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Abstract

The present work introduces the main regulatory issues faced nowadays in EU by policy-makers in the design of the electricity and natural gas markets. The dissertation consists of the following parts:

Chapter 2 introduces the new challenges that are currently engaging the European markets, under the perspective of the stronger integration expected in the next years. The coordination of the investments in new facilities and the rules governing their access, the increasing need of flexible resources as well as the integration of spot and forward markets will be some of the themes examined in this first section.

Chapter 3 focuses on the regulatory interventions aimed at increase the flexibility of the storage services in the Italian gas market. A first part of the work is devoted to describe the storage technologies, the services they provide and their current regulatory framework. The rest of the chapter discusses the main issues related to the elicitation of flexible resources and the attraction of investments in new storage infrastructures.

Finally, chapter 4 builds a model of competition to study the bidding strategies of the power generation firms in a day-ahead electricity market based on zonal pricing. The analysis shows the role that investments in the transmission network may have on the degree of market competition, final prices and social welfare.

Abstract Chapter 2

This chapter introduces some of the new challenges that are currently engaging the European energy markets, under the perspective of the stronger integration expected in the next years. The main issues are related to the interaction of market mechanisms with regulatory targets. The stability and the security of the energy supply, on one side, and the transition towards more competitive and efficient markets, on the other, impose to the involved actors the definition of priorities and instruments aimed at preserving the goal of the creation of a common European zone. This objective must be achieved in a period characterized by the massive penetration of renewable energy sources (RES). The themes of the better integration of the spot and forward markets, the coordination of the investments in new facilities and the rule governing their access, as well as, the increasing need of flexible balancing resources will be examined throughout the chapter.

Abstract Chapter 3

This chapter studies which regulatory interventions can be put to work to increase the flexibility of the storage services in the Italian gas market. The first part of this work is devoted to describe the storage technologies, the services they provide and their current regulatory framework, while the rest of the chapter discusses the main issues related to the elicitation of flexible resources and the attraction of investments in new storage infrastructures. Two main proposals ensue from this analysis. *First*, the Third-Party-Access (TPA) regime, at which the storage operators are subject, may depress entry in the storage industry to the extent that newcomers are not able to recover the initial cost of the investment. Exemption to TPA should than be granted on a case-by-case basis, but the

uncertainty about the regulatory regime introduces an additional risk for potential storage operators. In these situations, the institution of a public regulated *SSO (Storage System Operator)*, endowed with the monopoly of storage sites, may generate the required investments under the regulatory pressure. *Second*, the current mechanism of Peak and Uniform capacity allocation may enter in conflict with the security of supply to final users if shippers are not able to predict prices accurately. A complementary design based on the introduction of *supply option* may reduce the risk for the shippers related to excessive price volatility and provide the TSO with an adequate amount of reserves for short-term modulation.

Abstract Chapter 4

This chapter introduces a model of competition to study the bidding strategies of the power generating firms in a day-ahead electricity market based on zonal pricing. In this framework, two symmetric generators are located into two separate geographical zones, linked together with a limited capacity line, and compete in a multi-unit uniform price auction to supply electricity the day-ahead market. Two main results derive from the model. First, even if players are symmetric, asymmetric strategies and allocation may emerge in equilibrium. Second, a limited transmission capacity may provide an incentive to firms to induce a congestion of the power line in order to create an artificial monopoly and increase revenues in their zone. For a firm this strategy is conducted by increasing the price of its marginal unit above that of the competitor, forcing the consumers located in its zone to import electricity up to the point where the cable reaches the transmission limit. At this point the generator acts as a monopolist on the residual demand which remains unserved by importations. In equilibrium, however, one of the two

players must have an incentive to not mimic its competitor and decongesting the line. As a result the two zones separate in net-importer and net-exporter and firms play asymmetric mixed strategies. From a welfare perspective, an asymmetric allocation in not socially efficient since total generation costs are not minimized. Under certain conditions, the analysis indicate a scope for policies aimed at increasing line's transmission capacity in order to reduce the economic *"withholding"* of power units and improve the social welfare.

Chapter 1

Introduction

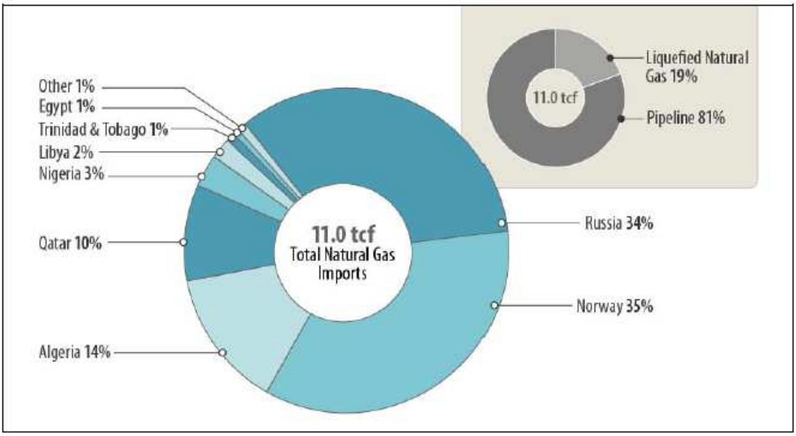
The European energy markets are living a period of big challenges. The need of switching to a low carbon economy and the integration of renewable energy sources (RES) into the current market design, the stability and adequacy of the offer to final consumers (security of supply) and the creation of a pan-European model for the development of the internal competitive market are the themes at the core of the political debate[1]. The European targets created new rooms for the regulatory intervention in the sector. The choice between a public subsidy and the creation of market mechanisms for the development of RES, the determination of the optimal market design for the remuneration of the investments in new power plants or, alternatively, which regulation for the harmonization of the congestion management are typical examples of the issues currently faced by policy-makers in EU.

