

An Institutional Frame to Compare Alternative Market Designs in EU Electricity Balancing

Jean Michel Glachant¹, Marcelo Saguan²

Abstract : The so-called “electricity wholesale market” is, in fact, a sequence of several markets. The chain is closed with a provision for “balancing,” in which energy from all wholesale markets is balanced under the authority of the Transmission Grid Manager (TSO in Europe, ISO in the United States). In selecting the market design, engineers in the European Union have traditionally preferred the technical role of balancing mechanisms as “security mechanisms.” They favour using penalties to restrict the use of balancing energy by market actors.

While our paper in no way disputes the importance of grid security, nor the competency of engineers to elaborate the technical rules, we wish to attract attention to the real economic consequences of alternative balancing designs. We propose a numerical simulation in the framework of a two-stage equilibrium model. This simulation allows us to compare the economic properties of designs currently existing within the European Union and to measure their fallout. It reveals that balancing designs, which are typically presented as simple variants on technical security, are in actuality alternative institutional frameworks having at least four potential economic consequences: a distortion of the forward price; an asymmetric shift in the participants’ profits; an increase in the System Operator’s revenues; and inefficiencies.

Index Terms— forward market, balancing mechanism, risk aversion, penalty, institutional framework, market design.

I. Introduction

The competitive electricity wholesale market is, in fact, a sequence of several markets. The sequencing of these markets serves to organise the interactions between a number of modules, by either merging or separating them. These notably include: a futures market, a “day ahead” forward market, a congestion management mechanism, a reserves market, a balancing market, sometimes an explicit market for transmission capacity, and sometimes also a market for generation capacity. The precise configuration of this sequence comprises the overall institutional arrangement of an electricity reform: its *market design*. Owing to the highly modular nature of this sequence, distinctions between the institutional arrangements of electricity reforms take the form of either numerous differences all along the sequence of modules, or of a few variations within a single module.

Our paper shall focus on a single link in this chain, the last one: real-time energy balancing. In this module, direct control over all operations of injecting or withdrawing power, from several minutes or hours before real time until its actual implementation in real time, is placed under the direct and exclusive authority of the transmission grid manager (TSO in Europe, ISO in the

This paper has been made with the support of the “ENERGIE” Project at SUPELEC (www.supelec.fr/ecole/eci/energie). We deeply thank P. Dessante, Energy Department at Supélec, France, for his exceptional help in making our project right.

¹ J.M. Glachant is permanent professor in economics at the University of Paris Sud, Faculté Jean-Monnet, 54 bd. Desgranges, 92331 Sceaux Cedex, France (email: jean-michel.glachant@jm.u-psud.fr; web site: www.grjm.net).

² M. Saguan is engineer and researcher in electrical engineering and economics at both Supélec and University of Paris Sud, Paris, France (email: marcelo.saguan@supelec.fr).

United States). This module is of the greatest importance, both technically and economically, since the impossibility of storing energy means that it has to be generated and consumed in “real time.”

However, this “balancing” module is neither the best known of the electricity reforms, nor the one with the greatest volume of activity. Of the competitive reforms in the European Union (**Glachant & Lévêque [1]**), the market modules that have received the most attention and analysis are, first, the exchanges (PXs), in which short-term (day ahead or intraday) and long-term (usually one month to one year = *futures*) energy contracts are traded and, also, OTC markets which deal with the same timeframes (with or without brokers). Next are the congestion management modules, which may be merged with, or separate from, day ahead markets, and which sometimes take the form of explicit transmission capacity markets. All together, these markets, which are the best known, account for over 95 percent of the volume of electricity trading.

In reality, the effective importance of any element in the sequence of electricity market modules is not necessarily determined by its volume of activity or by its visibility outside of the world of electricity professionals. As everyone had the opportunity to learn during the California crisis and the blackouts in New York and Rome, secondary mechanisms can be absolutely vital under some conditions. It is widely understood by now that the electricity sector presents a special combination of unique characteristics, such as: the impossibility of storing significant quantities; the range of variation and uncertainty in consumption and generation; the short-term price inelasticity of demand; and the constraint of ongoing real-time balancing of consumption and generation.

Given these properties, any economist would guess that the institutional arrangements that ensure real-time energy balancing must be much more than a technical feedback mechanism for the system, but rather a centrepiece in the competitive structure. Aside from their physical role in balancing global volumes of supply and demand, these arrangements also provide the sequence of electricity markets with the only real-time price formation mechanisms. Since this real-time energy is the only form of power that is physically tradable between wholesale market operators, its price provides the “real” basis for the entire chain of forward prices, from futures through day ahead, inclusively (**Hirst [2]**).

In practice, competitive reforms apply two broad variants of balancing arrangements. These are

easily distinguished, with one being a “real-time market” and the other a “balancing mechanism.” The principal difference between these two arrangements is that the “real-time market” uses its market equilibrium price to impute a value to electricity in real time, while the “balancing mechanism” imposes a penalty that creates a substantial gap between the purchase and sales price of power.

This penalty, specific to balancing mechanisms, is incorporated into the prices of the observed gap between the forecasted magnitudes of forward contracts (which are negotiated prior to real time, especially day ahead and intraday) and the real magnitudes of consumption and generation (measured continually by the Transmission Grid Operator as injections and withdrawals from the grid).

The main argument used in the European Union to rationalise imposing such a penalty is an engineering argument. The security of the electricity system, which is the top priority of the transmission system operator (TSO), would be imperilled if real-time energy market prices were used. Given that the primary electricity wholesale markets actually function as forward markets (regardless of the timeframe under consideration, in particular futures and day ahead or intraday markets), the argument advanced is that paying balancing power at its market value would provide an incentive to market agents to intentionally create imbalances in their forward market trading schedules. In this paper we will not examine this engineering argument regarding security—an economic analysis frame thereof can be found in (**Joskow and Tirole [3]**). We treat the choices of the engineers of European Union’s TSOs in terms of network security as an institutional given (**ENTSO [4]**). We do not propose an alternative security analysis or choice of security measures.

We limit our labours to an economic evaluation of the institutional arrangements already in place for balancing energy in real time. We are essentially comparing two types of existing arrangements: the market arrangement using market prices, which will serve as a benchmark, and the penalty-based balancing mechanism. This comparison has real empirical relevance within the European Union, since France and Belgium implement balancing mechanisms that rely on penalties (as does the United Kingdom, **Newbery [5]**), while the real-time market solution remains possible in the Netherlands. Moreover, France, Belgium, and the Netherlands are three bordering countries on continental Europe that are currently engaged in discussions on coordinating their PXs and on provisions for allocating interconnections. The fact that the

operation of these PXs and interconnections is linked to their balancing arrangements reinforces the interest in such an assessment.

Our paper will not address the technical details of balancing arrangements. Rather, it will concentrate on the economic properties of the two existing broad families of configuration (balancing mechanism vs. real-time market), treating them as institutional, rather than purely technical, arrangements. With “*institutional arrangement*,” we mean a set of rules of the game for economic agents that delimit their decision making powers, their information mechanisms, and their incentive structures. These economic agents are, on the one hand, the TSO, who sets the rules governing balancing, and, on the other hand, wholesale market participants (generators and retailers) who react to these balancing rules.

In the framework of a two-stage equilibrium model, a first stage, the forward market (day ahead and intraday) is followed by the real-time stage. Each participant in these markets, whether buyer or seller, forward or real-time, must confront substantial uncertainties, being forced to make decisions on the first market (day ahead, etc.) before having all the relevant information. Indeed, during the second, real-time, phase, a positive or negative randomness in consumption kicks in and has repercussions on production under the authority of the TSO. Both the generators and retailers in this market are characterised by risk aversion. They seek to maximise their utility as of the closing of the first of the two markets, which thus serves as a market for hedging the risks inherent in the nature of the second market. Since each of these two markets (forward and real-time markets) has an equilibrium, we can compute the quantities traded and the equilibrium price of electricity on each (forward price and real-time price).

Within this framework, we define penalties—which transform “real-time markets” into a “balancing mechanism”—in terms of a parameter modifying the price of positive and negative imbalances in the power measured in real time. The TSO compares the volumes committed on the day ahead (or intraday) market during the first stage with actual measurements of effective consumption and generation during the second stage.

We also define the time of the “Gate Closure” as a parameter. This is when the TSO definitively cuts off trades on forward markets and opens the second period, during which real-time balancing occurs under its authority. The exact timing of this division between the two markets dictates the set of information available to market participants, and thus impacts on the level of uncertainty they must confront when making decisions. The uncertainty increases with

the length of the delay between the closure of the forward market and the real-time market. It decreases as this delay shrinks. Numerical examples allow us to compare the economic properties of the two families of institutional balancing arrangements (*market vs. mechanism*).

In a further variant on the model, we allow generators to use different technologies. One group will dispose of a “*flexible*” technology, which can always respond to randomness after the closing of the forward market. The other group uses an “*inflexible*” technology—which cannot.

In our analysis we will distinguish between, and assess, four major potential economic consequences of the institutional diversity of balancing arrangements: (a) a distortion of the price on the forward market; (b) an asymmetric shift in the participants’ welfare (especially generators vs. retailers); (c) an increase in the TSO’s revenues, and; (d) inefficiencies.

The extent of the potential consequences of the different design alternatives draws our attention to the fact that balancing arrangements are not exclusively technical security provisions. Our paper reveals that engineers and regulators must account for economic analysis, as long as several different balancing arrangements exist that are acceptable to those responsible for the security of the grid.

