A Review of Liberalization and Modeling of Electricity Markets

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Abstract:
This paper provides a review on the restructuring of electricity markets around the word including the UK, Norway, Continental Europe, and the US. The focus of this review lies on aspects of competitiveness and regulation in generation and transmission markets and market design, whereas distribution and retail are not pursued in detail. Furthermore, an overview about current modeling trends regarding liberalized electricity markets is provided including a classification according to mathematical principles and a taxonomy of research topics analyzed with modeling approaches.

Key words: electricity, liberalization, restructuring, competition policy, international experiences, market modeling
JEL-code: L 94

1 Introduction

In the old days of vertically integrated, monopolistic supply, most modeling focused on technical processes and network calculations. However, this changed drastically in the last two decades as markets were opened for competition and economic modeling methods became applicable. The changeover instigated much debate over the best methods to design, operate, regulate, and analyze the new markets. The dominance of engineering analysis during the regulated era soon broadened to incorporate economics and engineering-economics studies. Governments, policy-makers, and regulators all need robust analyses to judge the implementation and effectiveness of new market rules. Competition authorities have to analyze the impact of mergers and acquisitions. Market operators need dependable software to run the systems. Companies need forecasts and investment analysis. And last but not least scientist rely on modeling techniques to analyze the market performance ex-post, understand market processes, and further develop the market given the future challenges of electricity markets world wide.

The literature that examines various aspects of electricity markets has expanded significantly to address research questions throughout electricity's value chain. The focus of this review lies on aspects of competitiveness and regulation in generation and transmission markets and market design whereas distribution and retail are not pursued in detail.

In Section 2 a review on the liberalization process of electricity markets around the world including the main motivation, the actual processes, and lessons learned is provided highlighting the current framework of competitive electricity markets to be assessed. In Section 3 an overview about current modeling trends regarding liberalized electricity markets is provided. A particular focus is on market design and market performance. The review does not go into detail on related issues including the growing debate about environmental aspects, or aspects on the retail side, i.e. smart metering and demand response, nor does it discuss the issue of actual operations from a technical point of view. The modeling techniques are first structured according to the underlying mathematical principles. Afterwards, a taxonomy of research topics analyzed with modeling approaches is presented including market power, investment analysis, price forecasts, network modeling, and market design.

2 Liberalization of Electricity Markets

Electricity markets around the world were for a long time either formed by vertically-integrated, state-owned companies, or private firms subject to governmental regulation that were often monopolies within their supply area. Following Shioshansi (2006a) the prime justifications for regulatory intervention are:

- Significant economies of scale and scope that favor large integrated utilities
- The natural monopoly character of electricity transport
- Segments of the electricity value chain that are regarded as indivisible
- The belief that private investment will not occur without long-term hedging.

Despite the assumed advantages, this market paradigm had many shortcomings, including: classical regulatory problems, e.g., the risk of over-investments and regulatory capture; little or no customer choice; price disparities; and an absence of incentives and technological innovation. It was not until the 1990s that this paradigm was rejected in favor of market-based approaches.[1] By the end of the century liberalization processes had been initiated in about 50 countries (Pollitt, 1999) although the process slowed after the dramatic failure of the California market in 2000-2001.

The change to free markets is based on several economic and policy motivations that differ strongly from country to country (Shioshansi, 2006a). Whereas developed countries hope to overcome the inefficiencies inherent in large, regulated companies, developing countries often initialize liberalization because governments lack money for necessary investments.[2] In addition the technological advancement of gas-fired turbines, in particular highly efficient combined cycle turbines, have broken the dominance of coal and nuclear plants and significantly lowered barriers to entry for private investors in generation.

The process of restructuring and liberalization is not a synonym for the same set of policies and measurements throughout the world. Several approaches and measurements have been taken. Sioshansi and Pfaffenberger (2006) distinguish:

- *Restructuring:* reorganizing the roles of market participants (including regulators and institutions), not necessarily a "deregulation" of the market,
- *Liberalization:* synonym of restructuring with the aim to obtain competitive (sub)markets,
- *Corporatization:* make state-owned institutions act like private ones,
- *Privatization:* selling state-owned assets to private stakeholders,
- *Deregulation:* removing or reducing of sector specific regulation, however, a misnomer as competitive markets still need some regulation.

According to Jamasb and Politt (2005) successful liberalization generally requires: sector restructuring, implementation of competitive wholesale markets and retail supply, incentive regulation

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[1] Sioshansi (2006b) also defines four phases of liberalization: 1; problems in existing system; 2; what is broke and how to fix it; 3. implementation of new market rules; 4. ongoing adjustment of reforms.

[2] Further motivations include political campaigns (Newbery, 2000), public debt (e.g., in Victoria, Australia), the growing complexity of regulation, and a need for more decentralized decision-making processes.

of the grid, independent regulation, and privatization. A successful liberalization thus requires a proper initial restructuring, a large share of government initiative, and political and regulatory endurance to overcome the drawbacks.

2.1 UK and Norway: First Movers

2.1.1 UK[3]

The British electricity market has been state-owned since its nationalization in 1947. The Central Electricity Generation Board (CEGB) possessed the monopoly on generation and transmission, distribution was divided into twelve Area Boards, and the Scottish market consisted of two vertically integrated companies. The sector was subject to governmental cost-plus regulation. The coal industry was also state-owned and sold 75% of its output to national generators. Thus the UK power plant fleet was largely focused on coal (Newbery, 2005a).

With the third election victory of the Thatcher government in 1987 the privatization of the industry appeared on the political agenda. The end results were an ambitious privatization process and the breakup of the CEGB (see Green, 2006). With the passage of the Electricity Act of 1989 a fundamental step was taken to transform the nationalized industry into a competitive market. The CEGB was split into four companies of which three were sold to private stakeholders: one grid company (National Grid) and two generators (National Power und PowerGen). The larger share of generation (about 60%, 40 plants with 30 GW capacity) went to National Power, leaving the remainder for PowerGen (40%, 23 plants with 20 GW capacity). Initially it was planned that the twelve British nuclear plants would be privatized with National Power hoping that the resulting company structure would be economically viable. However, this idea was abolished and the nuclear power plants remain state-controlled as Nuclear Electric.

The twelve Area Boards were reorganized into twelve Regional Electricity Companies (RECs) that jointly owned National Grid. The market was opened stepwise with the aim of full supplier choice for all consumers in 1998. The price-cap regulation of network tariffs as well as price regulation of non-eligible customers was transferred to the Office of Electricity Regulation (OFFER, later OFGEM). Competition in the wholesale market was expected to be spurred by the mandatory pool that defined clearing prices via supply bids and demand forecasts by National Grid.

In the first years prices increased slightly and there was a significant entry of new market participants into gas-fired power plants (aka Dash for Gas) (Figure 1). This entry was supported via long-term contracts for gas and electricity. RECs were allowed to offer Power Purchase Agreements (PPAs) to Independent Power Producers (IPPs) and in return could obtain property rights. This allowed the RECs to reduce their dependence on the two large suppliers. The PPAs in turn allowed the IPPs to sign long-term take-or-pay natural gas contracts. The entry support led to a significant capacity

[3] This case study is based on Newbery (2005a), Stubbs and Macatangay (2002), Thomas (2004).

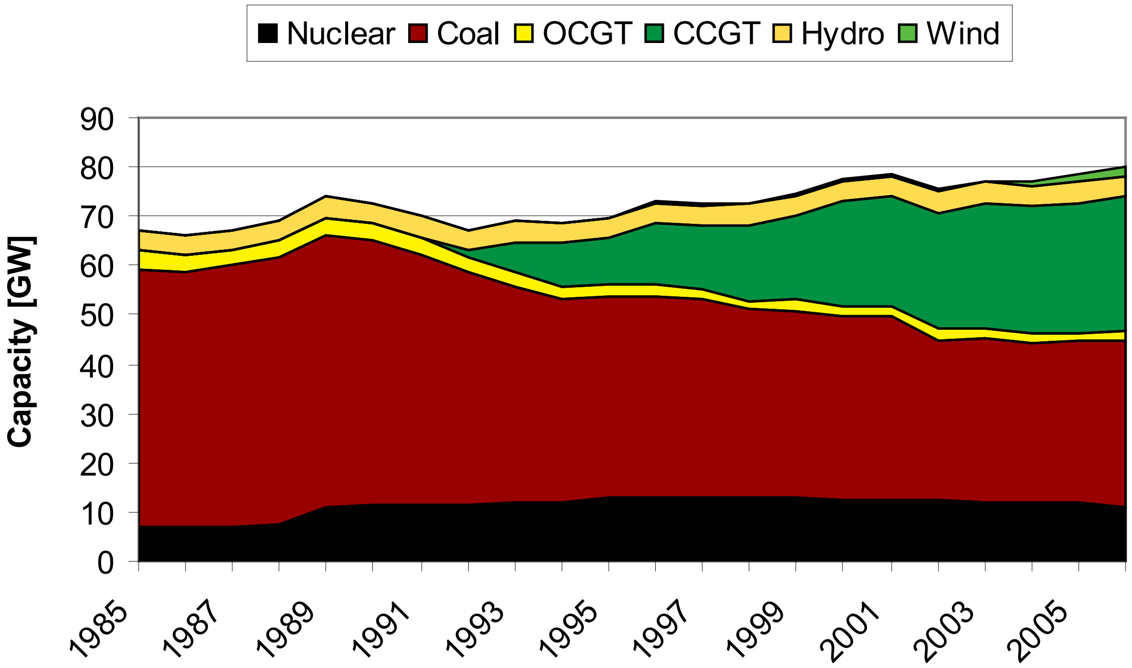
increase in natural gas-fired plants: within a few months 5 GW of new capacity had been contracted by IPPs and another 5 GW by the two incumbents.

In 1993 OFFER decided that the latest price developments meant a decoupling of fuel and electricity prices and consequently introduced a price monitoring as well as a divestiture of generation capacities to increase competition. In 1996 the state-owned nuclear plants were partly privatized (the older Magnox-reactors remained state-owned).

With the phase-out of the take-over protection for the RECs in 1995 a number of mergers and acquisitions took place that led to a rearrangement of the initially introduced separation between generation and supply.[4] Until 2002 all regional suppliers were acquired by other companies, and today the supply market is controlled by six vertically integrated suppliers while the generation segment is relatively competitive (Figure 2).