Despite of the big effort made by all the actors involved in the regulatory process[2], Chapter 1 shows how the unification of the regulation at EU level is still far from being complete and delays in the realization of

[1]To promote the debate and the coordination between the European national regulatory authorities, in 2009 the Third Energy Package adopted by the EU instituted the *Agency for the Cooperation of Energy Regulators* (ACER).

[2]In February 2014 the launch of the pilot project of market coupling in 14 EU Member represented an important step towards the unification of the day-ahead electricity markets in the North-Western Europe.

Figure 1: EU Natural Gas Imports in 2012



Source: BP Statistical Review of World Energy 2013.

Notes: The United States re-exported a minimal amount of LNG to Europe in 2012 and is included in Other. The percentages do not include imports from one EU country to another. Units are trillion cubic feet (tcf).

the essential facilities emerge within and across countries[3]. In particular, delays in the development of the European networks for gas and electricity are detrimental not only to the achievement of the goal of market unification but also for the security of supply and the diversification of fuel importation routes. As showed in Figure 1 below, in 2012 the European gas importations came mainly from Norway (35% of total imports), Russia (34%) and Algeria (14%). In 2030 the European Commission forecasted that 80% of EU natural gas needs will come from importations.

In this perspective, new investments in pipelines, LNG terminals and storage tanks may serve to the scope of reducing the dependency from the historical partners of EU and increasing long-distance importation of gas (for example USA[4] and South America).

Geopolitical tensions are not the only issues deriving by the lack of

[3] In the document of 15th November 2012 the European Commission indicated the 2014 as the year for the realization of the internal market.

[4] As several analysts argue, given the increasing production of USA shale-gas *"[. . .]The United States is expected to go from a net importer of natural gas to a net exporter by 2020"* (see (62))

adequate and coordinated investments in network capacity. The massive penetration of the intermittent and distributed generation, occurred in the last years in the electricity sector, introduced an additional source of instability in the EU system. *First*, the existence of small generating units connected directly to the distribution (low voltage) rather than the transmission (high voltage) power grid imposes a higher coordination between the subjects responsible for the management of the entire network. In this perspective, studies aimed at understanding how to increase the responsiveness of the demand to price variations and the design of dynamic and adaptive networks (smart grids) are assuming a central role in the public and scientific debate. *Second*, the possibility of short-term variations on the supply side requires the existence of flexible resources (reserves) able to cover unbalances between demand and supply in the real time. This not only reveal the high potentiality related to the development of grid-scale electricity storage technologies (batteries), but also shows how the interdependence between natural gas and electricity markets is increased, since real time unbalances in the electricity production are directly transferred to the upstream market for the fuel.

In Italy, almost 70% of the power production comes from the thermoelectric sector while natural gas amounts to 65% of the total production. Endowed with limited internal resources, Italy, the third highest European consumer of natural gas[5], imports the majority of gas for its consumption from abroad (in 2012 the percentage of imports on total consumption was around 97%[6]). The increasing of the liquidity of the spot market (PSV hub) helped to reduce the long-run dependency from external sources, generally based on long-term contracts with Take-Or-Pay clause[7], and provided additional tools for short-term modulation of the consumption. Notwithstanding, the Italian gas system is centered on its storage reserves. These are used to respond both to seasonal and short-term variations of the demand and production as well as for the real-time physical balancing of the grid by the TSO (Transmission System

[5]Sources: BP Statistical Review of World Energy 2013 and Eurogas.

[6]Source: see supra note 5.

[7]These contracts, generally inflexible, impose to the shippers very high renegotiation costs.

Operator). Shocks in the gas demand following, for instance, an instantaneous increase of CCGT (combined cycle gas turbine) consumption as a response to unexpected collapses of the electricity production from renewables, are compensated by making use of the gas reserve available into the system. However, the "flexibility" of the gas in stock depends on the storage site and its technical characteristics[8], as well as by the regulation for accessing the infrastructure and its services. These arguments are the subjects of the second chapter of this work. While the first part of chapter 2 describes the technology of gas stockpiling and the technical characteristics and costs of storage sites, the second part discusses the regulation currently adopted in Italy for the remuneration of the investments in essential facilities, the access to the infrastructures and the market mechanisms for the allocation of the storage capacity among the shippers. The analysis conducted shines a light on some of the criticalities that affects the Italian gas market and, in particular, those related to the application of the TPA (Third-Party-Access) regime for accessing the storage facilities and the conflicting coexistence of market mechanisms with system security targets for the allocation of the storage capacity. As chapter 2 shows, there is a scope for a direct public intervention for the realization of the infrastructures and for the introduction of mechanisms aimed at enhancing market competition yet preserving the security of supply.

Investments for the development of the network are ultimately fundamental to the promotion of a competitive European industry, expected to reduce the cost of energy to final consumers. In the wholesale electricity markets, a limited capacity of transmission between different geographic zones not only reduce the access to potential entrants (creating *de facto* regional monopolies) but, also, may induce strategic behaviors aimed at sustaining artificial higher prices for final consumers. While the economic literature focused extensively on the strategic bidding of the generation companies (gen.co.) in the day-ahead market[9] and the most

[8]The main parameters include the withdrawal and injection rates and the space capacity.