Our paper is organised as follows. Section II explores the principal characteristics of the real-time operation of electricity systems and the design of balancing arrangements. Section III briefly presents the most prevalent balancing arrangements in place in western continental Europe. Section IV introduces the two-stage equilibrium model, while in Section V a numerical simulation allows the potential economic consequences of the two families of arrangements to be evaluated. Finally, Section VI points out the importance of the economic properties of the different balancing design alternatives (shifts in prices, profits, and the technology mix in generation), and concludes.

II. Real-Time and balancing arrangements in electricity systems

Electricity systems are subject to a strong real-time constraint of permanent equilibrium between injections (generation) and withdrawals (consumption). Even small deviations from the equilibrium (imbalances) affect the frequency at which the system operates, which is expressed in Hz, until a modification in generation or consumption allows the normal state to be re-

established. In fact, many aspects of the electricity system were designed to function at a reference frequency—50 Hz in Europe. Divergences, even minor, from the reference frequency can destabilise or damage components of the transmission system and result in harmful consequences, such as blackouts.

Permanent balancing of the electricity system is made all the more difficult by the fact that electricity is very expensive to store (cf. the price of batteries). This absence of affordable storage is compounded by many uncertainties, especially in consumption, which is virtually always changing with no forewarning or commitment. As a result, electricity systems are continually adjusting their generation to maintain equilibrium, and the precise conditions of supply-demand equilibrium are only known when most of the uncertainties have disappeared. This is why balancing must be operated as near as possible to real time.

Uncertainties can originate from errors in demand forecasts (in particular owing to randomness in the climate or social events), errors in forecasts of output (as intermittence in wind power, variability in thermal efficiency, outages, etc.), or incidents affecting the transmission grid. Furthermore, intertemporal constraints on generation (cost or speed of starting up, or shutting down, plants; cost or speed of adjusting output) can impede the ability of certain plants to contribute to adjustments in generation for purposes of balancing. Flexibility in generation depends, in particular, on the technology used. Not all technologies are equally able to respond to short-term signals (from several hours to 15 minutes). Consequently, preparation for real-time balancing begins before the actual moment of “real-time.”

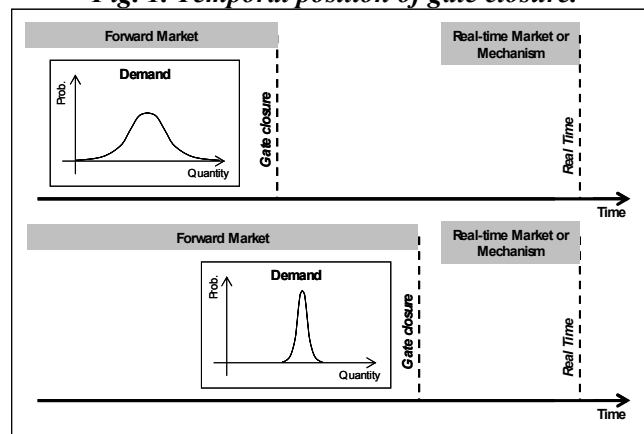
The fundamental economic consequence resulting from these characteristics of balancing and from flexibility in generation is that, in such a short timeframe (say, from one to three hours), we cannot leave management of overall electricity equilibrium in the hands of a decentralised market (**Wilson [6]**). This is why operation of the real-time system, in a real-time framework, is entrusted to a central authority who is responsible for the security of the system and enjoys special power: the manager of the transmission grid (generally known as the TSO in Europe). This is also why the rules of operation during this specific period are defined *ex ante* in a balancing arrangement.

Nearly all balancing arrangements are based on a process that is organised into successive steps (**ETSO [4]; Stoft [12]**). In this process, one aggregates the positions of contracts previously concluded on forward markets, and which have come to their day ahead or intraday

term, into the daily schedules. The daily schedules are transmitted to the TSO by authorised representatives of the actors on these markets. These forward physical notifications are used by the TSO to compute imbalances by comparison with actual measurements of injections and withdrawals read off the transmission grid in real time. These discrepancies are subsequently settled financially by those who are responsible for them, according to the provisions of the balancing arrangements.

In practice, the first physical notification of schedules, made a day ahead, is solely indicative. It can be modified until a fixed point in time, to wit the moment at which the TSO closes the intraday window on forward trading. This is why the closing of the forward market by the TSO is referred to as “Gate Closure.” At this precise moment, all schedules communicated to the TSO become final. They serve for computing the imbalances to be submitted for financial settlement. In this way, the timing of the gate closure demarks the closing of the forward markets and the opening of the real-time framework under the exclusive operational authority of the TSO. The temporal position of the gate closure is thus a key parameter of the design of the balancing arrangement, determining the volume of information available for decisions made on forward markets, and thus the level of uncertainty (Figure 1).

Fig. 1. Temporal position of gate closure.



This choice of temporal position of the gate closure occurs under several constraints. After the closing of the forward markets, the TSO needs time to analyse the information gathered (injections/withdrawals) and to compare this analysis with its own forecasts and with the general state of the grid and the system in order to establish how to best ensure overall security. Other constraints come into play for the participants in forward markets. For example, if the intraday

market (operating immediately prior to gate closure) is illiquid, not all participants will be able to find counterparties to offer them additional contracts to modify their daily schedules.

Consequently, the effective position of gate closure may, in practice, be further ahead of real time than the official position set out in the balancing arrangements.

Ever since the beginning of the electricity reforms, two different broad designs in balancing arrangements have emerged. Broadly speaking, on one side we find reforms having adopted a “*real-time market*” and relying on a single, real-time, price for power—this is most prevalent in the United States. On the other side, the reforms more typical of Europe have opted for “*balancing mechanisms*,” which may, or may not, be combined with bilateral contracts for supplying the balancing (**Boucher & Smeers [7]**). Within the framework of one or the other of these designs, the system operator (TSO in EU; ISO in the United States) performs ongoing adjustments to the electricity system using either supplies made available on the market or the balancing mechanisms, or by resorting to options negotiated in advance.³ The supplies retained by the TSO are then paid on either a pay-as-bid or a marginal pricing basis. If these supplies are inadequate to balance the system, in terms of either quantity or quality, the systems operator may exercise previously acquired options on various categories of reserves.⁴

The principal difference between these two contrasting conceptions of balancing arrangements lies in how they manage the settlement of imbalances.⁵ If the goal is to discourage imbalances (= negative imbalances, demand for balancing electricity) by imposing a supplementary penalty on the purchase price of balancing energy, the arrangement operates as a “*balancing mechanism*.” This penalty may be explicit, such as a multiplicative factor applied to the supply cost of the balancing mechanism, or implicit, integrated into the method by which the balancing price is computed. In general, balancing mechanisms provide for at least two different prices for imbalances. One price is applied to positive imbalances, in which energy supplied in excess of the schedule is remunerated at below the marginal cost of systems balancing. Another price exists for negative imbalances, in which energy supplies below the schedule are priced higher than the marginal cost of systems balancing. Some balancing mechanisms use more than two

³ Balancing supplies are also frequently used to manage grid congestion. However, we do not consider congestion management in this article.

⁴ Reserve markets or mechanisms, bilateral contracts, or obligatory orders may be used to constitute reserves of power. We assume that all of these arrangements function reasonably well, and that they do not interfere with the good functioning of energy markets. Consequently, we do not account for the arrangement put in place to constitute reserves.

⁵ Other design parameters are ignored here. These are: the basis on which imbalances are calculated (separation into distinct accounts for generation and consumption, or a single aggregate account, the unit of time on which imbalances are measured (10 min., 30 min., 1 hour), the transparency of the calculation of the price of imbalances, etc.

prices for imbalances. In particular, the sign of the overall imbalance in the system may be compared to the sign of each individual imbalance. This gives rise to two cases. The sign of the individual imbalance is the same as the sign for the entire system, in which case it will be penalised more severely since it contributes to the global imbalance. Or, the individual sign may be the opposite of the overall sign. Finally, the magnitude (absolute or relative) of the individual imbalance may be used to distinguish between several bands of imbalances prices.

The main argument advanced in Europe in defence of imposing penalties on imbalances is that market pricing could undermine the security of the electricity system. This is because participants in forward markets would have an incentive to increase the risk exposure of the electricity system by raising the amount of balancing power transacted during real time. In practice, penalizing real-time imbalances also has the effect of transferring some of the risk and the responsibility for balancing from the TSO to market participants. Since the penalty on balancing is anticipated *ex ante*, additional balancing will be implemented by the operators on the forward market before gate closure, and this will be observed by the TSO after gate closure.

We will not critique the logic underlying this reasoning since, in practice, it is the engineers of the TSOs who select the rules governing security and balancing. We accept these rules as given. We will limit our analysis to examining the economic consequences of the rules chosen by the TSOs. Since these rules are not identical across all TSOs, it is possible to compare them, bearing in mind that they are all meant to provide an acceptable level of security for at least one TSO.

However, for an economist, the use of penalties on a market, whether or not they are necessary to ensure the security of the system, will inevitably have economic consequences. Here, in particular, penalties modify the price of energy in real time, since it is this real-time price that constitutes the very basis of the entire chain of forward prices and energy is not storable (**Hirst [2]; Boucher & Smeers [7]**). In fact, it is this real-time arrangement that provides the only place on which physical energy can be traded between market participants. All other markets, which shut down prior to gate closure, function as forward markets on which prices and volumes are negotiated, but no energy actually changes hands. Consequently, it is of some interest *a priori* to examine what economic consequences may arise during real time from the imposition of a penalty on the price of real energy trades.