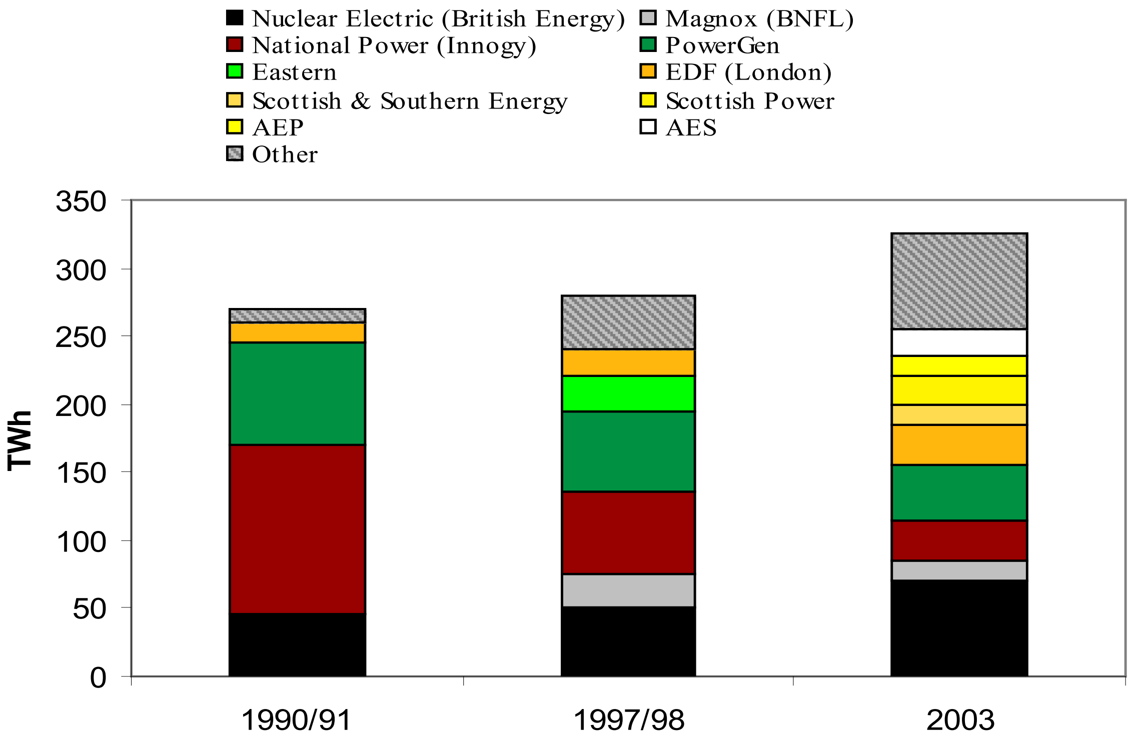
Another step in the reform process was the abolishment of the old pool model which was replaced by New Electricity Trading Arrangements (NETA) in 2001. Within NETA four voluntary, overlapping market segments exist: a bilateral market for long-term transactions, a forward market for standardized products, a spot market, and a reserve market. The main difference to the pool lies in the responsibilities of the system operators that have been reduced to network security leaving unit commitment and dispatch to the market participants. In 2005 the trading arrangements were extended to include the Scottish market. Thus with the „British Electricity Trading and Transmission Arrangements" (BETTA) the whole British island is coordinated by one wholesale market.

Figure 1: Generation capacities in Great Britain



Source: Eurostat

Figure 2: Generation in Great Britain



Source: Based on Green (2006, p. 2537 and p. 2538)

2.1.2 Norway and the Nordic Market[5]

The Norwegian market was the second to be fully liberalized in Europe. In 1990 the Norwegian Parliament approved the reform of the electricity market which was implemented in January 1991. The main motivations for the new energy market legislation were the need for cost savings and efficiency, price discrimination across consumer groups, regional price differences, and overinvestment. The core element of the reform was a decentralized free trade approach. The restructuring included a separation of the transmission system from the state-owned Statkraft into a new state-owned company, Statnett, while the remaining generation facilities were reorganized but remained with Statkraft. Other reforms included the introduction of a common carrier approach and grid access for third parties, retail opening, and the establishment of voluntary wholesale markets. Contrary to the UK, Norway had a spot market before liberalization in order to allow better management of the country's large hydro generation capacities (market for occasional power). The liberalized spot market Nordpool (operated by a subsidiary of Statnett) was, more or less, just the market for occasional power opened for market participants. Finally, markets for long-term transactions were also established.

[4] From 2000 on all suppliers had to fully unbundle their network operations.

[5] This case study is based on Amundsen and Bergman (2006), Amundsen and Bergman (2007), Friedholfsson and Tangeras (2008), Johnson (2003), and Midttun and Thomas (1998).

Unlike the UK, public ownership of Statkraft was maintained and thus a large share of generation facilities, about 30% of total production. The Norwegian approach aimed at introducing competition via structural competition and ownership concerns were considered a minor issue. Generation and supply were not split. The first phase of the market, 1991-1993, was characterized by low prices, a competitive market, and surplus supply. Similar to the British experience after liberalization, however, market power concerns gained ground as prices increased (Johnsen et al., 1999).

The other Nordic countries integrated their electricity sectors into the common Nordic market: Sweden joined in 1996, Finland in 1998, Western Denmark in 1999, and Eastern Denmark in 2000. All countries established state-owned system operators to manage the grid and balance supply and demand. The voluntary wholesale market Nordpool is jointly owned by the Transmission System Operators (TSOs) of the participating countries. Due to the coupling of several national markets no company has a dominant position although most of the large players are dominant in their home market (Table 1). The Nordic market was the first to introduce a combination of energy and transmission capacity auctioning. In case of a cross-border congestion signal by a TSO the bids in the market are allocated to several congestion areas pre-defined by country borders (in the case of Norway, up to four congestion areas). A different price is defined for each area. Transmission from one area to any other is priced with the difference of the area prices. Congestion within one area is managed via counter trading and re-dispatching of power plants. The resulting congestion rent is split between the TSOs.

The first major test of the Nordic market took place in 2002-2003 when unexpectedly dry weather reduced the available hydro generation, the major energy source in Scandinavia. Producers started to restrict supply in fall 2002 due to low reservoir levels and prices soon rose to three times the normal level. They remained high during 2003 before gradually normalizing. Although consumer prices also increased, politicians did not abolish liberalization or intervene in market processes. The high wholesale prices translated into higher retail prices and thus also to a slight demand reduction (particularly in Norway, less so in Sweden) that eventually helped to control the crisis. Post-crisis some researchers consider the event as proof of flawed markets, but others see it as a sign of market maturity (Newbery, 2005b).

Table 1: Generation structure in the Nordic countries (2004)

Company	Production [TWh]	Production share [%]	Home country
Vattenfall	70.5	18.6	Sweden
Fortum	50.7	13.4	Finland
Statkraft	34.3	9.1	Norway
Sydkraft (now E.ON Sverige)	34.0	9.0	Sweden
Pohjolan Voima	17.7	4.7	Finland
Teollisuuden Voima	15.9	4.2	Finland
Elsam (now DONG Energy)	14.6	3.9	Denmark
E2 (now DONG Energy)	10.8	2.8	Denmark
Others	130.5	34.4	
Total	**379.0**	**100**	

Source: Amundsen and Bergman (2007)

2.2 Continental Europe

Spurred by the liberalization in the UK and Scandinavia the European Commission (EC) undertook a reorganization of its electricity policy that resulted in the proposal of a liberalized, market-based, Europe-wide electricity market (Internal Electricity Market, or IEM). However, "Europe" is not a single entity with a central government to establish and administer new market arrangements. Therefore, the liberalization of continental Europe's markets can be summarized as a top-down approach in which the EC develops a road map for liberalization and monitors the process (Section 2.2.1), and the national governments choose how to implement its directives (Section 2.2.2). This political arrangement frequently obstructs the outcomes desired by the EC which is then forced to pursue new proposals.

2.2.1 The European Directives[6]

In the pre-liberalized world the EC regarded electricity not as a good but a service of economic interest. Thus it was not subject to the EU Treaties of Rome (1957) and Maastrich (1993) requiring open markets within the European Union. With the liberalization in UK and Scandinavia this view changed, especially after the European Court of Justice ruled that electricity is indeed a good (Meeus et al., 2005).

The process of liberalization began with the Electricity Directive 96/92/EC which was implemented in 1996 and had to be adopted by each country by February 1999.[7] This first directive, aimed at a gradual market opening, included:

- The introduction of "eligible customers" which could freely choose their supplier (at least 1/3 of the market in 2003)
- Three possible third-party access (TPA) models:
  - negotiated TPA
  - regulated TPA
  - single-buyer model
- Administrative unbundling of network activities, generation, and supply.

The EC did not address privatization, which was left to the national governments to resolve, since the utility sector in member states ranged from state-owned monopolies to regulated private firms.

The outcome of Electricity Directive 96/92/EC was unsatisfactory and a second directive was proposed at the European Council in Stockholm in 2001, which was later formalized as Directive 2003/54/EC. It reduced freedom of choice and shortened the deadlines to encourage convergence among the member states:

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[6] This case study is based on Green (2006), Jamasb and Politt (2005), Meuss et al. (2005), Moselle (2008), Newbery (2002), and Percebois (2008).

[7] A large body of institutions also became involved: Directorate-General of the EC developing and implementing European policies (DGTREN, DG Competition, DG Environment), the Florence forum, the Council of European Energy Regulators (CEER), the European Regulators' Group for electricity and gas (ERGEG), voluntary European associations (generators: Eurelectric, consumers: IFIEC, traders: EFET), and TSOs and their boards (UCTE, Nordel, ETSO).

- Eligible customers: all non-household customers free to chose from July 1, 2004; and all consumers free from July 1, 2007,
- Grid access: only regulated TPA permitted and a regulator required
- Unbundling: requiring legal unbundling for transmission after July 1, 2004, and for distribution after July 1, 2007.

The second directive ruled out the single buyer model and negotiated TPA, and required full market opening till July 2007 which aimed at largely increasing competition on electricity markets. However, declared market opening does not by definition mean effective competition. A particular focus was also put on the role of the regulator as a key market institution. The EC's second directive required the establishment of a regulator (if not already in place) and regulatory independence (see Larsen et al., 2006, on that issue). The second directive, only partially fulfilled in 2007, remains incomplete at the time of this dissertation in 2009.

