. It can then have a positive or negative impact on the total fee. It can vary from -3% to 3% of the amount of electricity going through the point. It is estimated once a year through forecasts and has a different value in winter.
- **Marketplace charge**. This charge can be thought as a variable connection fee, because it is volume dependent. The word "market place" is justified by the fact that the grid offers the possibility to trade without any distance constraints. Even if no trade is made, i.e. no electricity goes through a point, this charge has to be paid because the potential to use the network exists.
- **Use of grid charge**. This component reflects, through a two-level price (one for winter weekdays and one for the remaining periods), a "congestion cost" of the line from the point considered.

Chapter 3. Market structures and investment: a static model

Chapter 1 and 2 covered the general context in which electricity markets are reformed and gave an account of different industry trends. To give a rough summary, these changes are based on the confidence in competitive forces to improve the electricity industry performance. Regulation, guaranteeing a specific rate of return for investors, could lead in some cases to a less efficient market outcome than the competitive one. This will be shown here. However, by putting market-driven forces in the sector, non-competitive behavior could also arise. Actually, in liberalized contexts, mergers and profit-oriented decisions often result in use of market power, not only for short-term price decisions, but also for investment ones. This latter issue is of great concern for the future competitiveness of the industry.

This chapter contributes to the understanding of the investment problem after the reforms. In a simple model, meant only to illustrate this issue, we show the different static equilibria arising under different market structure assumptions. We first quickly review reasons to regulate and deregulate in order to set the context. Then we present the modeling of the regulated, monopolistic, competitive and oligopolisitc cases. We find and compare the equilibria under different assumptions. By doing so, we aim at characterizing the investment problem in deregulated markets. However, limits of the static approach call for dynamic models. This will follow in chapters 4 and 5.

3.1 The analysis of deregulated markets: market power, price and investment

3.1.1 Why regulate? Why deregulate?

The most accepted reason to regulate a market is because it shows natural monopoly characteristics, which can be identified by the presence of s*cale economies* (see Berg and Tschirhart, 1988). However, other political and strategic reasons can enter in the justification of regulation, such as wealth distribution and national safety. With globalization of markets and dominance of the *free-trade* ideology, regulated markets are more and more difficult to maintain, especially when economies of scales are not anymore significant. Technological developments in particular allow many operations and processes to be made at smaller scale, while still being competitive. For example, electricity production can now be done in gas-turbine units of 100 MW at a smaller investment cost than the traditional large coal units (of about 500 MW or more).

Technological developments, combined with the new economic paradigm, are usually mentioned to explain deregulation in sectors such as air transportation, telecommunication and energy. The expected outcome of this new competition is to reach lower prices for the consumers, and thus approaching optimal social welfare without the cost of regulating (financial or moral).

3.1.2 Literature review

Many policy papers call for reforming the electricity sector in order to introduce competition (see EIA, 1996, for an American perspective, and E.U., 1995 for an European one). However, the economic literature is far from being clear on the advantages or relevance of making such reforms. The book of Kwoka (1996), for example, surveys available comparative studies of market structures and makes its own study to conclude that there is no clear market structure that appears to be better than others. See also Pollitt (1997) for similar mixed results.

Although this topic is of great importance and has been much studied, there is no comparative model published in the literature on the influence of the market structure on the price and investment equilibrium. In the electricity sector, research tend to focus on market power in a specific situation, see for example Bolle (1992), von des Fehr and Harbour (1993), Newbery (1995), Green (1996), Brennan and Melanie (1998), without clearly comparing the regulated case with the other possible ones: competition, oligopoly and monopoly. When comes the time of addressing long-term issues like investment, crucial for a sector like electricity, the field becomes vastly open, with very few contributions. We can mention Wei and Smeers (1999), but otherwise it is fair to say that the economic literature on investment in competitive electricity market is not very large. Consequences of poorly planned investments can however be terrible, as reported by the *Wall Street Journal* (Rebecca Smith, May 11, 2000). Lack of capacity and shortages related to deregulation are already reported and also expected in the future.

By studying and comparing different market structures in term of quantity and investment equilibrium, we make a contributive step in the direction of a better understanding of what is at stake with deregulation. Our work illustrates that better equilibria than the regulated one could be very difficult to obtain. Indeed, the market structure needed to get this result would unlikely be sustainable.

3.2 Market structure and equilibria without capacity constraint

Let's take a market for an homogeneous good where the inverse demand can be represented by the following equation.

$$P = a - b \cdot Q$$

where P is the price, Q the total quantity available in the market and a and b positive parameters. The total quantity Q is produced in a context where there is no capacity constraint, meaning that the total capacity K is such that $Q < K$ is always true (in section 3.3 we consider the case where it is not). For some reasons, this market was regulated and is now deregulated. We are interested in comparing how the equilibrium can evolve in this process. We now present in turn the model for each market structure.

Regulated firm

The type of regulation we model is simple, but captures the essence of most regulations (rate-of-return regulation, see Berg and Tschirhart, 1988). The problem faced by the regulated firm is to maximize its profit, under a fixed rate-of-return constraint, applied on the invested capital. It can be written as in 3.1-3.2.

$$max\ (a - bQ_R) \cdot Q_R - c(Q_R) \tag{3.1}$$

$$such\ that\ (a - bQ_R) \cdot Q_R - c(Q_R) = r \cdot \sigma \cdot K \tag{3.2}$$

where Q_R is the quantity produced by the regulated firm,

$c(Q_R)$ is the cost function,

r is the annual rate-of-return allowed for the firm,

σ is the capacity cost,

K is the available capacity.

Let's note that the regulatory constraint (3.2) sets Q_R. The problem is formulated in this format only to parallel the presentation for other market structures.

Competition

In a pure competition model, each firm also maximizes its profit taking the price p as given when choosing its output q_C. The model is simply

$$max\ p \cdot q_C - c(q_C) \tag{3.3}$$

where q_C is the quantity produced by one firm ($Q_C = \Sigma q_C$ is the total output).

Given that capacity K is already available, the rational short-term behavior is to produce as long as the price is at least equal to the marginal cost (and that the average variable cost is not higher than the marginal cost). The investment cost σ and the regulated rate-of-return are not relevant here. The total capacity K neither, as long as an interior solution is assumed.

Oligopoly

In the oligopoly case, firms have an influence on the price. They also recognize the actions of the other players. We assume here a Cournot competition between the firms and look for the Nash equilibrium, at which none of the firms can improve its outcome given that the other ones maximize their profit. For the ease of comparison, we study a symmetric oligopoly with n similar firms. The problem faced by each of them is therefore

$$max\ (a - bQ_O) \cdot q_O - c(q_O) \tag{3.4}$$

where q_O is the quantity produced by one firm ($Q_O = \Sigma q_O$ is the total output).

Monopoly

The monopoly case is exactly similar to the regulated one, without the constraint. The model is then:

$$max\ (a - bQ_M)\cdot Q_M - c(Q_M) \tag{3.5}$$

We now compare the obtained equilibria under two different production cost structures. In the first one, we use a constant marginal cost function, and in the second one a convex, increasing marginal cost function. These two cost structures are interesting because they correspond to specific production cost situations in the electricity industry (hydro/nuclear and thermal production).

3.2.1 Constant marginal cost

With a constant marginal cost (as in hydro or nuclear power production), the cost function is simply

$$c(Q) = c\cdot Q \tag{3.6}$$

where c is a constant cost parameter.

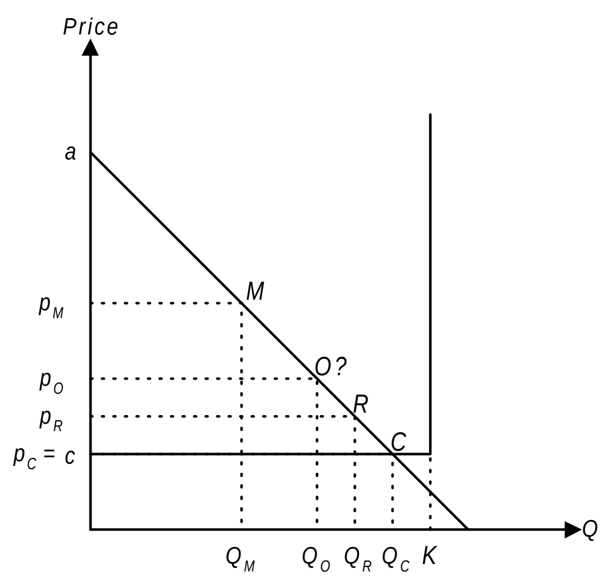
The solutions of problems 3.1 to 3.5 are given in table 1. All the solutions are straightforward to obtain because the objective function is concave, which is enough to guarantee existence and uniqueness of each equilibrium.

Table 3.1 Production under the different market structures

	Equilibrium quantity
Regulated	$Q_R = \frac{a-c}{2b} + \frac{1}{2b}\left(\sqrt{a^2 - 2ac + c^2 - 4bKr\sigma}\right)$
Competitive	$Q_C = \frac{a-c}{b}$
Oligopolistic	$Q_O = \frac{(a-c)n}{b(n+1)}$
Monopolistic	$Q_M = \frac{a-c}{2b}$

An illustrative representation of table 3.1 is given in figure 3.1. Points *M* and *C* are clearly set, as *R*, but the equilibrium point *O* depends on *n*, the number of players. It could indeed be anywhere between *M* and *C*, and thus be above or below *R*. An uncomfortable situation would exist after deregulation if we had $Q_O < Q_R$, resulting in higher prices than under regulation.

Figure 3.1 Equilibria under different market structures



Numerical illustration

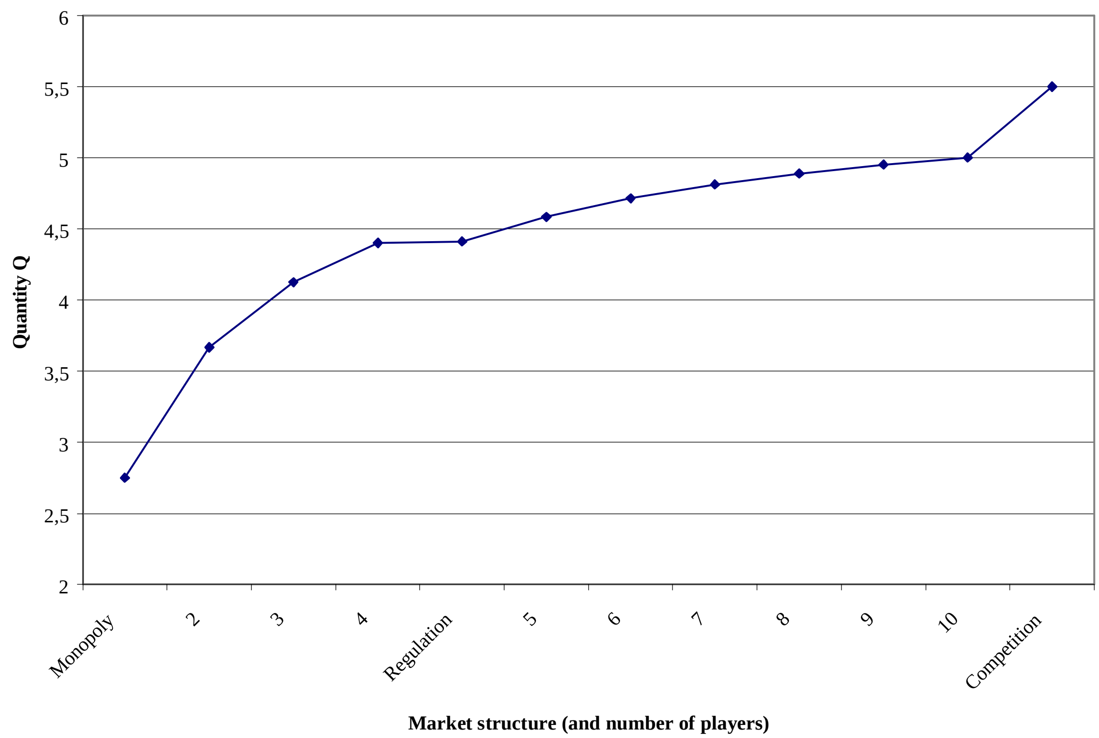
In order to illustrate the results obtained above, we now use some simple numerical values for the parameters in table 3.2.

Table 3.2 Numerical values of parameters

Parameter	Value
K	6
a	6
b	1
c	0.5
σ	20
r	0,04

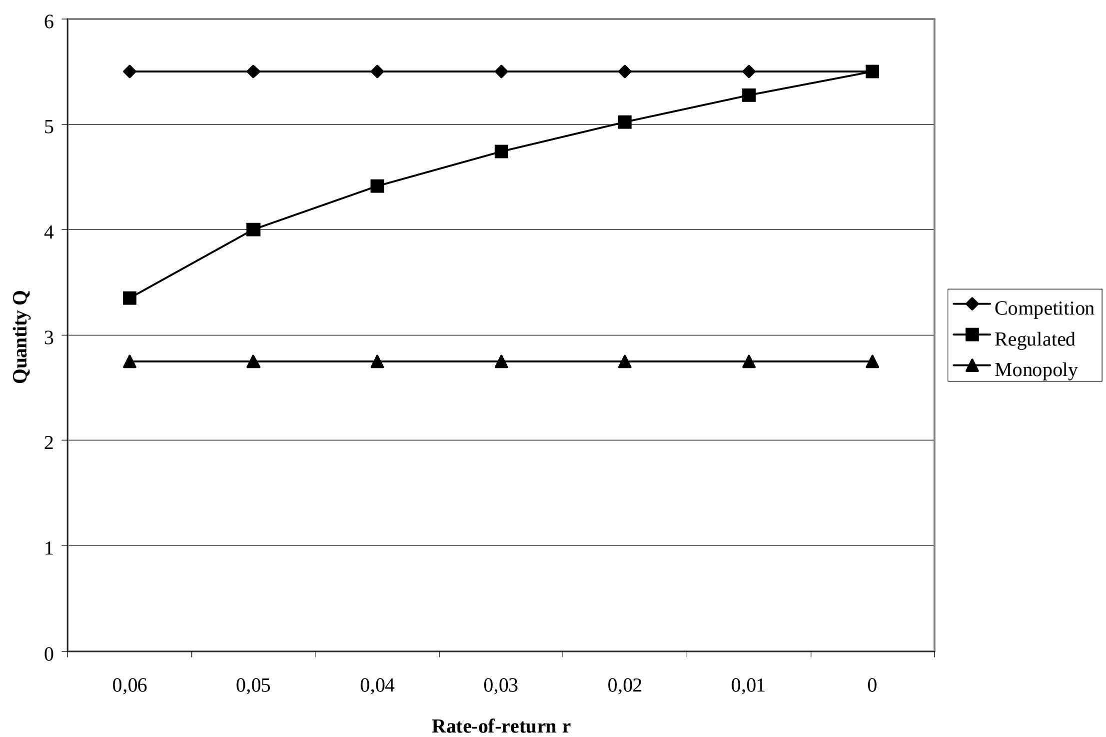
Using these values with the results of table 3.1, we get the following figure.

Figure 3.2 Quantity equilibria under the different market structures



We clearly see that the competitive outcome is difficult to obtain without a large number of players in this context. One has to decrease the allowed rate-of-return to zero to get this outcome under the regulated market structure (figure 3.3).

Figure 3.3 Quantity equilibria for different rate-of-return



3.2.2 Increasing marginal cost

When there are economies of scale, the cost function is concave, meaning that the marginal cost function is decreasing. In some types of industry, however, production units do not show scale economies in quantity, and are used in "merit order". This means that the production units with the lowest marginal cost are used first, and when more quantity is needed, production units with higher marginal cost become active. Each production unit usually have a constant production cost, but when a portfolio of units is held by a producer, a convex, increasing cost function can be used to model his marginal production cost. The functional form used here to model the marginal cost is therefore

$$c(Q,K) = c_1 + c_2(Q/K)^{\phi} \tag{3.7}$$

where c_1 is the smallest marginal cost,

c_2 is the largest marginal cost,

Q/K measures the percentage of capacity used,

ϕ is a efficiency parameter greater than or equal to one.

The total cost function would then be

$$C(Q,K) = c_1Q + (c_2K/\phi+1)(Q/K)^{\phi+1} \tag{3.8}$$

In the electricity industry, for example, when thermal units are used, this type of marginal cost function can be used to represent how the firms use their capacity to produce electricity. For convenience, $\phi = 1$ in the following.

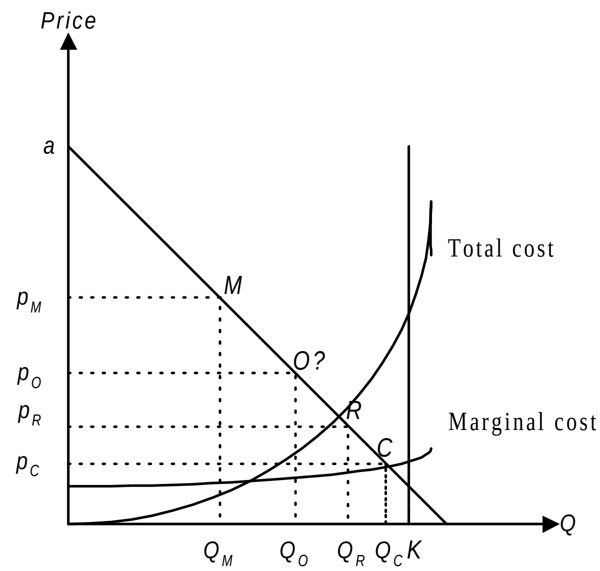
The solutions of problems 3.1 to 3.5 with this new cost function are now given in table 3.3. Again, all the solutions are straightforward to obtain because the objective function is concave, which is enough to guarantee existence and uniqueness[47]. For the oligopolistic case, $n+1$ is the total number of firms.

Table 3.3 Production under the different market structures

	Equilibrium quantity
Competitive	$Q_C = \frac{K}{2c_2}\left(-bK+\sqrt{b^2K^2+4c_2(a-c_1)}\right)$
Oligopolistic	$q_O = \frac{K}{2c_2(n+1)^2}\left(-2bK-bKn+\sqrt{b^2K^2(n+2)^2+4c_2(a-c_1)(n+1)^2}\right)$
Monopolistic	$Q_M = \frac{K}{2c_2}\left(-2bK+2\sqrt{b^2K^2+c_2(a-c_1)}\right)$

[47] For the regulated case, the analytical solution is much more complex. We do not present it here because it would add little to our exposition.

Figure 3.4 Equilibria under different market structures



Numerical illustration

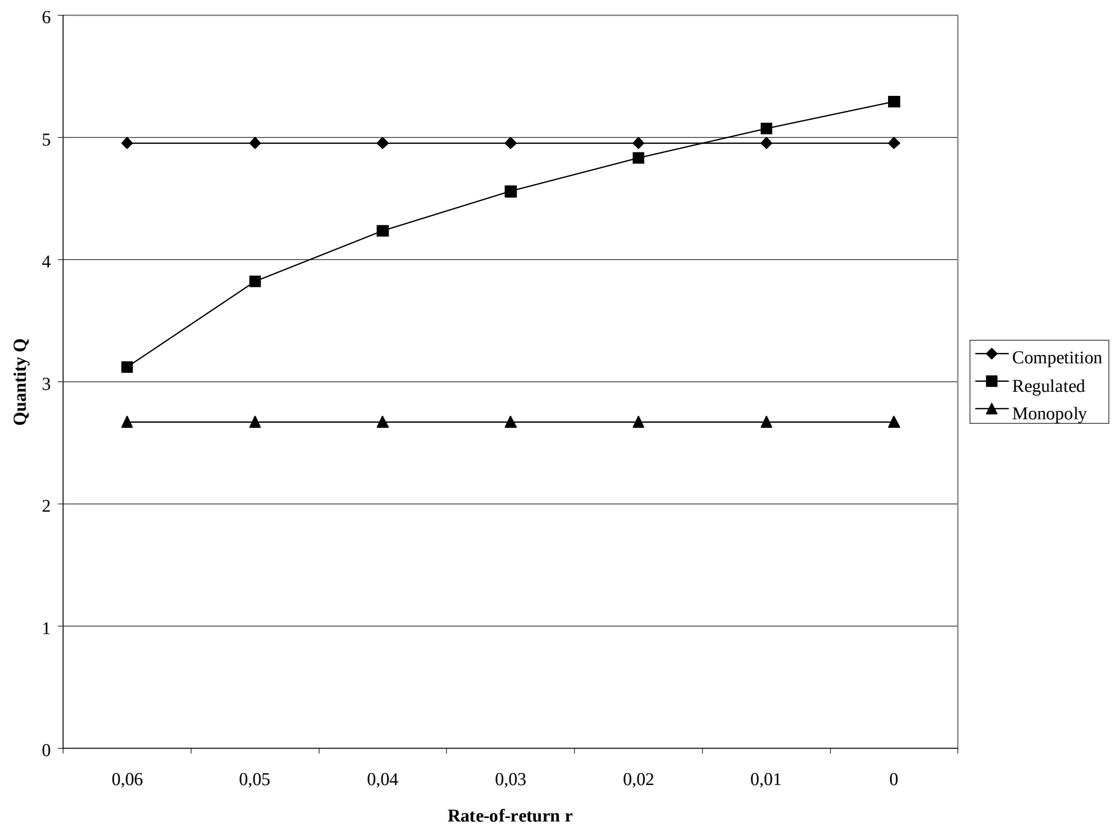
Again, we use the numerical values of table 3.4 to illustrate these equilibria.

Table 3.4. Numerical values of parameters

Parameter	Value
ΣK_i	6
A	6
B	1
c_1	0.5
c_2	0.8
σ	20
R	0,04

The total capacity K is equally divided between each firms in the oligopoly case (each has a capacity of K_i, which is used in the firm's cost function).

Figure 3.5 Quantity equilibria for different rate-of-return



In figure 3.5, we should notice that the regulated equilibrium could result in lower prices (higher quantities) than in the competitive equilibrium if the authorized rate-of-return is sufficiently low. This can be surprising because when the marginal cost is constant, the lowest price is attained in the competitive situation. In such case, profit cannot be made because the price simply covers the constant marginal cost of production of any unit. However, when the marginal cost function is increasing and convex, all units produced before “the marginal one” cost less to produce than this last one, although they are all sold at the same price: the marginal cost. Some profit is therefore made on all units except the marginal one. This explains why in Figure 3.5 a positive rate-of-return characterizes the competitive equilibrium. In the regulated case, if the return on investment cannot be as high as the "competitive" profit, then the regulated firm has to produce more than in the competitive equilibrium, in order to decrease the price to a lower level than marginal cost, where more than authorized profit is made.

Figure 3.6 Quantity equilibria under the different market structures

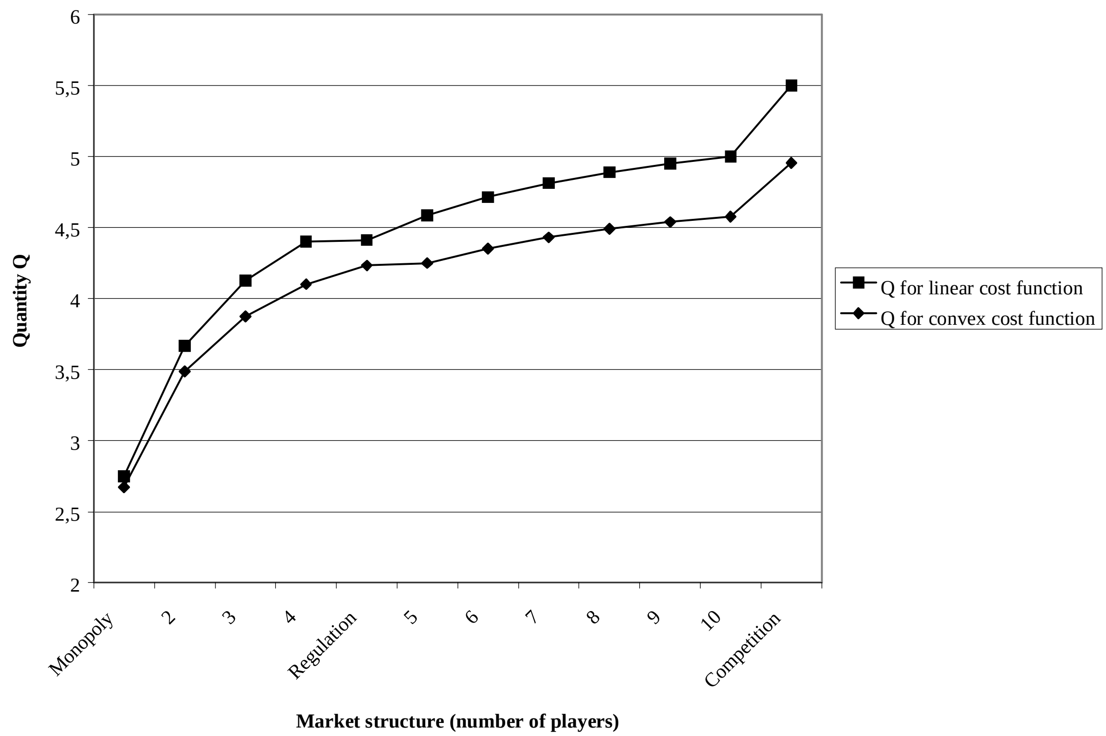


Figure 3.6 illustrates the fact that higher production costs (as it is the case in our second example) lead to smaller quantities in the market, for all market structures.

3.3 Market structure and equilibria with a binding capacity

In the previous section, capacity was assumed to be always available. But an important situation to study is when capacity is scarce, a situation resulting from a strong demand increase or the closure of some production units.

In this section we study the equilibria obtained under the different market structures previously presented. Instead of looking at the interior solution, we now observe the (capacity) constrained solution and see how investment takes place at a capital cost of σ per unit of capacity. This cost is an annualized cost, as used in some other studies of investment pattern (see e.g. Wei and Smeers, 1999). In this context, the decision variable is no longer Q, because $Q = K$ (as capacity limits production), but rather the investment variable I. We assume, for simplicity, that investment is instantaneously available. We also only look at the more interesting solution for convex cost (the constant marginal cost case would be straightforward to study).

The competitive, oligopolistic and monopolistic models are presented in the following, the regulated case will be discussed after.

Competition

As the pure competition case corresponds to the social welfare maximization case, we present here the equivalent maximization problem (which corresponds to the sum of the consumer surplus and the revenue, minus production and investment cost).

$$max\ a(K+I_c) - 0.5b(K+I_c)^2 - (c_1(K+I_c)+ c_2(K+I_c)/(\theta+1)) - \sigma I_c \tag{3.9}$$

where I_c is the total investment made under this market structure;

K is the total available capacity before investment;

θ is the same cost function parameter than previously (θ=1 here)

Oligopoly

In an oligopoly market, firms take into consideration the strategic impact of their action on the outcome, as well as the influence of the other players. Again, we study a symmetric oligopoly with n+1 similar firms. The problem faced by each of them is therefore

$$max\ (a - b(K+I_o)\cdot(k+i_o) - (c_1(k+i_o)+ c_2(k+i_o)/(\theta+1)) - \sigma i_o \tag{3.10}$$

where i_o is the quantity invested by one firm ($I_o = \Sigma i_o = (n+1)i_o$ is the total investment);

k is the individual capacity of each firm before investment;

K is the total available capacity before investment.

Monopoly

The monopoly case is like the oligopoly, with only one player. The model is then:

$$max\ (a - b(K+I_M)\cdot (K+I_M) - (c_1(K+I_M)+ c_2(K+I_M)/(\theta+1)) - \sigma I_M \qquad (3.11)$$

where the notation follows the same standard.