III. Balancing Arrangements in Western Europe

Since there is currently a movement toward the creation of harmonised regional markets in the European Union, and France, Belgium, and the Netherlands are in the midst of discussions toward this end, it is of particular interest to examine their example in depth (**Glachant & Leveque [1]**). A cursory look at the market design in these three bordering countries of Western Europe reveals that France and Belgium use balancing mechanisms (with penalties or an administrative fee), while an arrangement that resembles real-time markets prevails in the Netherlands (**ETS0 [4]**).

In Belgium, the balancing arrangement truly is of a “mechanism,” and not a “market,” type. Gate closure occurs a day ahead. There are 16 different types of imbalance prices. These prices depend on the sign of the individual imbalance (positive or negative), the sign of the global imbalance (positive or negative), and the magnitude of the individual imbalance (above or below a threshold). Prices on these imbalances are computed with respect to the day ahead price on two markets outside of Belgium (APX in the Netherlands and PowerNext in France). Different levels of penalties are applied to these day ahead prices on the exchanges. To illustrate, for imbalances in excess of the threshold, the price of negative imbalances is fixed at between 110 and 175 per cent, and that of positive imbalances between 25 and 90 per cent, of the day ahead reference price.⁶

The balancing arrangement in France also corresponds to a mechanism and not a market. There is no rolling gate closure, and notifications from the generators are only accepted during specific periods when the windows are open. The mechanism functions with four prices on imbalances, which depend upon the relationship between the global sign of the system imbalances and that of the individual imbalance. Imbalances with the same sign as that of the system are settled with a penalty defined by a constant (k) applied to the mean purchase price of energy to the TSO each half-hour. In 2005, this constant k was fixed at 15 per cent.⁷

In the Netherlands, the initial design of the balancing arrangement could match the definitions of either mechanism or real-time market, depending on the value of the parameter on the penalties. The price of the imbalance consists of an energy component, which is the marginal

⁶ Information from the Belgian TSO Elia. Website: www.elia.be.

⁷ Information from the French TSO RTE. Website: www.rte-france.com.

cost of balancing energy, and a penalty, called the “incentive component.” The amount of the penalty is fixed weekly, and it depends on the state of the system during the preceding weeks. This value fell from a mean of approximately 2 euros per MWh in 2001 to around 0.5 euros in 2002, then was fixed at zero in 2003. Consequently, this same arrangement now functions more like a real-time market: There are no more explicit penalties. Even though there are sometimes two prices for imbalances with different signs...it is of interest to note that the initial “mechanism” was able to metamorphose into a real-time market. Gate closure was set at one hour before real time.⁸

IV. The model

A. Overview

Interactions between forward and real-time markets in a context of uncertainty have been examined by **Bessembinder & Lemmon [8]**, **Siddiqui [9]**, and **Green & McDaniel [10]**. Bessembinder & Lemmon use a two-stage equilibrium approach to examine equilibrium in a perfectly competitive market with risk averse agents. Final demand is stochastic and completely inelastic in real time. Siddiqui completes the Bessembinder & Lemmon model by introducing a reserves market. In Green & McDaniel, the interaction between a forward market and a balancing mechanism is studied in a framework of perfect competition. Two types of pricing for the balancing mechanism (pay-as-bid and marginal price) are addressed in the case of risk neutral agents. None of these models account for the existence of penalties in real time, and a single (*flexible*) generation technology is retained.

In this section we present a two-period equilibrium model to examine the consequences of introducing a penalty during real time. We base our work on the Bessembinder & Lemmon model and add a few modifications. First, we introduce a real-time penalty to build our baseline model. Second, we introduce a new technology, inflexible generators, into our extended model.

We simplify the empirical diversity of existing balancing arrangements by only distinguishing between two types of arrangements. A “*pure real-time market*” arrangement, thus without

⁸ Information from the Dutch TSO Tennet. Website: www.tennet.nl.

penalties, and a “*balancing mechanism*,” with penalties. Consequently, the level of penalties applied to imbalances observed in real time is the parameter that transforms a real-time market into a balancing mechanism. The temporal position of gate closure is, in turn, represented by a parameter capturing the magnitude of the potential deviation from final demand (= the value of the standard deviation of demand) at real time.

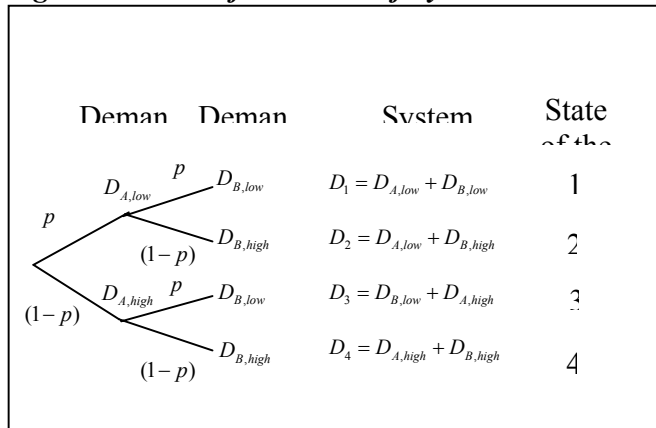
We also retain the assumption of perfectly competitive forward and real-time markets. We analyse production decisions as being independent over time, between two successive sequences of equilibria on two markets, on the basis that the impossibility of storing electricity makes the two markets independent of each other. To simplify, we also assume that all uncertainty is resolved in real time. Therefore, the only decisions made under uncertainty are on the forward market, and this uncertainty is solely attributable to the stochastic nature of demand.

Making decisions on the forward market is thus risky. The fact that agents are risk averse creates a demand for forward contracts to hedge against risks assumed up until real time (in a context of absence of risk aversion and perfect competition, agents would have no reason to buy on the forward market...). To model this behaviour, we assume that each agent maximises utility over a profit function of the form $E_{\omega}[U(\pi_{\omega})] \equiv E[\pi_{\omega}] - \frac{A}{2} Var[\pi_{\omega}]$, where ω is a stochastic variable describing the state of the world. The value of this variable is unknown to agents when they make their decisions on forward markets, but will be revealed in real time.

In this simple model, we only have two retailers, retailer A and retailer B, each of whom faces demands that are stochastic and inelastic in real time. We assume that these demands are independent: They are uncorrelated. Thus, each retailer confronts demands that may assume one of two states: a low level of demand ($D_{j,low}$) and a high level of demand ($D_{j,high}$), with probabilities p and $(1-p)$ respectively. Thus, the expected values of the two retailers' demands are: \bar{D}_A and \bar{D}_B . Total demand is the sum of the two individual demands of the retailers.

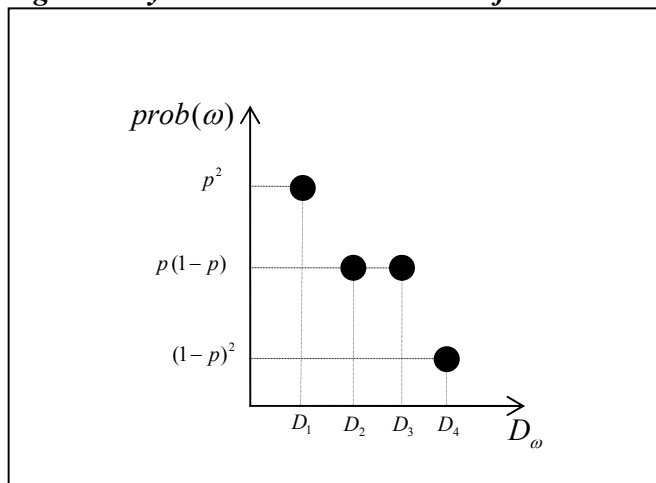
There will thus be at most four possible states of the world of System Demand (Figure 2).

Figure 2. States of the world of System Demand



On Figure 3 we see the distribution function of global demand.⁹

Figure 3. System demand distribution function.



We also assume that all agents know the distribution function of the stochastic variable, ω , and that the flexible generators have sufficient capacity to satisfy all possible demand (there are no structural problems with generation capacity or providing for reserves). This simplified model allows us to more easily study the consequences of introducing penalties in real time.

This section continues with a description of the agents and the TSO in Part B and a list of variables and parameters in Part C. Finally, Part D describes the baseline model, in which generation technology is flexible for all producers. In the appendix we provide an overview of the extended model with two types of generation technology: *flexible* and *inflexible*.

⁹ Note that the probability distribution function is asymmetric ($p > 0.5$). In our numerical examples, an asymmetric distribution is used to account for the convexity of the supply curve, which is ignored in our linear marginal cost model.

B. Market Participants and the TSO

In our two models, the baseline and extended model, we find four types of economic agents: two types of generators (flexible and inflexible), retailers, and the TSO.