A particular concern of the IEM development is the insufficient cross border capacity and the partly inefficient allocation mechanism. Starting with the liberalization process the Trans-European Energy Networks Program (TEN-E) was initiated. Since the first directive did not address the issue of cross border trade, to provide a framework and to establish more consistent trading, Regulation 1228/2003 was issued together with Directive 2003/54/EC. The regulation included a compensation mechanism for cross border electricity flows and harmonized cross border transmission charges and capacity allocation.

TEN-E together with Regulation 1228/2003 builds a framework for the cross border development. TEN-E, lists bottlenecks in need of upgrading, provides co-financing of feasibility studies, and to a small extent, co-financing of the actual grid investment. Following Regulation 1228/2003, revenues from capacity allocations are to be used for: (1) guaranteeing the availability of capacity; (2) network investments; or (3) reducing network tariffs. Regulators are often biased to take the latter option and reduce short-term tariffs (Meuss et al., 2005). The market-based allocation of interconnection capacity required by the regulation is now gradually being implemented which should lead to a full or partial coupling of national markets via implicit energy auctions (e.g., 2006, with France, Belgium and the Netherlands).

The EC issues yearly benchmark reports on the status of liberalization. The fourth report in 2005 concluded that although states were moving in the right direction, some were rather slow in doing so, and eight received a warning from the EC. The 2005 report also found that the market-based allocation of cross-border capacities should have been in place in 2004 but that 13 of the 25 most-congested connections had none (Meuss et al., 2005).

The EC's 2007 benchmarking report concluded that despite encouraging improvements, particularly in cross-border coordination, major barriers to achieving a single IEM still existed. EC legislation was insufficiently implemented; regulators were not empowered enough to encourage implementation of legal requirements; the industry needed to implement without compromise; and regulated energy prices were not resolved. The EC addressed the shortcomings in a third legislative package issued in September 2007:

- Unbundling:
  - ownership unbundling: the preferred option by the Commission (Torrit, 2008),
  - Independent System Operator (ISO): this option was included after France, Germany, and seven other member states have opposed the full unbundling in July 2007.
- Regulators:
  - harmonizing and strengthening the powers and duties of regulators,
  - ensuring independence,
  - mandating a co-operation between regulators.
- Creation of an European agency for the coordination of energy regulators (with limited powers, focused on cross-border issues),
- Establishment of an European Network for TSOs:
  - to develop harmonized standards regarding grid access,
  - to ensure coordination of operation,
  - to coordinate and plan network investments.

The third package fosters the integration and coordination between TSOs and regulators that has so far been voluntary. The slow progress of those voluntary approaches (e.g. the development of an Inter-TSO compensation mechanism for transit flows) and the slow regional integration of national markets were one reason for the formal adoption of the issue in the package. Only time will tell whether these problems can be resolved. Additionally, the relationship between the EU's ambitious environmental goals and the EC's market goals is of concern. From Table 2 we can conclude that Europe's desire for a single competitive market with many players, lower prices, and appropriate regulation is unfulfilled.

Table 2: Major electricity companies in continental Europe

Company	EDF France	SUEZ Belgium	EON Germany	RWE Germany	ENEL Italy	ENDESA Spain	IBERDROLA Spain
Sales in 2006 [bn €]	59	45	69	42	39	21	12
Capacity [GW]	131	48	54	43	46	39	38
Market share Origin	84%	75%	38%	30%	43%	44%	31%
Market share EU	24%	5%	14%	11%	10%	6%	4%
Main subsidiaries	- London Electricity - EnBW - Edison	- GDF	- PowerGen - Ruhrgas	- NPower - Thyssengas	- Endesa		- Scottish Power

Source: Percebois (2008)

2.2.2 The National Implementation

As discussed above, the EC's first directive failed to define a consistent program of implementation and subsequent legislative proposals and directives did not produce convergence among member states and a single IEM. Although the Commission has set guidelines in which way liberalization of the national markets shall proceed, it left a lot of issues open for the national governments to define. The directives make no recommendation or requirement regarding the actual wholesale market design. Thus either the national governments set up a market architecture (e.g. the mandatory pool in Spain) or left it to the industry to develop proper markets. Consequently, most of the trade transactions in the EU take place bilaterally and in over-the-counter (OTC) markets. Due to the intransparancy of those trades and the associated high transactions costs power exchanges were created due to private and partly public initiatives in most member states that provide reference prices and a standardized and anonymous trading platform. Furthermore, the topic of horizontal concentration has not been addressed and due to pre-liberalization structures the market concentration remained high in most member states. In addition, cross border mergers and acquisitions lead to a concentration process within Europe (Table 2).

Following, a brief review of the restructuring process in the important member states highlights the approaches national governments have taken to implement the directives.[8] Table 3 at the end of this section lists the key indicators for all member states.

Germany[9]

According to Germany's energy law of 1935 the country's electricity market was a private sector under state supervision. The federal Energy Industry Act of 1998 implemented the EC's first directive by requiring a non-discriminatory TPA and separate accounting sheets for companies but no real unbundling. German consumers were free to choose a supplier right from the start. Germany chose not to implement a regulator, basically allowing the market to self-regulate with an option of ex-post control by the government. This unsuccessful attempt to implement a TPA was abolished after the EC's second directive. Germany had to established an independent regulator via the federal Energy Act of 2005 which created the "Bundesnetzagentur" and transformed the negotiated TPA to a regulated TPA.[10] The 2005 law also required vertically integrated firms to unbundle.

The liberalization approach of the first phase increased the likelihood of cross-subsidies between the monopoly service and the competitive segments. Brunekreeft (2002) argues that the very low price level at the start of liberalization can be caused by vertical integrated firms keeping competitors out of the market via cross-subsidies. This may also explain why most of the new independent suppliers that entered the market in the first liberalization phase have vanished rapidly. The low prices together with excess capacity also contribute to the low market entry of new generation beside subsidized renewable

[8] The EC's benchmarking report of 2006 gives an in-depth country analysis of the implementation of its second directive (see EC, 2007a).

[9] This case study is based on Heck (2006).

[10] Companies with fewer than 100,000 customers can still be regulated by state agencies.

energies in the post-liberalization years. In 2000 exchange trading started in Leipzig and Frankfurt and was finally merged 2002 in the European Energy Exchange (EEX) in Leipzig which now provides the reference price for the German market. However, a large fraction of trades still takes place in bilateral and OTC transactions.

The German authorities' lack of concern about market power culminated in the allowance for the EON-Ruhrgas merger that combined the largest vertically integrated electricity and natural gas companies in Germany. Furthermore, Germany has four control areas which leads to inefficient doubling of network services particularly in the balancing markets (see Brunekreeft and Twelemann, 2005; and Riedel and Weigt, 2007). The balkanization within the country hampers efficient cross-border trade since there is no single platform for transaction to and from Germany. The EC considers Germany's high vertical and horizontal concentration and the prevailing cross-border congestion as the major barriers to new entry (EC, 2007a).

France[11]

Europe's second-largest electricity market is characterized by the dominant position of Electricité de France (EDF) of which the state holds a 90% share. EDF was a vertically integrated state-owned monopoly prior to the onset of market liberalization, and has never been privatized or split into several companies to foster competition. With the liberalization process in 2000 the regulator (CRE) was established which controls prices and investments. Network operation was transferred to RTE but the ownership remained with EDF. Legal unbundling took place under the EDF holding.

New generators tend to emerge slowly in a scenario with low-priced nuclear capacity and a dominant utility. To increase market competition a group of traders, generators, and grid companies formed the French energy exchange Powernext which associated in 2006 with the Belgian and Dutch exchanges in a trilateral market coupling.

The EC has criticized France. EDF's dominance combined with a retail policy to provide low, regulated tariffs in addition to competitive tariffs, make entry for new participants very difficult. In fact, the EC does not expect France to become competitive in the near future (EC, 2007a).

Benelux[12]

Until 1998 the *Dutch* electricity market was characterized by four large suppliers and 23 local distributers. The suppliers coordinated via the jointly operated company SEP to provide 80% of generation. All companies were regulated on a regional level. The liberalization process already underway before the first directive anticipated most of the changes demanded by the EC (Osterhuis, 2001). The federal Electricity Act of 1998 transformed the first directive into national law including legal unbundling, a regulated TPA, gradual opening of retail markets until 2004, and a regulator (DTe) which applied price cap regulation of network tariffs.

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[11] This case study is based on Glachant and Finon (2005), and IEA (2004).

The initial plan was to merge the four suppliers and SEP into one supplier that could compete in the European electricity market. However, due to different expectations of the four suppliers the merger idea was abandoned. Transmission assets remained with SEP and system operation was transferred to TenneT which is a state-owned company. Wholesale trade takes place in bilateral transactions and after 1999 on the energy exchange APX which TenneT purchased in 2001. On the generation side several mergers and acquisitions characterize the post-liberalization phase. The EC regards the Dutch market as one of the most liberalized in the EU.

The *Belgian* market was and is dominated by the private, vertically integrated company, Electrabel (now owned by GDF Suez), which controlled about 90% of generation and 80% of supply in the pre-liberalized market. In 1999 the first directed was transformed to national law that opted for a regulated market system without splitting the generation segment. Retail competition was introduced slowly, i.e. since 2003 consumers in Flanders were free to choose their supplier whereas Wallonia and Brussels opened up in 2007. Transmission service is tendered by the government for 20 years and is currently controlled by Elia. Due to the dominance of Electrabel and the resulting low liquidity of the Belgian wholesale market most transactions took place in bilateral trades.

The Benelux markets initialized a coupling to increase the efficiency of international trades: in November 2006 the Belgian energy exchange Belpex was established that is coupled with the Dutch APX and the French Powernext. Similar to Nordpool the three markets are cleared as a single entity in cases of unhindered cross-border flows, but are split up in cases of congestion. With the introduction of this trilateral market coupling price convergence sharply increased (De Jonghe et al., 2008).