Regulated firm

How would a regulated firm invest? This issue is more a policy question than an economic one, because different possibilities can occur, according to the objectives of the regulator. If the regulated firm produces less than its equilibrium level, it consequently makes more than its authorized return, then investment will be made to increase capacity until the equilibrium is reached. Simply by increasing its available capacity, capitalization is increased and the rate-of-return decreases to the target level. However, production could also increase with more capacity, resulting in a price reduction down to the acceptable level, where the total profit is equal to the allowed return.

For simplicity, we assume here an easy access to capital. The regulated firm will therefore simply increase its capacity to the unconstrained equilibrium identified in the previous section.

Table 3.5 shows the investment quantities obtain for these four market structures.

Table 3.5 Investment under the different market structures

	Investment equilibrium
Regulated	$I_R = K_{\text{unconstrained}} - K$
Competitive	$I_C = \frac{1}{3b}(3a - 3Kb - 3\sigma - 3c_1 - c_2)$
Oligopolistic	$i_o = \frac{1}{3b(n+2)}(3a - 3bK - 3bk - 3\sigma - 3c_1 - c_2)$
Monopolistic	$I_M = \frac{1}{6b}(3a - 6Kb - 3\sigma - 3c_1 - c_2)$

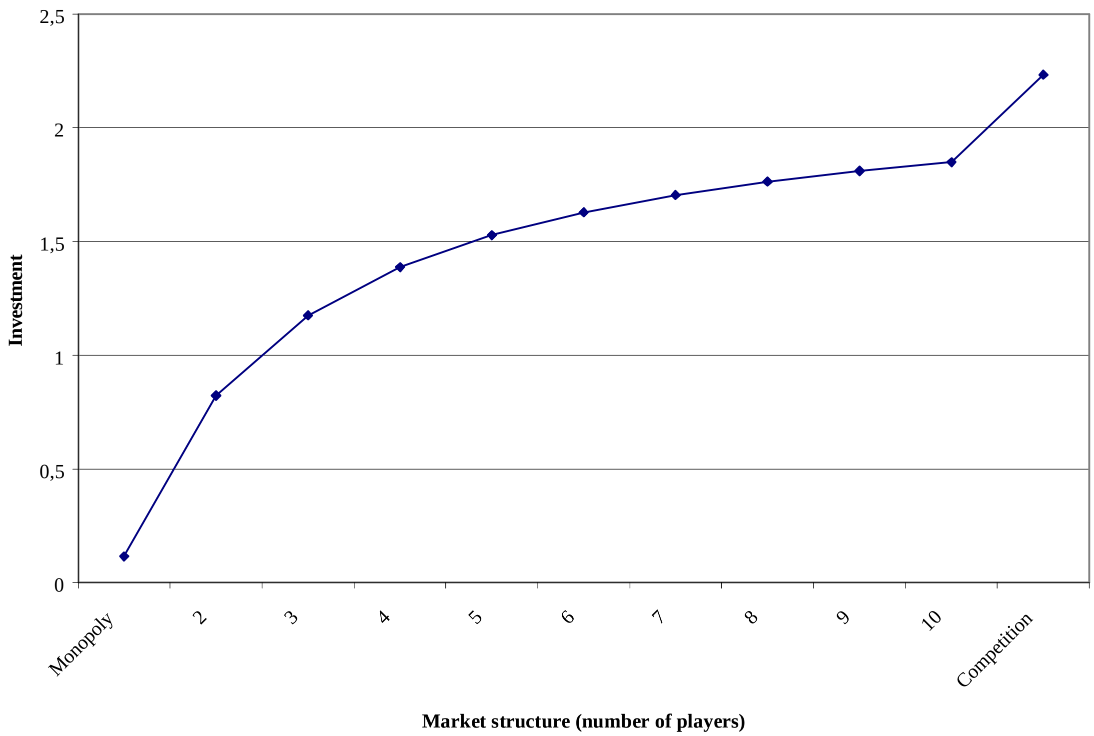
Numerical illustration

Let's assume the following simple values for our numerical illustration. The main changes are first the initial available capacity *K*, down form 6 to 2 to create the capacity constraint in all market structures, and second the value of σ, which is now annualized.

Table 3.6 Numerical values of parameters

Parameter	Value
K	2
a	6
b	1
c_1	0.5
c_2	0.8
σ (annualized cost)	1
r	0,04

Figure 3.7 Investment equilibria under the different market structures



In this highly constrained numerical example (initial capacity K has to be set at 2 to constrain the monopoly), we see how different the investment could be in different market structures. This illustrates a possible threat of electricity market reforms and possibly one of its limits.

3.4 Conclusion

These static examples sought to identify the different possible market outcomes when regulation is removed. Either one of the three market structures can occur: the competitive, the oligopolistic or the monopolistic one.

Market equilibria and investment are important factors to study in order to foresee the market behavior. The examples developed were designed to illustrate the problem and obviously suffer from a lack of dynamic and stochastic considerations. In the following chapters, we concentrate our work on the oligopolistic case (the situation most likely to happen and that has received less consideration from the literature), in a dynamic and stochastic context.

Chapter 4 introduces the game concepts needed to model the situation, with an emphasis on information structure issues, a critical aspect of dynamic games. Building on the conclusions of chapter 4, chapter 5 develops a numerical model of the investment dynamics for the Finnish electricity market.

Chapter 4. The dynamic investment problem

The previous chapter illustrated how the oligopolistic investment equilibrium compares to equilibrium in other market structures. Its relative position against the regulated and competitive cases is of significant importance since reforms in the market are likely to result in an oligopoly. We therefore continue to investigate this aspect by using game theory which is probably the most natural methodology to study oligopolies (see Friedman, 1977 and 1983). Static games have some shortcomings when investment and dynamic features need to be studied. Dynamic games, as presented here, offer a more suitable framework.

Sections 4.1 to 4.4 present the theory and sections 4.5 and 4.6 develop a model and compare the results under different information structures.

4.1 Typology of games

Game theory is a relatively new scientific field aiming at answering multi-player decision theoretic problems[48], most of them arising in economics. As the range of such problems is wide, many different types of games have been defined. Before presenting an overview of this typology, we introduce in table 4.1 the basic elements and notation used for describing a game.

Table 4.1 Elements of a game

N	set of players $N = \{1, \ldots, n\}$
U_i	decision space of player $i \in N$
u_i	decision of player $i \in N$; $u_i \in U_i$
V_i	strategy space of player $i \in N$
v_i	strategy of player $i \in N$; $v_i \in V_i$
v	vector of v_i
T	number of stages (time periods) in a discrete game
$[0,T]$	time interval on which the game is defined, $t \in [0,T]$
W_i	reward function of player i

[48] Its official birth could be said to be the publication of the classical book *Theory of Games and Economic Behavior* (von Neumann and Morgenstern, 1947).

A *game* can be defined as a multi-player decision situation where the final outcome of each player depends on the decisions taken by all the players. Game theory studies the “optimal” decision to make in such situations. If the players can negotiate and make coalitions, then the game is said to be *cooperative*. If not, when the players compete and cannot communicate nor make joint decisions, the game is *noncooperative*. When the outcome of the game implies only a transfer of wealth between players, the game is qualified as being *zero-sum*. If not, then it is a *nonzero-sum* game. Most of economic problems relevant to game theory are nonzero-sum games. The oligopoly situation we will study, for example, is such.

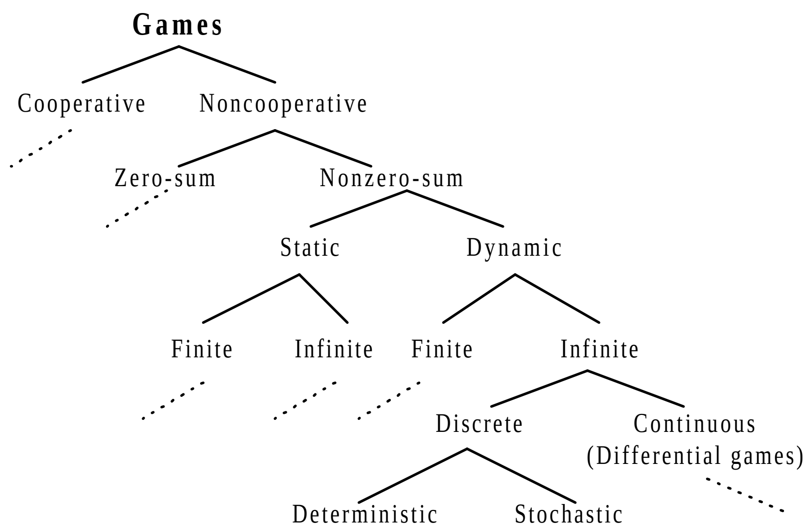
Another important division between games is their *static* or *dynamic* nature. Usually, when time is involved, a game becomes dynamic. However, a better characterization of a dynamic game would be a game where the *state* of the game (set of variables linked to the decision problem and indirectly influenced by the players' choices) is relevant for the players' outcome and evolves throughout the game. If the evolution of the state is irrelevant, that is when there is no future after the game, then the context is static.

A *finite* game involves a finite number of choice possibilities for the players, whereas an *infinite* game involves choice over a continuum. In dynamic games, decisions can be taken at discrete moments or continuously, giving rise to two distinct sub-families of games: *discrete* and *continuous* (stage) dynamic games. In discrete games, the evolution of the state is given through a difference equation, while in continuous games a differential equation is used. This explains why in the latter case the name *differential games* is also used.

When a player with a non-humanly controlled will is present (often called *nature*) and affects the outcome of the other players, the game is said to be *stochastic*. Otherwise, the game is *deterministic*.

Figure 4.1 gives an overview of the different types of games that can be set up, and for which important results and solving methods exist. The tree in figure 4.1 becomes more and more specific as it grows and focuses on the type of games we are the most interested in (noncooperative infinite discrete dynamic games). This explains why some branches of the tree are not developed further.

Figure 4.1 Families of games



A complete account on families of games can be found in Basar and Olsder (1999), where further subfamilies are defined (perfect or imperfect information games, repeated static games). For the sake brevity and because we do not deal with them, we only mention them here.

4.2 Solution concepts

Game theory studies the *optimal* decision to take in situations that can be described within the framework presented in section 4.1. However, "in multi-person decision making, *optimality*, in itself, is not a well-defined concept" (Basar and Olsder, 1999). This explains why within each type of game presented above, many different types of solution can be obtained, without one being more "optimal" than the others. One has to specify the kind of solution he desires for the game, or more precisely to identify the *solution concept* to use when solving the game. A solution is a *decision* (or a *strategy* when there are many decisions in the game) for each player that meets the requirements of the solution concept.

We will now speak of solutions with the understanding that in static contexts, solutions are unique decisions for each player and in dynamic contexts, solutions are strategies.

We now present four of the main solution concepts discussed in the literature, the *maximin solution*, the *Pareto solution*, the *Nash equilibrium solution* and the *Stackelberg solution*. A discussion on their relevance will follow.

Maximin solution

The maximin solution is a very conservative strategy providing a security level for the gains of the players which maximizes their minimal reward. The strategy v^*_i is the maximin strategy for player *i* if

$$\min_{v_j} W_i(v^*_i, v_j) \geq \min_{v_j} W_i(v_i, v_j) \text{ for all strategies } v_i$$

where v_j is the vector of strategies of all players but *i*;

W_i is player *i*'s reward function.

Pareto solution

A Pareto solution takes another standpoint and requires that no player can improve its reward without deteriorating the outcome of the other players. In other words, a Pareto solution is a non-dominated solution, meaning that no other solution gives an outcome at least as good for all players *i*. v^* is a Pareto solution if v^* is such that

$$W_i(v^*) \geq W_i(v) \text{ for all } i$$

where "≥" means that there is no v' such that for all *i* in v', $W_i(v') \geq W_i(v^*)$;

W_i being player *i*'s reward function.

Nash solution

The Nash solution, for the reasons we will see below, is the most used solution concept in noncooperative game theory. It is not only a solution but an equilibrium concept, so more stability is achieved when reaching this type of solution.

A Nash solution v^* is obtained when we have for all players i

$$W_i(v^*_1, \ldots, v^*_i, \ldots, v^*_n) \geq W_i(v^*_1, \ldots, v_i, \ldots, v^*_n)$$

Stackelberg solution

The Stackelberg solution is relevant when all players are not making their decisions simultaneously, but in turn, as in a hierarchical framework. In a two-player situation, one of the players, the leader, makes the first decision with the awareness of the other player's reaction. This latter player is called the follower. The leader will try to obtain the maximal reward given that he knows how the follower will react after his move. The strategy v^*_i of the leader i is a Stackelberg (equilibrium) solution if v^*_i maximizes the leader’s profit when the follower’s profit v^*_j explicitly takes into account the leader’s strategy in choosing its own one.

Relevance of the solution concepts

Although each solution concept is of interest because it corresponds to a possibly desirable situation, not all of them have the same relevance. The first requirement for a solution concept is to be an equilibrium in terms of individual rationality[49]. In an equilibrium, no other choice is better for any player, given the decision of the other ones. An equilibrium is therefore stable.

By definition the Nash solution is an equilibrium. Its characteristics made it the most used solution concept in game theory (in *noncooperative* game theory in fact, because in cooperative game theory, other issues arise because of the cooperative aspects).

The objective of many works in game theory is then to see in which circumstances the Nash equilibrium will **exist** and if it is **unique**. Existence is obviously very important to prove because if the game has no solution, then, most likely, it is not interesting. Furthermore, if the equilibrium is not unique, then the problem of choice among the many equilibria arises. New criteria external to game theory have to be used, making the choice of the solution impossible to justify from a game theoretic point of view. Uniqueness is indeed crucial because without it, it is difficult to claim that the game has been solved. No unambiguous solution can be proposed.

Before going into the results available on the existence and uniqueness of Nash equilibria, we introduce a last concept of great importance for dynamic games and for the rest of our work, the *information structure*.

4.3 Information structures

For dynamic games, where decisions are taken along a time scale, an important factor describing the game and influencing its solution is the *information structure* characterizing the process.

The information structure Φ is the set η containing values of the state variables x^t and s^t, where s^t is stochastic[50]. Three types of information structures are usually mentioned in the literature:

- the *open-loop information structure*, Φ_{OL}, where strategies depend only on time and on the initial conditions of the game;
- the *closed-loop information structure*, Φ_{CL}, where strategies depend on the whole history of state variables;
- and the *feedback information structure*, Φ_F, where strategies depend on the current state of the game.

They are formally defined as follows, where $e^t(s^{t'})$ is the expected value of $s^{t'}$ at $t<t'$.

$$\Phi_{OL} \equiv \{\ \eta^t : \eta^t = \{x^0, s^0, e^0(s^t)\}, \forall\ t \in [0,T]\}$$

$$\Phi_{CL} \equiv \{\ \eta^t : \eta^t = \{x^k, s^k, e^k(s^{t'}), k \leq t, t'>k\}, t \in [0,T]\}$$

$$\Phi_F \equiv \{\ \eta^t : \eta^t = \{x^t, s^t, e^t(s^{t'})\ , t'>t\}, t \in [0,T]\}$$

In the following, we will not consider anymore the closed-loop case, which does not easily lead to solutions and which is not very instructive in terms of realistic strategies. We will present solutions under the open-loop and feedback information structures[51], along with a

---

[49] Rationality is taken here as the maximization of the expected value of the outcome.
[50] We already introduce here the stochastic element s^t used subsequently.
[51] For these two information structures, the presentation is inspired by Kydland (1975).

third one: the *S-adapted open-loop information structure* (Haurie, Zaccour and Smeers, 1990). This information structure, formally very close to the open-loop information structure, allows nevertheless the open-loop strategies to adapt to the realization of the stochastic events, improving on some of the shortcomings of the open-loop solution. It can be formally defined as

$$\Phi_{SA} \equiv \{ \eta^t : \eta^t = \{x^0, s^t, e^t(s^{t'}), t'>t\}, t \in [0,T]\}$$

We now have the complete context describing the type of games we are interested in. Before developing our application on the dynamic investment problem, we review the existence and uniqueness results available in the noncooperative game theoretic literature. This will allow us to understand the limits inside which equilibria are shown to exist and be unique.

4.4 Some results on existence and uniqueness of Nash equilibria

In this section we present theorems of existence and uniqueness of Nash equilibria in *pure strategies*. We specify that we are dealing with pure strategies because other important results are available when mixed strategies are allowed.

Pure and mixed strategies

A *pure strategy* v_i is a sequence of decisions, or a decision rule, providing exactly one decision (action) to take at each decision point *t*. A *mixed strategy* is a probability vector π assigning a probability π_k to each possible pure strategy v_{ki} of player *i*.

A famous result of noncooperative game theory is the one presented by Nash (1951), that proves the existence of a Nash equilibrium solution in mixed strategies for all games with a finite number of pure strategies and players. This is a powerful result because such games do not necessarily reach an equilibrium in pure strategies. However, in many circumstances, mixed strategies are difficult to interpret. In economic contexts, for example, they do not appear to be realistic in terms of observed behavior of the players. This explains why mixed strategies are often not considered relevant and why our research focuses only on pure strategies.

4.4.1 Static case

Existence and uniqueness results available in the literature for Nash equilibria in noncooperative infinite static games are now exposed. Our main reference for this is Basar and Olsder (1999). We will state the existence and uniqueness theorems for different game contexts and will summarize the state of available results in table 4.1. All proofs are given in Basar and Olsder (1999).

To keep a notational consistency with Basar and Olsder (1999), instead of maximizing the reward function W_i, we will minimize the negative reward function $J_i = -W_i$.

Theorem 4.1 (4.3)[52] *For each player i, let U_i be a closed, bounded and convex subset of a finite-dimensional Euclidian space, and the negative reward function J_i: $U_1 \times \ldots \times U_n \rightarrow \Re$ be jointly continuous in all its arguments and strictly convex in u_i for every $u_j \in U_j$, $j \in N$, $j \neq i$. Then, the associated N-person nonzero-sum game admits a Nash equilibrium in pure strategies.*

The important characteristic here, in addition to continuity, is the convexity of J_i. Without convexity, a Nash equilibrium can only be found in mixed strategies (see Basar and Olsder, 1999, theorem 4.7, or Nash, 1951). After existence, uniqueness of equilibrium is a very desirable characteristic to have, because the choice over many different equilibria is problematic.

Proposition 4.1 of Basar and Olser (1999) provides a uniqueness result for two-player nonzero-sum games under some more technical conditions. As a rigorous presentation of this proposition would require significantly more notation without adding much to the understanding of the different cases where existence and uniqueness results are available, we do not go through it here. Basically, under convexity of the negative reward function, the uniqueness of the equilibrium can also be proven.

In an important sub-class of static games with quadratic cost functions, existence and uniqueness results are available. For these games, called *quadratic games*, existence and uniqueness of the equilibrium are proven even for *N* players. This is so because of the strict

[52] This second reference number, between parenthesis, corresponds to the reference number of the theorem in Basar and Olsder (1999).

convexity of the cost function. We now present this important case, which corresponds to the one we study in this chapter.

Let the negative reward function be for each player *i*

$$J_i = \frac{1}{2}\mathbf{u'R^iu} + \mathbf{r^iu} + \mathbf{c^i} \qquad (4.1)$$

where **u** is the matrix of all vector u_i and $\mathbf{R^i}$, $\mathbf{r^i}$ and $\mathbf{c^i}$ are matrices of parameters of appropriate dimensions. The first order condition is here sufficient to prove the uniqueness of the equilibrium because of the strict convexity of J_i. When solving these first order equations simultaneously for all players, it leads to the following equation

$$\mathbf{Ru} = -\mathbf{r} \qquad (4.2)$$

and we can state the proposition 4.1.

Proposition 4.1 (4.6) *The quadratic N-player nonzero-sum static game defined by the cost function* (4.1) *and with* $\mathbf{R^i} > 0$*, admits a Nash equilibrium solution if, and only if*, (4.2) *admits a solution* $\mathbf{u^*}$. *This Nash solution is unique if matrix* **R** *is invertible.*

In this class of games, existence and uniqueness are well established. In other classes of games, especially when the negative reward function is not convex, these results are seldom obtainable. Table 4.2 summarizes what we have presented.

Table 4.2 Results for the static case

	Existence	Uniqueness
N-person game	If J_i convex	Not proven in the general case
2-person games	If J_i convex	Under some technical conditions
Quadratic games	Yes	Yes

4.4.2 Dynamic case

Discrete noncooperative infinite *dynamic* games can be described by a *state equation*

$$x^{t+1} = f^t(x^t, u_1^t, \ldots, u_n^t,) \qquad (4.3)$$

and an additive reward function

$$J_i(v_1, \ldots, v_n) = \sum_{t=1}^{T} g_i^t(x^t, u_1^t, \ldots, u_n^t,) \quad (4.4)$$

where g_i^t is the reward of player i at period t and u_i^t are decisions taken at period t by player i, following their strategy v_i.

To state the adequate existence and uniqueness results for these games, the information structure of the game must be specified. We present here the available results for the open-loop and feedback cases. For the closed-loop case, no general results are available and uniqueness appears to be especially difficult to establish. It occurs only in some peculiar cases, when open-loop and closed-loop equilibria coincide (see Reinganum, 1982, or Fudenberg and Levine, 1988). Results for the S-adapted open-loop information structure can be imported from the open-loop case, because nothing formally distinguishes these two structures.

Open-loop information structure

In this information structure, the players only have access to the initial value of the state variable, x^0. This prevents them from optimizing their behavior according to the latest available information, but allows each player's problem to be written as a static equilibrium problem, under the dynamics constraints 4.3. All x^t terms in 4.4 can then be replaced by their value $f^{t-1}(x^{t-1}, u_1^{t-1}, \ldots, u_n^{t-1},)$ from 4.3. By doing such substitution backward from T to 0, the additive reward function J_i becomes a function of only u_i^t (and x^0). This makes the problem of finding the optimal strategy v_i (as a sequence of u_i^t) similar to solving of a static game.

The problem to be solved in this case is then formally a static problem, but it remains a dynamic problem because of constraints 4.3[53]. Existence and uniqueness results are therefore the same as those available for static games, and the solving, similar. For this reason, we do not present any further results (for more on this see Basar and Olsder, 1999).

[53] A debate exists on what is a *truly* dynamic problem. We acknowledge the fact that open-loop problems can be formally presented as static problems. However, they remain dynamic in our opinion because they describe a dynamic problem. Basar and Olsder (1999) are among the numerous authors to classify games in open-loop under the *dynamic game* heading because according to them, a multi-person decision problem is

As for the static case, an important special class of games for which existence and uniqueness results can be derived, is the *affine-quadratic* case, where f^t is an affine function and g_i^t a quadratic one. Results for these cases are well established and have been available for a long time, see e.g. Starr and Ho (1969) and Basar (1976).

Feedback information structure

For the feedback information structure, existence and uniqueness of the equilibrium can only be proven for the affine-quadratic cases (or closely related cases, see for example Clemhout and Wan, 1974). Writing here the theorems stating the existence and uniqueness of the equilibrium for linear-quadratic games would involve important additional notations, without contributing to our problem and its understanding. We therefore refer to Kydland (1975) or Basar and Olsder (1999, section 6.2.2) for these theorems and their complete proof.

Table 4.3 summarizes the available results for dynamic games.

Table 4.3 Results for the dynamic case

	Existence	**Uniqueness**
N-person game	Not proven in the general case	Not proven in the general case
2-person games	Not proven in the general case	Not proven in the general case
Quadratic games	Yes	Yes

4.5 Dynamic-oligopolistic models of investments

Having presented this game theoretic background, we have all the tools to start our study of the investment in an oligopolisitic electricity market. We first present the general features of the problem under study, then we discuss three different information structures: *open-loop*, *feedback* and the lesser known *sample-path adapted open loop information structures*. Results of these different information structures applied to our problem are presented in section 4.6. The objective of the last two sections (4.5 and 4.6) is to compare these results and to see how they can be used for the study of investment decisions in deregulated electricity markets. It relates and adds to the literature on dynamic oligopoly (see Fudenberg and Tirole, 1986, for a survey) in two ways. First, by investigating a three-period example in

"*dynamic* if the order in which the decisions are made is important". This will be the case in our investment an industry-based example, and second by comparing a relatively new information structure to the open-loop and feedback ones, the S-adapted information structure. This latter one will be seen to have very interesting properties that make its use attractive for larger scale problems.

4.5.1 The formal investment problem

In oligopolistic games, investment is often considered to be the strategic variable (control variable). When the timing of the investment makes a difference, because of the lag between the decision and its effect, some dynamics are introduced in the problem. The dynamics become even more significant when the problem is stochastic, because the investment decisions will be directly influenced by this uncertainty. The static analysis presented in chapter 3 is therefore not satisfactory. We develop in this section a formal model of investment in new capacities, taking into account the main features of the electricity market situation.

The model is a discrete time multi-player model of investment under stochastic demand growth. It aims at characterizing the dynamic investment pattern in an oligopoly confronted with linear production cost and quadratic investment cost. A finite set of random events can also affect the demand level. The model consequently falls into the range of linear-quadratic games, for which existence and uniqueness results have been mentioned. To keep the model simple and analytically tractable, we do not consider discounting and salvage values.

Each player decision problem is the following:

$$max\ W_i = \sum_{t=1}^{T} \left\{ q_i^t(s^t) \cdot P^t(Q^t, s^t) - C_1(q_i^t) - C_2(I_i^t) \right\} \qquad (4.5)$$

where W_i is the reward function of player i;

$q_i^t(s^t)$ is the production of player i at t, it is a state variable, function of the stochastic event s^t (defined in the next section);

model.

$P^t(Q^t, s^t)$ is the inverse demand function, with total quantity Q^t and event s^t as arguments;

I_i^t is the investment (decision) variable, which increases capacity with a one period lag;

$C_1(q_i^t)$ and $C_2(I_i^t)$ are respectively the production and the investment cost functions.

It is important to mention that in this model production equals full capacity, as during peak load periods in the electricity sector. This assumption is made to keep the model simple enough to be able to characterize the investment pattern.

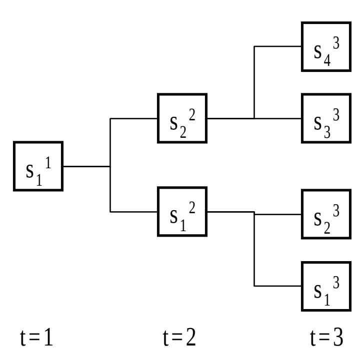
In the following we discuss the stochastic event s^t, the inverse demand function and the cost functions.

Stochastic event s^t

In each period t, a random event s^t occurs and affects the demand function. Let $S^t = \{s_1^t, s_2^t, \ldots, s_n^t\}$ be the set of all possible events s_k^t occurring at period t with probability π_k^t such that $\pi_k^t \geq 0$ and $\sum_{k=1}^{n} \pi_k^t = 1$.

The random event can be represented by an event tree as shown in the figure below (where $T = 3$).

Figure 4.2 Event tree for the stochastic event



The probability π_k^t of event s_k^t is linked to the conditional probabilities $p(s_k^t/s_h^{t-1})$, where s_h^{t-1} is the predecessor of s_k^t in the tree. When no ambiguity is possible, we use the notation s^t refer to the event realized at period t.

Inverse demand function

The inverse demand function $P^t(Q^t, s^t)$ gives the price P^t for the total quantity Q^t produced by the players and the realization s^t of the stochastic event. This function is chosen affine in Q^t:

$$P^t(Q^t, s^t) = a^t(s^t) - bQ^t$$

The random event s^t affects the demand law simply by changing the level of the parameter $a^t(s^t)$. The random events can be seen as the economic growth, affecting electricity demand by increasing more or less its level, with probability $p(s^t/s^{t-1})$.