[9]See, for instance, the model proposed by *(65)* and *(36)*or, more recently, *(22)* or *(43)*. As chapter 3 will describe, the main debate in the literature is related to the definition of

(socially) efficient market mechanism for the allocation of the transmission rights[10], less has been said about how transmission capacity affects the supply strategies of the firms.

(13) provided an important contribution to this area of research with the introduction of a Cournot model of competition where firms, located in two zones connected by a power line with a limited transmission capacity, compete to supply electricity in the same day-ahead market. Built on this network configuration, chapter 3 constructs a multi-unit auction model where firms are asked to submit to the power exchange a step supply function, containing a finite number of pair price-quantity, in a day-ahead market based on *zonal pricing*. The zonal pricing, assumed as the pricing method model in Europe, divides the (commercial) network in more zones and, for any couple of zones, generates different prices if the power lines are congested (i.e. the network constraints are binding). If no congestion on the grid occurs the price is, instead, unique on the entire territory[11].

The contribution of the analysis developed in chapter 3 is the inclusion in a basic theoretic model of a set of business rules closer to those currently adopted in EU by several power exchanges. If, on the one hand, this alternative approach is able to reproduce some of the results already present in the literature as, for instance, the adoption of mixed asymmetric strategies by the firms or the definition of a transmission capacity target for policy-makers, on the other, the model can be further generalized and easier applied to real market situations to forecast firms bidding strategies. This last aspect would be source of future research in the field, with the intent of evaluating regulatory interventions aimed at harmonizing the business rules in EU[12] and the dynamics of the investments

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the most appropriate approach for modelling the supply curve submitted by the firms for their power plants.

[10]Several authors studied the differences between the adoption of the uniform price auction (or system marginal pricing) and the pay-as-bid auction for the selling of power in the day-ahead market - see for instance (31; 32).

[11]An alternative format is the *"nodal"* pricing adopted by the PJM (USA) where the price is computed for each bus on the grid.

[12]Consider for instance, the market priority for the dispatching of renewables adopted in some countries to facilitate new investments or a revision of the zonal partition of the

undertaken by the TSOs.

transmission grid.

Chapter 2

The New Challenges of the European Electricity and Gas Markets

2.1 Introduction

In the recent years new challenges emerged for the European energy markets. These are principally related to the development of an European common market for electricity and gas and, to the same extent, to the integration of the renewable sources (RES) and Distributed Generation (DG)[1] in the energy systems. Notwithstanding the great advantages expected for all the community and in particular for final consumers, the integration of the European market proves to be a difficult task for several reasons. First, each member state has a different organization and regulation of its internal market, which varies a lot among countries. Therefore, the establishment of largely accepted settings require a big effort for the definition of the resources, the actors and the regulatory framework for operators. Secondly, the creation of a common mar-

[1]The Distributed Generation (DG) refers to the production of power from small scale generators, decentralized on the national territory and connected to the medium and low voltage grid.

ket zone stands on the ability of the systems to generate incentives for developing the essential infrastructural facilities within the entire supply chain: production, transmission, distribution and storage. Finally, the massive penetration of the renewable capacity and distributed generation introduces new difficulties that directly impact on the stability of the European systems. Both electricity and gas markets are than required to quickly adapt and generate flexible resources to assure the security of supply to final users. This adaptation is more complicated in the electricity industry, since power cannot be cheaply and easy stored. As a result, system stability asks for a higher coordination between gas and power sectors, both in the short and the long term, with the intent of increasing the value of future investments. Holding the perspective of the progressive unification of the European markets, these arguments will be discussed in the next sections as follow: first, the main obstacles to the achievement of a single European energy market and the expected regulatory interventions will be treated; successively, the major debates and trends in the electricity and gas sectors are described and analyzed. Despite of the strong correlation between gas and electricity, the analysis of the two sectors is conducted separately. This is motivated by the need of preserving the *specificity* of the interventions in the two industries.

2.2 Market Integration

The Energy policy is at the core of the EU integration. The third energy package (2009/72/CE and 2009/73/CE), that entered into force in 2009, imposed on the member states the achievement of several targets for their internal market. These are principally devoted to increase market competition, assure (at least) a legal unbundling between energy transmission and production and increase consumers protection.

Notwithstanding important measures have been adopted inside the member states, there is still much to do to integrate the markets into a single European system. Indeed, the European markets are still characterized by a regional dimension with different degrees of liquidity and a great variety of products exchanged. This motivated the EU Commission to intervene in the last years with policies principally oriented to guarantee a non discriminatory access to the essential facilities and attracting new investments into the sectors, with the scope of increase the liquidity inside the markets. These conditions have been recognized as a prerequisite for delivering the benefits of liberalization to final consumers.