Italy[13]

The Italian electricity sector, like the UK and France, was virtually controlled by one state-owned company (ENEL) since 1963. Starting with the Bersanie decree of 1999 that codified the first directive into national law ENEL was broken but not completely transferred to private hands, since the government retained a 60% share. Nevertheless, the Bersanie decree introduced competition in generation and (partially) retail, and separation of network activities by transferring all segments of the value chain to separate companies under ENEL SpA as the financial holding company.

In the generation segment ENEL was restricted to a maximum share of 50% and thus had to divest 15 GW: three of its generation companies had to be sold by 2003. The market was first split into a market for eligible customers and a market for all other customers. This market splitting was transitional, due to the deadlines mandated in the second directive. In 2001 a pool wholesale market opened which was "semi-compulsory" and supported by bilateral transactions. The new wholesale market included day-ahead, congestion, reserve, and balancing segments. A zonal system was used to address congestion problems.

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[12] This case study is based on London Economics (2004), Moselle et al. (2006), Osterhuis (2001), van Damme (2005), and Van Roy (2001).

[13] This case study is based on Ferrari and Giulietti (2005).

The network ownership was with ENEL Terna and network operation was transferred to GRTN (now GSE) in 1999 which guaranteed open access to the network according to the regulatory specifications of AEEG. Insufficient cross-border capacities limit the competitiveness of the Italian market which depends heavily on imports to meet demand. Congestion has increased significantly in recent years. The Marzano decree of 2002 simplified administrative barriers for new generation investments which indeed are taking place, but it will take some time to show the effects on the tight supply/demand situation. The Marzano decree also made GRTN the owner of the transmission grid to foster network investment incentives. The failure of Italy's grid in 2003 is partly a result of problems that have not been properly addressed during liberalization (Ferrari and Giulietti, 2005).

The Italian government's large share of ENEL hinders the development of competition since political interference too often constrains market developments. Despite such problems, the EC regards the Italian market as an attractive one, with the incumbent's dominant position and network congestion as the major issues needing resolution (EC, 2007a).

Spain[14]

In 1994 Spain passed the Spanish Electricity Sector Act (LOSEN) to reform the regulatory framework of its market and thus initiated at least some restructuring prior to the EC's first directive. However, actual implementation was delayed and in 1997 the Spanish Electricity Power Act implemented the first directive which opened the generation and retail markets to competition (with a gradual opening of the consumer market), guaranteed grid access, and legal unbundling. The Comisión Nacional del Sistema Eléctrico (CNSE) which had already been created with LOSEN was delegated as sector regulator.

The wholesale market was re-organized as a sequence including a uniform-priced day-ahead, several intra-day, and an ancillary market operated by Compañía Operadora del Mercado de Electricidad (OMEL). Participation is voluntary. However, consumers pay a capacity charge in addition to the energy price which is only re-assigned to market participants. This mechanism has discouraged extensive bilateral trading.

The pre-liberalized electricity sector consisted of a mixture of public and private companies. After several mergers the fragmented structure was replaced by two dominant companies (Endesa and Iberdrola) controlling about 80% of generation and retail. This high concentration bears a risk of market power abuse. However, via "Competition Transition Costs" payments[15] stranded costs were supposed to be recovered during a transition period and on the other hand market power mitigation was ensured (Newbery, 2005b) that kept prices down even during the shortage in winter 2000/2001.

The Spanish market provides an attractive environment for independent generators because the limited interconnection capacity to the lower-priced French grid restrains the high electricity prices. Furthermore natural gas is available via LNG imports. During the last several years new CCGT plants

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[14] This case study is based on Crampes and Fabra (2004).

[15] A variant of contracts for differences (CfD).

came online. Gas Natural, benefiting from its activity in the gas market, has been an active new entrant in the generation market.

Accompanying the Spanish liberalization the international electricity exchange was opened for market participants. However, the limited available capacities restrict the competitive potential of cross-border trade. Several projects to increase capacity between France and Spain have been delayed or abandoned. In 2001 the Portuguese and Spanish governments agreed to create a single Iberian Electricity Market (Mibel). It actually started in July 2007 with two divisions managing the derivate market (OMIP, Portuguese division) and the day-ahead and intraday market (OMEL, Spanish division). Both divisions are expected to merge into one Iberian Market Operator (OMI). The markets are managed with respect to transmission constraints. Thus in cases of congestions the single market is split into submarkets after Nordpool or the trilateral coupling of France, Belgium and the Netherlands (Capelo at al., 2008).

Table 3: Indicators of the liberalization of the IEM, 2005

Country	Unbundling		Market Model	Balancing	Capacity Top 3	Retail Top 3
	Trans.	Dist.				
Austria	leg.	leg.	Bilateral	market	75%	67%
Belgium	leg.	leg.	Bilateral	regulated	95%	90%
France	leg.	man.	Bilateral	market	95%	88%
Germany	leg.	acc.	Bilateral	market	70%	50%
Italy	own.	leg.	Bilateral	reg/TSO	75%	35%
Netherlands	own.	leg.	Bilateral	market	80%	88%
Portugal	own.	acc.	Bilateral	regulated	80%	99%
Spain	own.	leg.	Pool	market	80%	85%
UK	own.	leg.	Bilateral	market	40%	60%
Denmark	leg.	leg.	Hybrid	market	40%	67%
Finland	own.	acc.	Hybrid	market		30%
Norway	own.	leg./acc.	Hybrid	market		70%
Sweden	own.	leg.	Hybrid	market		44%

Source: Green et al. (2006)

2.3 United States[16]

The liberalization in the US has one major similarity with the European one: due to the absence of a centrally planned restructuring process liberalization in the US is characterized by diverging national processes.[17] Today the US is a mixture of liberalized states, states under traditional regulation, and states in delayed transition (see Figure 3).

The pre-liberalized US electricity market was characterized by a large number of private vertically integrated utilities which were primarily state-regulated. The large number of small utilities and operating control areas as well as state regulation limited investment in transmission capacity across

[16] This case study is based on Joskow (2005, 2006), Newbery (2005b).

[17] Furthermore, the US and EU15 electricity market are also of similar extend with about 600-700 GW and both markets are split into three synchronized areas (Newbery, 2005b).

regions. The US relied largely on state initiatives supported by the Federal Energy Regulatory Commission (FERC) and the Department of Energy (DOE) to promote national liberalization. In essence restructuring consisted of a transmission policy defined by FERC and DOE that opened networks to competition and state-level restructuring of wholesale and retail markets.

The US has three synchronized AC network areas which are divided into ten Regional Reliability Councils. These are further divided into 24 sub-regional reliability organizations. Following the northeast blackout in 1965 the reliability organizations and the North American Electric Reliability Council (NERC) were created to develop voluntary operating reliability criteria and coordination of long-term planning. However, NERC lacked the authority to set investment incentives. The roles of the councils, NERC and the reliability rules have not been adopted within the liberalization process which is one reason why there is an increase in transmission congestion in the US. The blackout of 2003, however, forced the federal government to prioritize grid planning.

Pre-liberalization, transmission pricing was state-regulated and most utilities provided "voluntary" transmission service for neighboring utilities which were regulated by FERC but the commission had no authority to require utilities to allow grid access to third parties.[18] The federal Energy Policy Act of 1992 removed legal barriers with respect to ownership restrictions (discussed below) and expanded FERC's authority to demand that utilities provide transmission service. With the state restructuring initiative in California FERC realized that transmission access needed to adapt to a completely new market setting and thus ordered two major rules in 1996. Order 888 requires transmission owners to provide third parties grid access at cost-based prices. FERC also issued a weak form of separation by restricting contracts between TSOs and affiliated companies. Order 889 required utilities that are involved in interstate transactions to participate in an Open Access Sametime Information System (OASIS) which provides necessary information for transmission customers. It also requires utilities to functionally separate transmission and unregulated wholesale functions.

The initiative for these two rules took place before many states began to consider major restructuring. The development of competitive wholesale markets and the consequent need for transparent system operations impelled FERC to issue Order 2000, in December 1999. The goal is a regional transmission platform that supports competitive wholesale markets and:

- Transfers system operation to independent operating entities (Regional Transmission Organizations, RTOs)
- Increases the regional scope of network operations
- Assigns responsibilities for maintaining short-term reliability to the independent entities
- Defines RTOs' minimum functions.

All TSOs within the jurisdiction of the FERC had to join one RTO which in principal meant to expand the ISO models established in the northeast (New England, New York, PJM) to the rest of the US. It also reflected FERC's missing authority to demand ownership restructuring since the transmission assets would remain with the TSOs.

The timing of Order 2000 shortly before the meltdown of the California wholesale electricity market was crucial given the demanding requirements. The general slowdown of the liberalization process also slowed reforming the transmission system. Thus Order 2000 did not lead to a complete transformation to RTOs. Frustrated with the implementation FERC issued a proposal for a Standard Market Design (SMD) in 2002. SMD required that ISOs would operate locationally priced wholesale markets; complete unbundling of transmission service; regional transmission planning; market monitoring; and resource requirements. SMD immediately faced strong opposition particularly in southern and western states and FERC soon retreated to focus instead on improving Order 2000.

The second aspect of liberalization in the US is the restructuring of wholesale and retail markets, mostly upon state initiative. It was initiated in 1978 with the Public Utility Regulatory Policy Act (PURPA) that allowed independent generation investments and until the mid 1990s 60 GW of new capacity (about 10% of the US generation capacity) joined the market (mainly in the Northeast, California, and Texas). FERC also issued regulations to ease the administrative barriers for IPPs. Beginning in 1998 with New Hampshire, Massachusetts, Rhode Island and California state restructuring began to foster wholesale and retail competition which enabled new generators to enter the market.

After 1996 about 100 GW of generation capacity had been divested, another 100 GW transferred to unregulated companies (see also Ishii and Yan, 2007; and Bushnell et al., 2005), and between 1999 and 2004, 200 GW of new capacity had been constructed of which 80% was unregulated. However, many merchant investors have encountered financial difficulties and the quantity of new capacity is declining. The restructured markets face a gap between what generators earn and what they need to recover their fixed costs. This is partly due to the inadequate wholesale market design including very low price caps[19] and out-of-market actions by the RTOs for reliability reasons. There is an ongoing debate about developing adequate wholesale markets for capacity investment (e.g., see Cramton and Stoft, 2005).