Cost functions

As the case with a unique generation unit, the marginal production cost is assumed constant with respect to quantity. The production cost function $C_1(q_i^t)$ is therefore chosen linear:

$$C_1(q_i^t) = c_1 \cdot q_i^t$$

For the investment cost function $C_2(I_i^t)$, the choice of its analytical format is less straightforward. For a long time, generation units showed increasing return on scale, making large investment projects more attractive. Average investment cost by MW of capacity was decreasing, calling for a concave cost function. However, new technological developments in generation ended these scale economies[54], and large investment projects are now more difficult to realize. For these empirical reasons and for analytical tractability, we choose the following quadratic convex investment cost function:

$$C_2(I_i^t) = 0,5 \cdot c_2 \cdot I_i^t$$

We ignore at this point the salvage value of investment because it would not affect qualitatively the results.

---

[54] See chapter 1 on the grounds for deregulation, especially the *technological argument* section.

Equilibrium

We are now interested in the equilibrium arising from such a context, but more specifically by the influence of the information structure on the equilibrium. The Nash equilibrium we are looking for is defined as the vector of investment strategy $v^* = (v_1^*, v_2^*, \ldots, v_m^*)$ for m players, where v_i^* is player i equilibrium strategy. The strategy v^* is such that for each player i we have

$$W_i(v^*) \geq W_i(v^{*(i)})$$

where $W_i(v^*)$ is the reward function of player i (see equation 4.5);

$v^{*(i)} = (v_1^*, v_2^*, \ldots, v_i, \ldots, v_m^*)$.

This is the standard definition of a Nash equilibrium. We now solve the model for the three different information structures of interest: the open-loop, the feedback and the S-adapted ones.

4.5.2 Open-loop information structure

The open-loop information structure leads to an equilibrium called the open-loop solution, or alternatively the *pre-commitment* solution. This latter name is justified by the fact that players do not update their knowledge during the game in order to adapt their strategies to the actual values of the state variables (which are in our context the capacities of each players and the demand's level). This means that the players ignore the capacity values and updated information on the stochastic event at time t. They reach an equilibrium where they take into account only the initial conditions of the game. For this equilibrium to be valid, they need to pre-commit themselves to act exactly as the strategies obtained dictate and to ignore new information during the game.

With capacity being a state variable, investment the control (or decision) variable, the open-loop structure will use expected values of the stochastic element. Because in this structure no adaptation can be done while information is disclosed, the expected value will provide the best approximation for the uncertain value of the demand parameter[55].

The equilibrium is found by solving simultaneously for all players the following problem:

$$max\ W_i = \sum_{t=1}^{T} \{(e^1(a^t) - bQ^t) \cdot q_i^t - C_1(q_i^t) - C_2(I_i^t)\} \qquad (4.6)$$

where $e^1(a^t)$ is the expected value of $a^t(s^t)$ computed with period 1's information;

$q_i^t = q_i^0 + \sum_{l=1}^{t-1} I_i^l$ (investment takes one period to be available);

$Q^t = q_i^t + \sum_{j=1; j \neq i}^{m} q_j^t$;

$q_j^t = q_j^0 + \sum_{l=1}^{t-1} I_j^l$;

I_j^t represents player i's expectation of players' j investment decisions.

The solutions will be $m \times (T-1)$ mappings (number of players times the number of investment periods):

$$q^0 \rightarrow I_i^t \qquad i=1,\ldots, m;\ t=1,\ldots, T-1$$

where q^0 is the vector of initial capacities, $q^0 = (q_1^0, q_2^0, \ldots, q_m^0)$.

The fact that in this information structure the decision variable depends only on the initial condition q^0 allows the problem to be solved as a static equilibrium problem.

4.5.3 Feedback information structure

In the closed-loop and feedback information structures, all players develop their strategies according to the latest information available. The solution found is then *subgame perfect* (see Selten, 1975), meaning that strategies are in equilibrium at any t even if the players have not played according to the optimal strategies prior to t. Open-loop solutions do not have

[55] In this specific case, it can easily be shown that solving for the expected value of the demand parameter is

this property. In a closed-loop structure, not only the latest information is used, but also all the previous information of the game. This is often considered as too demanding and not realistic, so we leave apart the study of the closed-loop information structure, as we previously said, and focus on the feedback one.

Feedback solutions are more difficult to obtain than open-loop ones because each player's problem never reduces to a standard equilibrium problem, as is the case in the solving of the open-loop equilibrium problem. The difference with the open-loop structure is that all I_i^t are not *decisions* but *decision rules* which are functions of the state. The following problem, when solved for all players, gives the feedback equilibrium.

$$R_i(I_i^t) = = max\ W_i(I_i^t) = (a^t - bQ^t) \cdot q_i^t - C_1(q_i^t) - C_2(I_i^t) + \sum_{l=t+1}^{T} R_i\,(I_i^l) \qquad (4.7)$$

where $R_i(I_i^t)$ is the value function of player i;

$q_i^t = q_i^0 + \sum_{l=1}^{t-1} I_i^l$ (investment takes one period to be available);

$Q^t = q_i^t + \sum_{j=1;\, j \neq i}^{m} q_j^t$;

$q_j^t = q_j^0 + \sum_{l=1}^{t-1} I_j^l$;

$I_j^t = g^t(q^t)$.

One needs to iteratively determine these decision rules through backward induction. A standard equilibrium problem is solved at time T, and solutions (functions of the previous state and decisions) are included in the problem of the previous period. This process ends with a single equilibrium problem where everything is written in terms of the initial state:

$$max\ W_i = \sum_{t=1}^{T} \{(e^1(a^t) - bQ^t) \cdot q_i^t - C_1(q_i^t) - C_2(I_i^t)\} \qquad (4.8)$$

The solution to the problems described with (4.8) will be m mappings (one for each players):

---

equivalent to maximizing the expected profit, because profit is linear in terms of demand.

$$q^0 \rightarrow I_i^1 \qquad\qquad i=1,\ldots, m$$

Previous solutions of similar problems (starting from period *T*) specify the investment decision rules for subsequent periods.

As seen earlier, unique feedback solutions can be found analytically for so called "linear-quadratic cases", where the value function to optimize is quadratic and the state dynamic is linear. These cases are well documented (Basar and Olsder, 1999, or the classical paper of Starr and Ho, 1969) and our case belongs to this category of problems.

4.5.4 S-adapted open-loop information structure

Probably the main shortcoming of the open-loop information structure is the fact that it provides a solution that needs the absolute pre-commitment of the players. The S-adapted open-loop information structure improves the open-loop solution by allowing decisions to vary according to the realization of the stochastic variable. The total pre-commitment is then reduced. However, players still cannot react directly to the current value of the capacity, so the S-adapted open-loop information structure, like the open-loop one, is not subgame perfect.

While improving the equilibrium solution from the open-loop solution, we keep computational simplicity. The main drawback of the feedback solution being its computational complexities, if the S-adapted solution can shed some light on the dynamics under study, some progress would then have been made. For more on this information structure, see Haurie, Zaccour and Smeers (1990).

The formulation in this information structure avoids the use of the expected value of the random parameters by attributing probability weights to each possibility. An objective function can be defined for each player, resulting in the optimal value for each weighted case.

$$max\ W_i = \sum_{t=1}^{T} \sum_{h \in S^{t-1}} \sum_{k \in S^t} \left\{ p(s_k^t / s_h^{t-1}) \cdot \left[q_i^t(s_k^t) \cdot P^t(Q^t, s_k^t) - C_1(q_i^t) - C_2(I_{ik}^t) \right] \right\} \quad (4.9)$$

where S^t is the set of possible events s_k^t at time *t*;

S^{t-1} is the set of possible events s_h^{t-1} at time $t-1$;

$p(s_k^t / s_h^{t-1})$ is the conditional probability of s_k^t given s_h^{t-1}.

The difference with the open-loop solution will be that a value of the decision variable I_{ik}^t will be defined for each possible case of the set S where investment is possible. The strategy obtained will therefore adapt to the realized values of the random event s_k^t.

The rest of the chapter concerns the comparison of the different equilibria resulting from these three information structures.

4.6 Comparison of equilibria under the different information structures

4.6.1 The model

The implemented model is exactly as the one presented previously (equation 4.5), with 2 players (m = 2) and 3 periods (T =3). This allows the strategic interaction between players and the time and stochastic dynamics to be illustrated.

The model is solved analytically under the three information structures, and comparisons of the solution are made through a sensitivity analysis on the production cost, the other player's capacity and the probability of s^t.

Since the units of the parameters are not important (as long as their relative value is respected), we can assign the value one to one parameter. We therefore choose b = 1 in the demand function, and adjust all other parameters where it is required.

Solution in open-loop

The model in open-loop takes the following form.

$$max\ W_i = \sum_{t=1}^{3} \{(e^1(a^t) - Q^t) \cdot q_i^t - c_1 q_i^t - 0{,}5 c_2 (I_i^{OLt})^2\} \qquad (4.10)$$

where $\quad e^1(a^t) = \sum_{k \in S^t} \pi(s_k^t)\ a^t(s_k^t)$ for t =1, 2, 3;

$$q_i^t = q_i^0 + \sum_{l=1}^{t-1} I_i^{OLl} \text{ for all } i;$$

$$Q^t = q_i^t + \sum_{j=1;\, j\neq i}^{m} q_j^t;$$

For each player, two investment decisions have to be made in the open-loop structure, one for each investment period: I_i^{OL1} and I_i^{OL2}. Since in the problem considered here both players face the same parameters and take their decisions simultaneously, their solution will be symmetric and $I_i^{OLt} = I_j^{OLt}$.

Solving the first order conditions of the above equilibrium problem simultaneously for players *i* and *j*, we obtain the following solution:

$$I_i^{OL1} = \frac{e^1(a^2)(c_2+3) + c_2 e^1(a^3) - c_1(2c_2+3)}{A} - \frac{(9+30c_2+23c_2^2+4c_2^3)q_i^0 + c_2(3+4c_2+2c_2^2)q_j^0}{AB} \qquad (4.11)$$

$$I_i^{OL2} = \frac{e^1(a^3)(c_2+3) - c_1 c_2 - 3e^1(a^2)}{A} - \frac{c_2(6+9c_2+2c_2^2)q_i^0 + c_2(-3+c_2^2)q_j^0}{AB} \qquad (4.12)$$

where $A = (9 + 9c_2 + c_2^2)$

$B = (1 + 3c_2 + c_2^2)$

Solution in feedback

The model in feedback takes the following form.

$$R_i(I_i^{Ft}) = max\ W_i(I_i^{Ft}) = (a^t - Q^t)\cdot q_i^t - c_1 q_i^t - 0{,}5c_2(I_i^{Ft})^2 + \sum_{l=t+1}^{T} R_i(I_i^{Fl}) \qquad (4.13)$$

At time t = 3, no investment can be made (production equals capacity, which depends on investment at t = 2). At time t = 2, an equilibrium problem including the equilibrium profit at t = 3 as a function of investment at t = 2 is solved.

The expected value $e_h^t(a^{t'})$ of demand level $a^{t'}$ for the period $t'>t$ when event $s_h^t \in S^t$ has occurred is given by

$$e_h^t(a^{t'}) = \sum_{k \in S^{t'/s^t}} p(s_k^{t'}/s_h^t)\, a^{t'}(s_k^{t'})$$

Again, for each player, two similar investment decisions have to be made, one for each period: I_i^{F1} and I_i^{F2}. Solutions will be symmetric.

By solving the first order conditions of the above optimization problem simultaneously for players i and j, and by the use of backward induction, we obtain the following solution:

$$I_i^{F1} = \frac{D}{E} - \frac{F_i}{E} q_i^0 - \frac{F_j}{E} q_j^0 \qquad (4.14)$$

where $D = \left(27+162c_2+351c_2^2+382c_2^3+333c_2^4+79c_2^5+14c_2^6+c_2^7\right)\left(e^1\left(a^2\right)-c_1\right)-$

$$c_2\left(3+13c_2+15c_2^2+7c_2^3+c_2^4\right)\left(2+c_2\right)^2\left(c_1-e^1\left(a^3\right)\right)$$

$$E = \left(3+13c_2+15c_2^2+7c_2^3+c_2^4\right)\left(27+63c_2+47c_2^2+13c_2^3+c_2^4\right)$$

$$F_i = \left(81+486c_2+1095c_2^2+1250c_2^3+799c_2^4+288c_2^5+54c_2^6+4c_2^7\right)$$

$$F_j = c_2\left(9+24c_2+26c_2^2+12c_2^3+2c_2^4\right)\left(1+c_2\right)\left(c_2+3\right)$$

$$I_i^{F2} = \frac{\left(1+c_2\right)\left(e_h^2\left(a^3\right)+c_1\right)-\left(3+2c_2\right)q_i^1+c_2q_j^1}{\left(2+c_2\right)^2-1} \qquad (4.15)$$

Solution in S-adapted open-loop

The model in the S-adapted open-loop information structure takes the following form:

$$max\ W_i = \{(a^1(s^1) - Q^1)\cdot q_i^1(s^1) - c_1 q_i^1(s^1) - 0{,}5c_2(I_i^{SA1}(s^1))^2\}$$

$$+ \left[\sum_{k \in S^2} \pi(s_k^2) \{(a^2(s_k^2) - Q^2) \cdot q_i^2(s_k^2) - c_1 q_i^2(s_k^2) - 0{,}5 c_2 (I_i^{SA2}(s_k^2))^2\} \right.$$

$$\left. + \sum_{k \in S^{3/s^2}} \pi(s_k^3) \{(a^3(s_k^3) - Q^3) \cdot q_i^3(s_k^3) - c_1 q_i^3(s_k^3)\} \right] \quad (4.16)$$

Now, the solution does not only give one investment decision for each player per period, but one for each possible s_k^t, at t=1, 2. As shown in figure 4.2, there are one s_k at t=1 and two at t=2. We denote the investment to make at s_1^1, s_1^2 and s_2^2 respectively by I_i^{SA1}, I_i^{SA2} and I_i^{SA3}. Once again, solutions for players i and j will be symmetric.

Solving the first order conditions of the above equilibrium problem simultaneously for players i and j, we obtain the following solution (a_k^t corresponds to the level of demand for event s_k^t and p_k^t is the probability of going to the lower next node from s_k^t):

$$I_i^{SA1} = \frac{-c_1(2c_2+3) + p_1^1 a_1^2 (c_2+3) + a_2^2 (c_2+3)(1-p_1^1) + p_1^1 c_2 p_1^2 a_1^3}{A} \quad (4.17)$$

$$+ \frac{p_1^1 c_2 a_2^3 (1-p_1^2) + p_2^2 c_2 a_3^3 (1-p_1^2) + c_2 a_4^3 (1-p_1^1)(1-p_2^2)}{A}$$

$$- \frac{(9+30c_2+23c_2^2+4c_2^3) q_i^0 + c_2(3+4c_2+2c_2^2) q_j^0}{AB}$$

$$I_i^{SA2} = -\frac{c_1 c_2 (c_2+3) + 3p_1^1 a_1^2 (c_2+3) + 3a_2^2 (c_2+3)(1-p_1^1)}{A(c_2+3)} \quad (4.18)$$

$$- \frac{-p_1^2 a_1^3 (9 - 3p_1^1 c_2 + 9c_2 + c_2^2) - a_2^3 (9 - 3p_1^1 c_2 + 9c_2 + c_2^2)(1-p_1^2)}{A(c_2+3)}$$

$$- \frac{3c_2 p_2^2 a_3^3 (1-p_1^1) + 3c_2 a_4^3 (1-p_1^1)(1-p_2^2)}{A(c_2+3)} - \frac{c_2(6+9c_2+2c_2^2) q_i^0 + c_2(-3+c_2^2) q_j^0}{AB}$$

$$I_i^{SA3} = -\frac{c_1 c_2 (c_2+3) + 3p_1^1 a_1^2 (c_2+3) + 3a_2^2 (c_2+3)(1-p_1^1)}{A(c_2+3)} \quad (4.19)$$

$$-\frac{3p_1^1p_1^2c_2a_1^3+3p_1^1c_2a_2^3\left(1-p_1^2\right)}{A\left(c_2+3\right)}$$

$$-\frac{-p_2^2a_3^3\left(9+3p_1^1c_2+6c_2+c_2^2\right)-a_4^3\left(9+3p_1^1c_2+6c_2+c_2^2\right)\left(1-p_2^2\right)}{A\left(c_2+3\right)}$$

$$-\frac{c_2\left(6+9c_2+2c_2^2\right)q_i^0+c_2\left(-3+c_2^2\right)q_j^0}{AB}$$

where $A=\left(9+9c_2+c_2^2\right)$

$B=\left(1+3c_2+c_2^2\right)$

A numerical example

Interpreting these results of investment strategies for the three different information structures is not straightforward. To allow more insights into the results, we give a simple numerical illustration of the strategies for the following values of the parameters. In the next subsection, we investigate how the results obtained under the different information structures behave when some parameter's value are changed.

Table 4.4 Value of parameters

			Player 1	**Player 2**
Initial capacity		q_i^0	0,2	0,2
Production cost		C_1	0,2	0,2
Investment cost		C_2	1	1
Probability		p_1^1	0,5	
		p_1^2 **and** p_2^2	0,5	
Demand level for event s_k^t	s_1^1	a_1^1	1	
	s_1^2	a_1^2	1,01	
	s_2^2	a_2^2	1,03	
	s_1^3	a_1^3	1,02	
	s_2^3	a_2^3	1,04	
	s_3^3	a_3^3	1,04	
	s_4^3	a_4^3	1,06	

Figure 4.3 Investment strategies under the three information structures

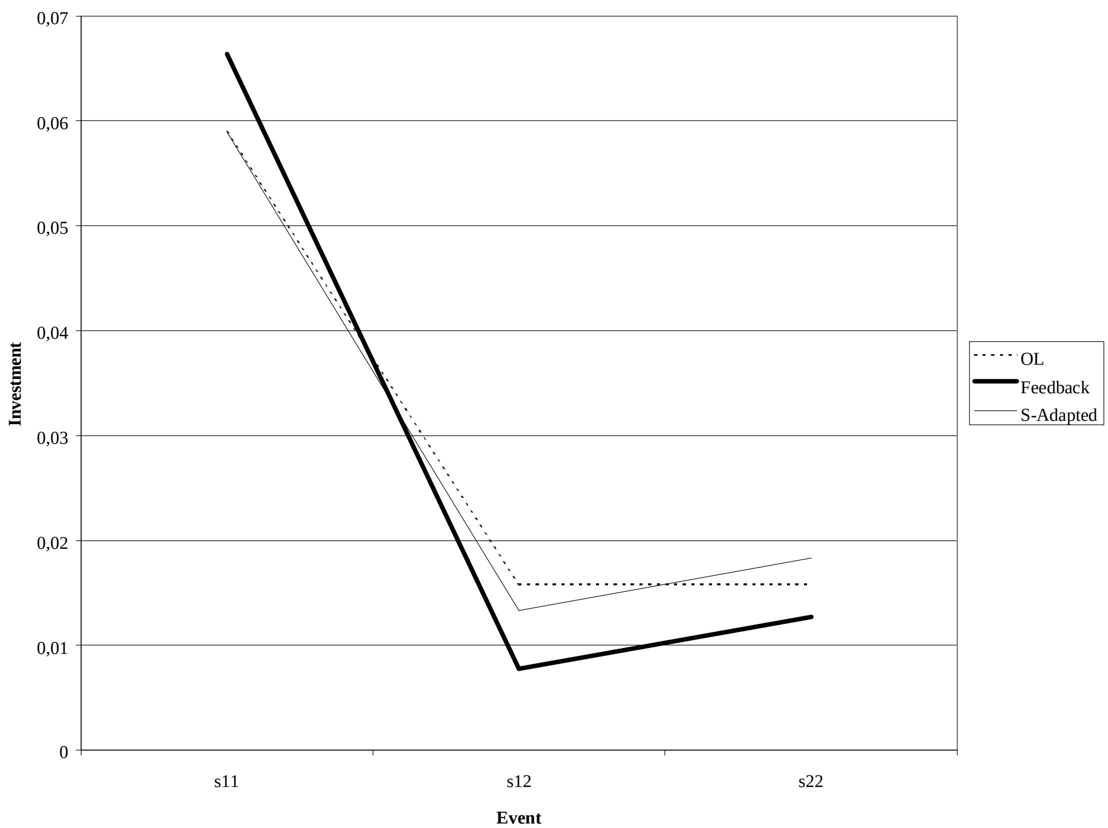


Figure 4.3 illustrates a well-known result when comparing the feedback and open-loop information structures (see Kydland, 1970, Fershtman and Kamien, 1987, Reynolds, 1991,

and Karp and Perloff, 1993). The feedback case leads to higher investments than the open-loop and S-adapted ones, as shown is table 4.5. In the low growth case (event s_1^2), because the open-loop solution does not adapt to the state, cumulative investment is higher.

Table 4.5 Cumulative investment at *t*=2

	Open-loop	Feedback	S-Adapted
Low growth (event s_1^2)	0.1494	0.1418	0.1414
High growth (event s_2^2)	0.1494	0.1581	0.1544

Two reasons explain why investment is not made exclusively in period one. First the quadratic cost structure of the investment cost function (a convex function), and second the expected increase in demand in period two. From the first reason, we understand that it is cheaper to invest in two different periods[56]. The second reason acknowledges the value of waiting for additional information. This is the most interesting point of our study: the open-loop solution cannot take this new information into account, so for any event in period two (s_1^2 or s_2^2), the investment is the same (I_i^{OL2}). With the S-adapted information structure, as with the feedback one, investment in period 2 adapts to the incremental knowledge available. This explains why both $I_i^{SA2} < I_i^{SA3}$ and $I_i^{F2} < I_i^{F3}$ (the expected value of demand level for period three is lower for event s_1^2 than for event s_2^2).

Other studies comparing the feedback and the open-loop structures (Kydland, 1970, Fershtman and Kamien, 1987, Reynolds, 1991, or Karp and Perloff, 1993) also find a more competitive outcome in the feedback case than in the open-loop one. By "more competitive", it is meant that players using the feedback information structure will invest more (or produce more, according to the context under study) than in the open-loop case, hence reducing the impact of their market power. The explanation for investing more is that in the feedback solution, by using a *decision rule* for their opponents instead of a single *decision*, they can take into account how these other players will react to their investment. By restraining from investment, one gives the others the profitable possibility to invest more. To prevent this, players take a more aggressive investment strategy and invest additional amounts from the open-loop case.

[56] A convex functions is such that $f(A+B) > f(A) + f(B)$.

This behavior makes the profit for all players higher in the open-loop information structure compared to the feedback one. In the S-Adapted case, profits are even superior to the open-loop case because investments can be adjusted to updated expectations about the future demand. Table 4.6 shows the expected profit for the three information structures in this numerical example.

Table 4.6 Expected profit

Open-loop	Feedback	S-Adapted
0,2361856	0,23360503	0,23619497

4.6.2 Comparison: comparative statics

Each I_i^t under the three information structures depends on some parameters. Table 4.4 summarized these parameters and showed the values of our numerical example. To get further insights on the three information structures used, we study the sensitivity of the solutions obtained (I_i^{OL1}, I_i^{OL2}, I_i^{F1}, I_i^{F2}, I_i^{SA1}, I_i^{SA2} and I_i^{SA3}) to three interesting parameters[57]: the production cost c_1, the initial capacity of the other player q_i^0 and the probability p_1^1.

Sensitivity to production cost

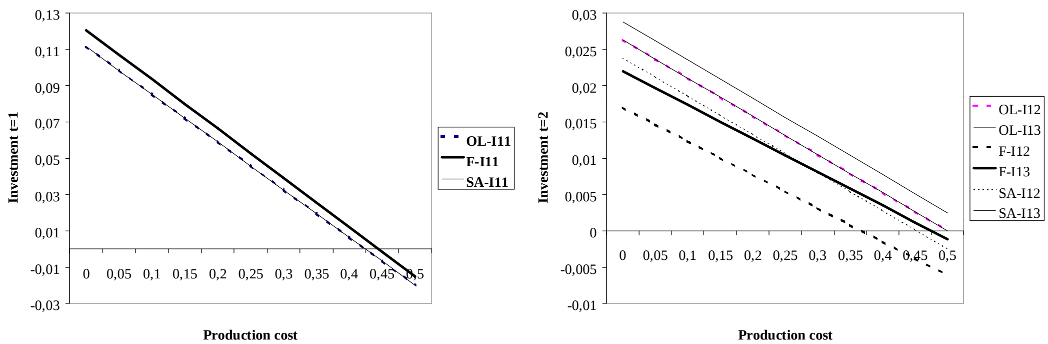
By differentiating according to c_1 the results for all I_i^t, we can see how sensitive each information structure is to production cost. Table 4.7 indicates the marginal variation of investment for a change in production cost and figure 4.4 illustrates these results with the data of the numerical example.

[57] A complete study would also include c_2, the probabilities p_1^2 and p_2^2, and possibly all the demand parameters a_k^t but this would add little to the understanding of the results and would lead to very heavy analytical formulas.

Table 4.7 Sensitivity to production cost at *t*=1

$\frac{d}{dc_1} I_i^{OL1} = -\frac{(2c_2+3)}{c_2^2+9c_2+9}$
$\frac{d}{dc_1} I_i^{F1} = -\frac{27+174c_2+415c_2^2+497c_2^3+434c_2^4+126c_2^5+25c_2^6+2c_2^7}{(3+13c_2+15c_2^2+7c_2^3+c_2^4)(27+63c_2+47c_2^2+13c_2^3+c_2^4)}$
$\frac{d}{dc_1} I_i^{SA1} = -\frac{(2c_2+3)}{c_2^2+9c_2+9}$

Figure 4.4 Player's *i* investment at *t*=1 (left) and *t*=2 (right) for different production costs



We clearly see investment decreasing in all information structures as the production cost increases. This result could be expected, as profit decreases with production costs. The left part of figure 4.4 shows the smaller investment in the first period for the open-loop and S-Adapted solutions (lower dashed and thin line), compared to the feedback solution (upper bold line). In period 2, investments are higher for both the open-loop and S-adapted cases, reflecting the fact that investment has been lower in the first period. The important pattern to notice is the adjustment of the S-adapted solution to the situation. According to the new expectations on future demand, investment is distributed around the "averaged" open-loop investment, given by the open-loop solution.

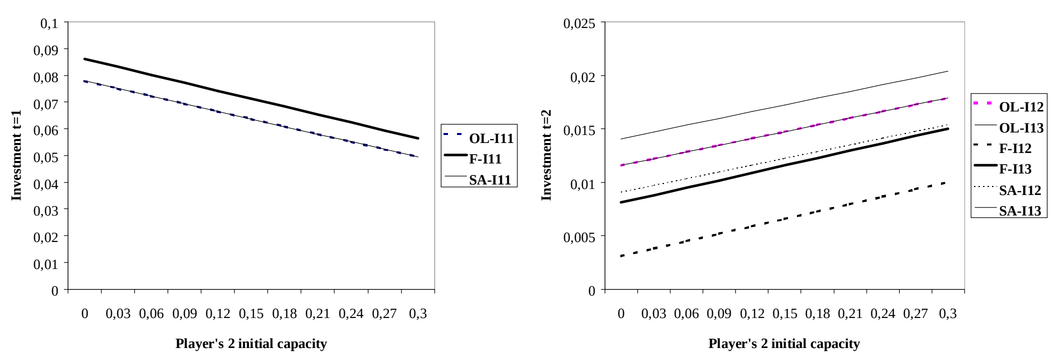
Sensitivity to initial capacity

The same type of analysis can be conducted for the other player's initial capacity. In all information structures, investment decreases in the first period as the other player has less capacity. In the second period, as investment has been smaller in the first period, the effect of the quadratic cost function obliges the player to invest more (but relatively little compared to the first period).