As highlighted by the European Commission (hereafter: EC)[2], the non discriminatory access to the infrastructure represents a major concern, since the historical advantages of the former monopolists can act as a barrier to entry. This may inhibit both EU and extra-EU operators to enter the wholesale and retail markets. To deal with this possibility, two directives of EC[3] gave the possibility to the countries to choose between a regulated or negotiated *third party access* (TPA) to the infrastructure recognized as essential facilities (high-voltage electricity transmission, high-pressure pipelines, gas storage site, etc...). The option that has been adopted across Europe however is not uniform, introducing so an additional source of complexity towards markets unification. (24) argues that, for a country, the choice of one mechanism rather than the other can be motivated by the degree of maturity reached by its internal market. Indeed, in a market characterized by a high level of competition the negotiated access to the infrastructure can be viewed as a desirable market-oriented approach. The cost for accessing the infrastructure so should reflect the effective willingness to pay of the operators in presence of scarcity of the resource (congestion). In a regulated TPA, instead, the regulator is charged with the task of defining the optimal tariff for the utilization of the facility. The determination of the tariff may (largely) differ across countries according, among the others, to the ownership of the facility (private or public nature), the incentive scheme adopted for investor remuneration and the presence of alternative resources for operators (for instance, interconnection vs. storage capacity). The harmonization of the tariff plans, both at wholesale and retail level, becomes so a crux point for the definition of a single trading area. An effort in this

[2]see (29).

[3]Directive 2009/72/EC (the "Electricity Directive") and Directive 2009/73/EC (the "Gas Directive").

sense has been made, for instance, in gas markets, with the Entry-Exit tariff plan for pipeline transportation. However, as markets liquidity is expected to increase in the next years, negotiation can be thought as more reflective of the operators' willingness to pay, inspiring than the introduction of market mechanisms for the allocation of the resources (ex. auctions).

Markets integration and development cannot disregard from the promotion of new investments in generation (production) and infrastructures. This is more than an issue in an area, the EU, where the supply is strongly dependent from external fuels. In the electricity sector, most European countries are investing in generation capacity, especially driven by the quick transition to renewable sources. In particular between 2005 and 2010 renewables reached the installed capacity of 288 GW[4]. Despite the great result achieved, the target of increasing the renewable capacity of 487 GW in 2020[5] remains far away. In fact, according to the notification arrived at the European Commission of planned investments in RES, only 40 GW are expected to enter the markets in the coming years[6]. In this context, large differences in generation capacity are still surviving among the member states. Indeed, it is difficult to find similar trends in all countries, exacerbating the need for a common European program. If, on the one hand, some countries record a structural situation of overcapacity in the power generation from fossil fuels (oil, gas and carbon), as for instance Italy, other countries are instead experiencing a boost in the investment for the generation from these sources (for instance Greece, UK, Spain and Germany). Major investments are also expected in the next years in nuclear energy in, among the others, UK, France, Finland and Sweden.

If integration is expected to contribute to the savings for final con-

[4]Source: (30).

[5]This is recognized as the target by the EC *Project Horizon 2020.*

[6]Source: see supra note 14. However, as indicated by the EC, the data published can underestimate the real amount of renewable capacity installed in EU-27. The document reports that *"The gap is probably explicable by the thresholds set in Regulation 617/2010 (reporting threshold set at 10 MW for photovoltaic projects and 20 MW for wind parks). This resulted in an underestimation of current capacity and future investment in electricity generation from renewables, as this type of investment is usually small-scale"*.

sumers, the lack of coordination among member state may have, given the long-run returns of investments, the effect of crowding out part of generation capacity. This aspect, together with additional factors that typically impact the electricity industry, has been one of the reason that led most countries to design mechanisms aimed at assuring an adequate level of capacity *(Capacity Market)*. These tools are at the center of an intense debate in Europe regarding their opportunity and implementation within the current electricity market architectures.

Along with generation capacity, additional infrastructural investments are expected to bring final benefits in the coming years. As it has been estimated by the EC, Europe's energy system requires investments for 210 billion Â€ by 2020[7]. These are devoted to *(i)* improving the high voltage electricity transmission and increasing the electric storage capacity and smart grid applications, *(ii)* improving the high pressure gas transmission and increasing gas storage capacity and LNG terminals. From EC's estimations, it emerges that the volume of investments for the period 2011-2020 will need to increase by 30% for gas and 70% for electricity compared to current levels.

With regard to the gas sector, a key role is attributed to new investments in LNG terminals. The reduction of internal gas production and, consequently, the increase of the energy dependence from extra-EU countries make investments in LNG (Liquefied Natural Gas) extremely important. Currently, around 20% of European gas importation is in the form of LNG. In 2010 the European import dependency comes mainly from Russia (35%), Norway (27%) and Algeria (14%). The diversification of energy sources must be accompanied by the development of adequate storage capacity. Indeed, even if the supply flow can be assumed to be quite stable during the year, the demand varies over time and storage is fundamental to respond quickly to these variations. However not all the facilities have the same degree of flexibility. As discussed in *(5)* the higher injection rates are associated with salt caver or LNG peak shaving. These facilities permit to rapidly cover hourly peaks and allow for a flexible modulation of the flows. Currently in Europe around 69% of gas

[7]Source: see supra note 14.

storage is in depleted fields, 19% in acquifer, 10% in Salt cavities and 2% in above ground storage (LNG peak shaving facilities). As expressed by the EC, while *"current EU storage capacity seems sufficient to cover seasonal demand, tight supply demand situations may appear in some regions due to the uncertainty of future gas demand and the uncertainty of the planned investments"*[8].