Retail competition was introduced in some states, mostly those with the highest regulated retail prices in 1996. The monthly utility bill shows a regulated component (network services) and a competitive component (generation and supply). Incumbents were generally required to continue to offer a regulated “default service”. Overall the switching numbers of household consumers have been low, with the exception of Texas and New York (Sioshansi, 2008). Only large industrial consumers have really exploited to the opportunities to switch suppliers. Some market critics fault state regulators for complicated rules that the average consumer finds difficult to understand, and failing to penalize marketers who neglect to inform consumers of the costs of switching.

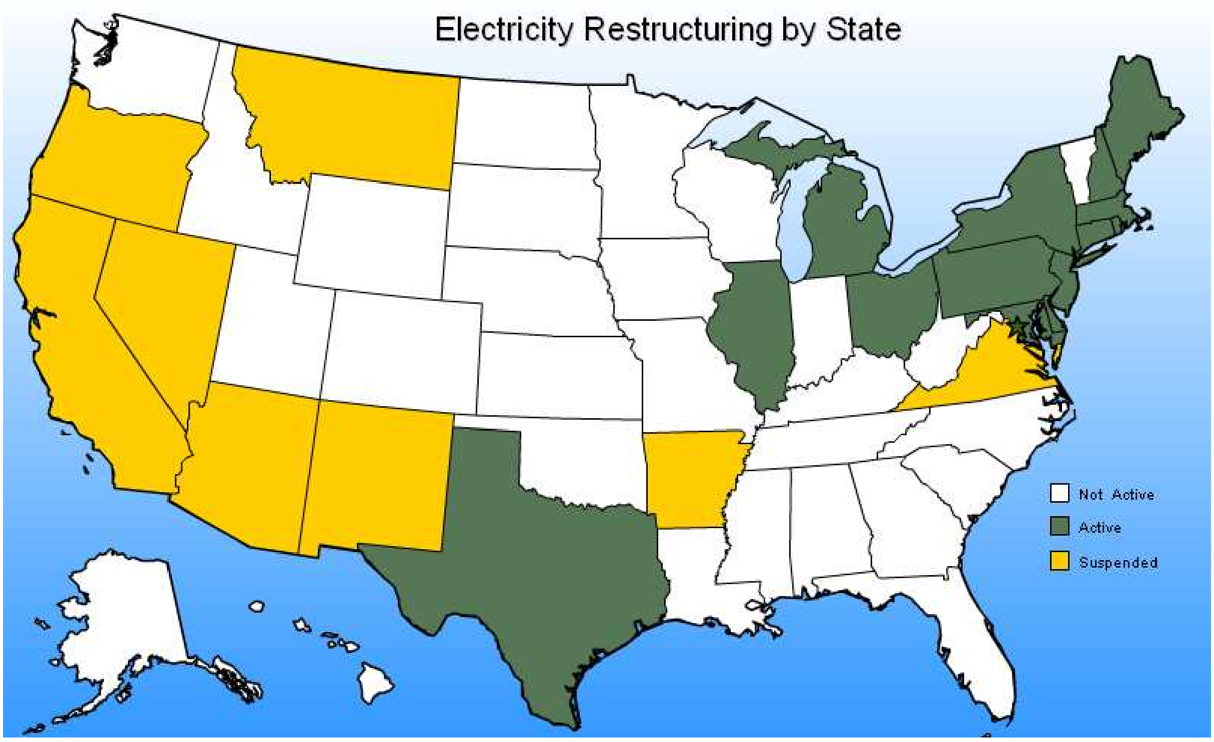
Absent national guidelines, the states took different paths. California adopted a pool-based system, divested incumbent generation, and introduced an ISO. However, the market design was so flawed that it finally broke down in 2000-2001 (e.g., see Blumstein et al., 2002; Joskow and Kahn, 2002; and

[18] The Federal Power Act of 1935 gave FERC jurisdiction over prices and terms of interstate transmission services.
[19] And similar measurements taken to mitigate market power.

Kumkar, 2002). In the northeast ISO-based markets with locational prices gradually developed. PJM started operating in 1998 and New England opened in 1999. In PJM vertical integration between retailers and generators remained (see Mansur, 2003) while in New England divestiture of generation assets from vertical integrated utilities occurred. However, many retailers then signed long-term supply contracts with the firms to which they divested. Texas adopted a system like NETA in the UK that relied heavily on bilateral transactions; only part of the state is ISO-adminstered (Adib and Zarnikau, 2006).

Following the California crisis and the eastern blackout in 2003, restructuring efforts in many states were suspended or cancelled even as the northeast and Texas continued to move forward. In summary, the US is a patchwork of fully liberalized markets, hybrids, and no liberalization at all (Figure 3).

Figure 3: Status of restructuring in the US



Source: EIA (2009)

2.4 Other Countries

The first country to introduce a market reform was Chile in 1982. However, the motivation for reforms in developing countries is often the need to increase capital for infrastructure maintenance and expansion. Between 1990 and 1999 private investments occurred in about 75 developing countries, amounting to 160 bn €, with the majority in the generation segment (Jamasb, 2006).

The restructuring processes generally followed the sequence of regulation, restructuring, and privatization. Beside those key elements many developing countries have specific structural issues.

Often developing countries have small electricity systems[20] that may favor approaches like the single buyer model. Often, political and institutional settings are unstable, enforcement of property rights and judicial independence is scarce or non-existent, and corruption, nepotism and opportunism make effective restructuring more complicated than in developed countries. Resources for specialized regulators and agencies may also be scare given the limited budgets. International development organization can play an important role in supporting the institutional settings and in promoting renewable energies.[21] Table 4 summarizes the restructuring processes in several developing countries. Victor and Heller (2007), Jamasb (2006), and Jamasb et al. (2005) provide an overview about the restructuring process in developing countries.

The restructuring process also did not stop before former centrally planned economies like Russia or still more or less centrally organized ones like China. The later emerged from a totally state-owned monopoly towards a more competitive setting but is still within the process (Xu and Chen, 2006). The Chinese electricity sector was until 1985 a state monopoly combining government and business function. In 1985 the government encouraged entry of new investors into the market but did not change the management system or the vertical integration. In 1997 structural problems in the industry led to a separation of government and business functions and some pilot competition projects. Finally in 2002 an electricity reform was initiated to break the monopoly structure and introduce competition to improve efficiency and lower costs. The State Power Corporation is split into two grid operators and five generators and a regulator supervises the market. Nevertheless, up to now only the generation segment is partly restructured. The establishment of wholesale markets, retail competition and open grid access are still in process (Xu and Chen, 2006).

Russia, as the fourth largest electricity producer in the world (behind the US, China, and Japan), had a transformation process underway in the 1990s when the Soviet Union fell apart and the centralized industry was opened for privatization. However, the electricity sector faced serious problems, including needed investments into infrastructure, cross-subsidies, and too-low, regulated tariffs. Although the implementation of a reform in 2001 retained strong regional elements, the goal was to attract foreign investment by introducing competition upstream and downstream, regulated grid access, and a stable regulatory environment (Engoian, 2006). In the first phase (2001-2005) a system operator and a dispatch center were established. However, much remains to be accomplished, such as the independence of the regulator which appears unlikely within the country's political framework.

The potential benefits of improved performance of liberalized electricity markets has also motivated other developed countries. Soon after the liberalizations in England and Norway, the Australian states Victoria (in 1994) and New South Wales (in 1996) set up pools, and New Zealand began its wholesale electricity market in 1996 (Al-Sunaidy and Green, 2006). Japan opened its electricity market to independent producers in 1995 due to high electricity prices and is slowly approaching restructuring

[20] About 60 developing countries have a system with less than 150 MW peak (Jamasb, 2006).
[21] Many developing countries have a high potential for renewable energy sources, but are still depending on energy imports.

(Asano, 2006). In Canada, Alberta and Ontario introduced competition. However, Ontario rescinded some of its liberalization due to public pressure following price increases.

With the extension of the European Union East and South-East Europe are on the way to liberalized electricity markets (Pollitt, 2009). Finally, Turkey has initiated restructuring (in 2001) and although the market structure has not changed dramatically, the process is still ongoing (Erdogan et al., 2008; Bagdadiohlu and Odyakmaz, 2009). Israel is proceeding with restructuring program in the years ahead (Tishler et al., 2008).

Table 4: Electricity liberalization in developing countries

Country	Liberalization	Capacity Top 3	Network arrangements	
			Trans	Dist
Argentina	1992: restructuring, wholesale competition and IPPs 1992/93: privatization	30%	rTPA	rTPA
Brazil	1995: partial restructuring 1999: wholesale competition and IPPs	40%	rTPA	rTPA
Chile	1982: restructuring 1985: privatization 1997: IPPs	67%	nTPA	nTPA
Colombia	1995: restructuring and wholesale competition 1996/97: privatization and IPPs	50%	rTPA	rTPA
Peru	1994: restructuring 1995-99: privatization, wholesale competition, and IPPs	100%	rTPA	rTPA
Bolivia	1995: restructuring 1996: wholesale competition 2000: IPPs	70%	rTPA	rTPA
El Salvador	1994/95: IPPs (pre-reform) 1998: restructuring 1998/99: privatization, wholesale competition	83%	rTPA	rTPA
Panama	1998: restructuring and privatization 2002: wholesale competition	82%	rTPA	rTPA
Pakistan	1996/97: IPPs 2000: restructuring	95%	SB	SB
Thailand	1995: privatization 1996: IPPs	100%	SB	SB
Malaysia	1995: IPPs 1997: restructuring	62%	SB	SB
Indonesia	1996/97: IPPs 2003: restructuring	100%	SB	SB

Source: Jamasb (2006)

Table 5: Electricity liberalization in developed countries

Country	Liberalization	Unbundling	Regulation	Retail opening Started	Full
Australia	1994: Electricity Industry Act of Victoria	own.	price cap	1994	n.a.
Canada	1998: Ontario, Energy Competition Act	own.	cost-based	1996	n.a.
Czech Republic	2000: Energy Act	leg.	price cap	2002	2006
Greece	1999: Electricity Law	leg.	cost-based	2001	2007
Hungary	2001: Electric Power Act	leg.	price cap	2003	2007
Ireland	1999: Electric Regulation Act	leg.	price cap	2000	2005
Japan	1995: Amendments to Electric Utility Law	acc.	cost-based	2000	-
Korea	2000: Act on Promotion of Restructuring of the Electric Power Industry	leg.	cost-based	-	-
Mexico	IPPs allowed	none	n/a	-	-
New Zealand	1992: Energy Ac and Companies Act	own.	ex post	1993	1994
Poland	1997: Energy Act	man.	cost-based	1998	2005
Slovakia	1998: Law on Energy	leg.	price cap	2002	2005
Turkey	2001: Energy Market Law	leg.	revenue cap	2002	2011

Source: Al-Sunaidy and Green (2006)

2.5 Lessons Learned

As is evident from the review above, electricity markets around the world are in various stages of liberalization. In general, reforms to create a new institutional arrangement that is able to provide long-term benefits have not been achieved everywhere. The question for policy-makers is whether liberalization was (and is) worth the effort. Peerbocus (2007) reviews empirical studies that assess the reforms in electricity markets. One problem of estimating the potential benefits is the design of a proper counterfactual benchmark that represents the state of the world if restructuring would not have occurred. The cost-benefit studies undertaken show that there are significant potential benefits to market liberalization. However, if the reforms are not properly implemented there is great risk of significant potential costs from market failures as evidenced by the California crisis. A further concern is who benefits from the efficiency gains: Newbery and Pollit (1997) show that the restructuring of the British electricity market leads to significant benefits of which the majority is allocated to producers. By contrast Littlechild (2007) estimates that the gains are shared about equally between producers and consumers.