Table 4.8 Sensitivity to player *j* initial capacity at *t*=1

$\frac{d}{dq_j^0} I_i^{\mathrm{OL1}} = -c_2 \frac{3+4c_2+2c_2^2}{\left(c_2^2+9c_2+9\right)\left(c_2^2+3c_2+1\right)}$
$\frac{d}{dq_j^0} I_i^{\mathrm{F1}} = -c_2\left(c_2+3\right)\left(c_2+1\right) \frac{9+24c_2+26c_2^2+12c_2^3+2c_2^4}{\left(3+13c_2+15c_2^2+7c_2^3+c_2^4\right)\left(27+63c_2+47c_2^2+13c_2^3+c_2^4\right)}$
$\frac{d}{dq_j^0} I_i^{\mathrm{SA1}} = -c_2 \frac{3+4c_2+2c_2^2}{\left(c_2^2+9c_2+9\right)\left(c_2^2+3c_2+1\right)}$

Figure 4.5 Investment of player *i* at *t*=1 (left) and *t*=2 (right) for different initial capacity of player *j*



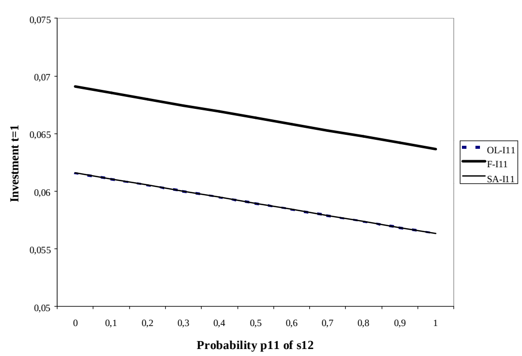
Again, the noticeable observation is the adjustment to updated expectations in the feedback and S-adapted cases, compared to a unique decision for the open-loop case.

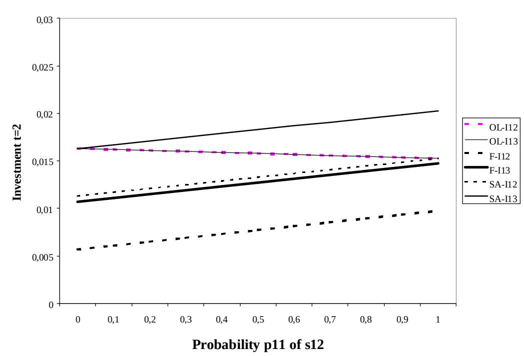
Sensitivity to initial probability

By analyzing[58] the sensitivity of player's *i* investment to the initial probability p_1^1, we can observe (on the left part of figure 4.6) that for all information structures, the investment in the first period decreases as the probability of low growth increases for the second period. This is an expected results, as the usual higher investment for feedback information structure.

In the second period, as shown in the right part of figure 4.6, either one of the two demand growth possibilities has realized, and investment is now driven by two factors: (i) the previous investment level and (ii), in the feedback and S-adapted cases, the demand level expectations for the third period. The first factor explains why investment grows with probability p_1^1: the more investment has been made in the first period, the less needs to be made in the second. The second factor explains why there are two different levels of investment for events s_1^2 and s_2^2. For s_1^2, the demand growth expectation for the next period is lower than for s_2^2, resulting in lower investment in period 2. At period 2, only the feedback and the S-adapted solutions can adapt to this information, and we clearly see that these solutions are parallel.

Figure 4.6 Player's *i* investment at *t*=1 (left) and *t*=2 (right) for different initial probabilities of low demand growth in the second period





The open loop and S-adapted results are the same for $p_1^1 = 0$ and $p_1^1 = 1$ (right part of figure 4.6) because in these two cases there is no difference between the two information structures.

4.6.3 Discussion

Having done this study of these three information structures, what can we conclude on their relative use? The main shortcoming addressed to the open-loop information structure is its commitment requirements to initial information, without being able to adapt. Feedback solutions, being subgame perfect, do adapt to any new information.

The S-adapted information structure, while still lacking subgame perfection, is a significant improvement over the open-loop structure because players can react to new information on the stochastic element. As we have seen in the results presented in this chapter, S-adapted solutions follow the disclosure of the stochastic element.

Recognizing the greater difficulty of finding feedback equilibria, the S-adapted solution offers an interesting way of studying dynamic situations where an important stochastic element is present and when the open-loop information structure cannot be ruled out because of the context.

Before concluding on the S-adapted information structure, one point still deserves a discussion, the extent to which a "choice" can be made over an information structure.

Is a choice possible between information structures?

An information structure should be used solely based on its relevance to the problem under study. According to the information available and used by each player at each decision point, a choice should be made on the adequate information structure.

In investment contexts, it is likely that all players update their market knowledge at each decision point, on the expected economic growth as well as on the capacity of their opponents.

This reasoning would rule out open-loop models, but could allow S-adapted models to be used, even if they fail to take completely into account the current state of the game. Indeed, when a feedback model is too complex to be built, an imperfect solution can still offer valuable insights, even if some hypothesis are not completely satisfied.

---

[58] This analysis has been made numerically, this is why closed form solutions are not presented here.

In the case of feedback models, it is known that their solutions are more competitive, but in line with the S-Adapted solutions. Adoption of the S-adapted information structure is supported by the need and interest of studying dynamic oligopolistic markets.

4.6.4 Conclusion

In this chapter, we have presented the game theoretical components needed to understand when and under which circumstances an equilibrium can be found and proven to be unique. This study allowed us to be certain that in the investment game studied, under the three information structures, a unique equilibrium could be found.

A relatively new information structure has been used: the S-adapted information structure. Although sharing the same formal characteristics as the standard open-loop information structure, it allows adaptation of decisions to a stochastic event, a very interesting feature to be included.

This last information structure improves the open-loop information structure while keeping its computational simplicity. S-adapted solutions are not subgame perfect, but tend to parallel feedback solution, and therefore to offer insights on the investment pattern of the game. The next chapter builds on this conclusion to investigate the investment game in the Finnish electricity market. A similar continuous choice model could not have been done using a feedback information structure, due to tougher computational requirements that would have been implied.

Chapter 5. A Stochastic Dynamic Game Model of the Finnish Electricity Market[59]

5.1 Introduction

Newly deregulated network industries, especially the electricity industry, have been the subject of many analyses during the last years (see for instance Gilbert and Kahn, 1996, Zaccour, 1998). Numerous papers also deal with competitive aspects (see the models reviewed in chapter 1: Bolle, 1992, Green and Newbery, 1992, and von der Fehr and Harbord, 1993, Green, 1997) and have greatly improved our understanding of firms' behavior in the new organizational framework. They have largely achieved their objective, which is to assess players' possible market power and its impact on prices to consumer. However, this literature focuses on static situations, ignoring investment decisions and therefore competition in the long run. Given a certain concern about adequate long-term electricity supply, now that investment decisions are no longer dictated by a central coordinator but are the result of a usual profitability analysis, appropriate dynamic competitive models are definitely needed (e.g. Smeers, 1997). Up to now, very few dynamic models have been proposed. In the realm of two-stage models, von der Fehr and Harbord (1995, 1997) assumed that utilities choose investment in the first stage and price competition takes place in the second one. They isolate different effects in an oligopolistic market that have an impact on investments in capacity. These effects are twofold. First, they tend to induce under-investment to improve the players' market power. Second, they direct investment to specialized technologies having a marginal cost that affects spot prices to the players' advantage. These results are of great interest but do not give much insight on investment dynamics for multi-period settings. The case of investment in multi-technologies is further analyzed in a long-term perspective in Andersson and Håsé (1997) but in a *perfect competition* setting.

[59] An adapted version of this chapter has been submitted for publication under the title "A Stochastic Dynamic Game Model of the Finnish Electricity Market" (Pineau and Murto, 1999).

Regarding investments, exogenous stochastic factors, such as the electricity demand growth, have a considerable importance. Unstable market growth creates risk, and this unavoidably influences investment decisions. In the electricity industry, where capacity costs are high, incorporating this element is therefore important.

Further, as has been observed in other deregulated network industries (e.g. airlines and telecommunications), electricity may also, more than a century after its invention, be increasingly seen as a service rather than a commodity. Deregulation removes the obligation to serve and allows different pricing strategies. More specifically, peak load and base load constitute at least two distinct market segments open for electricity companies, where prices can vary considerably.

This chapter suggests a model that takes into account to a large extent the characteristics briefly discussed above. Indeed, we consider a multi-market segment oligopolistic dynamic model taking into account electricity demand growth, as an exogenous stochastic element. Although one may think that the very purpose of deregulation is to converge to perfect competition, one can argue that in many countries the game still involves very few competitors enjoying some market power. Further, given what has been said above, the dynamic aspect and the link with demand growth seem to be reasonable features of a model. We assume also that a utility can choose between different production technologies to satisfy demand. The model is written in terms of the Finnish industry.

The literature dealing with dynamic imperfect competition is huge. In the energy area, Salant (1982) was probably the first to develop a dynamic game model of the oil market and many others followed (see for instance, Mathiesen et al., 1987, Haurie et al., 1988, and De Wolfe and Smeers, 1997, for models of the European gas market or Hobbs and Kelly, 1992, and Younes and Ilic, 1998, for studies of transmission prices and constraints in electricity). The modeling effort was accompanied by algorithmic developments for the computation of imperfect competition equilibria of games played on networks (see for example Murphy et al., 1982, Harker, 1984, Dafermos and Nagurney, 1987, Nagurney, 1988).

This chapter belongs naturally to this literature stream. It adds to other contributions in three respects. First, the suggested model is dynamic which is not very usual in the literature dealing with competition between newly deregulated electric utilities. Second, it explicitly takes into account the interaction between electricity production, investment and demand growth. Third, to the best of our knowledge, it is the first attempt to study the Finnish market using dynamic game theory. Further, while dynamic game theory is seen as a powerful analytical tool, lack of empirical applications has limited its appeal to decision-makers. Hopefully, this application will clearly show that dynamic game models can be very useful to them.

5.2 The Finnish electricity market

5.2.1 Deregulation of the Finnish electricity market

Finland is a country without any significant natural energy resources. As a consequence, no single impetus has been given to electricity generation and all generation technologies have been developed. The resulting energy supply sector is thus one of the most diversified in the world. Benefits of this situation are first that different characteristics of each technology are exploited, and second that independence from a unique supply origin is achieved. Table 5.1 shows the share of each energy source in Finland. At the moment, however, prospects for increasing the use of some of these technologies (hydro and nuclear) are very limited, due to the restricted availability of sites and socio-political considerations. These constraints are acknowledged in the model.

Table 5.1 Electricity supply by energy source in 1998 (Nordel, 1999)

Energy source	Electricity supply (TWh)	Share of electricity supply	Installed capacity (MW)	Share of capacity
Nuclear	20 985	27.1%	2 640	16.1%
Hydroelectric	14 602	18.9%	2 937	17.9%
Other thermal	31 572	40.8%	10 864	66.0%
Other renewable	72	0.0%	17	0.0%
Imports	10 237	13.2%	-	-
TOTAL	**77 468**	**100%**	**16 458**	**100%**

This diversity in production is partially explained by the large number of firms that have always been involved in electricity generation (more than 100 according to Finergy and Sener, 1997). However, domination by larger producers, long-term contracts and restricted access to the transmission network prevented the electricity market to be really competitive. Conversely to most countries where the electricity industry structure was under governmental control, lack of competition in the Finnish market was not due to governmental implication. Indeed, laws and governmental policies in Finland have never enforced neither vertical nor horizontal integration, so that no monopolies existed, except in the distribution sector[60]. The *Electricity Market Act* (EMA) endorsed in 1995 by the Finnish parliament was then less of a major change in the industry structure than a transfer of responsibility, mainly at the transmission level.

If no real break-down of the industry structure had to be done in Finland, what was the raison d'être of the EMA? As reported in IEA (1994), key features were the opening of transmission and distribution networks and separation of bookkeeping for firms involved at the same time in production, transmission and distribution. Free access to the transmission network was achieved with the creation of Fingrid in 1997, a single network operator and owner of most of the high voltage transmission network. Opening of the distribution network was completed in 1998, with retail competition.

[60] Even transmission was not a monopoly in Finland. A really surprising and unique feature of the previous Finnish electricity market was the presence of *two* concurrent national grids (see for example M.T.I., 1997, page 53).

In short, although the EMA sought to increase competition within the Finnish market and to improve integration with other Nordic countries[61], "deregulation" consisted only in a transfer of responsibility in the transmission sector and a few changes in the law at the distribution level. No major modifications in the generation level were performed, nor in the organization of trade, as we will see in the following subsections.

5.2.2 Generation and consumption levels

Electricity consumption in 1996 amounted to approximately 70 TWh (Nordel, 1998). Producers were the state-owned company Imatran Voima Oy (IVO, now known as Fortum), industries and municipally owned energy firms. As it is still the case today, producers of the latter two categories did it mainly for their own usage, while Fortum supplied approximately 30% of the Finnish electricity consumption. The large number of electricity producers in Finland is also linked to the fact that many municipalities and industries produce their own power. It can be said that, due to their small size, these companies constitute a competitive fringe. A large number of industrial firms are grouping their production under a common structure, *Pohjolan Voima* (PVO), supplying 20% of total consumption. With the development of electricity markets, PVO might be interested in selling its electricity in a more profit-oriented way. Its production would then not only be directed to its industrial owners, but to all market segments.

Consumption in the electricity market can be split between base and peak load periods. For approximately 80% of the time[62], the electricity consumption level requires a *base load* capacity. For the other 20% of the time, characterized by high demand, a higher *peak load* capacity is needed.

5.2.3 Price formation in the Finnish spot market zone

Each country participating in the Nordpool spot market has one or many price zones. Finland represents one price zone, and we concentrate our analysis on this one. The Finnish spot market functions in a simple way. Each seller declares the quantity of electricity he is

---

[61] First Sweden and Norway.

willing to sell at a certain price and time. Buyers also inform the spot market operator of their needs. The deal is closed whenever supply and demand conditions meet.

As in any spot market, if supply is abundant, price will tend to decrease, and if supply is scarce, prices will rise. Demand levels also have a major influence on price. Supply becomes relatively abundant in base load periods with low levels of demand. Conversely, in peak load periods, supply is more limited as demand approaches the maximal capacity available at that time. Prices will therefore be at a higher level.

Suppliers are free to offer whatever quantity they want in the spot market. It can therefore be assumed that some strategic behavior could take place on their side, as long as they represent a large share of the supply, big enough to influence the market price. In the Finnish market, this situation seems to be case for the main producers, Fortum and PVO, as discussed previously.

5.3 A dynamic-stochastic model of electricity market

5.3.1 The scope of the model

In this section, we formulate a quantitative model to characterize the competition between electricity producers in a deregulated electricity market. The purpose is to study how electricity prices, production levels and investment unfold in the absence of central regulation. The main assumption is that the firms' behavior is fully determined by profit maximization. The model is defined for the Finnish electricity market, but the requirements that led us to the specific model formulation are general and could apply to many other countries as well.

In the electricity market that evolves in time, there are two types of decisions the firms have to make. In the short term, the firms have to decide on their production patterns in order to maximize the profit with given capacities. On the other hand, the firms have to decide how much to invest in new production capacity in order to maximize the profits in the long run. These investment decisions have to be made under high uncertainties concerning the future.

---

[62] See for example Confederation of Finnish Industry and Employers (1998).

Also, the firms acknowledge that the optimal investment level is conditional on the investments of the other firms.

Before formally stating the dynamic game model of the Finnish electricity industry, we informally discuss the three most crucial features of the model (relevant for almost any model of the like). Namely, they are the strategic behavior of the players in the short run (i.e. the strategic variables defining the market equilibrium), the information structure adopted and finally the incorporation of uncertainty in the model.

5.3.2 Cournot or Bertrand behavior?

Assumptions on whether firms use price or quantity as the decision variable lead to the two well known Bertrand and Cournot paradigms[63]. As electricity is a non-storable good[64], production has to be sold instantaneously and price competition seems in that respect to be the adequate assumption for players in generation. Hobbs (1986) has chosen such a paradigm to analyze the electricity market for the state of New York. In the English pool, bids of generators are not prices, but rather the different levels of quantity they are willing to produce at different price levels. One approach to model this context is to use *supply functions*, as done in several studies of the English pool such as Bolle (1992), Green and Newbery (1992) and Green (1997) (see Klemperer and Meyer, 1989, for the theory). Von der Fehr and Harbord (1993) criticize the use of supply functions by questioning the relevance of the chosen analytical form. Supply functions also lead to many equilibria which complicates the interpretation of the results. Furthermore, the many different systems in pools and electricity markets do not allow the use of this approach universally. These models also study the market from a short term point of view, where quantity competition is less feasible, because quantities are mainly set by physical capacity.

Quantity competition models become attractive when investment is to be determined endogenously. Indeed, the physical investment is no more "disconnected" from production levels. In this context, one considers a two-stage model where capacity levels are decided

---

[63] See Friedman (1986) for a general presentation.
[64] At least without uneconomic operations.

upon in the first stage and prices in the second. This is the structure adopted by von der Fehr and Harbord (1997), in a framework similar to the one used by Kreps and Scheinkman (1983), and Davidson and Deneckere (1986). The outcome of such a setting is close to the Cournot outcome, even if price competition takes place in the second stage. Our purpose is to go beyond the two-stage paradigm to be able to assess production and especially investment strategies. In such a long-term context, where trades are mainly based on the spot market price, the Cournot assumption of quantity competition becomes appropriate as long as all suppliers freely decide the quantity they offer on the market. Generators then have to decide upon their quantity strategy for the whole horizon. This Cournot assumption is also used in many other energy models (e.g. Salant, 1982, Haurie et al., 1988, or Andersson and Bergman, 1995).

5.3.3 The information structure: S-adapted

We use discrete time periods to model the dynamics of the market. In a multi-period game model, as seen in chapter 4, the information structure used is important when assessing the soundness of the strategies. The choice has to be made between the feedback, the open-loop or the S-adapted open-loop information structure.

The attractiveness of the subgame-perfect feedback solution has to be balanced with other considerations. In the feedback information structure, solving of model is difficult, because the strategy spaces are much larger than in the open-loop case, for instance. A feedback information structure would call for the use of backward induction. However, the scope of the model considered in this paper (many periods, stochastic events and continuous investments and production decisions) prevents an implementation of this approach for the model developed.

Furthermore, the feedback information structures are also subject to criticism. It is not necessarily very realistic to assume that when making their decisions, the firms fully utilize all the updated available information about the state variables (capacity of players), and also acknowledge that other firms do and will do so in the future. Expecting such refined behavior from firms might be spurious.

Haurie et al. (1990) introduce in their paper an information structure called S-adapted, which is well suited to the situation we are considering. This structure is similar to the open-loop one, except that the strategies of the players adapt to the sample path of the stochastic variable. In our case, the stochastic variable is the demand growth (see next section for more discussion on this). Their paper demonstrates that the Nash solution corresponding to this information structure can be calculated using stochastic equilibrium programming techniques. This means that possible realizations of the stochastic variable form a tree-type structure, but instead of using the optimization criterion as in stochastic programming, the Nash-Cournot equilibrium computation is performed over the whole sample space so that the players maximize their expected profits. As a result, the computation of the equilibrium is in principle not different from computing a static Nash-Cournot equilibrium.

The Nash equilibrium corresponding to the S-adapted information structure can be said to lie halfway between the feedback and open-loop equilibria. It bears some of the main properties of the normal open-loop solution. For instance, the solution is not subgame perfect[65]. Also, the equilibrium corresponds to the situation where the players have to commit themselves to certain action patterns at the beginning of the game. Nevertheless, in the S-adapted case this commitment is conditional to the stochastic variable and actions are therefore not predetermined as in the open-loop solution. The interested reader is referred to Haurie et al. (1990) for a full discussion of S-adapted information structure. In Haurie et al. (1988) another application is developed.

We believe that the S-adapted open-loop solution offers valuable insight into the dynamic market under uncertainty. It is relevant in the electricity field, where it can be argued that the firms usually stick to certain investment plans for some time. Strategic plans, stability of decisions with regards to the shareholders and imperfect information on the other players are also reasons to believe that a short and mid term commitment is realistic. Moreover, it is more likely that the firms adapt their investment decisions to external shocks rather than to

[65] However, to prevent a typical misunderstanding on the properties of different equilibrium concepts, it should be emphasized that open-loop Nash equilibrium, as well as the S-adapted one, are time consistent (Basar and Olsder, 1995, use the term «weak time consistency», see pages 256-259).

the investment decisions of the other firms, at least in a medium time scale such as the one used. In that sense also, the chosen solution concept can be a useful representation of the producers' actions.

Finally, with no other models available to analyze investment dynamics under uncertainty in an oligopoly context, this characterization gives a first contribution to the analysis. It could also serve as a benchmark case for future analysis using different information structures.

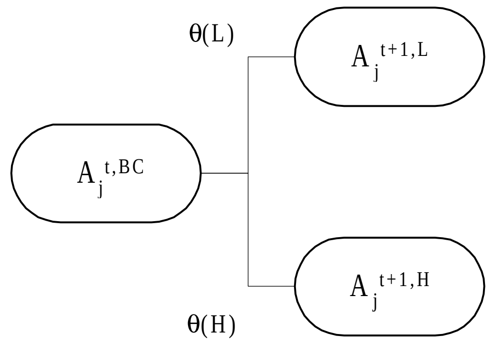
5.3.4 Stochastic electricity demand growth

Energy consumption growth, as well as economic growth, is forecasted by many organizations due to its importance in the world economy. However, forecasts are never completely reliable and uncertainty should be included in any analysis. Due to the importance of demand growth in electricity production and investment, we model here two growth possibilities for each period. According to the forecasts of IEA (1997), electricity consumption level in Finland should grow by 3.8% in 2000, followed by a yearly growth of 2.4% until 2005 and finally 1.9% to the end of 2010. To reflect these various growth levels, we use a stochastic growth with two discrete levels (0 and 3%) in each period.

Event trees are often used to model stochastic events as in Haurie et al. (1988) and Kanudia and Loulou (1998). Figure 5.1 shows a typical node where two growth levels can occur, with their own probability. The growth level is denoted s^{τ} and can be high (H) or low (L)[66]. The history of all successive growth levels from the first period to τ is $\bar{s}^{\tau}$. The demand parameter A_j^t is affected by the realization of a particular growth level.

[66] It corresponds to the stochastic event of chapter 4.

Figure 5.1 Event tree for demand growth scenarios (BC = *base case*, L = *low*, H = *high*)



When the model has many periods, these nodes form an event tree, which branches at each period resulting in a growing number of nodes per period. A given path through the tree corresponds to one scenario of events. The strategies of the players at each node take into account all possible future nodes and the probabilities they will face. The solution of the model gives the actions of the players under all possible scenarios. It takes into account the fact that the players do not know during the game which sample path will be realized.

5.3.5 The formal definition of the model

The Finnish electric industry is represented by many strategic players and a competitive fringe in production. At each period, players choose their investments and quantities to be produced by each production unit and decide to which of the two market-segments they sell their electricity. The time horizon is finite (10 years). It is divided into five two-year periods. This setting is explained by the following reasons.

First, the production strategies need a certain commitment from players, as they cannot constantly and so easily change their production planning. The time period of two years is approximately the time for implementation of new thermal production units. Second, the horizon considered is long enough to let investment take place in new thermal capacity. Put differently, a short time horizon may not involve positive investment due to the fact that actual capacities are sufficient to fulfill the demand. In this framework, each player seeks to maximize its discounted stream of profits. For simplicity, we assume that all players adopt the same market discount rate.

The notations are as follows[67]:

i = 1, …, m	player (generator)
l = 1,2	production unit of generator i (l = 1 is hydro/nuclear; l = 2 is thermal)
j = 1,2	load period (j =1 is base load; j = 2, peak load)
h_j	number of hours in a year for load period j (h_1 = 7008, h_2 = 1752)
n	number of years in a period (n = 2)
τ = 1, ..., 5	period
s^τ	demand growth level at τ (random variable)
$\bar{s}^\tau = \{s^1,...,s^\tau\}$	history of growth level development from 1 to τ (one scenario)
$\theta(\bar{s}^\tau)$	probability of $\bar{s}^\tau$
$K_{il}^\tau(\bar{s}^{\tau-1})$	capacity of player i unit l at period τ (MW)
$I_{il}^\tau(\bar{s}^\tau)$	capacity addition of player i in type l at period τ and $\bar{s}^\tau$ (MW)
$\Gamma_l(I_{il}^\tau)$	cost of investment in type l capacity (Euro/MW)
$V_{il}(K_{il}^5)$	salvage value of the capacity of type l for player i at period 5
$q_{ilj}^\tau(\bar{s}^\tau)$	production of i in unit l for load period j at period τ and $\bar{s}^\tau$ (MWh)
$q_{il}^\tau(\bar{s}^\tau) = \sum_j q_{ilj}^\tau(\bar{s}^\tau)$	total quantity produce by generator i in unit l at period τ and $\bar{s}^\tau$ (MWh)
$Q_j^\tau(\bar{s}^\tau) = \sum_i \sum_l q_{ilj}^\tau(\bar{s}^\tau)$	total quantity for load period j at period τ (MWh)
$C_{ilj}(q_{il})$	total production cost function of generator i in unit l at laod period j (Euro)
$P_j^\tau(Q_j^\tau)$	inverse demand function in segment j at period τ (Euro/MWh)

As stated above, each player maximizes its expected profit W_i. The argument $\bar{s}^\tau$ is omitted when no confusion is possible.

$$Max\ W_i =$$

$$\sum_{\tau=1}^{5}\left\{\beta^\tau \sum_{\bar{s}^\tau}\left\{\theta(\bar{s}^\tau)\sum_{l=1}^{2}\left[\sum_{j=1}^{2} n\cdot\left[q_{ilj}^\tau(\bar{s}^\tau)\cdot P_j^\tau(Q_j^\tau, s^\tau) - C_l(q_{ilj}^\tau)\right] - \Gamma_l(I_{il}^\tau)\right]\right\}\right\} + \beta^5 \sum_{\bar{s}^5}\left\{\theta(\bar{s}^5)\sum_{l=1}^{2}\left[V_{il}(K_{il}^5)\right]\right\} \quad (5.1)$$

[67] Money is expressed in Euro; 1 Euro ≈ 1U.S.$

subject to the constraints

Investment (State equation) $K_{il}^{\tau+1}(\bar{s}^{\tau}) = K_{il}^{\tau}(\bar{s}^{\tau-1}) + I_{il}^{\tau}(\bar{s}^{\tau})$ (5.2)

Production capacity $0 \leq q_{ilj}^{\tau}(\bar{s}^{\tau}) \leq K_{il}^{\tau}(\bar{s}^{\tau-1}) \cdot h_j$ (5.3)

Non negativity $q_{il}^{\tau}(\bar{s}^{\tau}), I_{il}^{\tau}(\bar{s}^{\tau}) \geq 0$ (5.4)

The objective function 5.1 is simply the discounted sum over all five periods of expected revenues minus total production and investment costs, plus the salvage value. As each period represents two years, where similar production decisions are made, the net profit before investment is multiplied by n = 2. We do not consider transmission price for two reasons. The first is that transmission price is negligible compared to production cost. The second is that in Finland, transmission is never a limitation for trading nor could become a strategic advantage for one generator. This is so because the policy of the transmission grid is to maintain over-capacity on all lines and to take upon itself any congestion problem (by buying out of merit power to compensate for limits imposed by bottlenecks). In such a context, ignoring transmission pricing and constraints is almost not a simplification.