- **Flexible generators:** There are N_{FG} identical flexible producers. They can sell their electricity on the forward market or in real time. Their cost function is quadratic: $CT_{FG_i}(X_{FG_i}) = \sigma_{FG} X_{FG_i}^2 / 2$. These generators can make and change output decisions up to real time.
- **Inflexible generators:** There are N_{IG} identical inflexible producers. Owing to the nature of their generation technology, they must make their output decisions before gate closure. Afterwards, they cannot modify these decisions. Consequently, they only sell on the forward market. Their cost function is quadratic: $CT_{IG_i}(X_{IG_i}) = \theta_{IG} X_{IG_i}^2 / 2$.
- **Retailers:** Retailers have no control over the real level of their clients' consumption, which is stochastic and inelastic in real time. Retailers buy electricity on the forward and real-time markets, and then resell it to their clients at a price fixed in advance in a multi-period contract: P^C . The exact volume of electricity demand for which each retailer will be responsible in real time, $D_{j,\omega}$, remains unknown at the time of decision making on the forward market. Since retailers' forward purchases never exactly correspond to their clients' actual consumption, they will be in surplus or deficit positions at real time. They buy the corresponding quantities from, or sell them to, the TSO, who manages the balancing. In the case of positive imbalances, the TSO will pay retailers the real-time price (for a real-time market) or this price reduced by $1/k$ (for a balancing mechanism). In the case of negative imbalances, retailers pay the price of the imbalance to the TSO, either at the market price (on a real-time market), or at this price multiplied times k (on a balancing mechanism). When $k = 1$, the price of the imbalance equals the real-time price, and the balancing arrangement is of the "real-time market" type. When $k > 1$, the

arrangement is of the “balancing mechanism” type.

- **The TSO** is responsible for balancing the electricity system and, consequently, managing the equilibrium between supply and demand in real time.

C. Variables and parameters

Parameters:

- ω state of the world.
- $prob(\omega)$ probability of state of the world ω ,
- D_ω global electricity demand in state of the world ω ,
- σ_{FG} slope of the marginal cost curve for flexible generators,
- N_{FG} number of flexible generators,
- θ_{IG} slope of the marginal cost curve for inflexible generators,
- N_{IG} number of inflexible generators,
- k penalty coefficient,
- A_{FG} risk aversion coefficient for flexible generators,
- A_R risk aversion coefficient for retailers,
- P^C fixed price at which consumers buy from retailers.

Quantity variables:

- $X_{FG_i}^F$ quantity sold on the forward market by flexible generator i ,
- $X_{IG_l}^F$ quantity sold on the forward market by inflexible generator l ,
- $X_{R_j}^F$ quantity purchased by retailer j on the forward market,
- $X_{R_j,\omega}^{RT}$ quantity bought or sold by retailer j in real time (imbalance),
- $X_{FG_i,\omega}^{RT}$ quantity bought or sold by the flexible generator i in real time,
- X_{FG_i} quantity produced by flexible generator i ,
- X_{IG_l} quantity produced by inflexible generator l .

Price variables:

- P^F forward price,
- P_ω^{RT} real-time price for state of the world ω ,
- $IP_{j,\omega}^{RT}$ price of retailer j 's real-time imbalances for state of the world ω .

D. Baseline Model

Here we solve the optimisation problem of the two types of market participants (generators

and retailers) by drawing on the market equilibrium presented in Bessembinder & Lemmon. Since we have two markets (forward and real-time), there are two stages to the agents' optimisation problem. In principle, these agents first take a position on the forward market on the basis of forecasted real-time conditions. Subsequently, in real time, when the state of demand is revealed, these agents conduct their real-time transactions in the absence of all uncertainty.

Our approach to modelling begins with agents' real-time decision making, given that they consider their positions on the forward market, and forward prices, to be given. Once we have determined the optimal positions and the prices in real time for each state of the world, we will be able to work backwards in time to establish optimal positions and equilibrium prices on forward markets.

1) *Real-time transactions*

In real time, the state of the world ω occurs. Thus, there is no more uncertainty. The TSO is responsible for managing the equilibrium and ensuring that the balancing constraint is satisfied for this state of the world. Real-time equilibrium conditions are defined by:¹⁰

$$\forall \omega \quad \sum_i X_{FG_i, \omega}^{RT*} = - \sum_j X_{R_j, \omega}^{RT*} \quad (1)$$

Furthermore, positions on the forward market have already been assumed and the forward price already determined. Therefore, they can be treated as fixed. Consequently, we can compute real-time positions and the real-time price, knowing that each agent seeks to maximise profit π_ω .

Flexible generators

Flexible generator i 's profit can be written:¹¹

$$\pi_{FG_i, \omega}(X_{FG_i, \omega}^{RT}) = P^F X_{FG_i}^F + P_\omega^{RT} X_{FG_i, \omega}^{RT} - \frac{\sigma_{FG}}{2} X_{FG_i}^2$$

Given that the output of the flexible generator must equal the quantity sold on the forward market plus (minus) the quantities sold (bought) in real time,

$$(X_{FG_i, \omega} = X_{FG_i}^F + X_{FG_i, \omega}^{RT}),$$

the necessary first-order conditions are:

¹⁰ The negative sign on this equation is attributable to the correspondence between the signs on the imbalances and the language used in balancing mechanisms to define positive and negative imbalances from the perspective of the TSO.

¹¹ Variables designated with * are considered optimal and fixed.

$$\forall \omega ; \forall i \quad \frac{\partial \pi_{FG_i, \omega}(X_{FG_i, \omega}^{RT})}{\partial X_{FG_i, \omega}^{RT}} = 0 = P_{\omega}^{RT} - \sigma_{FG}(X_{FG_i, \omega}^{RT*} + X_{FG_i}^F)$$

and so:

$$\forall \omega ; \forall i \quad X_{FG_i, \omega}^{RT*} = \frac{P_{\omega}^{RT}}{\sigma_{FG}} - X_{FG_i}^F \quad (2)$$

Retailers

In real time, retailers buy (or sell) the difference between effective demand that actually materialises, $D_{j, \omega}$, and their previous purchases on the forward market $D_{j, \omega}^F$. Consequently, the quantities bought (or sold) in real time are:

$$\forall \omega ; \forall j \quad X_{R_j, \omega}^{RT*} = X_{R_j}^F - D_{j, \omega} \quad (3)$$

The price of imbalances depends on the sign and is defined by:

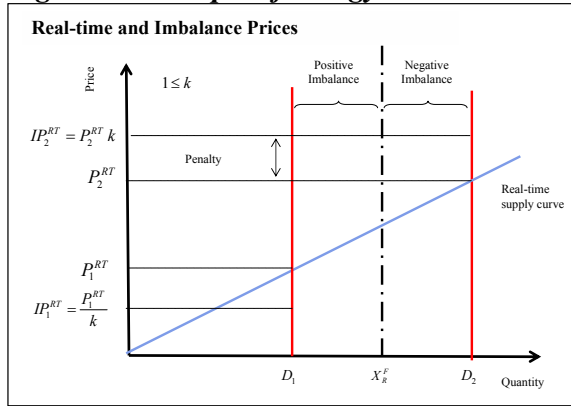
$$IP_{j, \omega}^{RT} = \begin{cases} \text{if } X_{R_j, \omega}^{RT*} \leq 0 & P_{\omega}^{RT} k \text{ (negative imbalance)} \\ \text{if } X_{R_j, \omega}^{RT*} > 0 & P_{\omega}^{RT} \frac{1}{k} \text{ (positive imbalance)} \end{cases} \quad (4)$$

where k is the penalty coefficient ($k \geq 1$).

Notice that, if $k = 1$, then the price of imbalances equals the price of energy.

Figure 4 gives an example of computing the imbalance price.

Figure 4: Example of energy and imbalance prices in real time¹²



2) Forward Market

Returning now to the time at which positions were taken on the forward market, we can find the equilibrium conditions on this market and the optimal quantities sold by each agent participating in it.

¹² This example corresponds to the case of a single retailer on the market (demand can only assume two states).

Equilibrium conditions on the forward market are expressed by the following equation:

$$\sum_j X_{R_j}^F = \sum_i X_{FG_i}^F \quad (5)$$

From equations (1), (2), (3) and (5), we find that:

$$\forall \omega \quad P_\omega^{RT} = D_\omega \frac{\sigma_{FG}}{N_{FG}} \quad (6)$$

where $D_\omega = \sum_j D_{j,\omega}$ is global demand for the state of the world ω .

Flexible generators

On the forward market, we can express the profit of flexible generators as:

$$\pi_{FG_i,\omega}(X_{FG_i}^F) = P^F X_{FG_i}^F + P_\omega^{RT} X_{FG_i,\omega}^{RT} - \frac{\sigma_{FG}}{2} (X_{FG_i}^F + X_{FG_i,\omega}^{RT})^2$$

The optimisation program of flexible generators now consists of choosing $X_{FG_i}^F$ so as to maximised expected utility,

$$E_\omega[U(\pi_{FG_i,\omega})] \equiv E[\pi_{FG_i,\omega}] - \frac{A_{FG}}{2} Var[\pi_{FG_i,\omega}],$$

for a given forward price P^F ,

$$\text{where } E[\pi_{FG_i,\omega}(X_{FG_i}^F)] = \sum_\omega prob(\omega) \pi_{FG_i,\omega}(X_{FG_i}^F)$$

$$\text{and } Var[\pi_{FG_i,\omega}(X_{FG_i}^F)] = \sum_\omega prob(\omega) (\pi_{FG_i,\omega}(X_{FG_i}^F) - E[\pi_{FG_i,\omega}(X_{FG_i}^F)])^2.$$

Therefore, the first-order necessary conditions are:

$$\forall i \quad \frac{\partial E[U(\pi_{FG_i,\omega}(X_{FG_i}^F))]}{\partial X_{FG_i}^F} = \frac{\partial \left(E[\pi_{FG_i,\omega}(X_{FG_i}^F)] - \frac{A_{FG}}{2} Var[\pi_{FG_i,\omega}(X_{FG_i}^F)] \right)}{\partial X_{FG_i}^F} = 0$$

From this equation, along with (2) and (6), we can derive:

$$X_{FG_i}^F = \frac{P^F - E[P_\omega^{RT}]}{A_{FG} Var[P_\omega^{RT}]} + \frac{Cov[\rho_{FG_i,\omega}, P_\omega^{RT}]}{Var[P_\omega^{RT}]} \quad (7)$$

where $E[P_\omega^{RT}]$ and $Var[P_\omega^{RT}]$ are the expected value and the variance of the real-time price, respectively, and $\rho_{FG_i,\omega}$ is generator i 's unhedged profit (i.e. with $X_{FG_i}^F = 0$), we have

$$\rho_{FG_i,\omega} \equiv \pi_{FG_i,\omega}(X_{FG_i}^F = 0) = \frac{1}{2} \frac{\sigma_{FG}}{N_{FG}} D_{\omega}^2.$$

$Cov[\rho_{FG_i,\omega}, P_{\omega}^{RT}]$ is the covariance between the unhedged profit and the real-time price.