To monitor the progress made in the realization of the investments, the member states will need to achieve a more efficient data exchange. The instrument adopted to accomplish with this goal is the Ten-Year Network Development Plans (TYNDP's) instituted by the European Network of Transmission System Operators for Electricity and Gas (ENTSO-E and ENTSO-G). The target of these documents is to improve the exchange of data and defining models for the development of the grid in a pan-European perspective. These documents result to be more important in as much as they provide a combined view on the development of the networks for electricity and gas. The important role played by gas-fired power plants and the massive renewables penetration of the last years ask for a closer relationship between gas and electricity market. The reason is related to the need of flexible production to face the higher volatility imposed by the intermittent capacity. Being the natural gas the main source for electricity production in most European countries, an imminent variation of electricity demand or supply have repercussions on the upstream market for fuel. Part of the flexibility asked to electricity production is transferred to the gas market, which must be endowed of flexible resources as well. This closer relation impacts importantly on the market variables both in the short and in the long run. In the short term, the price for the use of flexibility resource is expected to emerge in one or both markets, according to the inter-sector elasticity, while in the long-term this has an impact on the geography of the investment and the security of supply.

Two further considerations are centered on the overcoming of the administrative tariffs to final consumers and the improvement of the energy efficiency. The termination of regulated tariffs has been recognized

[8]See (30).

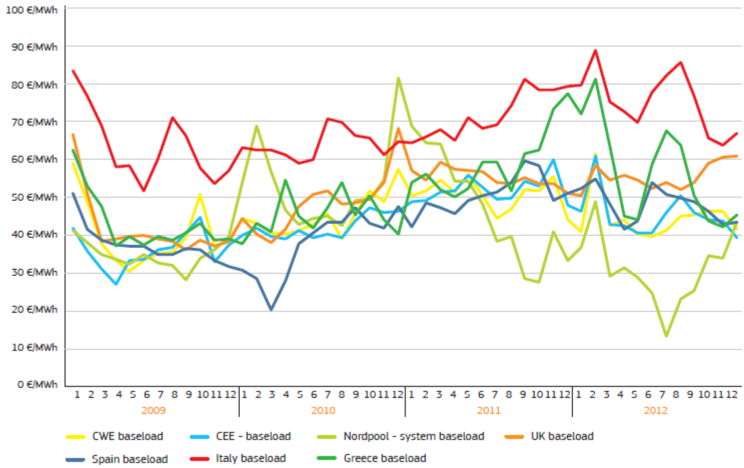
by the EC as one of the main goal for the realization of mature energy markets. The main reasons can be summarized in these two points: first, price signals and investments must be driven by the competitive forces rather than a central definition of the costs for all consumers; second, regulated tariffs depress entry in the market if not *cost reflective*, reducing so the attractiveness for the consumers to switch to other operators. The tariffs may, for instance, be set too low (below the market cost), making real competition impossible. To ride this problem out, the demand must play an active role on the determination of the equilibrium prices and quantities, which currently is prevented by the absence of adequate tools for observing and responding to price variation (smart meters).

Finally, an important scope of European policies is the improvement of the energy efficiency. The target of 20% reduction of CO2 in 2020 has to be pursued by the *national plans for energy efficiency* and supervised by the EC. In this scenario a key role is assigned to new technologies that will be able to reduce energy consumption (e.g. smart meters) and energy production (e.g. cogeneration, zero-emission buildings).

2.3 The Challenges of the Electricity Markets

The European energy markets are divided in a spot market and in a forward market. In the electricity *spot market* the power is negotiated with the day of delivery close to the real time. The spot market is generally organized in a *primary market*, that run before the day of delivery (day-ahead) and a *secondary market*, that allows generators to successively adjust their position. To complement the design, the network manager acquires the resources for balancing the grid in real time on the *ancillary service market*. All these markets may include sub-stages that run in different periods in time. In the *forward market* the operators trade power with a future delivery (e.g. weekly, monthly, yearly). In both cases (spot or forward) the transactions may occur on regulated or non regulated platform (Over the Counter - OTC). In the regulated spot market a Power Exchange determines for each relevant period (e.g. hourly or half-hour) of the delivery day the equilibrium prices and quantities, according to

Figure 2: Comparisons of monthly electricity baseload prices in regional electricity markets



Source: EC Quarterly Report on European Electricity Market - 3rd and 4th quarters 2012.

some allocation mechanism, with the most common being the pay-as-bid and the marginal pricing auction. By looking at the spot prices realized across Europe, it appears clear the segmentation of the European electricity industry at regional level. Figure 2 shows the prices realized on the European power exchanges from 2009 to 2012.

From the figure it is possible to appreciate the price spread across Europe. For instance, the spread in 2012 between IPEX (Italian Power Exchange) and NordPool[9] (Nordic Country) for the baseload product was around 45 Â€/MWh. Notwithstanding the different dynamics of consumption (seasonal peaks reached in July for Italy while in December for Nordic Countries), there is a substantial disparity of prices among the regions. This differentiation can be interpreted as the combination of two factors: significant differences in generation capacity technologies across states and a limited interconnection capacity.

[9] The Nord Pool is the power exchange operating in Norway, Denmark, Sweden, Finland, Estonia and Lithuania and represents the most liquid market in Europe.