Given the experiences of the last two decades it is clear that there is no standard formula to ensure a successful outcome, and that in the end variations of well-functioning market designs are possible. Joskow (2008) lists desirable features which he calls the "textbook model". The textbook model shows that restructuring is indeed a demanding task for governments to implement:

- Privatization of state-owned monopolies
- Vertical separation of competitive and regulated segments
- Horizontal restructuring of the generation segment

- Implementation of a single independent system operator for the network
- Creation of voluntary public wholesale markets
- Active demand side institutions
- Efficient grid access and capacity allocation
- Unbundling of retail tariffs
- Creation of independent regulatory agencies and establishment of market monitoring
- Transition mechanisms.

Not all markets have implemented these key elements, yet they are functioning quite well, e.g., the Nordic market has no full privatization. Every set of reforms must fit the underlying market characteristics (see Woo et al., 2003) and different approaches must also reflect the political understanding of the reform process. Thus Newbery (2002) sees deregulation in the US as a relaxation of regulatory price control recognizing a high probability of market power whereas the EU approach introduces wholesale markets assuming that they will be naturally competitive.

Percebois (2008) shows that liberalization does not go hand in hand with price reduction and that some consumers may bear a net loss of surplus due to price convergence. Joskow (2008) also summarizes further lessons learned from international experiences and hints at ongoing discussions and unresolved problems:

- The textbook model provides a sound guideline for reforms and a departure is likely to lead to performance problems
- Energy markets should be integrated with allocation of transmission capacity (locational pricing approach)
- Market power should be dealt with by ex-ante structural methods
- Network regulation of transmission and distribution is important but often neglected
- Well-functioning transmission investment framework remains a challenge
- Resource adequacy is an ongoing issue
- Retail market design and default service conditions are important for successful retail programs
- Vertical (re)integration of generation and supply is likely to be efficient, but has inherent market power problems
- Demand response in spot markets needs more attention
- Deregulation is an ongoing process ("reform of reforms")
- Strong political commitment is necessary for a successful transformation.

Sioshansi (2006a, b) and Sioshansi (2008) summarize the points to be clarified in future research. They emphasize the resource adequacy problem and whether capacity markets are needed for generators to recover their fixed costs and provide adequate signals for investments (e.g., see Cramton and Stoft, 2005; and Adib et al., 2008). Still unresolved is the question of vertical integration of generation and supply. On the one hand it provides a hedge for generators to manage price volatilities

(Chao et al., 2008), but it reduces market liquidity and may increase market power abuse. The problem of resource adequacy also translates into transmission and distribution although in this case a proper incentive regulatory approach is needed.

Sioshansi (2006b) sees diverging developments in the role of the regulator: the purpose can either be to provide a level playing field for market participants and monitor the market (an approach most markets have taken), or as a central agency to set concrete rules and steps to follow (an approach in some countries that has produced disappointing liberalization results). Other topics of future development include the progress of market integration, ways to promote and integrate demand response in the wholesale markets, promotion of renewables and the question of centralized versus decentralized markets, and finally the ongoing climate change debate and its impact on electricity markets.

What will the future structure of electricity markets look like? Will there be full liberalization, limiting regulation to networks and monitoring tasks, or will it swing back to integration and strong regulation of all segments? Following Correlje and de Vries (2008) the end result may be hybridized structures.[22] Hybrid markets generally fall into three categories:

- Liberalized markets that are not fully privatized
- Privatized markets that are not fully liberalized
- Markets where the regulator intervenes in the key decisions of market players.

Although these types of markets were initially considered to represent transition stages it appears that they may become permanent in some countries, due to slowing progress, lack of political will, more pressing economic problems within a country, and so on. Whether this is a serious problem is still a matter of debate.

3 Modeling of Electricity Markets

Modeling electricity markets has accelerated in recent years because of the growing need for more sophisticated methodologies. Higher computational speeds now allow quicker and more complex simulations to be performed. Prior to liberalization operational models were applied for cost-based or pure technical analyses, but they were inadequate for understanding the emerging market structures. As the former centralized planning approach shifted to a more decentralized focus, cost-based approaches were replaced by profit maximization, and ex-post regulation was transformed to ex-ante benchmarking. A growing number of interest groups and stakeholders, including former monopolized or regulated firms, new entrants, new system and market operators, regulators and governmental agencies, and researchers and academics welcomed the new analytical tools.

In the context of market economics, research can draw upon a large body of economic modeling theory and application. However, the specific characteristics of electricity (e.g., non-storability,

[22] Following Sioshansi (2008) the word „hybrid“ may be a bad choice as the worst instead of the best elements of regulation and competition may be combined.

inelastic demand) present a challenge to apply those principals and derive robust model results. Furthermore, market outcomes are influenced by electro-technical, thermodynamic, and mechanical restrictions that require a combination of economic and technical modeling.

The wide array of interest groups and the underlying characteristics are reasons for the large variety of model techniques applied to different aspects of electricity markets. Several studies that provide an overview of the modeling approaches used for electricity markets (see Nanduri and Das, 2009; Ventosa et al., 2005; Day et al., 2002; Kahn, 1998; and Smeers, 1997) attempt to classify them according to some arbitrary criteria based on mathematical characteristics or on application orientation. The sections below classify the market models according to model structure and discuss their applications. This review of electricity market models is intended to provide a rough guideline of the recent developments that have been addressed by modeling approaches.

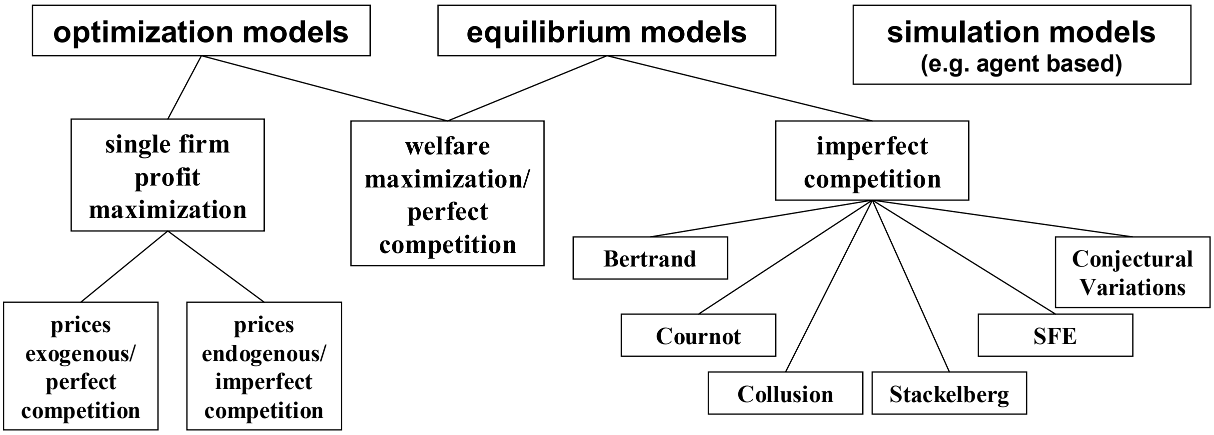
3.1 Classification of Model Types

Following Ventosa et al. (2005) electricity market models can be classified according to their structure into three types: optimization, equilibrium, and simulation models. These can be further categorized according to the market environment assumed: perfect or imperfect competition. Figure 5 is a schematic of this classification.

Optimization models maximize or minimize a specific objective which is typically a single firm's profit subject to technical or economic constraints. If one assumes perfect competition the market price is an exogenous variable while under imperfect competition the firm can influence market prices. One can also examine the entire market via welfare maximization or cost-minimizing approaches. To analyze a market with several players, particularly an imperfect market setting, an equilibrium model is best since it can combine different players' market behaviors. Strategic behavior can be defined ranging from classic Betrand and Cournot competition to the mathematically more demanding Supply Function Equilibrium (SFE) model.

Simulation models can be applied if the considered problem becomes too complex to apply a formal equilibrium model. They typically represent market agents via specific assumptions and rules and thus allow a wide array of strategic behaviors and market representations.

Figure 4: Classification of model types



Source: Following Ventosa et al. (2005), Day et al. (2002), and Smeers (1997)

3.1.1 Optimization Models

The main advantage of optimization models is the availability of optimization algorithms that allow large-scale models with a multitude of technical or economic restrictions. However, the focus on a single objective value reduces the complexity these models can obtain with respect to market behavior.

The simplest form of an optimization model is profit maximization under fixed deterministic market prices which resembles perfect competition. This problem can generally be expressed as a linear program (LP) or mixed integer linear program (MILP). The model type can be improved by introducing uncertainty of the price e.g., via a distribution function. This method bears similarities to risk management methods and thus allows analyses of risk hedging methods. On a single-firm level the next family of model types includes the possibilities to influence the market price assuming the supply of its competitors as given (leader-in-price model). Again, the model type can be differentiated in deterministic and stochastic models depending on the representation of the demand function (Ventosa et al., 2005).