Let us define for each player the vector $v_i = \{ q_{ilj}^{\tau}(\bar{s}^{\tau}), I_{il}^{\tau}(\bar{s}^{\tau})\}$, which contains all decision variables (for all i, j, l, τ and $\bar{s}^{\tau}$). Let Ω_i be the set of all admissible actions for player i and $\Omega = \prod_{i=1,\ldots,m} \Omega_i$ the set of admissible actions for all players.

Definition: $v^* = \{ v_1^*, \ldots, v_m^* \} \in \Omega$ is an open-loop S-adapted Nash-Cournot equilibrium if for $\forall v_i \in \Omega_i$ and $\forall i = 1, \ldots, m$:

$$W_i(v^*) \geq W_i(v_1^*, \ldots, v_{i-1}^*, v_i, v_{i+1}^*, \ldots, v_m^*)$$

Proposition: If the cost functions $C_{ilj}(\cdot)$ and $\Gamma_l(\cdot)$ are convex and continuously differentiable, and the revenue function $q_{ilj}^{\tau} \cdot P_j^{\tau}(\cdot)$ is strictly concave, then there exists a unique open-loop S-adapted Nash-Cournot equilibrium for the problem (5.1) - (5.4).

As seen in chapter 4, convexity of the negative reward (or profit) function is the main requirement for the truth of existence and uniqueness of solution for an equilibrium in open-loop. In section 5.4.3 and 5.4.4 we introduce the convex cost functions used in this model, and from our linear demand curve, it is obvious that our revenue function is strictly concave. A similar proposition is stated in Haurie et al. (1988, 1990). They refer to Friedman (1977) for its proof, but one could alternatively use the reference we gave, Basar and Olsder (1999).

An alternative proof of the proposition can be found in the economic literature. Indeed, the existence and uniqueness of the oligopolistic Nash-Cournot equilibrium is well established in many papers. See for example Murphy, Sherali and Soyster (1982)[68], who prove that under strict convexity of the cost function *or* strict concavity of the revenue function (which is our case), the oligopolistic equilibrium is unique. The S-adapted formulation does not change anything structurally to the problem. What the S-adapted formulation adds is simply an addition of similar terms, weighted by a probability.

In this case, the closed form solution for the problem would be very large and difficult to handle. Numerical solutions can give insightful results and allow more illustrative conclusion. We therefore adopted this perspective for the sake of this study.

Equilibria in oligopolistic energy markets have been investigated from a computational point of view in many papers since Salant (1982), where one of the first multi-period oligopolistic energy models was developed. More specifically, Murphy, Sherali and Soyster (1982) developed a mathematical programming approach for determining oligopolistic market equilibrium, which was improved by Harker (1984) and Marcotte (1983) with the use of variational inequalities. Algorithms for variational problems were already available (see for example Pang and Chan, 1982), so that efficient tools could be used when the oligopolistic market equilibrium problem was reformulated with variational inequalities. Number of applications followed, especially in traffic assignment and network equilibrium. Harker and Pang (1990) give a survey of these applications beside a more global overview of the theory

[68] Lemma 5, page 101, Murphy, Sherali and Soyster (1982).

and algorithms[69]. See also Nagurney (1993) for a general presentation of variational inequality and their applications to network economics.

Generally, two main approaches for finding the equilibrium of such problems exist. We solved the problem using both of them. The first one is to directly solve the necessary conditions of the Nash equilibrium. Writing the first order optimality conditions simultaneously for all players' results in a nonlinear complementary problem. A general purpose complementarity code like MILES (Rutherford, 1993) can then be used in solving this.

The second approach is less direct and uses an optimization-based algorithm. The Nash-Cournot game we are considering corresponds to the optimization problem (1) solved simultaneously for all players. If (1) is reformulated as a minimization problem, then it is possible to prove from the first order conditions that the optimal solution x^* of the game is the solution of the following variational inequality $VI(\nabla W,X)$[70]

$$\nabla W\,(x^*)^T \cdot (x-x^*) \geq 0,\ \forall\, x \in X$$

where X is the compact and convex set of feasible solutions, defined by equations (2)-(4), for all players. Decision variable values for all players at the equilibrium are grouped in vector x^*. $W(x^*)$ is the vector containing the objective functions for all players, in a minimization format. $\nabla W(x^*)$ includes the derivatives of $W_i(x^*)$ with respect to x (that is the gradient of each player's objective function).

We then use the *nonlinear Jacobi* algorithm, also known as the diagonalization or relaxation algorithm. Harker (1984), among many others, uses this algorithm. It takes each player in turn and optimizes its profit with fixed values for other players' decision variables. Successive applications of these optimizations lead to the global equilibrium, if conditions for convergence are respected. Our model is a direct extension of Harker's model, which respects conditions of convergence stated by Pang and Chan (1982). Basically, what is

[69] Books like Bertsekas and Tsitsiklis (1989) and Nagurney (1988) also give the necessary background to implement variational inequality algorithms in oligopolistic game settings.
[70] See Nagurney (1988) page 5 or Kinderlehrer and Stampaccia (1980) page 1-2 for a proof of this.

needed for convergence is concavity of the profit function and that the initial vector x^0 be in a suitable neighborhood of x^*.

5.4 Set of data

5.4.1 Players

For our base case drawn on the main features of the Finnish electricity market, we consider two players roughly representing Fortum and PVO, plus a third one, standing for the rest of the supply side. This third player is studied under different behavioral assumptions (strategic and competitive). When considered as a strategic player, its behavior would correspond to the choice of a "PVO-style" strategy from these many producers. It would imply a merger between them, resulting in one single strategic entity. When considered as a competitive fringe, this third player has no market power. Table 5.2 presents production and capacity data in the Finnish market for 1996.

Table 5.2 Capacity in Finland, 1996 (IVO, 1997; PVO, 1997, and Nordel 1998)

		Total capacity MW	Total production TWh
Fortum	Nuclear and hydro	2500	21.0
	Thermal	3000	
PVO	Nuclear and hydro	1200	15.3
	Thermal	1800	
Others	Nuclear and hydro	1590	33.7
	Thermal	5710	
		15800	70

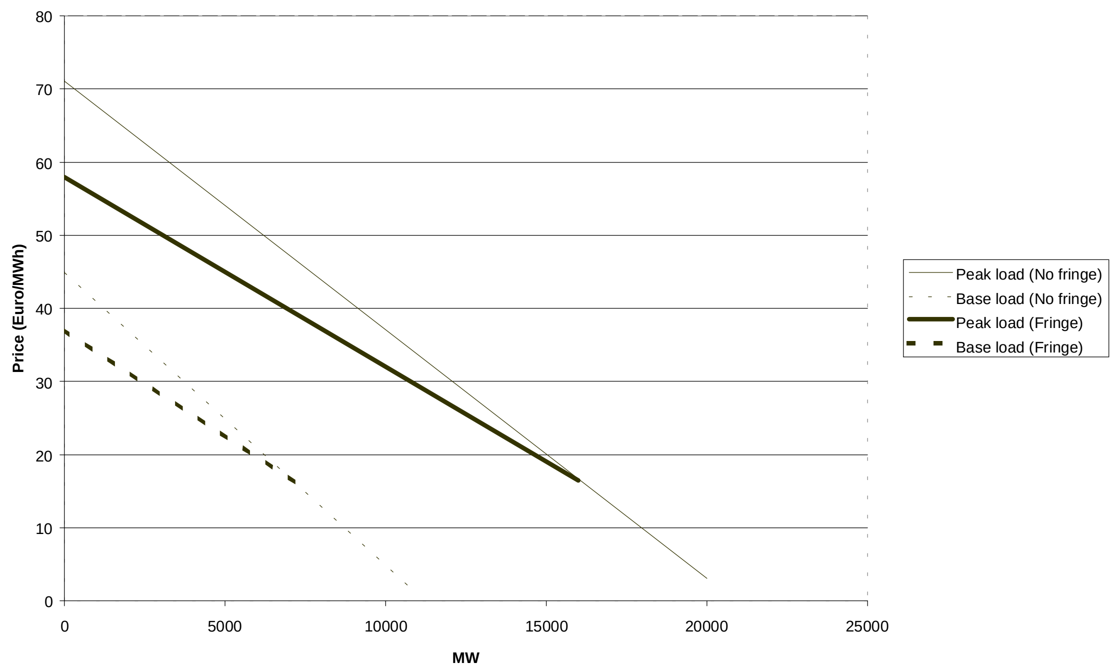
5.4.2 Demand

Consumers in each market segment are represented by the following inverse linear demand function

$$P_j^\tau(Q_j^\tau, s^\tau) = A_j^\tau(s^\tau) - B_j \cdot \; Q_j^\tau(\bar{s}^\tau) \qquad (5.5)$$

where $A_j^\tau(s^\tau)$ and B_j are parameters scaling the level of demand. These parameters depend on the load period j and for the first one, on the level of growth. They were set using the price elasticity of demand η_j for load period j at time $\tau = 0$ and the observed price of electricity[71] in the two load periods. We discuss how elasticity is set in the sensitivity section 5.5.5. Figure 5.2 shows these demand curves for the base and peak load periods.

Figure 5.2 Peak and base load demand at τ = 1



When the third player is considered as a competitive fringe, it serves demand at marginal cost. It is therefore possible to "subtract" the share of demand covered by the fringe. The remaining demand, covered by the strategic players, is shown on figure 5.2 in bold font.

5.4.3 Cost structure

Production cost functions are different for hydro and nuclear units on one hand (l = 1) and thermal units on the other hand (l = 2). Their functional forms are presented in equations 5.7 and 5.8 respectively. They are similar to those used in Andersson and Bergman (1995).

$$C_{i1}(q_{i1}^{\tau}) = g_1 \cdot q^{\tau}_{i1} \qquad (5.6)$$

[71] Prices were approximated at 100 and 200 Finnish Marks per MWh (16.82 and 33.64 Euro/MWh), for respectively base and peak load periods, with loads of 7000 and 11000 MW (based on Nordel, 1998).

$$C_{i2}(q^{\tau}_{i2}) = g_2 \cdot q^{\tau}_{i2} + (K^{\tau}_{i2} \cdot b_2/\phi+1)(q^{\tau}_{i2} / K^{\tau}_{i2})^{\phi+1} \qquad (5.7)$$

In the production cost function 5.7 for hydro and thermal units, g_1 is the same for all players. For simplicity, we use the same marginal cost for hydro and nuclear power. In 5.8, g_2 is the cheapest production cost and (g_2 + b_2) the highest. The parameter ϕ is greater than one. This function allows for a rapid increase of production cost as quantity grows and is produced by more expensive thermal units. This can be seen more easily from the marginal cost function:

$$c_{i2j}(q^{\tau}_{i2j}) = g_2 + b_2(q^{\tau}_{i2j} / h_j \cdot K^{\tau}_{i2})^{\phi} \qquad (5.8)$$

Table 5.3 shows the marginal production costs of some technologies, used in different *blocks* of the load duration curve.

Table 5.3 Marginal production cost of different technologies (Confederation of Finnish Industry and Employers/Finland Promotion Board, 1998)

Technology	Marginal production cost (Euro / MWh)
Nuclear	4.20
Thermal (lowest)	15.14
Thermal (highest)	40.36

5.4.4 Investment cost

Investment cost function $\Gamma_l(\cdot)$ for technology l is assumed linear and increasing:

$$\Gamma_l(\cdot) = a_l \cdot I \qquad (5.9)$$

Nuclear and hydro production units are very costly in terms of new developments and are not open options in Finland, at least in the short term[72]. Therefore we do not allow for investments in these technologies in the model. In contrast, thermal technologies are readily available, within a short implementation time. Investment costs used in the analysis for the base case and low investment cost case are 340 000 and 170 000 Euro / MW respectively[73].

[72] Finland does not have any free hydro sites to use, but is still discussing the possibility to build a new nuclear power plant. However, this option seems unlikely in the present situation.

[73] Thermal investment cost for the base case is taken from the Table 14 in the *Financial - Investor-Owned Electric Utilities* section of the Energy Information Administration web site (www.eia.doe.gov). For comparison purposes, examples of variable and fixed costs in electricity production for different technologies are presented in Andersson and Håsé (1997).

Physical depreciation is not included in the model (existing capacity remains the same through time). Generation units have indeed a very long life expectancy, and with adequate maintenance, their capacity is not really altered with time. They even hardly close down completely. For example, in 1997 not a single MW of capacity was shut down in Finland and only 0.4% of the total Nordic capacity was decommissioned (Nordel, 1998).

However, the financial value of capacity is decreasing each year. As technology evolves and gains in efficiency, the value of a power plant diminishes each year. A 2% depreciation rate is used to reflect this loss in competitiveness of older units. A sensitivity analysis is made on this value to assess how reactive to depreciation the results are. Investments made during the horizon considered will then have a salvage value equal to their initial purchase cost, minus 2% of depreciation each year.

5.4.5 Time length

We are considering five decision periods, lasting two years each. A discount factor $\beta = 0,95$ is used. This 10-year horizon is interesting because it gives a mid-term perspective on production and investment, where major capacity changes are unlikely because no major investment in hydro and nuclear power can take place. Only smaller investments in additional thermal units can occur.

5.5 Results and sensitivity analysis

5.5.1 Market structure scenarios

From the 1996 situation presented in table 5.2 (not structurally different from the 1999 situation), we develop three different assumptions on the Finnish generation capacity. Each of these assumptions is a possible scenario and presents some highlights on how merger and concentration could affect the market price.

- **Competitive fringe (A).** In this first scenario, we stay close to the actual situation (presented in table 5.2) by assuming a strategic behavior for the two large players (Fortum[74] and PVO) and a competitive behavior for the third one. Capacities are as in

[74] From here on we use Fortum instead of IVO, to reflect the change of name in 1998.

table 5.2, but the fringe is assumed not to invest and only reacts to the production choices of the two other players.

- **Strategic with acquisitions (B).** It is assumed that some of the fringe capacity is divided between Fortum and PVO, and also that the nuclear and hydro capacity comes under their control[75]. The rest of the fringe becomes a third strategic player and obtains one third of the thermal capacity. The merger and acquisition pressures of the market justify this scenario. This scenario will be considered as the "BASE CASE".
- **Strategic no acquisition (C).** Simply as a benchmark, we assume in this last scenario that the original fringe capacity merges together and constitutes a third strategic firm. This assumption, however, gives it a dominant capacity, that would probably not be allowed by the two other players, who might acquire some of the fringe capacity (as in the previous scenario).

Table 5.4 shows the initial capacities of the three scenarios considered.

Table 5.4 Scenario description - Capacities (MW)

		Players' capacity		
Scenario		Fortum (strategic)	PVO (strategic)	Other
A - Competitive Fringe	*Nuc./Hydro*	2500	1200	1590
	Thermal	3000	1800	5710
B - Strategic with acquisitions	*Nuc./Hydro*	3250	1950	-
	Thermal	4000	2800	3710
C - Strategic no acquisition	*Nuc./Hydro*	2500	1200	1590
	Thermal	3000	1800	5710

With the tree structure of the model, two random choices at each node and five periods, the results consist in 16 equally likely different paths through the fives periods. Presenting the data for these 16 possible paths would not only be a confusing task, but also unnecessary because many of these paths are almost similar. Thus, we only present three important possibilities:

- **No growth case.** In this extreme case no growth occurs in any period.
- **Average growth case.** Here 0 and 3% growth alternate during the five periods.
- **High growth case.** The maximum demand growth of 3% is realized each year.

The resulting prices in each of the five time periods, for the base and peak load market segments are presented in figures 5.3 and 5.4. It can be mentioned that all the obtained results are of the same magnitude as the real prices observed in the market during peak and

[75] The size and risk of nuclear power plants explain the pressure to centralize ownership. In the case of hydro power plants, their successive position in rivers justifies concentrated management.

base load periods (see for example www.nordpool.no for the actual spot prices in Nordic currencies).

Figure 5.3 Base load prices in 3 demand growth paths - 3 company structure assumptions

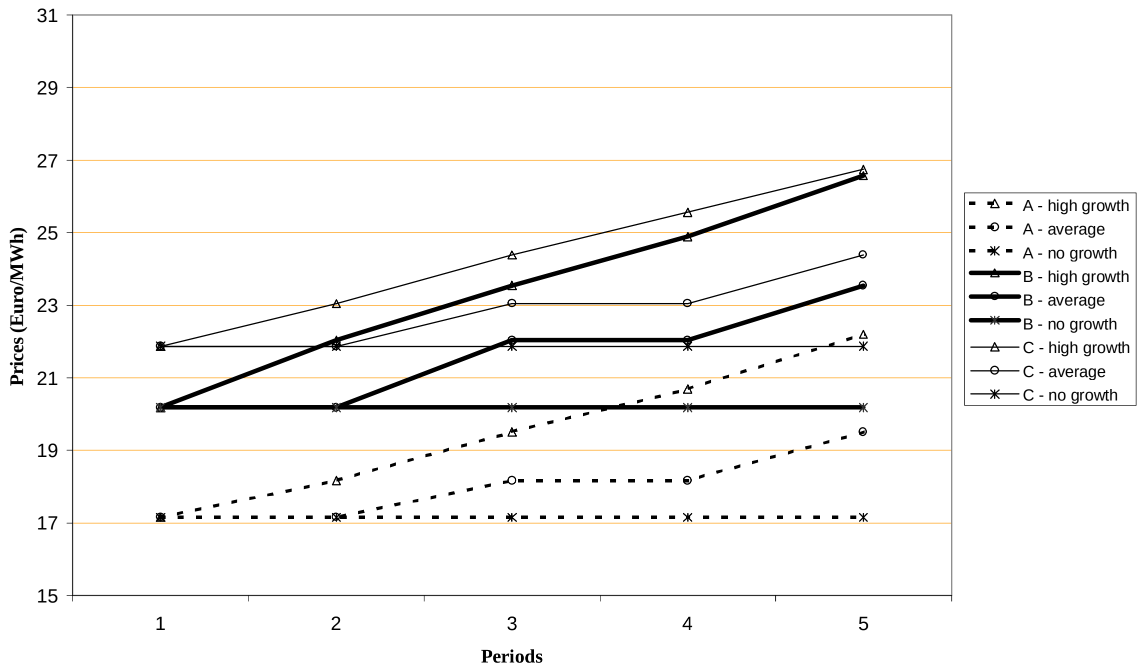
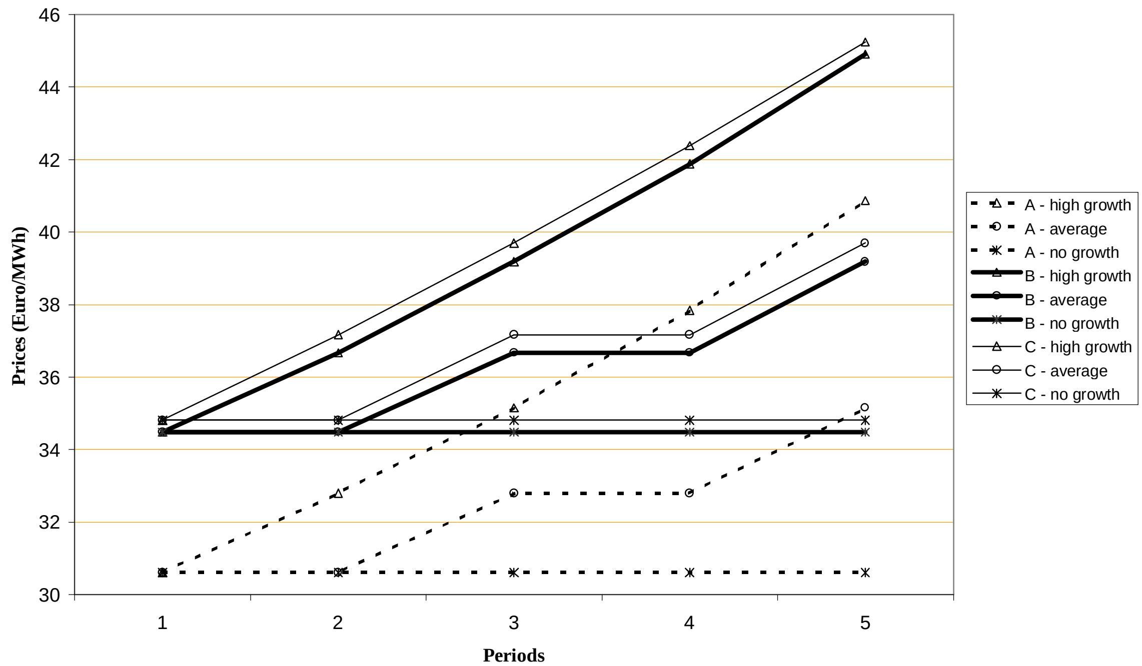


Figure 5.4 Peak load prices in 3 demand growth paths - 3 company structure assumptions



The first result easily seen from these figures is that the lowest prices are reached in the competitive fringe scenario (A). This shows how important is the presence of small players in the market, acting as price takers, especially in the peak load period when the effect of market power is more stringent.

In all three cases, almost no investment takes place. High cost and limited horizon prevent investment to be profitable. These results of the model concur with the actual observation in the market. Indeed, the focus of firms on short-term profitability and the uncertainty on future price make investments unlikely to take place. An interesting pattern observed in the outcome of the model is that as demand grows, the capacity becomes more and more binding in peak load periods, giving room for more market power from the players. Figure 5.4, compared to figure 5.3, shows that prices are rising more in the peak load period that in the base load, because in base load the exceeding capacity prevents a stronger exercise of market power.

5.5.2 Analysis of the number of players

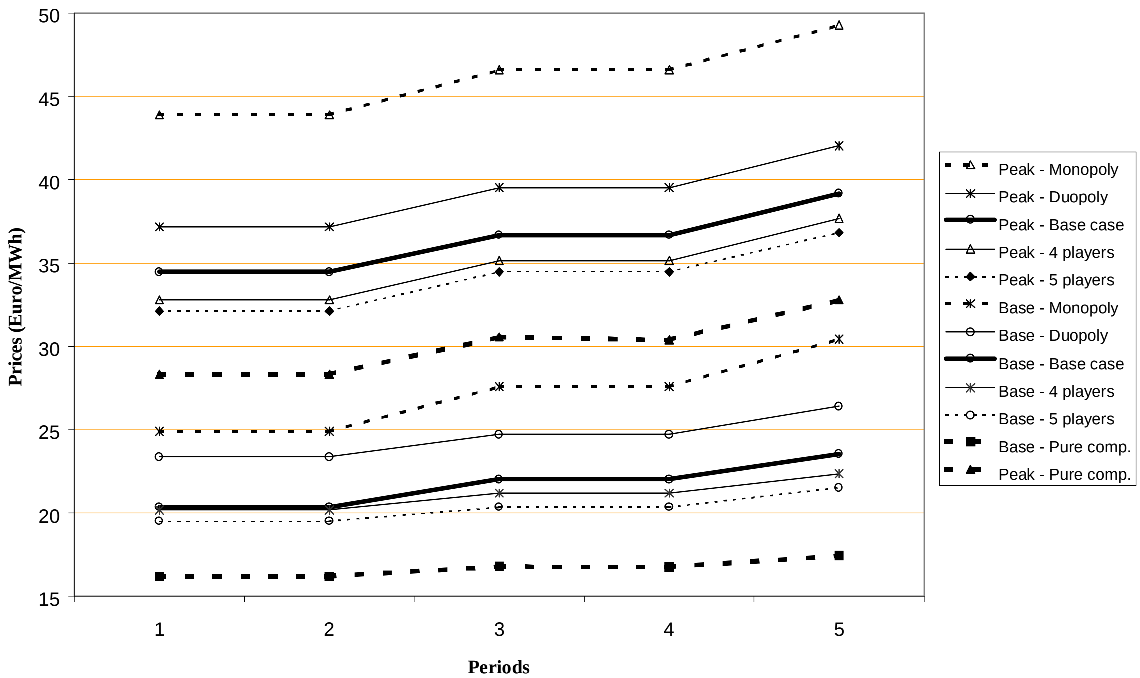
Because of the uncertainty concerning the number of players in the future, we study the impact of this point on the results of the model. As a reference point, we also give the pure competition (marginal cost) equilibrium. Table 5.5 gives the players' capacities, at period 1. The total capacity is always 15,500 MW. The 3-player case we are considering here is the base case (B - Strategic with acquisition).

Table 5.5 Scenario description - Initial capacities (MW)

		Players' capacity				
Scenario		Player 1 (Fortum)	Player 2 (PVO)	Player 3	Player 4	Player 5
Monopoly	*Nuc./Hydro*	5000	-	-	-	-
	Thermal	10500	-	-	-	-
Duopoly	*Nuc./Hydro*	3295	1995	-	-	-
	Thermal	5855	4655	-	-	-
BASE CASE	*Nuc./Hydro*	3250	1950	-	-	-
3-player	*Thermal*	4000	2800	3710	-	-
4-player	*Nuc./Hydro*	2500	1200	795	795	-
	Thermal	3000	1800	2855	2855	-
5-player	*Nuc./Hydro*	2500	1200	530	530	530
	Thermal	3000	1800	1903	1903	1903

The analysis clearly shows the advantage of a large number of players to reduce the impact of market power. The pure competition price is however still well below the 5-player case, both in peak and base load (bold dotted curves in figure 5.5). Here again, the impact on market power is more acute for peak load than base load periods. Figure 5.5 shows the market prices for the five periods, under the average demand growth path, when one to five players are competing.

Figure 5.5 Base and peak load prices for different numbers of players



As expected, the number of players intensifies competition and prices decrease as more players come into the market. There are no investments in the monopoly, duopoly and in the 4-player cases. However, some small investments are observed in the 3 and 5 players cases (respectively 66 MW and 8.1 MW). This result is due to the fact that in these two cases some players have lower initial capacities, relative to the others. It is therefore optimal for them to increase it. Indeed, table 5.5 shows that in the 4-player case, the capacities of all players are more even. We analyze later the investment behavior in a hypothetical situation where initial capacities are much lower.

5.5.3 Investment cost analysis

It would seem natural, at first sight, to make all investments at the beginning of the game. The positive effects of investment would then be observed throughout the game horizon. However, two elements offer opposite incentives. The first one is the demand growth uncertainty, which threatens the profitability of investments in case of low growth. With such uncertainty, players tend to wait if the demand goes up before investing (firms acknowledge the *value of waiting*). The second element is the discounting of the cost and the depreciation of the capacity value. Therefore, it is not optimal to invest too early.

We do not observe significant new capacity addition with the base case investment cost parameters (see section 5.4.4). A relatively small 66 MW of new capacity is added in period 4, in case of high growth. With lower investment costs, however, some investment does take place from the initial period. Table 5.6 shows the results. In the base case, player 3, who starts with a lower initial capacity, makes the investment in period 4, only in the case of high demand growth. In the "low investment cost" case, player 3 invests more massively from the beginning, and continues in case of demand growth. Players 1 and 2, starting from higher capacities, do not invest.

Table 5.6 Total investments (MW) in 3 demand growth paths - Various investment costs

	Demand growth path	**Period**				
		1	**2**	**3**	**4**	**5**
BASE CASE 3-players	*No growth*	-	-	-	-	-
	Average	-	-	-	-	-
	High	-	-	-	66.33	-
Low Investment costs	*No growth*	11.33	-	-	-	-
	Average	11.33	-	708.26	-	-
	High	11.33	790.91	784.63	819.87	-

Impact of increased capacity on price is illustrated in figures 5.6 and 5.7. Especially during peak load, increased capacity leads to significant reductions in prices in the three-player situation. This stresses out the importance of exceeding capacity to relieve customers from the exercise of market power.