Retailers

Similarly, we can express retailer j 's profit:

$$\pi_{R_j,\omega}(X_{R_j}^F) = P^C D_{j,\omega} - P^F X_{R_j}^F + IP_{j,\omega}^{RT} X_{R_j,\omega}^{RT}$$

Retailer R_j seeks to select $X_{R_j}^F$ so as to maximise: $E_{\omega}[U(\pi_{R_j,\omega}(X_{R_j}^F))] \equiv E[\pi_{R_j,\omega}(X_{R_j}^F)] - \frac{A_R}{2} Var[\pi_{R_j,\omega}(X_{R_j}^F)]$

The first-order necessary conditions are:

$$\forall j \quad \frac{\partial E[U(\pi_{R_j,\omega}(X_{R_j}^F))]}{\partial X_{R_j}^F} = 0$$

Using these equations and (3), we can write:

$$\forall j \quad X_{R_j}^{F*} = \frac{E[IP_{j,\omega}^{RT}] - P^F}{A_R Var[IP_{j,\omega}^{RT}]} - \frac{Cov[\rho_{R_j,\omega}, IP_{j,\omega}^{RT}]}{Var[IP_{j,\omega}^{RT}]} \quad (8)$$

where $E[IP_{j,\omega}^{RT}]$ and $Var[IP_{j,\omega}^{RT}]$ are the expected price of imbalances and the variance of this price, respectively.

$\rho_{R_j,\omega}$ is the unhedged profit of retailer j , (i.e. $\rho_{R_j,\omega} \equiv \pi_{R_j,\omega}(X_{R_j}^F = 0) = P^C D_{j,\omega} - IP_{j,\omega}^{RT} D_{j,\omega}$).

$Cov[\rho_{R_j,\omega}, IP_{j,\omega}^{RT}]$ is the covariance between retailer j 's unhedged profit and the price of imbalances.

For the special case of no penalties ($k = 1$), we have:

$$\forall j \quad X_{R_j}^{F*} = \frac{E[P_{\omega}^{RT}] - P^F}{A_R Var[P_{\omega}^{RT}]} - \frac{Cov[\rho_{R_j,\omega}, P_{\omega}^{RT}]}{Var[P_{\omega}^{RT}]} \quad (9)$$

3) Equilibrium price

We can now use equations (4), (5) and (6), in conjunction with the optimal forward positions (equations (7) and (8)), to determine the equilibrium forward price P^F .

For example, solving the penalty-free case ($k = 1$) yields:

$$P^F = E[P_{\omega}^{RT}] + \frac{N_{FG}}{2\sigma_{FG}} \frac{1}{\frac{N_{FG}}{A_{FG}} + \frac{2}{A_R}} \times \left(2(E[P_{\omega}^{RT}] - P^C) Var[P_{\omega}^{RT}] + Skew[P_{\omega}^{RT}] Var[P_{\omega}^{RT}]^{\frac{3}{2}} \right)$$

Where $E[P_{\omega}^{RT}]$, $Var[P_{\omega}^{RT}]$, and $Skew[P_{\omega}^{RT}]$ are the expected value, the variance, and the skewness of the real-time price, respectively.

This result is equivalent to that of Bessembinder & Lemmon. When there is no penalty in real time (the “real-time market” case), the forward price of electricity depends on expectations on the real-time price, the statistical properties of total demand, and the parameters of generation costs (variance and skewness of real-time prices).

To solve the cases with a penalty ($k > 1$) we must make an assumption regarding the sign of the imbalances. Let $D_{j,low} \leq X_{R_j}^F \leq D_{j,high}$, then the prices of the imbalances can be defined for every state of the world. This assumption must be confirmed in the numerical simulations.

Given the complexity of the equation, we will not provide an analytical solution. In the next section, we present numerical simulations effected with Mathematica®.

V. Numerical simulations & Discussion

In this fifth section, we use numerical simulations to examine the economic consequences of using penalties in real time.

We shall look at three different cases:

- *A benchmark case*—this is the case of a real-time market (*no penalty*, $k = 1$),
- *A case we call mechanism No. 1*, this is a balancing mechanism with a medium penalty of ($k = 1.2$).
- *A case we call mechanism No. 2*, this is a balancing mechanism with a high penalty of ($k = 1.4$).

Each of these three cases is examined for *two types of gate closure* (closing of the forward market far from, or near to, real time). We represent the various temporal positions of the gate closure in terms of their impact on the magnitude of the uncertainty affecting the decision making. This is captured by modifying the magnitude of the standard deviation of the demand to ($Std_{sys1} = 10$) or ($Std_{sys2} = 20$).

All these cases are computed in the framework of our *baseline model*, within which all

generators are flexible: They can change their output decisions up to real time.

In our *extended model*, we also have inflexible generators (alongside flexible generators) who must make output decisions before the closing of the forward market. In this case we only compute results for an intermediary position of gate closure ($Std_{Sys1}=15$).

A. Parameters

The parameters of the models must be determined. We simplify this task by borrowing the parameters from Bessembinder & Lemmon. In a future version of this model we will conduct sensitivity analysis. However, we are already quite certain that the signs of the estimates will not be affected, even if their absolute values change.

An asymmetric distribution was selected for demand (a positive coefficient of skewness: ($p>0.5$) to account for the substantial convexity of the generators' supply curve, which is not explicitly incorporated in our model—marginal costs are linear despite quadratic cost functions).

To account for the various temporal positions of the gate closure, the different potential states of individual demand are expressed as functions of the expected value and a standard deviation.

We have: $D_{j,low} = \bar{D}_j - \sqrt{(1-p)p} Std_j / p$ and $D_{j,high} = \bar{D}_j + \sqrt{(1-p)p} Std_j / (1-p)$. We can show that $\bar{D}_j = E[D_{j,\omega}]$ and $Std_j = \sqrt{Var[D_{j,\omega}]}$. The expected value of global demand is $\bar{D}_{Sys} = \bar{D}_A + \bar{D}_B$, and its standard deviation, $Std_{Sys} = \sqrt{Std_A^2 + Std_B^2}$.

The characteristics of demand parameters were chosen to represent various types of agents participating in the markets.

In particular, type “A” retailers represent large net buyers (who thus benefit from bulk discounts on their large orders) or retailers who are vertically integrated with generators. Other retailers, called type “B”, represent small-scale net purchasers and those that are not vertically integrated: $\bar{D}_A > \bar{D}_B$ and $Std_A = Std_B = Std_{Sys} / \sqrt{2}$. This explains why the ratio of the standard deviation of demand to the expected value of demand is greater for type B retailers than for type A retailers $Std_B / \bar{D}_B > Std_A / \bar{D}_A$.

Generators can only be vertically integrated or large-scale net sellers. Consequently, they can easily handle an outage in a single one of their plants, and they do not have to deal with any in-house risk resulting from their own output decisions.

All of these parameters are represented in Table I.

TABLE I - PARAMETERS

Description	Symbol	Value
Number of flexible generators	N_{FG}	10
Probability of low demand realization	p	0.8
Risk aversion coefficient for flexible generators	A_{FG}	0.1
Risk aversion coefficient for retailers	A_R	0.02
Fixed Price to consumers	P^C	35
Coefficient of cost for flexible generators	σ_{FG}	3
Expected demand for retailer type A "Less Exposed"	\bar{D}_A	200/3
Expected demand for retailer type B "More Exposed"	\bar{D}_B	100/3
Demand standard deviation for retailer type A	Std_A	$Std_{sys}/\sqrt{2}$
Demand standard deviation for retailer type B	Std_B	$Std_{sys}/\sqrt{2}$

In our *extended model* (with both flexible and inflexible generators), we set the number of inflexible generators at $N_{IG}=10$. The coefficient on the flexible generators' costs changes from $\sigma_{FG}=3$ to $\sigma_{FG}=6$, and the cost coefficient for inflexible generators is fixed at $\sigma_{IG}=6$. Thus, the global supply curve always corresponds to the supply curve in the first example.

B. Preliminary Results

Preliminary results from our *baseline model* (in which all producers are flexible) are presented in Tables II and III.

The results from our *extended model* (with both flexible and inflexible generators) are presented in Table IV.¹³

¹³ In our extended model we only have a single gate closure position because one generation technology is inflexible.