The generation park determines which technology meets the demand at the margin. Despite the strong penetration of the renewable generation, characterized by the lowest marginal cost, the strong dependence on gas in some countries (for instance Italy and UK) determined a correlation between electricity and gas prices. Such a relation is relaxed in those area where a large part of the off-peak demand is satisfied by nuclear generation (France and Nordic Countries) or hydroelectric power (Nordic Countries). Figure 4 in Appendix shows the trends between the fossil fuels price index and the electricity price index from 2002 to 2012. As one can observe, the correlation between power prices and the long-term gas contracts decreased in the last two years, highlighting the effect of the massive penetration of renewables and, how it will be discussed in the next section, the increase of the liquidity of gas spot markets, where operators are able to trade gas in a more flexible way compared to long-term agreements. Coherently with the price differentials observed in EU, the physical (and commercial) flows on the grid show the attitude of countries in dividing in net importer and net exporter. Figure 5 in Appendix shows the monthly cross-border physical power flows in the EU-27 from the end of 2009 to 2012. It emerges clearly the net exporting position of the central western Europe (CW), as opposed to the South Eastern Europe (especially from the second part of 2011) and Italy.

In a marginal pricing system, the absence of any connection limitation (unlimited cross-border capacity) will determine the same price in all markets. In fact, generators located in any part of the continent will compete in the same market and the price they would receive will be determined by the last offer, in the economic merit order, needed to meet demand at the margin. The limited interconnection among countries reduces the room for generators located in a member state to trade in other spot markets. This create the need for grid managers to allocate this scarce resource (cross border capacity) to operators located in different member states in a non discriminatory and efficient way. Currently this is done by using auction for trans-border capacity that are run by an independent organization at a supranational level[10]. The key issue be-

[10]See www.casc.eu

comes than the definition of the efficient mechanism for the allocation of the capacity. At the moment two are the options that have been widely employed: the explicit allocation and the implicit allocation. An *explicit allocation* represents a capacity, in terms of physical transmission rights, directly assigned to the operators *before* the power delivery period. These rights can be allocated with products that may vary with respect to the time of delivery (monthly, yearly, weekly, etc...) and with different seasonal modularity (flat or flexible contract). An *implicit allocation*, instead, assigns physical rights *simultaneously* with the power trade in the spot market. Practically this means that the spot markets of each member state must run exactly the same allocation model – the algorithm - in each relevant period of the delivery day. In other words, the implicit allocation treats alternative spot markets as a *unique* competing zone. This second allocation is also known as *Market Coupling*. In terms of commercial flows, the market coupling provides always an efficient solution since, in case of congestion, the power on the frontier follows the price spread, if any, that realizes on the different nodes of the grid. Compared to the explicit allocation, however, the market coupling requires a higher level of integration and the adoption of the same algorithm for clearing the internal market. The market coupling can be centralized or decentralized. In the first case the market run only once, in any relevant period, and the commercial flows are subject to all the network constraints that apply to the two original zones involved into the coupling. In the second case the two zones run (contemporaneously) their internal market and network constraints are considered separately. Despite the final allocation is the same, the flow of information differs according to the type of solution adopted.

The massive *Renewables* penetration occurred in the recent years challenges the stability of the interconnected power systems. In 2010 the percentage of renewables on the total European capacity was around 20%[11], but this value is expected to increase in the next years. According to the investments notified by member states, the UK, the Netherlands, Lithuania, Estonia and Cyprus will more than double their existing ca-

[11] Source: See supra note 14.

pacity for electricity generation from renewables. The intermittence of this production and its high volatility implies the use of resources for balancing the grid that must be flexible enough to meet instantaneous variation of demand. This is particularly important in those hours when photovoltaic (PV) generation falls down simultaneously with a peak in demand (generally late evening hours) or in those areas where wind generation is particularly concentrated, for instance, during the night and in the early morning hours. Given the high cost connected to power storage, on the one side, the transmission system operators (TSOs) are forced to acquire more flexible resources for balancing the grid in the ancillary market. This represents a major cost for the system, especially if some resource that were previously turned off, i.e. with no injections scheduled as resulting from the spot market, must be activated. On the other side, the effect on the spot market of the increased renewable generation is the "crowding out" of *programmable* thermoelectric production, since the marginal cost of the former results to be sensibly lower. This in turn reduces the reserves available to the TSOs for rapid balancing operation and increases the cost for the system (for instance, related to the agreement for load shedding). The regime of subsidies, direct or indirect, that has been pursued in EU so has to pay attention to the consequences that this may have on the stability of the systems. The process of subsidy revision asked by the EC has the target to propose a better harmonization of the different form of intervention and reduce the distortion for final consumers, who finally share the cost of the public intervention and the alteration of market competition.

The contemporaneous integration of renewable capacity, that looks down the spot prices, and the increase of the risk related to its intermittency, that reducing the adaptability of the systems to extreme demand fluctuations (system *adequacy*) generates instead price peaks, represents for the producers a major source of uncertainty about future returns. Given the long times required for the completion of power plants, such uncertainty may discourage investments in power generation, giving rise to the classic "boom and bust" cycle in the power industry. Indeed, during periods of scarcity of available capacity, price peaks are more frequent and attract new investments, while when spot prices are too low the investments are stagnant (*"missing money"* problem[12]). When scarcity appears, however, the lack of coordination among producers impose a "prudential" investment, with the result that the new total capacity will fall below the social optimal level. For these reasons, the regulatory debate in Europe is focusing on the opportunity of introducing regulations aimed at integrating *energy-only* markets (where costs are recovered from energy and operating reserves) with non-discriminatory mechanisms for the remuneration of the capacity (*capacity markets*). Among the forms of intervention considered it can be mentioned the *capacity payments* (fixed or variable payment awarded to all/part of the capacity declared/actually available), *capacity auction* (where the TSO launches several years before delivery an auction and selects at least cost resources to satisfy projected peakload demand) and *reliability option* (where the capacity options that are auctioned give right to reimbursement if the spot price exceeds some contractual price). The design of non discriminatory and non-distortionary mechanisms for assuring adequate available capacity to the systems will be at the core of the next regulatory European interventions.