Figure 5.6 Base load prices for 3 demand growth paths - Various investment costs

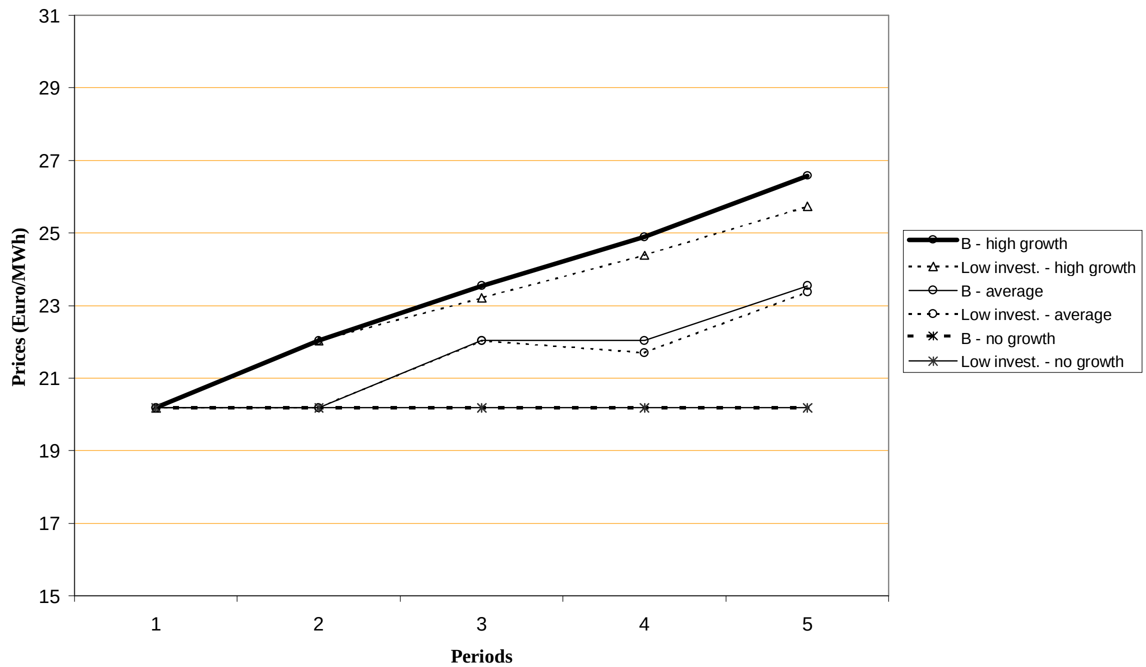
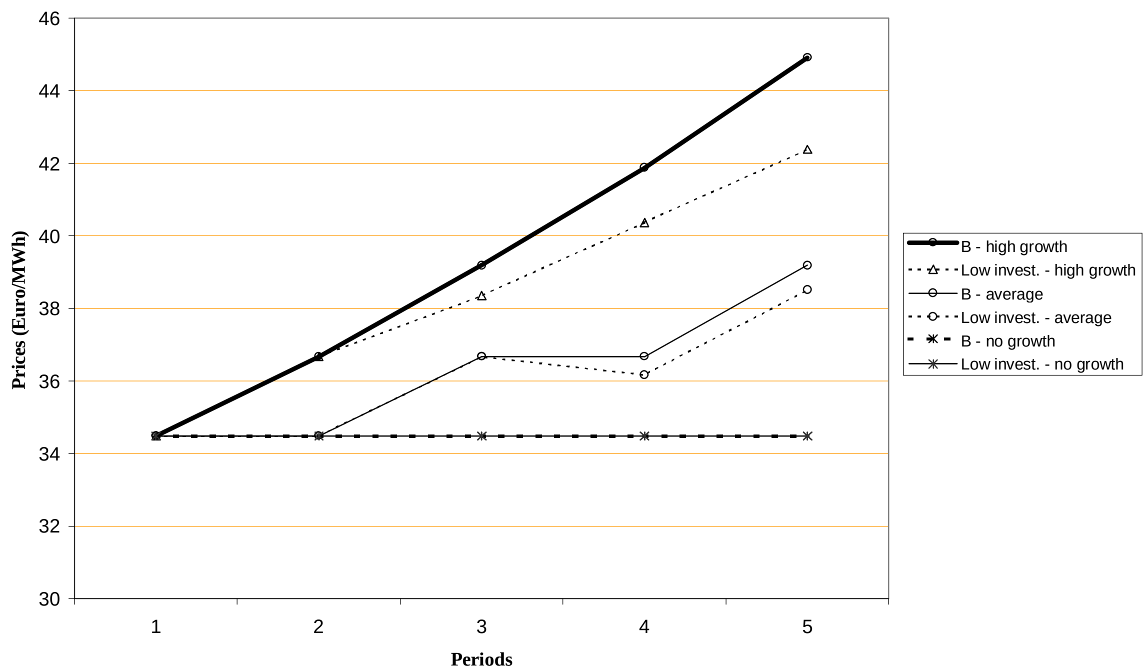


Figure 5.7 Peak load prices in 3 demand growth paths - Various investment costs



As table 5.6 shows, investment is difficult to obtain. This is an issue for concern for many reasons. First, reliability problems could occur in peak periods if capacity is not maintained sufficiently high. Unregulated market players are not there to secure supply, but to ensure their maximum profit. No reliability constraint can therefore be enforced, leaving the market price and possibly shortages make the rationing when capacity is needed. Second, in an uncertain environment and with market power possibilities (especially if mergers reduce the total number of players), intentional *non*-investment could pave the way to higher prices. This effect is even more intense in high demand growth scenarios, as illustrated by our results. These results also corroborate the findings of von der Fehr and Harbord (1995, 1997).

However, these results should be put in perspective with possible new entry and with supply from other countries. These two factors can alleviate the market power illustrated here. But although these external forces do exist, one should not forget that other countries face a similar situation, with limited investment possibilities. Therefore, new foreign competition could not easily enter the market. Furthermore, transmission constraints between countries limit exchanges. Concerning new entries in the domestic production market, barriers to entry, even if lower than a decade ago, are still high. Uncertainty and delay for building new units are also non-negligible.

5.5.4 Depreciation rate analysis

The depreciation rate used in all the previous computations was 2% per year. Here we illustrate the impact of a higher depreciation rate (4%) and of no depreciation rate, first on investment (table 5.7), and then on prices (figures 5.8 and 5.9). In these figures, A means high depreciation, B means base case, and C means no depreciation.

Table 5.7 Total investments (MW) in 3 demand growth paths - Various depreciation rates

	Demand growth path	Period				
		1	**2**	**3**	**4**	**5**
A - High Depreciation (4%)	*No growth*	-	-	-	-	-
	Average	-	-	-	-	-
	High	-	-	-	-	-
B - BASE CASE 2%	*No growth*	-	-	-	-	-
	Average	-	-	-	-	-
	High	-	-	-	66.33	-
C - No depreciation	*No growth*	-	-	-	-	-
	Average	-	-	-	-	-
	High	-	-	268.92	804.93	-

Figure 5.8 Base load prices in 3 demand growth paths - Various depreciation rates

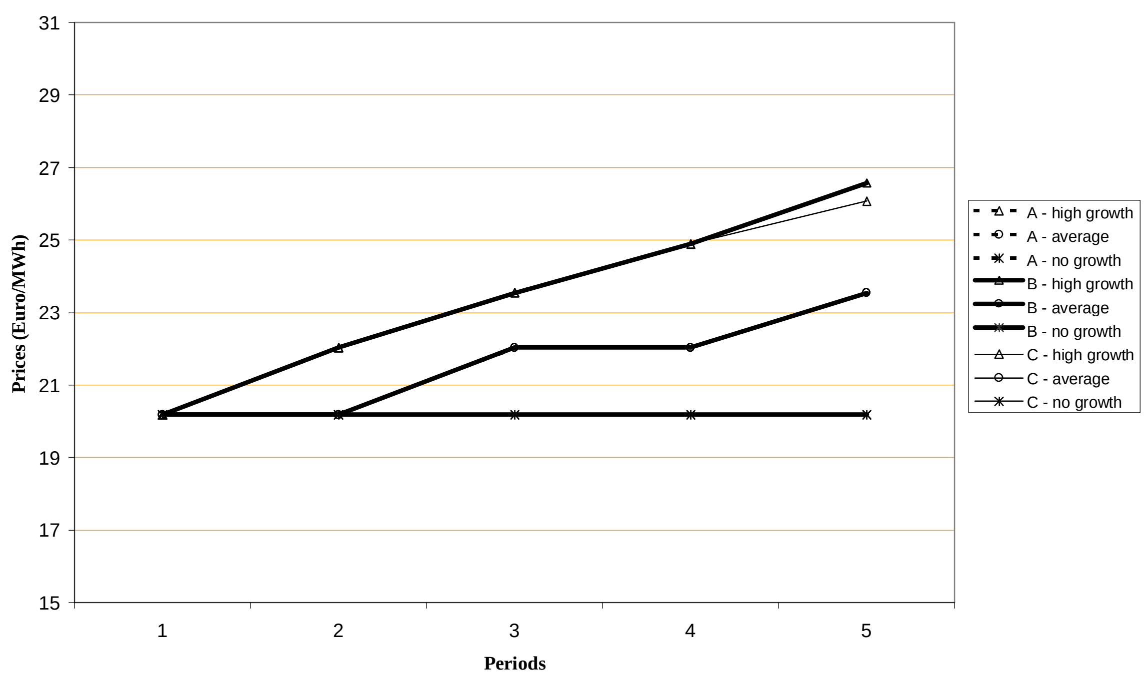
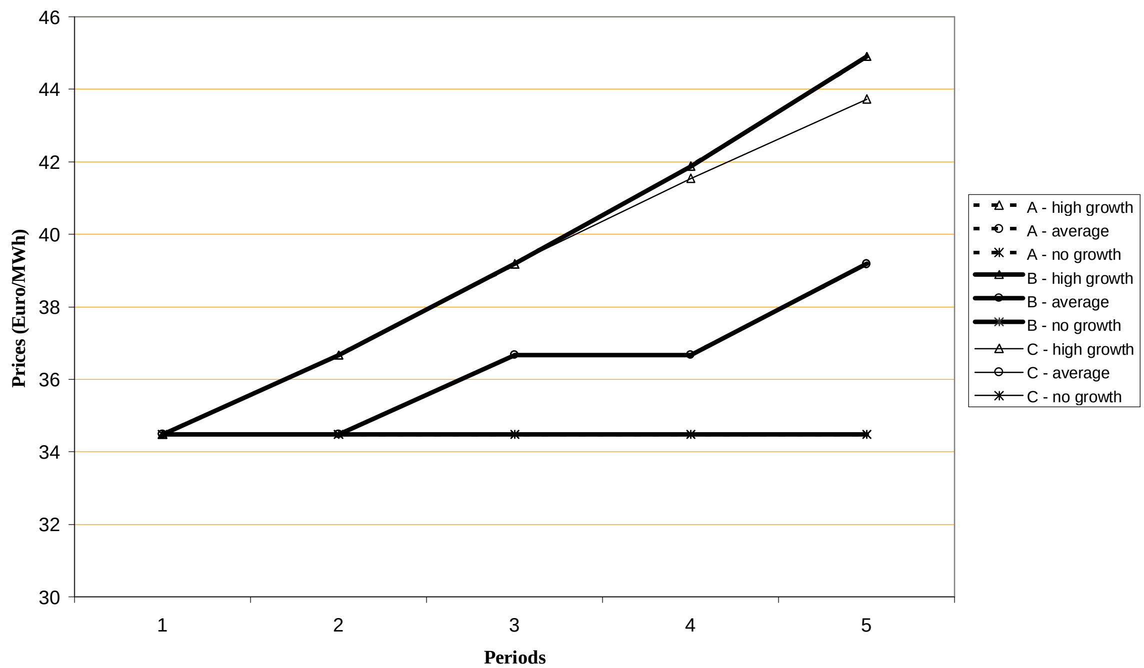


Figure 5.9 Peak load prices in 3 demand growth paths - Various depreciation rates



With no depreciation, it is clear that investment is almost «free» (the players get their money back at the end of the horizon, they only pay the time value of money). But even in that case, only the third player, with less initial thermal capacity is investing, and only in case of high demand growth. The impact of higher capacity on price can only be seen in case of high growth demand, with a slightly lower price in periods 4 and 5.

5.5.5 Analysis of the demand elasticity

We used empirical estimations of the elasticity of demand to guide our analysis. However, different estimates for different market segments and for short and long term periods can be found in the economic literature dealing with this topic. Also, different methodologies can be used and consensus is seldom achieved on the ideal one. They are well surveyed in Atkinson and Manning (1995). We base our choices on data from Bentzen and Engsted (1993), and Elkhafif (1992) because they are recent and conform to those in Atkinson and Manning (1995). Their estimation is between -0.4 and -0.6. Only for residential consumption, Bernard et al. (1996) found an elasticity near -0.9.

We assume here that base load demand is less elastic than peak load demand, because by definition, base load consumption cannot be moved to another time. See table 8 for the values used. The resulting prices are shown in figures 5.10 and 5.11. In the figures, A means low elasticity, B means base case, and C means high elasticity.

Table 5.8 Production cost of different technologies (Confederation of Finnish Industry and Employers/Finland Promotion Board, 1998)

	Base load period	Peak load period
A - Low elasticity	-0.4	-0.7
B - BASE CASE 3-players	-0.6	-0.9
C - High elasticity	-0.8	-1.1

Figure 5.10 Base load prices in 3 demand growth paths - Various elasticity assumptions

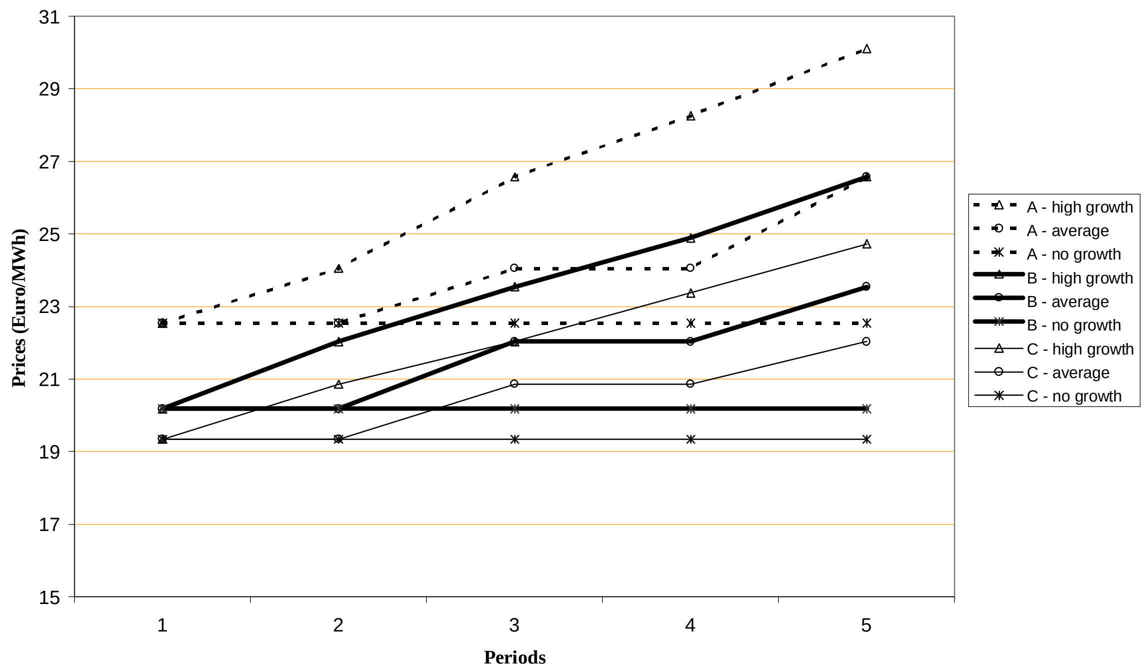
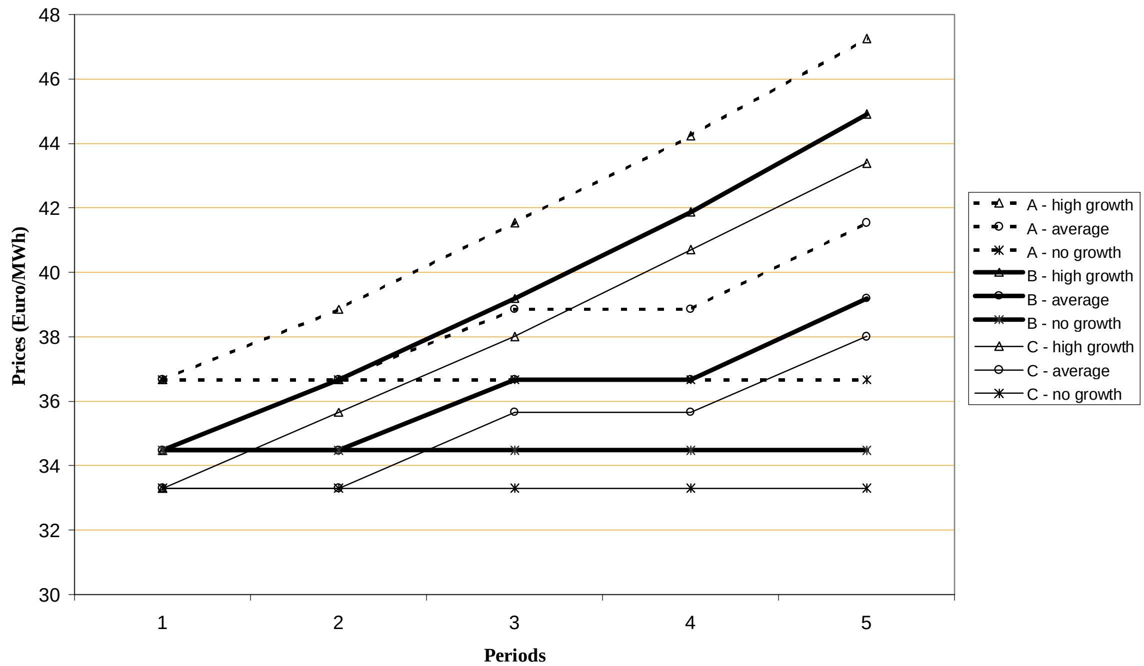


Figure 5.11 Peak load prices in 3 demand growth paths - Various elasticity assumptions



The change in elasticity has a smaller impact on the peak load price in relative terms than in the base load one. This is due to the market power pressure present in the two situations. In peak load, as this pressure is already high, elasticity changes cannot really relieve consumers from expensive electricity. Figures 5.10 and 5.11 illustrate the wider variations in prices in base load period than during peak load one.

Concerning investment, player 3 invests moderately (19.9 MW) in the low elasticity case in period 4, in case of high growth. In case of high elasticity, its investment increases to 184.72 MW.

5.5.6 Sensitivity analysis on probabilities

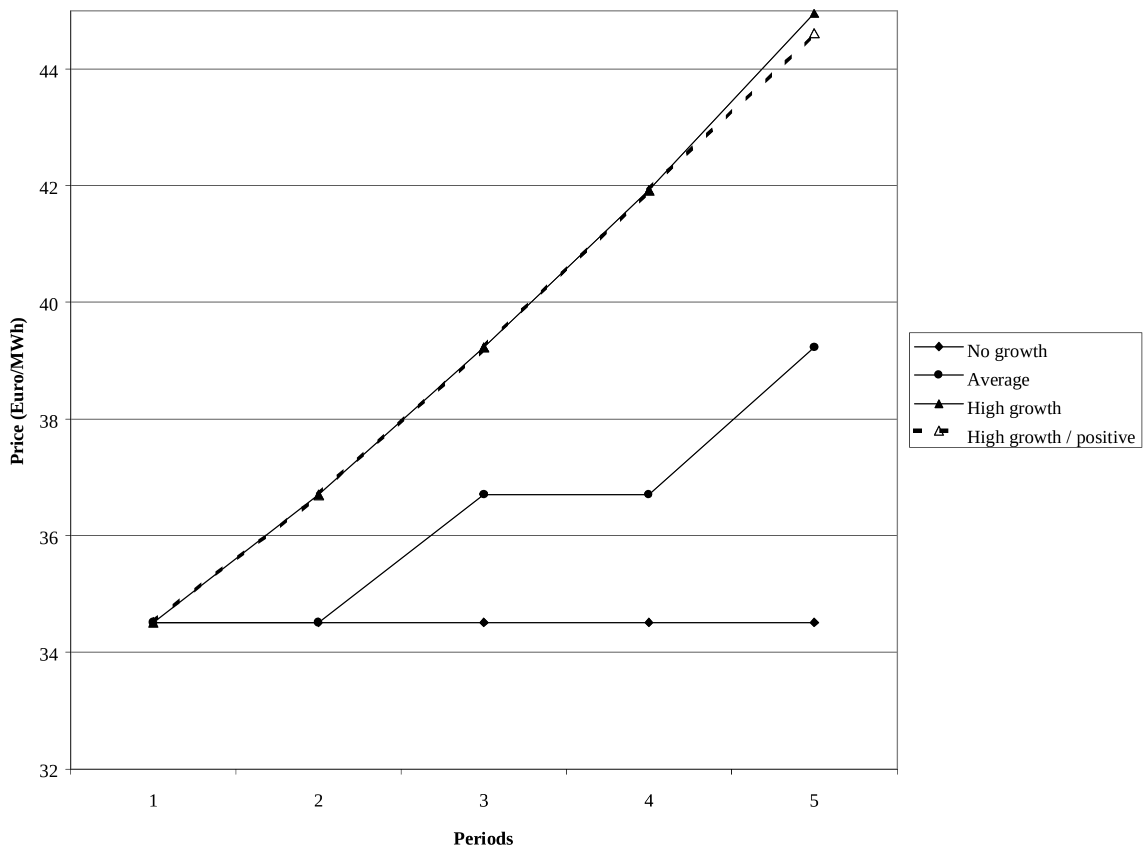
At each node, until now, the probability of realization of a high demand growth for the following period was equals to the no growth possibility. Two different *bayesian* approaches are now explored. In the first, called the *positive indication case*, players know that when a high demand growth occurs in one node, then it is more likely (probability of 0.7) that another high growth node will follow. Conversely, when no growth is occurring, it is an indication that no growth will follow (with again a 0.7 probability). Growth is therefore an indication of growth in this case.

In the second approach, the *negative indication case*, the actual demand growth state gives the indication that the *other* growth possibility will follow, with a probability of 0.7. In both cases, then, some information on the future is obtained from the actual demand state.

These two approaches have been implemented in the model for some computations. The results show almost no difference between the different cases (base, positive and negative cases), as if the information contained in these probabilities was not really valuable for the players. Only in the high growth scenario, in the positive indication case, some more investment occurs, based on the fact that it is more likely that the demand will continue to grow. This translates into a slightly lower peak load price at period 5 (see the dotted line in figure 5.12)

The low influence of probability can certainly be explained by the fact that investment is not profitable for any players in this context. The new information available is these two cases are therefore not sufficient to really make any difference. In our last analysis, we investigate a hypothetical case where the initial capacities are much lower than the actual ones. This allows for a more explicit illustration of the investment dynamics.

Figure 5.12 Peak load prices in 3 demand growth paths - Various probability assumptions



5.5.7 Exploratory case: low initial capacities

The previous analysis was made with initial capacities already near the unconstraint equilibrium. This resulted in few investment, even under particularly favorable conditions (e.g. low cost, low depreciation rate). The market power could however be illustrated for the two different demand levels examined (base and peak load periods).

In order to analyze further the investment dynamic and its links with the use of market power, we now study an exploratory case where initial capacities are well below the level used. From 15,500 MW, the total capacity available at period 1 is now down to 2,000 MW, equally divided between nuclear and hydro units one hand, and thermal units on the other. When there are many players, the capacity is equally divided between them. This new scenario will allow us to see how investment and market power are influenced by the market structure, varying from a monopoly to a competitive situation.

Table 5.9 presents the total investment under our three usual growth scenarios (no growth, average growth and high growth) for five different market structures.

Table 5.9 Total investments (MW) in 3 demand growth paths for different numbers of players

	Demand growth path	**Period**					
		1	**2**	**3**	**4**	**5**	**Total**
Monopoly	*No growth*	5213.88	-	-	-	-	*5213.88*
	Average	5213.88	-	630.63	-	-	*5844.51*
	High	5213.88	733.13	767.23	825.80	-	*7540.06*
Duopoly	*No growth*	7864.65	-	-	-	-	*7864.65*
	Average	7864.65	-	830.78	-	-	*8695.43*
	High	7864.65	971.64	1017.31	1095.84	-	*10949.44*
3-player	*No growth*	9193.46	-	-	-	-	*9193.46*
	Average	9193.46	-	930.76	-	-	*10124.23*
	High	9193.46	1090.84	1142.29	1230.81	-	*12657.41*
4-player	*No growth*	9986.48	-	-	-	-	*9986.48*
	Average	9986.48	-	990.79	-	-	*10977.28*
	High	9986.48	1162.39	1217.31	1311.81	-	*13677.99*
5-player	*No growth*	10517.04	-	-	-	-	*10517.04*
	Average	10517.04	-	1030.79	-	-	*11547.83*
	High	10517.04	1210.07	1267.30	1365.79	-	*14360.20*

This table clearly illustrates how total investment grows with the number of players, a situation even more visible in figure 5.13, where total investment in the three growth scenarios is plotted for up to 12 players. The shape of the investment curve shows that adding new players doesn't increase significantly the level of competition as soon as there are five or six players in the market.

Prices in figures 5.14 to 5.16 reflect the large investment made in the initial period (in the base case, 3-player, scenario), where all players largely invest, resulting in a much lower market price in period 2. After period two, depending on the demand growth, some investment is made or not, and prices either increase or stay at their level. Table 5.16 shows that even in case of investment, there is never enough capacity addition to maintain the price at its initial level. All players partly use the demand growth to increase their profit.