TABLE II
BASELINE MODEL RESULTS (ONLY FLEXIBLE GENERATORS)
WITH NEAR GATE CLOSURE (STANDARD DEVIATION OF SYSTEM DEMAND OF 10)

Near real-time gate closure (Std _{sys} =10)		Benchmark	Case 1	Case 2
		No penalty (k=1)	Med. penalty (k=1.2)	High penalty (k=1.4)
Prices	Forward price	29.49	29.64	30.11
Forward Quantity	Retailer type A	66.48	67.32	69.90
	Retailer type B	33.14	33.98	36.57
	Flexible Generators	99.62	101.30	106.47
Expected Profit	Retailer type A	352.33	307.94	236.29
	Retailer type B	168.61	129.27	73.14
	Flexible Generators	1464.06	1478.52	1526.22
Expected Utility	Retailer type A	348.52	303.00	230.25
	Retailer type B	164.81	124.33	67.09
	Flexible Generators	1461.48	1476.68	1525.03
TSO's expected revenue		0.00	69.27	149.35
Cost and efficiency	Total Expect Utility	1974.8	1973.3	1971.7
	Efficiency	100.00%	99.92%	99.84%
	Production Cost	1515.0	1515.0	1515.0
	Productive efficiency	100.00%	100.00%	100.00%

TABLE III
BASELINE MODEL RESULTS (ONLY FLEXIBLE GENERATORS)
WITH FAR GATE CLOSURE (STANDARD DEVIATION OF SYSTEM DEMAND OF 20)

Far real-time gate closure (Std _{sys} =20)		Benchmark	Case 1	Case 2
		No penalty (k=1)	Med. penalty (k=1.2)	High penalty (k=1.4)
Prices	Forward price	28.91	31.57	33.83
Forward Quantity	Retailer type A	70.45	74.15	77.29
	Retailer type B	37.12	40.82	43.96
	Flexible Generators	107.58	114.97	121.24
Expected Profit	Retailer type A	350.19	70.77	-189.77
	Retailer type B	147.16	-43.55	-228.79
	Flexible Generators	1442.65	1740.53	2024.31
Expected Utility	Retailer type A	311.50	21.14	-241.86
	Retailer type B	108.47	-93.18	-280.88
	Flexible Generators	1423.00	1719.11	1985.94
TSO's expected revenue		0.00	172.25	334.25
Cost and efficiency	Total Expect Utility	1843.0	1819.3	1797.4
	Efficiency	100.00%	98.72%	97.53%
	Production Cost	1560.0	1560.0	1560.0
	Productive efficiency	100.00%	100.00%	100.00%

TABLE IV
EXTENDED MODEL RESULTS (FLEXIBLE & INFLEXIBLE GENERATORS)
WITH MIDDLE GATE CLOSURE (STANDARD DEVIATION OF SYSTEM DEMAND OF 15)

Middle real-time gate closure (Std _{sys} =15)		Benchmark	Case 1	Case 2
		No penalty (k=1)	Med. penalty (k=1.2)	High penalty (k=1.4)
Prices	Forward price	29.9	31.5	32.8
Forward Quantity	Retailer type A	70.6	72.5	74.1
	Retailer type B	37.2	39.2	40.7
	Flexible Generators	57.9	59.2	60.2
	Inflexible Generators	49.9	52.5	54.6
Expected Profit	Retailer type A	270.1	85.2	-74.9
	Retailer type B	101.5	-31.4	-148.8
	Flexible Generators	813.7	922.0	1019.8
	Inflexible Generators	747.1	827.0	895.6
Expected Utility	Retailer type A	212.6	22.4	-138.0
	Retailer type B	44.0	-94.2	-211.9
	Flexible Generators	790.9	893.6	977.9
	Inflexible Generators	747.1	827.0	895.6
TSO's expected revenue		0.0	125.9	227.9
Cost and efficiency	Total Expect Utility	1794.7	1774.7	1751.5
	Efficiency	100.00%	98.88%	97.59%
	Production Cost	1567.5	1571.3	1580.4
	Productive efficiency	100.00%	99.76%	99.18%

C. Discussion of the results

Four economic consequences appear in these numerical simulations: (1) a distortion of the forward price; (2) an asymmetric shift in the welfare of market participants; (3) an increase in the TSO's revenues; and (4) inefficiencies.

1) *Distortion of forward prices and over-contracting*

The use of penalties in real time changes the opportunity cost to participants on the forward market. This results in distortions in the forward price. Figures 4 and 5 present modifications to forward prices for the various cases under study.

Penalties increase the volatility of both the price of imbalances and the covariance between

retailers' unhedged profits and these prices. This is why retailers prefer to buy more on forward markets to hedge their profits. This creates tension on the forward market and results in a distortion of the price on this market.

Fig. 5 Influence of penalty on Forward Price in our baseline model (only flexible generation technology)

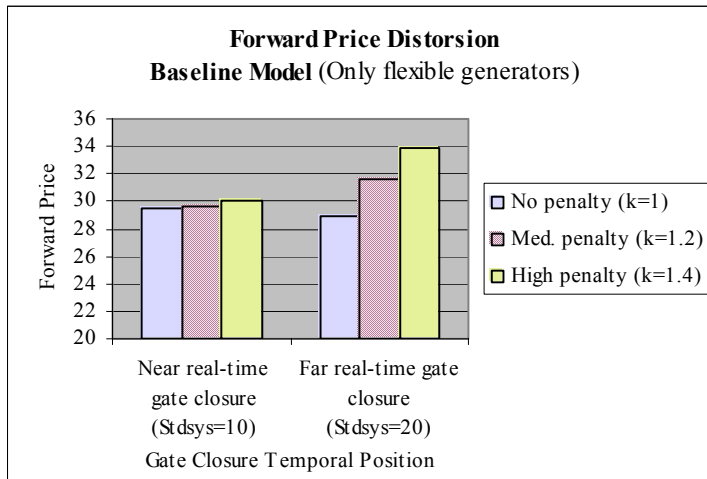
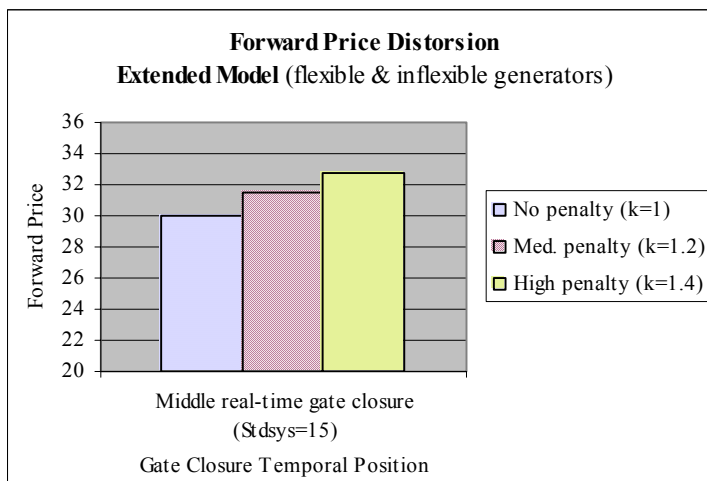


Fig. 6 Influence of penalty on Forward Price in our extended model (with two generation technologies)



The distortion of the forward price may modify how the cost of hedging risks is allocated between market participants and create a barrier to entry for some agents (cf. the next section). Furthermore, these distortions may create the appearance of market power being exercised, owing to the reappearance of a “price/cost” markup, even when the market is competitive

(Smeers [11]). Another result of the penalties is over-contracting. Figures 7 and 8 illustrate this with the rate of forward purchases by retailers and expected individual demand. We can see that retailers almost always seek to buy more than the expected demand, and that this effect is exacerbated when a penalty is imposed. Of course, over-contracting is greater when the retailer is more exposed (= *type B retailer*).

Fig. 7 Influence of penalty on forward purchase for retailer type A (less exposed retailer).

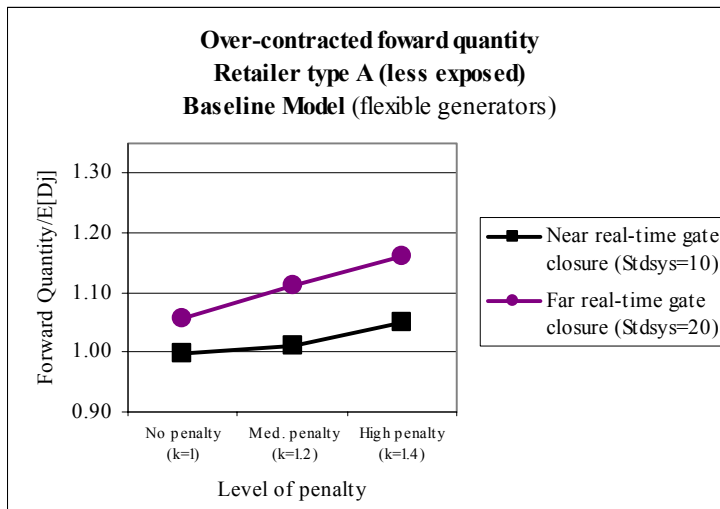
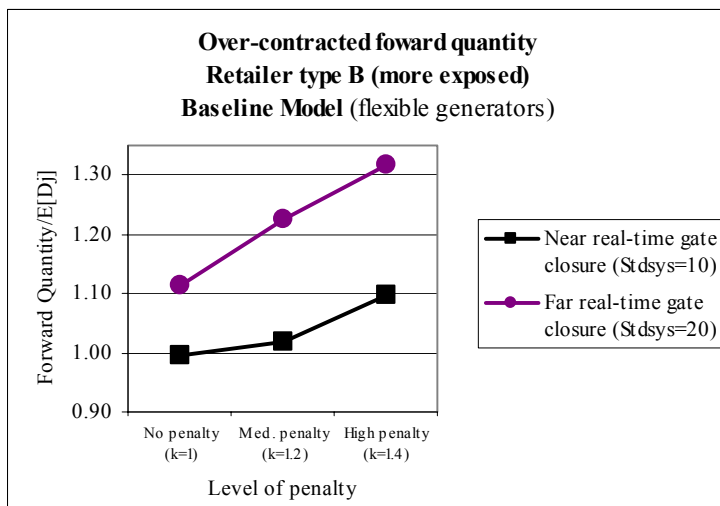


Fig. 8 Influence of penalty on forward purchase for retailer type B (more exposed retailer)



2) Asymmetric shifts in market participants' welfare

The introduction of penalties does not have the same effect on all market participants. This can be seen by examining how their expected utilities change with the introduction of penalties.