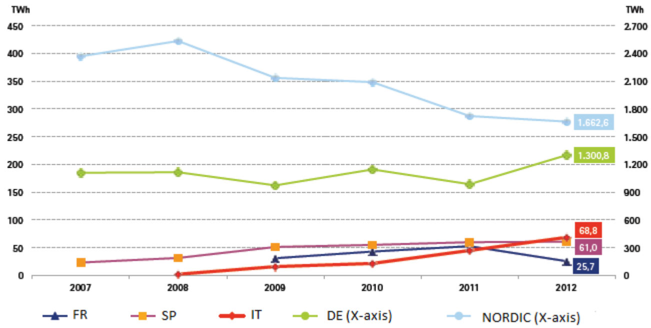
With regard to *forward markets*, the current situation in Europe shows large differences: very liquid and integrated markets, as those in Northern Europe[13], live together with younger markets, as for instance the IPEX and OMIP (the Spanish Power Exchange). Figure 3 shows the volumes traded on the main power exchanges in the period 2007-2012.

From the figure above it is possible to appreciate the different degree of development of the forward markets in Europe. The volume traded in the Nord Pool is the highest in Europe while the Mediterranean area is the less liquid, although Spain and Italy are experiencing low growth rates. Forward markets are regarded as an important instruments by operators since they permit to diversify their selling (and buy) strategies, hedging from the risk of the spot price volatility and channel the expec-

[12] The "missing money" problem is brightly described in *(20)*.

[13] As for instance the Nord Pool and the APX-ENDEX (the Power Exchange operating in Netherlands, UK and Belgium).

Figure 3: Volumes traded on the main forward markets in 2007-2012



Source: GME (Italian Power Exchange- IPEX), Annual Report 2012

tations about future prices. For these reasons their complete evolution is perceived as an essential part of the liberalization process and is central in the energy polices of (several) member states.

The complete harmonization of European markets passes through new investments in the relevant infrastructures. Following market liberalization, a first issue for European countries was the choice of which paradigm for the management of the power networks. For high-voltage transmission, European members opted for the creation of a *regulated TSO* who is responsible for managing the grid and is unbundled with the production activity. A TSO, differently from an ISO (Independent System Operators), owns the network and makes the relevant investments in transmission. In addition, it offers the service of grid balancing (minimizing the cost for the system), guaranteeing a non discriminatory access to market operators. However, there is no uniformity on the entity and the number of TSO that are entitled of managing the network inside each power system. Most European countries opted for the definition of a natural monopoly where the remuneration of the TSO is set by an independent regulator.

In the market based approach the TSO is provided with the instruments for dispatching the energy on the grid directly from the generators admitted to participate to the *ancillary service market*. There is not an univocal design that defines the instruments that can be used by the TSO and which products must be offered by producers. The task for the European regulation than is the definition of the resources available on the ancillary market as well as the relevant time (e.g. hour or half-hour) for the computation of operators unbalances. The big challenge in this sense is represented by the adoption of an *European Network Code*, preliminary the creation of a common balancing area, that defines the services that can be offered by operators also outside the country where the grid unbalance occurs.

2.4 The Challenges of the Gas Markets

The European gas systems are living a period of deep change, characterized by a faster transition from a "rigid" market structure, grounded on the cornerstone of system stability protection and security of supply, towards a wide liberalization process, intended to introduce new actors and increase efficiency and competiveness. This required the harmonization of EU regulation and the adoption of a variety of interventions with the scope of increasing the regional cooperation. Among the several activities that are currently involving the member states, it is worth to mention the implementation of the *Network Code on Capacity Allocation Mechanism (CAM NC)*, aimed at introducing rules for the management of trans-border capacities and legally binding starting from 2015. Gas TSOs and regulators (convened in Europe within the agency for the cooperation of energy regulators – ACER) are appointed, among the others, for the design of the allocation mechanism, the definition of the products and the development of IT platforms. With regards to the capacity allocation mechanism, EU regulators opted for the introduction of competitive auctions and defined the rules for the determination of the total capacity auctioned by TSOs. The allocation gives the physical right to the shipper to deliver gas in some of the nodes (entry and exit points) of the European network. In order to recover the operating costs for the transportation, the auctions should include an entry fee (reservation

Table 1: Traded Volumes on the main European Gas Hubs (GWh)

Country	Platform	2008	2009	2010	2011	2012	Var. Y-1
IT	*PSV*	173.741	260.588	479.146	641.135	**719.206**	12%
AT	*CEGH*	166.020	253.340	378.660	435.010	**525.100**	21%
NL	*TTF*	636.885	803.530	1.122.114	1.597.906	**1.979.126**	24%
BL	*Zeebrugge*	505.579	721.205	724.010	769.797	**742.462**	-4%
UK	*NBP*	1.344.935	11.507.039	13.672.222	14.185.474	**14.170.099**	0%

Source: GME (Italian Power Exchange – Annual Report), 2012

price), based on the Entry-Exit tariffs[14] for accessing the network. The additional revenues of the auctions than can be used to reduce final consumers bill or invested in network development. The code, together with the regulation on the *congestion management procedure* (CMP), is expected to provide signals to operators about the value of accessing the grid in presence of limited capacity.