Figure 5.13 Total investment for different market structures

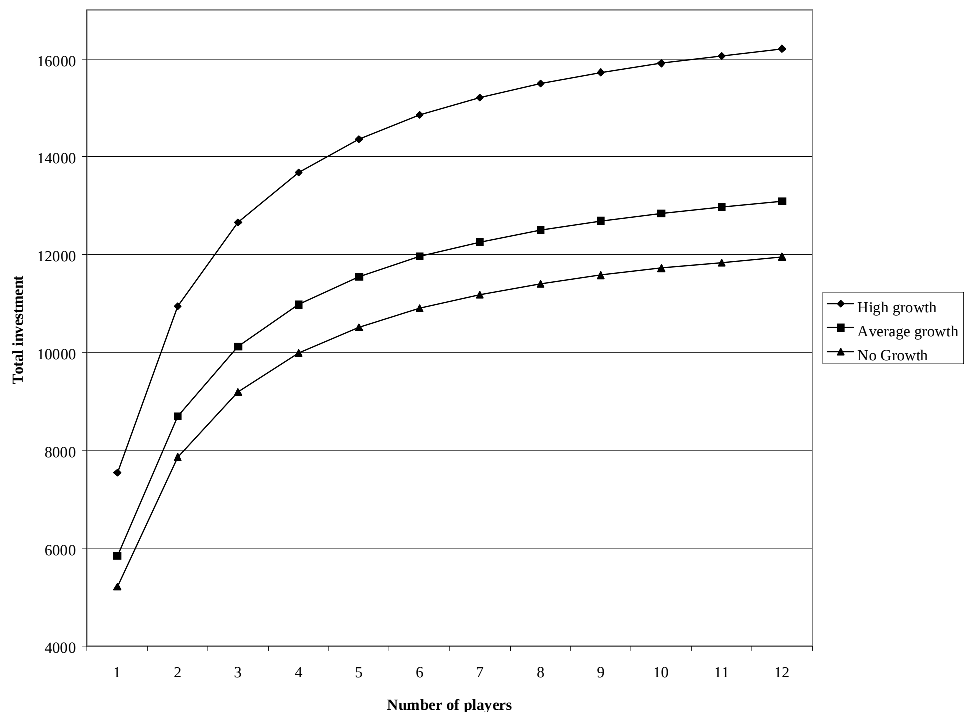


Figure 5.14 Prices for different numbers of players - No growth case

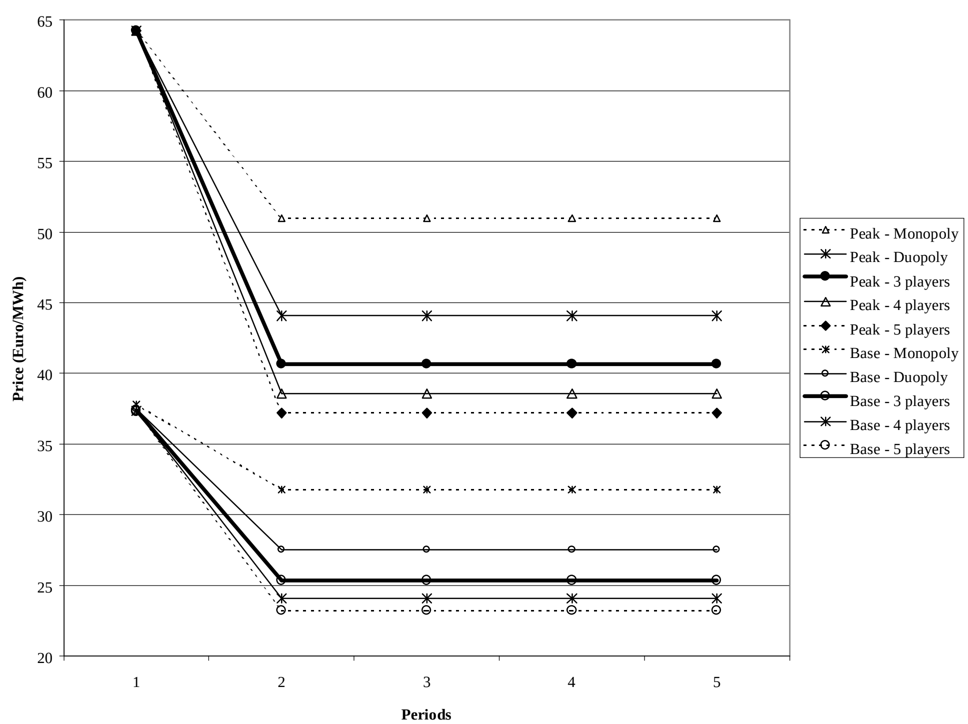


Figure 5.15 Prices for different numbers of players - Average growth case

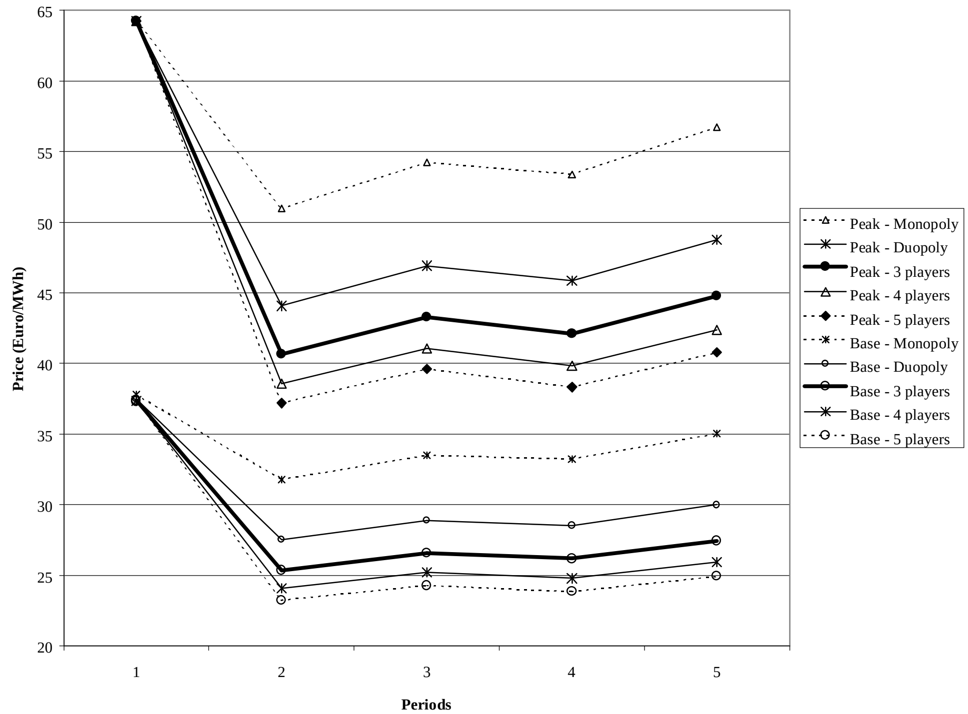
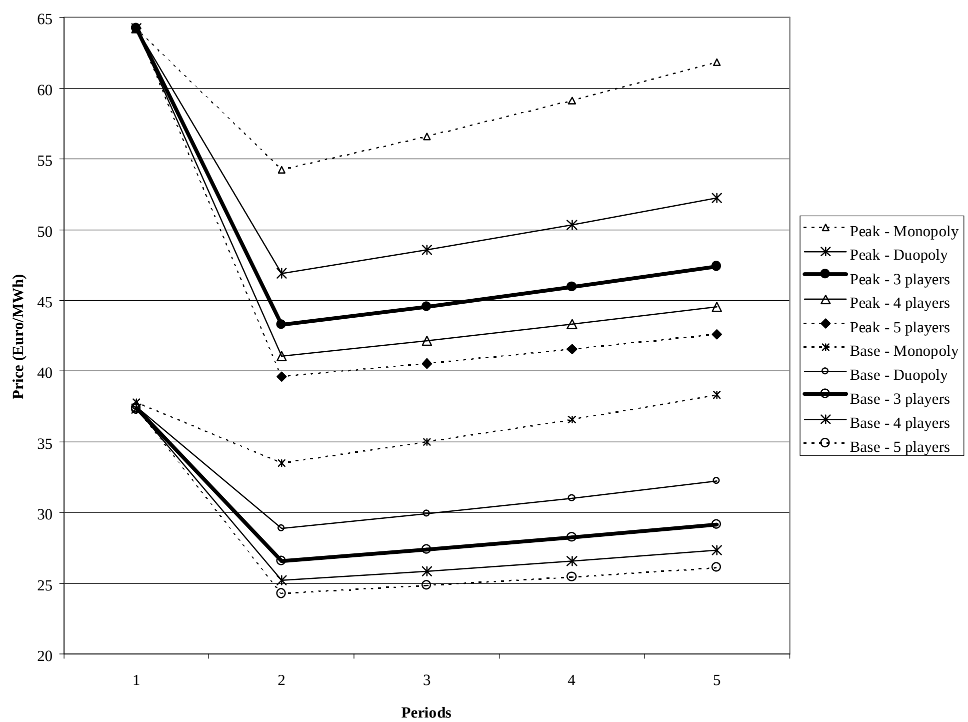


Figure 5.16 Prices for different numbers of players - High growth case



5.6 Conclusion

We constructed a dynamic-stochastic Nash-Cournot model for a simplified version of the Finnish electricity market. Base and peak load market segments and the two groups of production technologies were characterized in a context of stochastic demand growth. Two algorithms were applied to compute the oligopolistic equilibrium in an S-adapted open loop information structure. Although lacking some characteristics of the closed-loop information structure, our approach gives valuable results. Good insights can thus be developed on how players plan, and also how they would react in the future in different demand growth scenarios. In this respect, our model offers a helpful description of the dynamic production-investment problem.

Market power was illustrated for different situations, as in many other contributions, but for one of the first times in a dynamic and stochastic context. The results of our model indicate that investments are difficult to obtain. Under different characterizations of the market (number of players, investment cost, depreciation rate and price elasticity), investments were always very limited. These results stress out a possible threat on reliability and low prices in the electricity sector, when large players are present in a free market. Indeed, strategic behavior coupled with uncertainty of demand growth can limit investment compared to a "pre-deregulation" situation.

Further research could take the following directions. First, extensions to other neighboring countries would add in the relevance of such modeling, especially in Scandinavia where the electricity markets are becoming more and more integrated. This step would, however, require the integration of transmission issues, which constitutes an important aspect of the electricity business between countries. There is no lack of modeling challenges in the economics of electricity transmission.

5.7 Appendix: Solving methodology

5.7.1 Computation of market equilibria

The refinement of economic analysis, in particular with the developments of game theory, combined with the recent strength of computer technologies, gave rise and importance to many computable equilibrium models.

Harker and Pang (1990), Harker (1993) and Nagurney (1993) give a comprehensive presentation of the theory and applications of these models. They cover all the following elements:

- empirical contexts where the need to study economic equilibrium arise;
- characterization of the equilibrium by a set of conditions;
- proof of existence and uniqueness under explicit assumptions;
- formulation of the equilibrium conditions in an equivalent problem, for which computational techniques exist;
- presentation of algorithms to reach the solution.

In the field of energy economics, Smeers (1997) gives a general overview of the relevance of computational models. He covers many applications studying the gas and electricity markets under different perspectives (which mainly correspond to the assumption made on the behavior of market players). His main contribution is to relate the different models and to give a perspective on their possible use for policy making and market studies. Based on this, he draws conclusions on further research avenues and on the relevance of these approaches. Our model was an attempt to go further in one direction he pointed out.

This section presents some methodological aspects used in computation of market equilibria. We focus our attention on the two last points, formulation of the equilibrium conditions and solving algorithm. We have indicated to the reader the aforementioned texts for an in-depth coverage of the topic and for mathematical proofs.

5.7.2 Two solution approaches

In the problem dealt with in this chapter (see section 5.3.5), the Nash equilibrium in an S-adapted information structure corresponds to the maximization problem (5.1) - (5.4) solved simultaneously for all players. Although we model a dynamic situation, we are able to use some mathematical programming techniques. The dynamic of the systems is tackled through the investment constraint (5.2).

We developed two approaches to numerically solve the model with the programming language GAMS. The first formulates the complementary conditions (coming from the Kuhn-Karush-Tucker first order conditions of the problem), and uses the general purpose complementary code MILES written for GAMS (see Rutherford, 1993). This approach was found to give very fast numerical results. The second approach iteratively solves the player's maximization problem until convergence is reached. We elaborate more on these approaches below, but we can already mention that (similar) numerical results were obtained much more slowly with the second one.

Solution through a nonlinear complementarity problem

This approach is very straightforward and takes advantage of GAMS' capacities to solve mixed complementarity problems (MCP) with a solver meant for that. The idea is simply to write the complementary conditions in GAMS, and to ask to find the values satisfying them. When the problem is well behaved, the solving is done in a few seconds, at least for the problem we had at hand.

As complementarity problem are variational inequalities, this approach can be said to solve the variational inequality formulation of the equilibrium conditions. The other approach is now described.

Variational inequality formulation and optimization-based algorithms

Equilibrium in oligopolistic energy markets have been investigated from a computational point of view in many papers since Salant (1982), where one of the first multi-period oligopolistic energy model was developed. More specifically, Murphy, Sherali and Soyster

(1982) developed a mathematical programming approach for determining oligopolistic market equilibrium, which was improved by Harker (1984) and Marcotte (1983) with the use of variational inequalities. Algorithms for variational problems were already available (see for example Pang and Chan, 1982), so that efficient tools could be used when the oligopolistic market equilibrium problem was reformulated with variational inequalities. Number of applications followed, especially in traffic assignment and network equilibrium. Harker and Pang (1990) give a survey of these applications beside a more global overview of the theory and algorithms[76].

The Nash-Cournot game we are considering corresponds to the optimization problem (5.1) - (5.4) solved simultaneously for all players. If we reformulate the problem as a minimization problem, then it is possible to prove from the first order conditions that the optimal solution x^* of the game is the solution of the following variational inequality $VI(\nabla W,X)$[77]

$$\nabla W(x^*)^T \cdot (x-x^*) \geq 0, \ \forall x \in X \tag{5.10}$$

$W(x^*)$ is the vector containing the objective functions for all players (in a minimization format) and $\nabla W(x^*)$ the vector of each player objective function's gradient.

$$\nabla W(x^*) = \begin{bmatrix} \nabla W_1(x^*) \\ \vdots \\ \nabla W_m(x^*) \end{bmatrix}$$

The vector x^* contains the decisions variables' values for all players at the equilibrium. See Nagurney (1993) for a general presentation of variational inequality and their applications to network economics.

We then use the *nonlinear Jacobi* algorithm, also known as the diagonalization or relaxation algorithm. Harker (1984), among many others, uses this algorithm. It suits well this kind of model because the steps of the algorithm follow the assumed behavior of players in a Nash-Cournot setting. Indeed, the algorithm takes each player in turn and optimizes its profit with

---

[76] Books such as Bertsekas and Tsitsiklis (1989) and Nagurney (1988) also present the necessary background to implement variational inequality algorithms in oligopolistic game settings.

[77] See Nagurney (1988) page 5 or Kinderlehrer and Stampaccia (1980) page 1-2 for a proof of this.

fixed values for other players' decision variables. Successive applications of these optimizations lead to the global equilibrium, if conditions for convergence are respected. Our model is a direct extension of Harker's model, which respects conditions of convergence stated by Pang and Chan (1982). Basically, what is needed is convexity of the profit function and that the initial vector x^0 be in a suitable neighborhood of x^*. Then the sequence $\{x^k\}$ generated by the Jacobi method will converge to x^*.

5.7.3 More background on variational inequalities

Harker and Pang (1990), Harker (1993) and Nagurney (1993) are the main references on the use of finite dimensional variational inequalities in economics. Variational inequalities were first developed in infinite dimension to study certain types of differential equations (see Glowinski, Lions and Trémolières, 1976, or Kinderlehrer and Stampacchia, 1980).

Their use in formulating the equilibrium conditions can be helpful to solve the problem at hand because some numerical solution techniques already exist to solve a variational inequality. The idea behind the use of variational inequalities is to break down the main problem into smaller sub-problems, for which a solution technique exists, and to solve these sub-problems iteratively until the solutions converge (if they can be expected to converge).

The general iterative scheme

To introduce the algorithmic solution of the variational inequality problem, we first need to present the *general iterative scheme* of Dafermos (1983). Let us rewrite the variational inequality (VI) problem (5.10) with the following notation.

We seek a vector $x^* \in K$, where K is a compact, closed convex subset of $\Re^n$, such that

$$F(x)^T(x - x^*) \geq 0 \text{ for all } x \in K \qquad (5.11)$$

where $F: X \rightarrow \Re^n$ is a continuous, continuously differentiable function. We also assume the existence of a smooth function

$$g(x,y): K \times K \rightarrow \Re^n \qquad (5.12)$$

such that

- $g(x,x) = F(x)$ for all $x \in K$,
- for all $x, y \in K$, the n × n matrix $\nabla_x g(x,y)$ is symmetric and positive definite.

The general iterative scheme is then composed of these three steps.

Step 0

Start with an initial value $x^0 \in K$ and set the iteration counter $k = 1$.

Step 1

Compute the value x^k by using the previous value x^{k-1} in the following variational inequality sub-problem:

$$g(x^k, x^{k-1})^T(x - x^k) \geq 0 \text{ for all } x \in K \tag{5.13}$$

Step 2

If $|x^k - x^{k-1}| \leq \varepsilon$, where ε is a strictly positive tolerance term, then stop. If not, set $k = k + 1$ and return to step 1.

The sub-problem to solve in step 1 is easier to solve than the initial VI problem (5.11) for two reasons. The first is that the number of decision variables is reduced, because we used some values x^{k-1} to compute an optimal value for x^k. The dimension of the problem is thus much smaller. The second reason is that some approximation for the function $g(x,y)$ can be used, allowing the solution of sub-problem (5.13) to correspond to a more standard problem, for which a known solution technique is readily available.

Solving the sub-problem

Two main categories of function approximation $g(x,y)$ are used, *linear* and *nonlinear* functions. In linear approximations, the choice of $g(x,y)$ is such that the sub-problem (5.13) will correspond to the first order condition of a quadratic programming problem. In nonlinear approximations, $g(x,y)$ is rather defined as the first order condition of a nonlinear optimization problem. In both cases, it is easy to construct the corresponding problem, and to solve it.

By iteratively solving the same problem for all values of the vector *x*, keeping all other fixed, we converge step by step toward the equilibrium solution, if all conditions of convergence and uniqueness are respected.

For more on the different possible approximations of $g(x,y)$ and these conditions, we refer to Harker and Pang (1990), Harker (1993) and Nagurney (1993).

Conclusion

The five chapters of this thesis unfolded in two directions: (i) towards the review and analysis of the institutional and economic motivations of electricity markets reforms, and (ii) to the construction of a dynamic model framed to analyze investment and price levels in an oligopolistic electricity market.

In the first part, a comprehensive presentation of the economics of the electricity sector has been made. A new context, arising from economic and technology progresses, is the main driving force of the observed deregulation trend. We have seen the different restructuring possibilities, both from a theoretical and practical standpoint. The review of the situation in many countries and for representative firms led us to understand the key elements for effective reforms: disintegration of the generation sector and open access in transmission and to customers. Existing threats on prices and investment have also been stressed. Indeed, the possible concentration of firms at the generation level could give market power to firms in the supply side and be damaging for consumers.

Chapter two on the Finnish case gave an even more precise description of the diversity in electricity market deregulation approaches, and its analysis, jointly with other cases, allowed us to see the multiple methods for assessing industrial structures. From the available econometric and simulation-modeling methods, we adopted the latter one and the second part of the thesis was built from this perspective.

To shed a more formal light on the price and investment equilibrium problem, chapter 3 compared the evolution of equilibria in a static context under different market structures. We showed, in different examples, that the oligopolistic equilibrium needed to be investigated further and could result in problematic market results from a social point of view (by having prices above the regulated solution, in certain circumstances). As the appropriate modeling approach clearly needed to include more dynamic aspects, we developed this aspect in the two last chapters.

Chapter 4 offered a methodological summary of different sub-families and available results in game theory. We focused on noncooperative discrete infinite dynamic games, which is an adequate framework to cast the investment problem of deregulated electricity markets. Known results on existence and uniqueness were reported, and a relatively new information structure was compared to the open-loop and feedback ones: the *S-adapted information structure*. This allowed a deeper dynamic analysis of investment in deregulated electricity markets to be achieved. The comparison of the S-adapted equilibrium to the open-loop and feedback ones showed that improvements from the open-loop solution were possible without involving the computational complexities of the feedback solution.

This observation sustained the larger model developed in chapter 5, where price and investment in the Finnish electricity market are studied in a 10 year horizon. The model results showed that investment was difficult to obtain when market power pressure was strong. The importance of having a significant share of competitive players (modeled as the competitive fringe) was stressed.

Electricity markets deregulation is not a simple and innocuous change in the economy. Due to the critical role of electricity in modern society, it can have an important impact on the competitiveness of all economic sectors and on the social welfare. A deep understanding of the roots of regulation and deregulation is therefore absolutely essential, along with a clear understanding of the equilibrium prospects in the reformed markets. This thesis contributed to both of these two critical issues.

References

Amundsen E.S. (1997). "Gas Power Production, Surplus Concepts and the Transformation of Hydro Electric Rent Into Resource Rent", *Resources and Energy Economics*, vol. 19, 241-259.

Amundsen E. and Bergman L. (1998). "Electricity Deregulation: the Norwegian-Swedish Way", *Conference Proceedings of the 24th Annual International Conference of the International Association for Energy Economics*, Québec: Université Laval, vol. 2, 417-425.

Andersson B. and Bergman L. (1995). "Market Structure and the Price of Electricty: An Ex Ante Analysis of Deregulated Swedish Markets", *The Energy Journal*, vol. 16 (2), 97-110.

Andersson B. and Håsé E. (1997). "Power Production and the Price of Electricity: an Analysis of a Phase-out of Swedish Nuclear Power", *Energy Policy*, vol. 25 (13), 1051-1064.

Atkinson J. and Manning N. (1995). "A Survey of International Energy Elasticities", in Barker et al. (eds.).

Averch H. and Johnson L. (1962). "Behavior of the Firm under Regulatory Constraint", *The American Economic Review*, vol. 52 (5), 1052-1069.

Banks F.E. (1996). "Economics of Electricity Deregulation and Privatization: An Introductory Survey", *Energy*, vol. 21 (4), 249-261.

Barker J. Jr., Tenenbaum B. and Woolf F. (1997). *Governance and Regulation of Power Pools and Systems Operators: An International Comparison*, World Bank Technical Paper No. 382, Washington: The World Bank.

Barker T., Ekins P. and Johnstone N. (eds.) (1995). *Global Warming and Energy Demand*, London: Routledge.

Basar T. (1976). "On the Uniqueness of the Nash Solution in Linear-Quadratic Differential Games", *International Journal of Game Theory*, vol. 5 (2/3), 65-90.

Basar T. and Olsder G.J. (1982) and (1992). *Dynamic Noncooperative Games*, New York: Academic Press.

Basar T. and Olsder G.J. (1995) and (1999). Second edition. *Dynamic Noncooperative Games*, New York: Academic Press and Philadelphia: Society for Industrial and Applied Mathematics.

Baumol W.J. (1977). "On the Proper Cost Tests for Natural Monopoly in a Multiproduct Industry", *The American Economic Review*, vol. 67 (5), 809-822.

Baumol W.J. and Bradford D.F. (1970). "Optimal Departure From Marginal Cost Pricing", *The American Economic Review*, vol. 60, 265-283.

Beenstock M. (1991). "Generators and the Cost of Electricity Outages", *Energy Economics*, vol. 13 (4), 283-289.

Bentzen J. and Engsted T. (1993). "Short and Lond-run Elasticities in Energy Demand: A Cointegration Approach", *Energy Economics*, 9-16.

Berg S.V. and Tschirhart J. (1988). *Natural Monopoly Regulation: Principles and Practice*, Cambridge: Cambridge University Press.

Bernard J.-T., Bolduc D., and Bélanger D. (1996). "Québec Residential Electricity Demand: a Microeconomic Approach", *Canadian Journal of Economics/Revue canadienne d'économique*, vol. 29 (1), 92-113.

Bertsekas D.P. and Tsitsiklis J.N. (1989). *Parallel and Distributed Computation: Numerical Methods*, Englewood Cliffs: Prentice-Hall.

Bohn R.E., Caramanis M.C. and Schweppe F.C. (1984). "Optimal Pricing in Electrical Networks Over Space and Time", *RAND Journal of Economics*, vol. 15 (3), 360-376.

Boiteux M. (1949), "La tarification des demandes en pointes", *Revue Générale de l'électricité*, vol. 58, 321-340. (in French)

Boiteux M. (1960). "Peak-load Pricing", *The Journal of Business*, vol. 33, 157-179 (translation of Boiteux M., 1949).

Bolle F. (1992). "Supply Function Equilibria and the Danger of Tacit Collusion: The Case of Spot Markets for Electricity", *Energy Economics*, vol. 14 (2), 94-102.

Borenstein S., Bushnell J. and Knittel C.R. (1998). "Market Power in Electricity Markets: Beyond Concentration Measures", *POWER Working Paper*, PWP-059, University of California.

Bråten J. (1997). "Transmission Pricing in Norway", *Utilities Policy*, vol. 6 (3), 219-226.

Brennan D. and Melanie J. (1998). "Market Power in the Australian Power Market", *Energy Economics*, vol. 20, 121-133.

Brown G. and Johnson M.B. (1969). "Public Utility Pricing and Output Under Risk", *The American Economic Review*, vol. 59 (1), 119-128.

Brown S.J. and Sibley D.S. (1986). *The Theory of Public Utility Pricing*, Cambridge: Cambridge University Press.

Burns S. and Gross G. (1990). "Value of Service Reliability", *IEEE Transactions on Power Systems*, vol. 5 (3), 825-834.

Bushnell J. and Oren S. (1997). "Transmission Pricing in California's Proposed Electricity Market", *Utilities Policy*, vol. 6 (3), 237-244.

Cardell J.B., Hitt, C.C. and Hogan W.W. (1997). "Market Power and Strategic Interaction in Electricity Networks", *Resources and Energy Economics*, vol. 19, 109-137.

Caves D.W., Herriges J.A. and Winde R.J. (1990). "Consumer Demand for Service Reliability in the Electric Power Industry: a Synthesis of Outage Cost Literature", *Bulletin of Economics Research*, vol. 42 (2), 79-119.

Chao H.-p. (1983). "Peak Load Pricing and Capacity Planning with Demand and Supply Uncertainty", *The Bell Journal of Economics*, vol. 14 (1), 179-190.

Chao H.-P., Oren S.S., Smith S.A. and Wilson R. (1986). "Multilevel Demand Subscription Pricing for Electric Power", *Energy Economics*, 199-217.

Chao H.-p. and Peck S.C. (1996). "A Market Mechanism for Electric Power Transmission", *Journal of Regulatory Economics*, vol. 10.

Chao H.-p. and Peck S.C. (1997). "An Institutional Design for an Electricity Contract Market and Central Dispatch", *The Energy Journal*, vol. 18 (1).

Chao H.-p. and Wilson R. (1987). "Priority Service: Pricing, Investment, and Market Organization", *The American Economic Review*, vol. 77 (5), 899-916.

Clemhout S. and Wan H.Y. Jr. (1974). "A Class of Trilinear Differential Games", *Journal of Optimization and Theory and Applications*, vol. 14 (4), 419-424.

Coase R.H. (1937). "The Nature of the Firm", *Economica*, vol. 4.

Confederation of Finnish Industry and Employers/Finland Promotion Board. (1998). "Neste and Ivo Merge into Largest Energy Group in Nordic Countries, *Finnfacts*, March 1998.

Confederation of Finnish Industry and Employers. (1998). *Teollisuuden Energiakatsaus 1/98* (In Finnish)

Crew M. and Kleindorfer P.R. (1978). "Reliability and Public Utility Pricing", *The American Economic Review*, vol. 68 (1), 36-40.

Dafermos S. (1983). "An Iterative Scheme for Variational Inequalities", *Mathematical Programming*, vol. 26 (1), 40-47.

Dafermos S. and Nagurney A. (1987). "Oligopolistic and Competitive Behavior of Spatially Separated Markets", *Regional Science and Urban Economics*, vol. 17, 245-254.

Davidson C. and Deneckere R. (1986). "Long-run Competition in Capacity, Short –run Competition in Price, and the Cournot Model", *Rand Journal of Economics*, vol. 17 (3), 404-415.

Demsetz H. (1968). "Why Regulate Utilities?", *Journal of Law and Economics*, vol. 11, 55-65.

De Wolf, D. and Smeers, Y. (1997). "A Stochastic Version of a Stackelberg-Nash-Cournot Equilibirum Model", *Management Science*, vol. 43 (2), 190-197.

Doucet J.A. (1988). *Differential Pricing of Electricity through Interruption Insurance*, Unpublished doctoral thesis, University of California, Berkeley.