Figures 9 and 10 represent changes affecting the benchmark (our benchmark being the reference case with no penalty).

Fig. 9 Influence of penalty on welfare changes (with only flexible generators and near real-time gate closure).

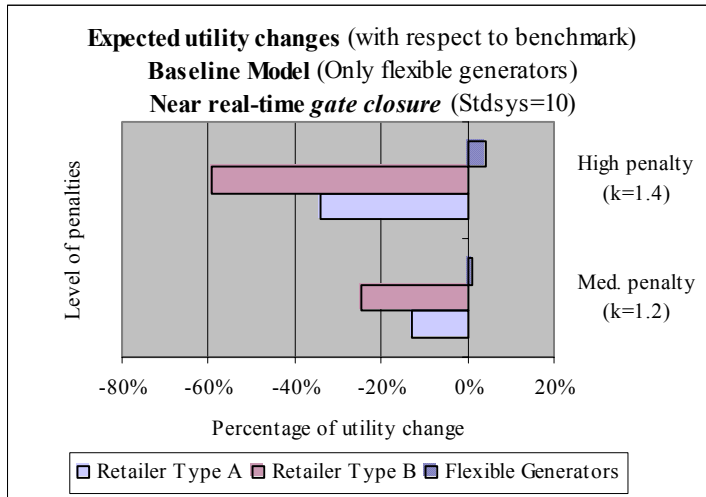
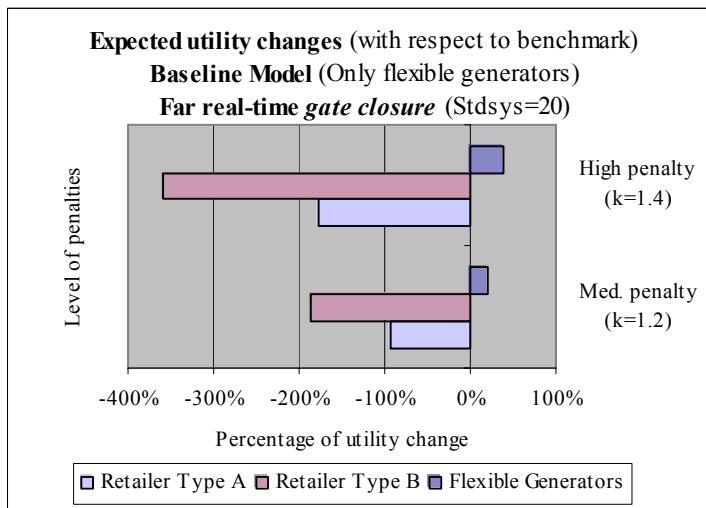


Fig. 10 Influence of penalty on welfare changes (with only flexible generators and far real-time gate closure).



Two primary consequences are observed.

The first is a redistribution of welfare between retailers and generators. Net purchasers on the forward market are retailers, and their welfare diminishes. Generators are net sellers, and their welfare increases. It may be tempting to consider this transfer of welfare to correspond to a service rendered by flexible generators in real time. However, in our extended model (both

flexible and inflexible technologies) we observe that inflexible generators also benefit from this transfer. This shines the spotlight on the nature of the redistribution between buyers and sellers on the forward market.

The second consequence is that penalties have a greater impact on small, vertically disintegrated agents (*Type B retailers*) than on those that are large or integrated. Type B retailers (which are both small and disintegrated) see their welfare fall twice as much, proportionally, as type A retailers (which are large or vertically integrated in generation).

Therefore the use of penalties creates a barrier to entry to agents that are small or not vertically integrated in generation. The balancing mechanism harms all agents who need to contend with greater uncertainty (retailers or aggregators with small client bases, small generators, wind generators, etc.). This barrier may deter some agents from entry, and thus undermine the dynamics of competition.

3) *Increased revenues for the TSO*

Introduction of a penalty diverts revenues to the TSO (cf. Figures 11 and 12).
of the electricity system attributable to the TSO further penalizing market participants.

Fig. 11 Influence of penalty on TSO Revenue (only flexible generators)

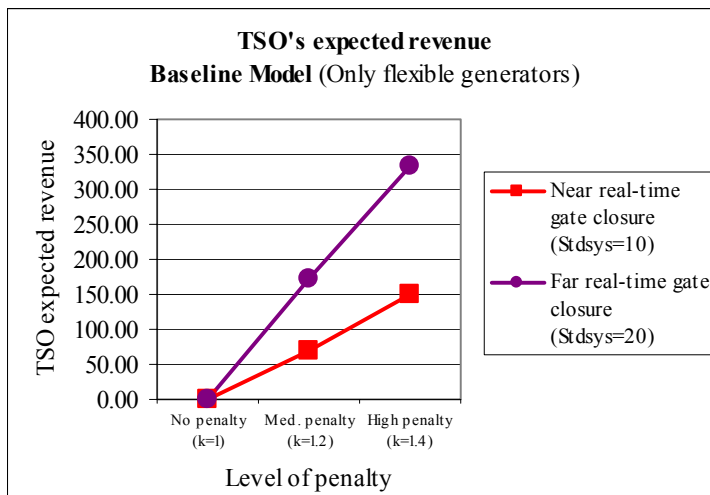
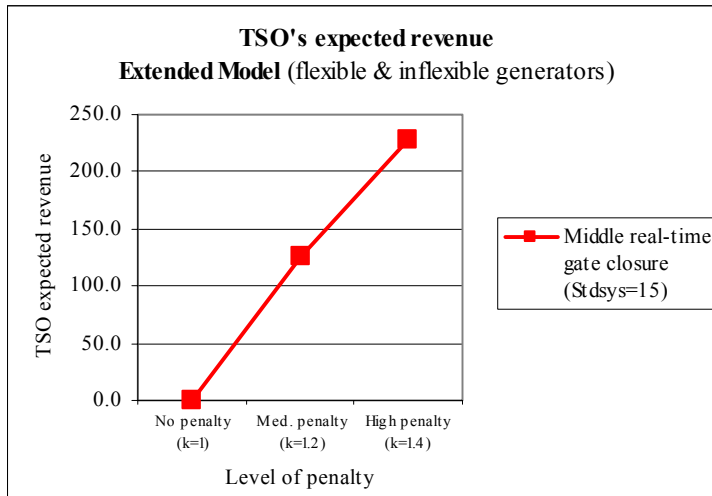


Fig. 12. Influence of penalty on TSO Revenue (flexible and inflexible generators)



The TSO’s revenues (flippantly referred to as the “*beer fund*”) increase with the level of the penalties and the temporal distance of the gate closure. This revenue mechanism does not provide the TSO with the right incentives to create the best design for the balancing arrangement, for which the grid has a real need in real time. The fact that the TSO’s revenues automatically increase when the level of the penalty rises and the gate closure moves ahead in time does not provide any useful evidence regarding the exact improvement in the security.

It is important to observe that the welfare of large generators also increases with the level of the penalties. Since, in some countries, TSOs, large generators, and vertically integrated generators may all be quite closely knit, and all have a great deal of say in choosing the market design rules, we may fear that a poor initial choice of balancing arrangements may be followed by a lengthy period in which these faulty bases are entrenched. This will make it very difficult to improve this setup after the fact.

4) Inefficiencies

In our baseline model, in which all producers are flexible, efficiency in generation is not undermined by the introduction of penalties. Inefficiencies that crop up are attributable to the fact that penalties increase the volatility of profits and that, since market participants are risk averse, their expected utility decreases.

Fig. 13 Penalty decreasing efficiency in the baseline model (all generators being flexible)

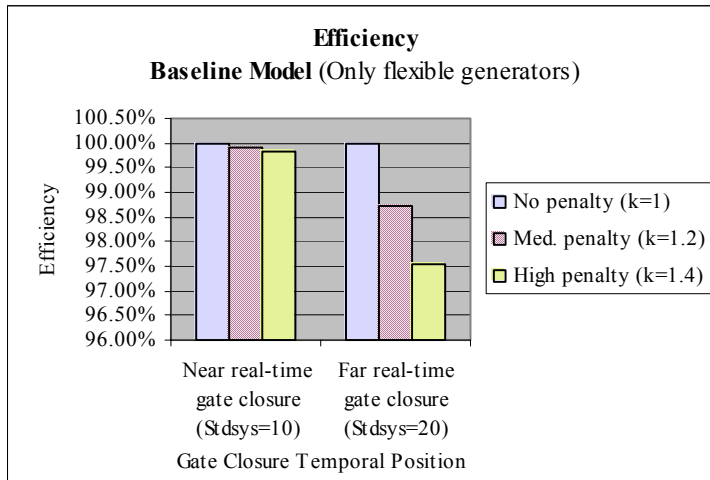
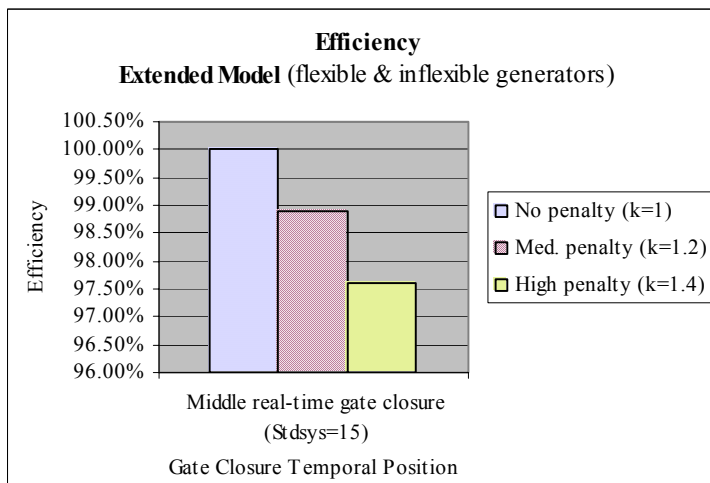


Figure 14 reveals the impact of penalties in the model with two generation technologies (flexible and inflexible). Here, inefficiencies in generation arise as inflexible producers make poor output choices because of price distortions on the forward market. It is important to notice that inflexible generators primarily take their cue from forward prices in deciding on output levels. Another important consequence of introducing penalties into the dual technology model is that real-time prices and imbalance prices are affected by excess generation from the inflexibles.