Another branch of optimization models addresses whole markets by maximizing the total welfare given the supply and demand functions, or by cost minimization given a fixed demand level. The obtained price and quantity results are numerically identical to a competitive equilibrium setting. However, the formulation via a welfare maximizing or cost-minimizing social planer does not include the single firm's profit decisions or trader activities. Hence it represents a completely different type of market representation in economic terms. The advantage of an optimization formulation lies in the simplicity of adding additional constraints (power flow calculations, network constraints, etc.) which would otherwise need a complete reformulation of an equilibrium model. Furthermore, mixed integer formulation can be addressed in an optimization framework but presents a large obstacle in equilibrium analyses.

3.1.2 Equilibrium Models

Equilibrium models simultaneously satisfy each of the considered market participants' first order conditions of their profit maximization (Karush–Kuhn–Tucker/KKT conditions) and the market clearing condition equaling supply and demand. The KKTs and market clearing define a mixed complementarity problem (MCP) or can be formulated as variational inequalities. The solution to an equilibrium problem (if it exists) satisfies the Nash equilibrium condition that no market participant wants to alter its decision unilaterally (see Day et al., 2002).

The advantage of equilibrium models compared to optimization models is the capability to address several market participants' profit maximization simultaneously. Thus insights can be gained about the impact of strategic behaviors on market outcomes. The main drawback is that they require convex optimization problems for the players to guarantee that the KKT conditions define an optimal solution and the existence of a market equilibrium. The convexity assumption is incorrect for many specific problems in electricity markets, e.g., the unit commitment process (requiring binary decisions), or AC power flow dispatch. Therefore equilibrium models generally make strong assumption to keep their problems convex. Similar to optimization models the solver algorithms for equilibrium models are capable of handling large datasets and thus allow the application of strategic market models to large-scale approximations of real markets.

The strategic interactions of competitors within the market can take several forms following the concepts of game theory and industrial organization. Day et al. (2002) differentiate six types:

- Betrand Strategy (gaming in prices): the decision variable is the price offered by the firm
- Cournot Strategy (gaming in quantities): the decision variable is the supply by the firm given a demand function
- Collusion: the principal idea is a maximization of joint profits of the colluding firms; the concrete collusion design with possible side payments and penalties can vary
- Stackelberg: a "leader" is defined that correctly accounts for the reaction of "followers" that do not consider how their reactions affect the leader's decisions,
- Conjectural Variations: the reaction of competing firms to a firm's own decisions is anticipated via functional relations,[23]
- SFE: firms compete by bidding complete supply functions instead of a single supply.

In addition to imperfect markets, equilibrium problems can also be applied to analyze a perfect competitive market by assuming that prices are fixed and the firms are profit maximizers.

[23] General Conjectural Variations assume that the output of other firms depends on one's own output decision and include Cournot, Collusion, and Competition as special cases. Conjectured Supply Functions assume that the output of rivals is anticipated to respond to the price. They can be seen as a generalization of the Stackelberg setting and superficially resemble the SFE (see Day et al., 2002, p. 599).

3.1.3 Simulation Models

The complexity of electricity markets often requires simplifications to obtain a solution within a equilibrium framework. Simulation models provide a flexible setting for market analysis when formal equilibrium approaches are no longer feasible. Agent-based models have emerged as a preferred tool for dynamic market analyses. Static equilibrium approaches typically neglect the fact that market participants base their decisions on historic information which accumulates over the market processes. Agent-based approaches can overcome these drawbacks and provide a compromise between fully flexible linguistic models and restrictive analytical models (Richiardi, 2003).

The main feature of agent-based modeling is that market participants are modeled as computational agents that are goal-oriented and adaptive. Following Tesfatsion (2002) the procedure is as follows: (i) define a research question to resolve, (ii) construct an economy with an initial agent population, (iii) define the agents' attributes and the structural and institutional framework, (iv) let the economy evolve over time, and (v) analyze and evaluate the simulation results.

Tesfatsion (2006) divides four strands of agent-based research: 1. the empirical or descriptive strand analyzing why and how global regularities result from agents' interactions; 2. the normative strand using agent-based models for market design analyses; 3. the theory generation; and 4. improving the models. The majority of electricity-related papers are focused on the market design analysis.

Weidlich and Veit (2008) provide a review and critical assessment of agent-based electricity market models. Their comparison shows these similarities and differences of applied agent-based approaches:

- Majority of models neglect transmission constraints
- Majority of models assumes demand side as fixed
- Agents' learning task is mostly set to profit-maximizing bids
- The learning representation and modeling of behavior follow no trend
- Majority of studies focus on market power and market mechanisms.

Weidlich and Veit (2008) also note that agents' learning behavior differs in most models; usage of one specific learning algorithm is seldom clearly justified; and most papers miss an empirical model validation. Another open question is the interpretation of results. Generally the simulation is run for a specific number of iterations and the last ones are aggregated as model outcome. The flexibility of agent-based approaches is a large drawback since the heterogeneity limits the comparability. Nevertheless, they represent an interesting opportunity for modeling complex market structures which make them well suited for electricity markets.

3.1.4 Other Model Types

In addition to these classifications combinations of several types are possible. A maximization program with equilibrium constraints (MPEC) requires a single objective to be optimized (e.g., a single firm profit) that is subject to some form of equilibrium (e.g., the locational price formulation of an ISO). This approach can be used to obtain a Stackelberg game solution. However, the computational ability to solve those models is still limited.

If the single objective is replaced by more objective functions that are maximized simultaneously, one has an equilibrium problem with equilibrium constraints (EPEC). This model type is, in principle, fitted to represent the complex nature of market interactions without the limiting restrictions of Stackelberg games to define a leader. However, the computational capacities for EPECs are very restricted and further progress on the algorithm side is necessary to enable applications to electricity markets.

Additional mathematical methods are applied to transform the demanding MPEC and EPEC approaches into "simpler" problems that can be solved with the existing algorithms. Gabriel and Leuthold (2009) present an approach to solve two-stage Stackelberg games based on disjunctive constraints and linearization which in the end leads to a replacement of the MPEC by a MILP, thus allowing the inclusion of binary problem types like unit commitment. Other methods include Lagrangian relaxation to decompose large-scale problems into smaller sub-problems.

With the increasing attention on environmental and cross-sectoral issues, general equilibrium (CGE) models can be used to analyze electricity markets and simultaneously assess the impact on the economy as a whole (e.g., see Wing, 2006, and Böhringer, 1998).

3.2 Application of Models in Electricity Markets

Although most research questions can be analyzed with each of the types described above, several modeling techniques are more suited for one topic than another which is largely defined by the necessary technical detail level required (which often makes equilibrium approaches obsolete) and the desired degree of market competition and company behavior (which favors equilibrium approaches).

Following a structuring of research topics analyzed with modeling techniques as well as a snapshot on applied studies is presented. Further topics not mentioned in detail include the improvement of modeling approaches, comparison of models, and technically oriented models. The structuring of these research fields is arbitrary. Researchers have invented a variety of structural taxonomies, for example, Ventosa et al. (2005) present structuring models according to the degree of competition, time scope of the model, uncertainty modeling, interperiod links, transmission constraints, generation system representation, and market modeling. Hobbs (2007) distinguishes large-scale models for grid operation and planning that apply numerical solutions; very small models for gaining insights within policy debates by applying easily-tracked structures; and "in-between" models for forecasting and impact analyses of policies. Based on an evaluation of energy model research in 2006, Hobbs (2007) also reviews the need to develop modeling capabilities that are presently unavailable.

3.2.1 Market Power in Wholesale Markets

Unfortunately, most liberalized electricity market are dominated by a few large suppliers and market power remains a permanent concern. Since static approaches like the Herfindahl-Hirschman Index (HHI) or other concentration measures are insufficient to capture the dynamic nature of electricity markets, modeling approaches have been widely used to assess market power and all model types have been applied in this critical area of research. Optimization models are typically limited to reproduce the perfect competitive prices and quantities; nevertheless the definition of a competitive benchmark via these models provides an estimation of price markups if compared to observed market outcomes (e.g., see Joskow and Kahn, 2002, for California; Wolfram, 1999, for the UK; and Weigt and Hirschhausen, 2008, for Germany). Many studies applying more complex methods also employ the marginal cost benchmark to classify their results.

Equilibrium models make it possible to model strategic company behaviors and thus reproduce observed market outcomes as well as estimate future outcomes. Cournot-type models are commonly used to model strategic competition in electricity markets (e.g., see Kahn, 1998; Bushnell et al., 1999; and Ellersdorfer, 2005). Due to the short-term inelastic demand the obtained prices are typically too high. Therefore, further restrictions, i.e. forward contracts, are introduced to bring prices down (see Bushnell et al., 2008). Other types of strategic interactions that overcome the price shortcoming of Cournot models are also used (e.g., SFE in Green and Newbery, 1992).

Simulation models also allow different strategic behaviors and furthermore present a framework to test consequence of market power along several market segments. Weidlich and Veit (2008) conclude in their survey that a large share of agent-based models deals with market power issues under different market structures and mechanisms e.g. the comparison of pay-as-bid and uniform priced auctions.

3.2.2 Investments in Generation Capacities

Pre-liberalization, markets were typically subject to cost-plus regulatory schemes, investment decisions bore low risk, and cost coverage was of little concern. The post-liberalization environment requires far more complex investment analyses to account for the uncertainties and price impacts of each investment. Investment research can be divided into two streams: the actual investment decision from the firm or market viewpoint, given uncertain future returns and changing market environments, and the interaction of investments and market prices under strategic company behaviors.

The simplest way to determine the profitability of investment decisions is to conduct a net present value analysis taking into account several future scenarios. Here, the model focuses more on the actual future price forecast (discussion follows in the next section), whereas the investment decision can be handled with an optimization approach. The so-called real options approach (Dixit and Pindyck, 1994) uses techniques applied in finance, such as tree approaches (e.g., Tseng, 2001) and Monte-Carlo simulation techniques (e.g., Roques, 2006); Ronn (2002) provides examples and case studies for real options approaches in electricity. Other research examines specific investment questions (e.g., Auerswald and Leuthold, 2009, commodity price uncertainty; Ishii and Yan, 2004, regulatory uncertainty; Bøckman et al., 2008, hydro generation). Also deriving from the financial sector are analyses based on the mean-variance portfolio theory that account for the revenue-risk distribution of different generation assets (e.g., Roques et al., 2008).