Doyle C. and Maher M. (1992). "Common Carriage and the Pricing of Electricity Transmission", *The Energy Journal*, vol. 13 (3), 63-94.

Dupré R. and Patry M. (1998). "Hydroelectricity and the State in Québec and Ontario: Two Different Historical Paths", *Deregulation of Electric Utilities*, Zaccour G. (ed.).

Einhorn M. and Siddiqi R. (eds.) (1996). *Electricity Transmission Pricing and Technology*, Boston: Kluwer Academic Publishers.

Electricity Market Authority. (1997). *Electricity Transmission Pricing in Finland*, unpublished document.

El-Hawary M.E. and Christensen G.S. (1979). *Optimal Economic Operation of Electric Power Systems*, New York: Academic Press.

Elkhafif M.A.T. (1992). "Estimating Disaggregated Price Elasticities in Industrial Energy Demand", *The Energy Journal*, vo. 13 (4), 209-217.

Energy Forum of Finland. (1997). *Energy in Finland 1997*.

Energy Information Administration. (1996). *The Changing Structure of the Electric Power Industry: An Update*, DOE/EIA-0562(96), Office of Coal, Nuclear, Electric and Alternative Fuel, Washington: U.S. Department of Energy, December 1996.

Energy Information Administration. (1997). *Annual Energy Review 1996*, Washington: U.S. Department of Energy.

Energy Information Administration. (undated). *The Restructuring of the Electric Power Industry: A Capsule of Issues and Events*, Washington: U.S. Department of Energy.

Enron (1999). *Enron Energy Outlook 1999-2020*. Huston: Enron.

European Union. (1995). *An Energy Policy for the European Union*, White Paper, Com(95)682.

Exelby M.J. and Lucas N.J.D. (1993). "Competition in the UK Market for Electricity Generating Capacity: A game theoretic Analysis", *Energy Policy*, vol. 21 (4), 348-354.

Farrer T.H. (1902). *The State in Its Relation to Trade*, London : Macmillan.

Fershtman C. and Kamien M.I. (1987). "Dynamic Duopolistic Competition with Sticky Prices", *Econometrica*, vol. 55 (5), 1151-1164.

Finnish Energy Industry Federation (FINERGY) and Finnish Electricity Association (SENER). (1997). *E.L.E.C.T.R.I.C.I.T.Y. in Finland: Generation - Consumption - Transmission - Market*, brochure.

Fingrid. (1997). *Transmission Power: In Finland, From Finland, To Finland*, brochure.

Fingrid. (1998). *Grid Service 1.11.1998 - 31.12.2001*, memorandum, Grid and Customer services, July 1, 1998.

Fouquet R., Pearson P., Hawdon D. and Robinson C. (1997). "The Future of UK Final User Energy Demand", *Energy Policy*, vol. 25 (2), 231-240.

Friedman J.W. (1977). *Oligopoly and the Theory of Game*, Amsterdam: North Holland.

Friedman J.W. (1983). *Oligopoly Theory*, Cambridge: Cambridge University Press.

Friedman J.W. (1986). *Game Theory With Applications to Economics*, New York: Oxford University Press.

Fudenberg D. and Tirole J. (1986). *Dynamic Models of Oligopoly*, Chur: Harwood Academic Pubishers.

Fudenberg D. and Levine D.K. (1988). "Open-loop and Closed-Loop Equilibria in Dynamic Games with Many Players", *Journal of Economic Theory*, vol. 44, 1-18.

Gellings C.W. and Chamberlin J.H. (1993). *Demand-Side Management: Concepts and Methods.*, second edition, Lilburn: The Fairmont Press.

Gerda T.W. and Varaiya P.P. (1993). "Markets and Pricing for Interruptible Electric Power", *IEEE Transactions on Power Systems*, vol. 8 (1), 122-128.

Geroski P., Gilbert R.J. and Jacquemin A. (1990). *Barriers to Entry and Strategic Competition*, Chur: Harwood Academic Publishers.

Gilbert R.J. and Khan E. (eds.) (1996a). *International Comparisons of Electricity Regulation*, Cambridge: Cambridge University Press.

Gilbert R.J. and Khan E. (1996b). "Competition and Institutional Change in U.S. Electric Power Regulation", *International Comparisons of Electricity Regulation*, Gilbert R.J. and Khan E. (eds.).

Glowinski R., Lions J.L. and Trémolières R. (1976). *Analyses Numériques des Inéquations Variationelles: Méthodes Mathématiques de l'Informatique*, Paris: Dunod. (in French)

Grace A. (1994). *Optimization Toolbox User's Guide*, Natick: The MathWorks.

Green R.J. (1996). "Increasing Competition in the British Electricity Spot Market", *Journal of Industrial Economics*, vol. 44 (2).

Green R.J. (1997). "Increasing Competition in the British Electricity Spot Market", *Journal of Industrial Economics*, vol. 44 (2), 205-216.

Green R.J. (1998). "Electricity Deregulation in England and Wales", *Deregulation of Electric Utilities*, Zaccour G. (ed.).

Green R.J. and Newbery D.M. (1992). "Competition in the British Electricity Spot Market", *Journal of Political Economy*, vol. 100 (5), 929-953.

Guerrien B. (1996). *Dictionnaire d'analyse économique: microéconomie, macroéconomie, théorie des jeux, etc.*, Paris: Éditions La Découverte. (in French)

Gunn C. (1997). "Energy Efficiency vs. Economic Efficiency? New Zealand Electricity Sector Reform in the Context of the National Energy Policy Objective", *Energy Policy*, vol. 25 (4), 445-458.

Hämäläinen R.P., Mäntysaari J., Ruusunen J. and Pineau P.-O. (2000). "Cooperative Consumers in a Deregulated Electricity Market - Dynamic Consumption Strategies and Price Coordination", Hämäläinen R.P., Mäntysaari J., Ruusunen J. and Pineau P.-O., *Energy*.

Harker P.T. (1984). "A Variational Inequality Approach for the Determination of Oligopolistic Market Equilibrium", *Mathematical Programming*, vol. 30, 105-111.

Harker P.T. (1986). "Alternative Models of Spatial Competition", *Operations Research*, vol. 34 (3), 410-425.

Harker P.T. and Pang J.-S. (1990). "Finite-Dimensional Variational Inequality and Nonlinear Complementary Problems: A Survey of Theory, Algorithms and Applications", *Mathematical Programming*, vol. 48, 161-220.

Harker P.T. (1993). "Lectures on Computation of Equilibria with Equation-Based Methods", *CORE Lecture Series*.

Harker P.T. (1991). "Generalized Nash Games and Quasi-Variational Inequalities", *European Journal of Operations Research*, vol. 54, 81-94.

Haurie A., Zaccour G., Legrand J. and Smeers Y. (1988). "Un modèle de Nash-Cournot stochastique et dynamique pour le marché du gaz", *Modélisation et analyse des marchés du gaz naturel – Actes du colloque*, Haurie A., Poirier A., Zaccour G., and Smeers Y. (eds.), Montréal: HEC, GERAD, CETAI.

Haurie A., Zaccour G. and Smeers Y. (1990). "Stochastic Equilibrium Programming for Dynamic Oligopolistic Markets", *Journal of Optimization Theory and Applications*, Vol. 66 (2), 243-253.

Herriott S.R. (1985). "The Organizational Economics of Power Brokers and Centrally Dispatched Power Pools", *Land Economics*, vol. 61 (3), 308-313.

Hjalmarsson L. (1996). "From Club-regulation to Market Competition in the Scandinavian Electricity Supply Industry", in Gilbert and Khan (eds.).

Hobbs B.F. (1986). "Network Models of Spatial Oligopoly with an Application to Deregulation of Electric Generation", *Operations Research*, vol. 34 (3), 395-409.

Hobbs B.F. (1992). "Using Game Theory to Analyze Electric Transmission Pricing Policies in the United States", *European Journal of Operational Research*, vol. 56, 154-171.

Hogan W.W. (1992). "Contract Networks for Electric Power Transmission", *Journal of Regulatory Economics*, vol. 4 (3).

Hogan W.W. (1993). "Markets in Real Electric Networks Require Reactive Price", *The Energy Journal*, vol. 14 (3), 171-200.

Hogan W.W. (1997). "A market power model with strategic interaction in electricity networks", *The Energy Journal*, vol. 18 (4), 107-141.

Hogan W.W., Read E.G. and Ring B.J. (1996). "Using Mathematical Programming for Electricity Spot Pricing", *International Transactions in Operational Research*, vol. 3 (3/4).

Hunt S. and Shuttleworth G. (1996). *Competition and Choice in Electricity*, Chichester: John Wiley & Sons.

Hydro Québec (1997). *Tarifs d'électricité 97*. (in French)

International Energy Agency. (1994). *Energy Policies of IEA Countries - 1993 Review*, Paris: OECD/OCDE.

International Energy Agency. (1997). *Energy Policies of IEA Countries - 1997 Review*, Paris: OECD/OCDE.

International Energy Agency. (1996). *Energy Prices and Taxes - 3rd Quarter 1996*, Paris: OECD/OCDE.

IVO (1997). *Annual Report 1996*.

Joskow P.L. (1998). "Electricity Sectors in Transition", *The Energy Journal*, vol. 19 (2).

Joskow P.L. and Schmalensee R. (1983). *Markets for Power: An Analysis of Electric Utility Deregulation*, Cambridge: The MIT Press.

Kahn A.E. (1989). *The Economics of Regulation: Principles and Institutions*, Cambridge: The MIT Press.

Kahn E. and Baldick R. (1994). "Reactive Power is a Cheap Constraint", *The Energy Journal*, vol. 15 (4), 191-201.

Kanudia A. and Loulou R. (1998). "Robust Responses to Climate Change Via Stochastic MARKAL: The Case of Québec", *European Journal of Operational Research*, vol. 106, 15-30.

Karamardian S. (1971), "Generalized Complementary problem", *Journal of Optimization Theory and Applications*, vol. 8, 161-168.

Karp L.S. and Perloff J.M. (1993a). "Open-loop and Feedback Models of Dynamic Oligopoly", *International Journal of Industrial Organization*, vol. 11, 369-389.

Kidd S.W. (1998). "Nuclear Power in a World of Deregulated Energy Markets", *Conference Proceedings of the 24th Annual International Conference of the International Association for Energy Economics*, Québec: Université Laval, vol. 1, 283-288.

Kinderlehrer D. and Stampaccia G. (1980). *An Introduction to Variational Inequalities and Their Applications*, New York: Academic Press.

Klemperer P.D. and Meyer M.A. (1989). "Supply Function Equilibria in Oligopoly Under Uncertainty", *Econometrica*, vol. 75 (6), 1243-1277.

Koster J.M.M. (1998). "Organizing for Competition: An Economic Analysis of Electricity Policy in the Netherlands", *Energy Policy*, vol. 26. (9), 661-668.

Krapels E.N. (1996). "Marketing BTUs: Gas, Electricity Lead Oil in Innovation", *Oil & Gas Journal*, Vol. 94 (45), 66-69, November 4, 1996.

Kreps D.M. and Scheinkman J.A. (1983). "Quantity Precommitment and Bertrand Competition yield Cournot Outcomes", *Bell Journal of Economics*, vol. 14, 326-337.

Kwoka J.E. (1996). *Power Structure: Ownership, Integration, and Competition in the U.S. Electricity Industry*, Boston: Kluwer Academic Publishers.

Kydland F. (1975). "Noncooperative and Dominant Player Solutions in Discrete Dynamic Games", *International Economic Review*, vol. 16 (2), 321-335.

Lowrey C. (1997). "The Pool and Forward Contracts in the UK electricity Supply Industry", *Energy Policy*, vol.25 (4), 413-423.

Marchand M.G. (1974). "Pricing Power Supplied on an Interriptible Basis", *European Economic Review*, vol. 5, 263-274.

Marcotte P. (1983). "Quelques notes et résultats nouveaux sur le problème d'équilibre d'un oligopole", *R.A.I.R.O, Recherche opérationnelle / Operation Research*, vol. 18 (2), 147-171.

Mathiesen L., Roland K. and Thonstad K. (1987). "The European Natural Gas Market: Degrees of Monopoly Power", in *Natural Gas Markets and Contracts*, R. Golombeck, M. Hoel and J. Vislie (eds.), Amsterdam: North Holland.

Matsukawa I. and Fujii Y. (1994). "Customer Preferences for Reliable Power Supply : Using Data on Actual Choices of Back-up Equipment", *The Review of Economics and Statistics*, vol. 76 (3), 434-446.

Meyer R.A. (1975). "Monopoly Pricing and Capacity Choice Under Uncertainty", *The Amercian Economic Review*, vol. 65 (3), 326-337.

Midttun A. and Summerton J. (1998). "Loyalty or Competition? A Comparative Analysis of Norwegian and Swedish Electricity Distributors' Adaptation to Market Reform", *Energy Policy*, vol. 26 (2), 143-158.

Ministry of Trade and Industry, Department of Energy. (1997a). *Network Pricing in the Finnish Electricity Supply Industry*, Publication B:173, Helsinki.

Ministry of Trade and Industry. (1997b). *Electricity Market in Finland*, brochure.

Miran L.J., Samet D. and Tauman Y. (1983). "Axiomatic Approach to the Allocation of a Fixed Cost Through Prices", *Bell Journal of Economics*, vol. 14 (1), 139-151.

Mitchell B.M., Manning W.G. jr. and Acton J.P. (1978). *Peak-load Pricing: European Lessons for U.S. Energy Policy*, Cambridge: Ballinger Publishing Company.

Monnier L. (1983). *La tarification de l'électricité en France: Origines, Bilan, Perspectives*, Paris: Economica. (in French)

Munasinghe M. (1979). *The Economics of Power System Reliability and Planning: Theory and Case Study*, Baltimore: The Johns Hopkins University Press (A World Bank Research Publication).

Munasinghe M. and Gellerson M. (1979). "Economic Criteria for Optimizing Power System Reliability Levels", *The Bell Journal of Economics*, vol. 10, 353-365.

Murphy F.H., Sherali H.D. and Soyster A.L. (1982). "A Mathematical Programming Approach for Determining Oligopolistic Market Equilibrium", *Mathematical Programming*, vol. 24, 92-106.

Myllyntaus T. (1991). *Electrifying Finland: The Transfer of a New Technology into a Late Industrialising Economy*, London: MacMillan Academic and Professional.

Nagurney A. (1988). "Algorithms for Oligopolistic Market Equilibrium Problems", *Regional Science and Urban Economics*, vol. 18, 425-445.

Nagurney A. (1993). *Network Economics: A Variational Inequality Approach*, Dordrecht: Kluwer Academic Publishers.

Navarro P. (1996). "Electric Utilities: The Argument for Radical Deregulation", *Harvard Business Review*, January-February, 112-125.

Nash J. (1951). "Non-cooperative Games", *Annals of Mathematics*, vol. 54 (2), 286-295.

Newbery D.M. (1995). "Power Markets and Market Power", *The Energy Journal*, vol. 16 (3), 39-66.

Newbery D.M. (1998). "Viewpoint - Freer Electricity Markets in the UK: A Progress Report", *Utility Policy*, vol. 26 (10), 743-749.

Newbery D.M. and Green R. (1996). "Regulation, Public Ownership and Privatization of the English Electricity Industry", *International Comparisons of Electricity Regulation*, Gilbert R.J: and Khan E.P. (eds.).

Nordel (1998). *Annual Statistics*, Web page, www.nordel.org.

Nordel (1999). *Annual Statistics*, Web page, www.nordel.org.

North Amercian Electric Reliability Council (November 1994). *Regional Reliability Criteria: Summary of Regional Criteria and Guides for Planning Reliable Bulk Electric Systems*.

North Amercian Electric Reliability Council (October 1996). *Reliability Assessment 1996-2005: The Reliability of Bulk Electric Systems in North America*.

Olsen O.J. (ed.). (1995). *Competition in the Electricity Supply Industry: Experience from Europe and the United States*, Copenhagen: DJ∅F Publishing Copenhagen.

Oren S.S. and Doucet J.A. (1990). "Interruption for Generation and Distribution of Electric Power", *Journal of Regulatory Economics*, vol. 2, 5-19.

Oren S.S. and Smith S.A. (1992). "Design and Management of Curtailable Electricity Service to Reduce Annual Peaks", *Operations Research*, vol. 40 (2), 213-228.

Oren, S.S. (1999). *Integrating Real and Financial Options in Demand-Side Electricity Contracts*, paper presented in the workshop *Coordination in Deregulated Electricity Markets*, March 22-24, Finland.

Organisation for Economic Co-operation and Development. (1997a). *Application of Competition Policy to the Electricity Sector*, OECD/GE(97)132, Paris: OECD/OCDE.

Organisation for Economic Co-operation and Development. (1997b). *Report on Regulatory Reforms*, vol. 1, Paris: OECD/OCDE.

Pachauri R.K. (1975). *The Dynamics of Electrical Energy Supply and Demand: An Economic Analysis*, New York: Praeger Publishers.

Pang J.S. and Chan D. (1982). "Iterative Methods for Variational and Complementary Problems", *Mathematical Programming*, vol. 24, 284-313.

Panzar J.C. and Sibley D.S. (1978). "Public Utility Pricing Under Risk: the Case of Self-Rationing", *The Amercian Economic Review*, vol. 68 (5), 888-895.

Pfeifenberger J.P., Hanser P.Q. and Ammann P.R. (1997). "What's the Cards for Distributed Resources?", *The Energy Journal*, Distributed Resources Special Issue.

Pineau P.-O. (1995). *Le rôle de la causalité dans la théorie de la décision*, unpublished Master thesis, Université de Montréal (in French).

Pineau P.-O. (1998). "Peak Load Problem, Deregulation and Reliability Pricing", *Deregulation of Electric Utilities*, Zaccour G. (ed.).

Pineau P.-O. (2000). "Déréglementation des marchés de l'électricité et enjeux sociaux et environnementaux: un état de la situation dans les pays nordiques", *Gestion*, vol. 25 (1), 66-74 (in French).

Pineau P.-O. and Murto P. (1999). "A Stochastic Dynamic Game Model of the Finnish Electricity Market", research paper. (Downloadable from www.hut.fi/Units/SAL/Publications).

Pineau P.-O. and Hämäläinen R.P. (2000). "A Perspective on the Restructuring of the Finnish Electricity Market", *Energy Policy*, vol 28 (3), 181-192.

Pollitt M.G. (1997). "The Impact of Liberalization on the Performance of the Electricity Supply Industry: An International Survey", *The Journal of Economic Literature*, vol. 3 (2), 3-31.

Primeaux W.J. Jr. and Nelson R.A. (1980). "An Examination of Price Discrimination and Internal Subsidization by Electric Utilities", *Southern Economic Journal*, vol. 47 (1), 84-99.

PVO (1997). *Annual Report 1996*.

Ramsey F.P. (1927). "A Contribution to the Theory of Taxation", *Economic Journal*, vol. 37, 47-61.

Read E.G. (1997). "Transmission Pricing in New Zealand", *Utilities Policy*, vol. 6 (3), 227-235.

Reinganum J.F. (1982). "A Class of Differential Games for Which the Closed-Loop and Open-Loop Nash Equilibria Coincide", *Journal of Optimization Theory and Applications*, vol. 36 (2). 253-262.

Reynolds S.S. (1991). "Dynamic Oligopoly with Capacity Adjustment Cost", *Journal of Economic Dynamics and Control*, vol. 15, 491-514.

Rutherford T. (1993). "MILES: A Mixed Inequality and Non-Linear Equation Solver", In *GAMS - The Solver Manuel*, Washington DC: GAMS Development Corporation.

Rudnick H. and Raineri R. (1997). "Transmission Pricing Practices in South America", *Utilities Policy*, vol. 6 (3), 211-218.

Rännäri O. (1995). "Reform of the Finnish Electricity; Plans and Expectations", *Competition in the Electricity Supply Industry: Experience from Europe and the United States*, Olsen O.J. (ed.).

Sabin D.D. and Sundaram A. (1996). "Quality Enhences Reliability", *IEEE Spectrum*, 33 (2), 34-41-

Salant S.W. (1982). "Imperfect Competition in the International Energy Market: A Computerized Nash-Cournot Model", *Operations Research*, vol. 30 (2), 252-280.

Sauders B. (1996). "Oil/Gas Firms Take Lead Among New Breed of Energy Megamaketers", *Oil & Gas Journal*, September 16, 1996.

Selten R. (1975). "Reexamination of the Perfectness Concept for Equilibrium Points in Extensive Games", *International Journal of Game Theory*, vol. 4, 25-55.

Sharkey W.W. (1982). "Suggestions for a Game-Theoretic Approach to Public Utility Pricing", *Bell Journal of Economics*, vol. 13, 57-68.

Sherman R. and Visscher M. (1978). Second Best Pricing with Stochastic Demand", *The American Economic Review*, vol. 68 (1), 41-53.

Schmalensee R. (1979). *The Control of Natural Monopolies*, Lexington: Lexington Book.

Schweppe F.C., Caramanis M.C., Tabors R.D. and Bohn R.E. (1988). *Spot Pricing of Electricity*, Boston: Kluwer Academic Publishers.

Schmitt N. and Weder R. (1998). "Sunk Costs and Cartel Formation: Theory and Application to the Dyestuff Industry", *Journal of Economic Behavior & Organization*, vol. 36, 197-220.

Siddiqi S.N. (1993). *Reliability Differentiated Pricing and Optimal Planning for Electrical Power Systems*, Unpublished doctoral thesis, University of Texas at Austin.

Sioshansi F. (1990). *Pricing & Marketing Electricity: New Directions in Power Supply*, Special Report No 2016, London: The Economist Intelligence Unit.

Southern Company (1999). *1998 Overview*. Atlanta: Southern Company.

Smeers Y. (1997). "Computable Equilibrium Models and the Restructuring of the European Electricity and Gas Markets", *The Energy Journal*, vol. 18 (4).

Smith, R. (2000). "Deregulation and Heavy Demand Leave Electricity Providers Short for the Summer", *The Wall Street Journal*, May 11, 1.

Spiller P.T. and Martorell L.V. (1996). "How Should It Be Done? Electricity Regulation in Argentina, Brazil, Uruguay, and Chile", *International Comparisons of Electricity Regulation*, Gilbert R.J: and Khan E.P. (eds.).

Spulber D.F. (1993), "Monopoly Pricing", *Journal of Economic Theory*, vol. 59, 222-234.

Starr A.W. and Ho Y.C. (1969). "Nonzero-Sum Differential Games", *Journal of Optimization Theory and Applications*, vol. 3 (3), 184-206.

Statistics Canada (1996). *Electric Power Capability and Load*, 57-204.

Sutton J. (1991). *Sunk Costs and Market Structure: Price Competition, Advertising, and the Evolution of Concentration*. Cambridge: The MIT Press.

Tan C.-W. and Varaiya P. (1993)."Interruptible Electric Power Service Contracts", *Journal of Economic Dynamics and Control*, vol. 17, 495-515.

Tishler A. (1993). "Optimal Production with Uncertain Interruptions in the Supply of Electricity: Estimation of Electricity Outage Costs", *European Economic Review*, vol. 37 (6), 1259-1274.

Tollefson G., Billinton R., Wacker G., Chan E., and Aweya J. (1994). "A Canadian Customer Survey to Assess Power System Reliability Worth", *IEEE Transactions on Power Systems*, vol. 9 (1), 443-150.

Train K.E. (1991). *Optimal Regulation: The Economic Theory of Natural Monopoly*, Cambridge: The MIT Press.

Tschirhart J. and Jen F. (1979). "Behavior of Monopoly Offering Interruptible Service", *The Bell Journal of Economics*, vol. 10, 244-258.

Turnovsky S.J. (1971). "A Model of Consumer Behavior Under Conditions of Uncertainty in Supply", *International Economic Review*, vol. 12 (1), 39-53.

U.S. Department of Energy. (1998a). *Comprehensive Electricity Competition Act*, Bill.

U.S. Department of Energy. (1998b). *Comprehensive Electricity Competition Act: Supporting Analysis*, DOE/PO-0057, Office of Economic, Electricity and Natural Gas Analysis and Office of Policy and International Affairs.

Varian H.R. (1987). Intermediate Microeconomics: A Modern Approach, New York: Norton.

Varian H.R. (1992). *Microeconomic Analysis*, 3rd edition, New York: Norton.

Vickrey W. (1971). "Responsive Pricing of Public Utility Service", *Bell Journal of Economics*, vol. 2, 337-346.

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

von der Fehr N.-H.M. and Harbord D. (1995). "Capacity Investment and Long-Run Efficiency in Market-Based Electricity Industries", *Competition in the Electricity Supply Industry: Experience from Europe and the United States*, Olsen O.J. (ed.), Copenhagen: DJOF publishing.

von der Fehr N.-H.M. and Harbord D. (1997). "Capacity Investment and Competition in Decentralised Electricity Markets", *Memorandum from Department of Economics*, University of Oslo, No 27, November 1997.

von Neumann L. and Morgenstern O. (1947). *Theory of Games and Economic Behavior*, 2nd edition, Princeton: Princeton University Press.

Wei J.-Y. and Smeers Y. (1999). "Spatial oligopolistic electricity models with Cournot generators and regulated transmission prices", *Operations Research*, vol. 47 (1), 102-112.

Weiss L.W. (1975). "Antitrust in Electric Power Industry", *Promoting Competition in Regulated Markets*, Phillips A. (ed.), Washington: Brookings Institution.

Walker C.D. and Lough T. (1997). "A Critical Review of Deregulated Foreign Electric Utility Markets", *Energy Policy*, vol. 25 (19), 877-886.

Williamson O.E. (1979). "Transaction-Cost Economics: The Governance of Contractual Relations", *Journal of Law and Economics*, vol. 22 (2), 233-262.

Wilson R. (1992?). *Nonlinear Pricing*, Cambridge: Cambridge University Press.

Woo C.-K. (1988). "Optimal Electricity Rates and Consumption Externality", *Resources and Energy*, vol. 10, 277-292.

Woo C.-K. and Toyama N. (1986). "Service Reliability and the Optimal Interruptible Rate Option in Residential Electricity Pricing", *The Energy Journal*, vol. 3 (3), 123-136.

Woo C.-K. and Pupp R.L. (1992). "Cost of Service Disruptions to Electricity Consumers", *Energy*, vol. 17 (2), 109-126.

Wood A.J. and Wollenberg B.F. (1996). *Power Generation, Operation and Control*, 2nd edition, New York: John Wiley & Sons.

Yajima M. (1997). *Deregulatory Reforms of the Electricity Supply Industry*, Westport: Quorum Books.

Younes Z. and Ilic M. (1998). "Generation Strategies for Gaming Transmission Constraints: Will the Deregulated Electric Power Market Be an Oligopoly?", *Proc. 31st Annual Hawaii International Conference on Systems Science*, 112-121.

Zaccour G. (ed.) (1998). *Deregulation of Electric Utilities*, Boston: Kluwer Academic Publishers.

WWW links

Électricité de France - www.edf.fr

Electricity market authority of Finland - smk.inet.fi

Energy Information Administration - www.eia.doe.gov

Enron - www.enron.com

European Union's server - europa.eu.int

FERC - www.ferc.fed.us

Fingrid - www.fingrid.fi

Fortum - www.fortum.com

Hydro-Québec - www.hydro.qc.ca

OECD - www.oecd.org

Office of Electricity Regulation - www.open.gov.uk/offer/offerhm.htm

Nordpool - www.nordpool.no

Southern Company - www.southernco.com

Systems Analysis Laboratory electricity page - www.hut.fi/Units/Systems.Analysis/Teaching/Mat-2.142/elmarket

U.S. Department of Energy - www.doe.gov