Fig. 14 Penalty decreasing efficiency in the extended model (generators being flexible or inflexible)



VI. Conclusion

We have examined the economic consequences of using penalties in balancing arrangements. Running a few numerical simulations on the basis of a two-period equilibrium model, we have found four principal economic consequences: (1) a distortion of the forward price; (2) an asymmetric shift in the welfare of market participants that primarily impacts on small and disintegrated agents; (3) an increase in the TSO's revenues; and (4) inefficiencies. The magnitude of these consequences increases as the temporal position of the gate closure moves away from real time.

Of course, the models we use are subject to several limitations, especially since they are based on strong assumptions (perfect competition, no constraints on generation capacity, no constraints on grid capacity, no reserves market, etc.). Therefore, we must seek to eliminate some of these assumptions in future work. We shall also conduct a sensitivity analysis to see how the results react to changes to the parameters.

Nonetheless, in light of these preliminary results, and given the current situation in which countries in the western European Union continue to seek to improve and harmonise their market designs, we wish to underline that economic consequences of this type cannot continue to be ignored by decision makers... whether TSOs or regulators.

We do not deny that balancing provisions are extremely important for the security of the grid and the good functioning of the electricity reforms. However, it is clear now that these balancing arrangements are not technical security mechanisms. Rather, they are institutional arrangements in which the TSO sets the rules of the game for other agents, with implications not only in real time, but also on forward markets (day ahead and intraday).

In their choice of the temporal position of gate closure, TSOs define the structure of information available to agents making decisions on forward markets, and by extension the level of uncertainty entering into their decisions. With the combination of gate closure positions and penalty levels, TSOs define the incentive system that applies to decisions made under uncertainty by other agents who are risk averse. Moreover, these rules of the game have asymmetric impacts on retailers and generators, on small, vertically disintegrated and large, vertically integrated generators, and on flexible and inflexible generators. These rules may also function as barriers to entry for small, disintegrated actors.

In conclusion, the security mechanisms that are TSO's balancing arrangements are not neutral

in terms of their impacts on wholesale markets or the competitive dynamics on these markets. Since there exist several alternative designs for balancing arrangements, it is not unreasonable to expect TSOs and regulators to account for the economic consequences of the various models when they establish the architecture of the wholesale market: either during the initial market design, or during a later review in light of the experience accumulated in other countries.

Even though there currently exists a strong preference in Europe for conserving “balancing mechanisms” and for delaying the implementation of “balancing markets,” it remains that the time is right to conduct a comparative study of the existing balancing arrangements, since several bordering countries are seeking to create closer links between their PXs and their provisions for allocating interconnections in order to lay the foundation for a new regional market.

VII. Appendices

A. Extended model with two generation technologies (flexible and inflexible)

In this extension, we introduce a new generation technology, which is inflexible, alongside the flexible technology of our baseline model. Inflexible generators must determine their level of output within the uncertain framework of the forward market, since their output cannot be adjusted beyond gate closure. They make decisions by observing the forward market.

To simplify, we assume that inflexible generators do not voluntarily take positions of imbalance in real time. Consequently, they generate exactly the quantity that they sold on the forward market ($X_{IG_i} = X_{IG_i}^F$). The goal of the inflexible generator l is thus to select $X_{IG_i}^F$ (or X_{IG_i}) so as to maximise profit. This profit function is given by:

$$\pi_{IG_i}(X_{IG_i}^F) = P^F X_{IG_i}^F - \frac{\theta_{IG}}{2} X_{IG_i}^F{}^2.$$

The first-order necessary condition is:

$$\frac{\partial \pi_{IG_i}(X_{IG_i}^F)}{\partial X_{IG_i}^F} = 0 = P^F - \theta_{IG} X_{IG_i}^F{}^*$$

$$\text{and so } X_{IG_i}^F{}^* = \frac{P^F}{\theta_{IG}} \quad (10)$$

The conditions for equilibrium on the forward market (5) become:

$$\sum_i X_{FG_i}^F{}^* + \sum_l X_{IG_l}^F{}^* = \sum_j X_{R_j}^F{}^* \quad (11)$$

From equations (1), (2), (3), and (11), we find that:

$$\forall \omega \quad P_{\omega}^{RT} = \left(D_{\omega} - \sum_I X_{IG_i}^F \right) \frac{\sigma_{FG}}{N_{FG}} \quad (12)$$

where $D_{\omega} = \sum_I D_{j,\omega}$ is global demand for the state of the world ω .

Thus, equation (7) becomes:

$$X_{FG_i}^F = \frac{P^F - E[P_{\omega}^{RT}]}{A_{FG} \text{Var}[P_{\omega}^{RT}]} + \frac{\text{Cov}[\rho'_{FG_i,\omega}, P_{\omega}^{RT}]}{\text{Var}[P_{\omega}^{RT}]} \quad (13)$$

where $\rho'_{FG_i,\omega}$ is the unhedged profit of flexible generators (i.e. with $X_{FG_i}^F = 0$), whence:

$$\rho'_{FG_i,\omega} = \pi_{FG_i,\omega}(X_{FG_i}^F = 0) = \frac{1}{2} \sigma_{FG} (D_{\omega} - \sum_I X_{IG_i}^F)^2.$$

We can now use equations (4), (11) and (12), along with the optimal positions on the forward markets (equations (8), (10) and (13)), to find the market equilibria. (P^F , P_{ω}^{RT}).

VIII. Thanks

The authors wish to express deep gratitude for the assistance and comments received from M. Massoni and C. Gence-Creux of the *Commission de Régulation de l'Énergie* (CRE), P. Dessante from Supélec, D. Finon (CIRED at the CNRS), as well as Y. Perez, C. Hiroux and M. Mollard from the ADIS-GRJM at the Université Paris Sud. However, all the results, opinions, conclusions, recommendations, and (lamentably) errors remain the entire responsibility of the authors.

IX. Bibliography

- [1] Glachant, J.M. and Leveque, F. (2005). *Electricity Single Market in the European Union: What to do next?* Discussion paper of the European Union research project SESSA, Sept 2005, (http://www.sessa.eu.com/documents/bruxellesp/SESSA_report_wp1.pdf). Working Paper CEEPR 2005-15 at MIT (web.mit.edu/ceepr). Main results presented at IDEI conference, Toulouse, May 2005.
- [2] Hirst, E. (2001). *Real-time Balancing Operations and Markets: Key to Competitive Wholesale Electricity Markets*. Edison Electric Institute, April 2001.
- [3] Joskow, P. and Tirole, J. (2004). *Reliability and Competitive Electricity Markets*, MIT department of Economics working paper N° 2004-17, October 2004.
- [4] ETSO (2003). *Current state of balance management in Europe*. Available from ETSO website (<http://www.ets-net.org/upload/documents/BalanceManagementinEurope.pdf>), December 2003.

- [5] Newberry, D. (2005). *Refining Market Design*, Discussion paper of the European Union research project SESSA, Sept 2005, (http://www.sessa.eu.com/documents/bruxellesp/SESSA_report_wp3.pdf).
- [6] Wilson R. (2002). Architecture of electric power markets. *Econometrica*, 70(4), 1299-1340.
- [7] Boucher, J. and Smeers, Y. (2002). Towards a common European Electricity Market – Path in the right direction...still far from an effective design. *Journal of Network Industries* 3(4), 375-424, 2002.
- [8] Bessembinder, H. and Lemmon, M. (2000). Equilibrium Pricing and Optimal Hedging in Electricity Forward Markets, *Journal of Finance*, Vol. 57, pp. 1347-1382, 2002.
- [9] Siddiqui, A. S. (2002). *Equilibrium Analysis of Forward Markets for Electricity and Reserves*. PhD dissertation, University of California, Berkeley, 2002.
- [10] Green, R. and McDaniel, T. (1999). *Modelling Reta: A model of forward trading and the balancing mechanism*.
- [11] Smeers Y. (2005). *How well can one measure market power in restructured electricity systems?* Discussion paper of the European Union research project SESSA, Mai 2005, (http://www.sessa.eu.com/documents/wp/D14.1_Smeers.pdf). Main results presented at IDEI conference, Toulouse, May 2005.
- [12] Stoft, S. (2002). *Power System Economics*. IEEE Press, Wiley-Interscience.