The question of investment and strategic behavior can be addressed, e.g., with two-stage equilibrium approaches. Kreps and Scheinkman (1983) show that assuming Cournot competition of the first stage (investment) and Betrand competition on the second (wholesale) leads to an overall Cournot outcome. Murphy and Smeers (2005) provide an in-depth discussion of algorithmic issues arising from different market structure assumptions on this issue. Zoettl (2008) studies the types of generation capacities in which strategic firms invest. He concludes that under imperfect competition firms have strong incentives to invest in capacities with low marginal costs, while at the same time the total capacities chosen are too low from a welfare point of view. Uncertainty of future developments generally leads to a slowing down of investment decision while strategic behaviors may increase investments due to entry deterrence. However, a full theoretical treatment is not yet available (Smeers, 1997).

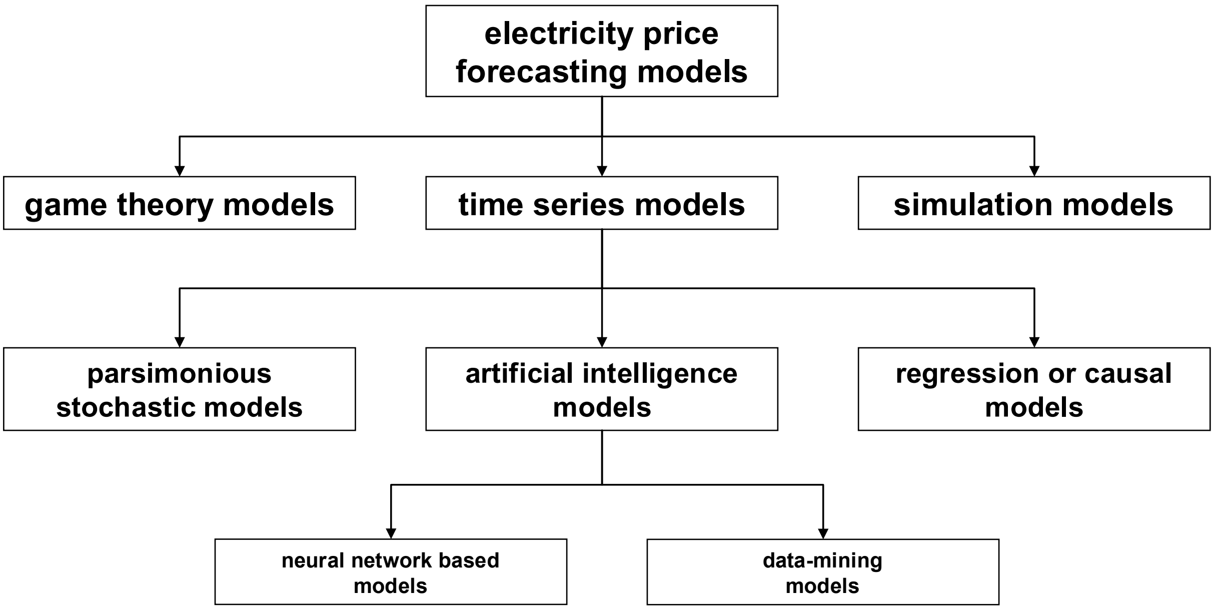
3.2.3 Price Forecasting

Price forecasting plays a major role in decision processes like trading and investments and is crucial to the performance of profit-oriented firms. Future prices are influenced by factors including basic market characteristics, uncertainties, strategic behaviors (both the firm's and its competitors), and temporal effects. Consequently, an equally wide array of modeling techniques and empirical approaches can be applied. Aggarwal et al. (2009) review price forecasting in deregulated electricity markets, and distinguish three trends of price forecasting models: game theory, time series, and simulation models (Figure 5).

Game theory models are based on the equilibrium concept and thus are applied if strategic interactions are explicitly modeled. Simulation models can reproduce the complex nature of markets, but require detailed system operation data to produce robust forecasts. Thus, time series models are an alternative since they focus on past behavior and do not require detailed market structure data. Aggarwal et al. (2009) further classify time series models into parsimonious stochastic models which are inspired by financial literature and include methods like autoregressive and moving average models; regression or causal models where the future price is modeled as a function of some exogenous variables; and artificial intelligence models that map input-output relations without exploring the underlying prices. The latter can further be divided into artificial neural network-based models and data-mining models.

Price forecasting is normally aimed at either determining the average price, peak prices, or the price profile for a specific period for the day-ahead market in the relatively short term. Other market segments are still largely neglected (Aggarwal et al., 2009).

Figure 5: Classification of price forecasting models



Source: Following Aggarwal et al. (2009)

3.2.4 Network Modelling

Modeling networks and power flows is in itself a purely technical task. Sophisticated engineering tools and commercial programs exist to derive specific operational figures, but in an economic context these models are generally too detailed because their focus is the actual power delivered. Therefore, for economic modeling purposes power flow calculation is often approximated, or for a large part of research, neglected.

When network constraints must be considered, the most common model approach is the DC load flow model (DCLF) that approximates the full AC load flow by neglecting reactive parts (Stigler and Todem, 2005). Overbye et al. (2004) compare the DCLF approach with a full AC-model to determine the impact of neglecting reactive power issues. They conclude that the results are close to the full AC formulation. However, the difference can become significant in cases of high reactive and low real power flows. The main advantage of DCLF is its applicability to large-scale problems with many capacity constraints and agents (Day et al., 2002).

Including the network can be seen as an (sometimes necessary) add-on to electricity market modeling that increases the scope of the model, but not necessarily the research focus. For example, a plant investment decision can be analyzed within a network framework if significant congestion may alter prices in regions (e.g., Smeers, 2006), price forecasts need to account for network constraints if resembling a locationally priced market, or market power can be analyzed with and without an underlying network formulation depending on the market clearing process to be simulated. Hobbs (2001) analyzes the impact of arbitrageurs in a Cournot market setting with network constraints. Neuhoff et al. (2007) show the complexity of deriving robust results of strategic models with an underlying network calculation. Bautista et al. (2007) show that the introduction of reactive power increases the strategic space for market participants, and thus the results differ from a simple DC approximation. However, they are unable to classify the extent to which simplified assumptions provide misleading market results.

Purely network-related research topics center upon market design questions (see next section) or oftentimes have a large technical focus, e.g., voltage support. Of particular concern are the necessary grid extensions most electricity markets require due to increased demand, an increase or change in generation capacities, or existing bottlenecks (e.g., at cross-borders). Leuthold et al. (2009) address the possible costs of a welfare optimal extension of the European network with respect to wind integration. Other studies look at national extension plans (e.g., DENA, 2005, for Germany; Hondebrink et al., 2004, for the Netherlands; or Haidvogel, 2002, for Austria). A special issue of the IEEE Transactions on Power Systems (2007) addresses the research problems pertaining to "Transmission Investment, Pricing, and Construction." Latorre et al. (2003) provide a review and classification of models on transmission expansion planning.

3.2.5 Market Architecture

Optimal market design and the comparison of outcomes from different designs is another research concern. As is evident from the liberalization processes presented in Section 2 there is no perfect decentralized market architecture, and as a result, all model types are utilized. Research on market design can be divided into three streams: the design of a specific market segment; the interaction of company behavior on different market segments; and the institutional setting and regulatory impacts.

Regarding market segment analysis discussions are ongoing about the revenue adequacy of wholesale markets and the question of capacity markets (e.g., Gribik et al., 2007); the design of ancillary services and reserve markets (e.g., Glachant and Saguan, 2007); network operation and congestion management (Christie et al., 2000); cross-border auction design (e.g., Leuthold and Todem, 2007); pricing mechanisms (Bin et al., 2004); and demand side response (e.g., Holland and Mansur, 2006).

Since firms tend to be involved in more than one segment of the electricity value chain, the concern about strategic interactions across market segments is also subject to modeling analyses. Focusing on strategic interactions, equilibrium approaches are applicable. Possible interactions include the relationship between forward and spot markets (basic concept for Cournot competition developed by Allaz and Villa, 1993); interactions between markets for reserve capacities and spot markets (Wieschhaus and Weigt, 2008); transmission allocation and market power (Gilbert et al., 2004); and investment in generation and network facilities (Rious et al., 2008).

The complexity of the interactions between several market segments require flexible simulation models. Following Weidlich and Veit (2008) a large share of agent-based models focuses on market power and market mechanisms analyses, including vertical integration and market power (Rupérez Micola et al., 2006) and dynamics between forward and spot markets (Veit et al., 2006).

The more general question is how best to design the institutional setting and analyze the potential impacts of the regulatory framework on market participants. There is an ongoing debate about the welfare optimal way to enhance transmission investment either by regulation or merchant approaches (see Joskow and Tirole, 2005). Chao and Peck (1998) analyze the possibilities to design an incentive scheme for system operators to obtain welfare optimal reliability. A consistent inter-TSO compensation is still unsolved in the EU (Dietrich et al, 2008). Environmental aspects and their implementation within the market architecture have gained attention, including the interaction of emissions trading and electricity prices (Rathmann, 2007); interaction of renewable support and wholesale prices (Weigt, 2009); the design of the European Emission Trading scheme (Böhringer et al, 2005); and the interactions of emissions trading and renewable support mechanisms (Abrell and Weigt, 2008).

4 Conclusion

This paper has reviewed electricity market liberalization and the application of various modeling techniques. Starting in the 1990s with the UK, electricity markets around the world have been (and still are) restructured, transforming the former monopolized sector into partially decentralized competitive market segments. International experiences show that this process is neither straightforward nor riskless. Nevertheless, the lessons learned to date from successful and even less successful liberalization attempts can be used to shape future markets as well as to provide guidelines for countries that are at the beginning stages.

In the wake of liberalization a large and differentiated body of modeling techniques and approaches has developed that aims to understand the process, help market participants to cope with the new market environment, and in the end to improve the market architecture that ensures a stable, competitive, and sustainable electricity market.

The complexity of the commodity electricity and the different market structures and architectures around the world are reflected in the modeling approaches applied, ranging from "simple" optimization approaches over equilibrium concepts to simulation models and the large range of analyzed topics.

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