European gas markets are organized at what is defined the *virtual hubs*. The latter represents a virtual point of exchange, generally located in between an entry and exit point on the transmission grid, aimed at reproducing in a simplified model the (meshed) network. The current picture of the European hubs includes very liquid markets, that benefits from the proximity to production sites, as for instance Zeebruge (Belgium), TTF (the Netherlands) and NBP (UK) and hubs with a lower degree of liquidity, as for instance, PEG (France) and CEGH (Austria). The volumes of the main European hubs are indicated in Table 1[15]:

Notwithstanding the large differences surviving across the member states, it is possible to get a glimpse of the ongoing process of convergence occurring in the recent years. In some hubs, as for instance PSV (Italy) and CEGH, transactions are increasing, revealing so the higher trading propensity of the operators. The spreading of gas markets has important consequences on the refueling and amount of resources that are available to the shippers (gas supplier). These can be summarized in the reduction of the *take-or-pay* (TOP) share of shippers supply con-

[14] For a discussion about the tariffs for the access to the transmission grid the reader can see (45) or *(4)*.

[15] The volumes indicated in the picture are those traded outside the regulated markets (OTC). Non regulated markets include, indeed, the great majority of transactions contrarily to the more recent regulated spot markets.

tracts and in the increase of system flexibility through real time trade. In fact, the diversification of gas sources permits to reduce the risks and costs for the shippers related to short term demand variations. These are generally expected to be high because when shippers cannot adjust their position into the market, the gas which is offered has generally a *flat modularity*, in accordance with the long-term clause that shippers signed with non-EU exporter (Take-or-Pay or TOP clause). These agreements generally include the option for a shipper to withdrawal gas up to fixed amount under the payment of a fixed price. The price must be paid independently by the decision to take or not the gas from the grid. Therefore, these contacts results to be "rigid" to demand variations, determining so a big cost for the shippers for varying their supply strategies. Moreover, as showed in some works[16], these clause can generate also anti-competitive effect, to the extent that the transmission grid is "overbooked" by those operators conditioned on TOP.

The progresses made by EU markets alleviates also the troubles deriving from the increasing need of *flexible resources for electricity production*. Shippers, indeed, can contract the gas close to the day of delivery, reducing the uncertainty about future demand. As discussed in the previous section, the higher volatility in the electricity production deriving from the transition to low CO2 emission systems, implies a higher coordination between power generation and the supply of fossil fuels. This generates an additional variable on firms' decision to invest in traditional power plants. Indeed, a firm can decide to build a new generator close to where the commodity is abundant in the market, or alternatively, to use intensively the transmission network to bring the fuel to the plant. This decision depends on the transmission cost, the possibility to access the grid and the availability of "speedy" resources in the fuel market.

An important source of flexibility is already available in the transmission network. These reserves (*line-pack*) are generally used for balancing purpose (*buffering*). However, the shippers can be unbalanced and use this stock for trading in the spot market. Being the line-pack a scarce resource, dependent on the volume of gas inside the pipelines, there is

[16]For instance, *(60)*.

a problem related to its allocation. The unbalances of the shippers are adjusted in the *gas balancing market*, where the TSO buys or sells gas to correct the overall system unbalance. The balancing price should therefore reflect the value for the operators of the utilization of gas, including line-pack, in the real time. However, the current design of balancing markets do not allow to observe the real-time price of gas and some time is left to the shippers for adjusting their position, after which the balancing price is determined. In this case the final price for the utilization of line-pack reserves may reveal to be not cost-reflective. In fact, some operators may have convenience to overusing pipeline reserves when their value (in the spot market) is high and reduce their unbalances only when the unbalance price is expected to be low. The balancing time thus is still an open issue. If on the one hand, hourly balancing can be considered very costly for the shippers and reduce the possibility to arbitrate in the spot market, on the other hand, end-of-the-day balancing provides the higher flexibility to the shippers but may generate anti competitive behaviors.

Gas storage plays an essential role in providing additional resources to market players (including balancing reserves) and flexibility to the system. Depleted fields, aquifers and salt caverns allow for arbitrage in the spot market and permit to stabilize prices between seasonal cycles. At the same time, storage reserves can be used to meet short-term demand peaks and accumulation when the demand is low. Storage services offer a combination of capacity (space) and injection/withdrawal rates that varies across technology and can be used for different purposes. LNG terminals, for instance, allow for fast variation of gas supply and provide the highest flexibility to operators. This implies a strategic regulation on the new investments for essential facilities that must be pursued in the next years. LNG industry, for example, can be defined as a competitive business, but the return of the investment are related to the rules governing the access to the infrastructure (*Third Party Access*) which can depress the investments.

Finally, gas storage is determinant in stabilizing supply to final consumers. The importation of gas from non-EU countries, indeed, includes an additional risk, connected to the geographical routes during transportation. Europe is therefore subjects to external sources and, consequently, to potential disruptions in case of political conflicts. This generates a risk on the *security of supply* that can concludes in period with scarce importations of gas (for instance, during *gas crises*)[17]. In these situations member states rely more on their (strategic) storage reserves and diversify their importation (eg. LNG importations from American countries). The attraction of new investments into the storage sector and the launch of new sites will represent an important objective for EU regulators in the coming years[18].

2.5 Conclusions

Electricity and gas markets in Europe are evolving faster, pushed by the need of creating a common market, ensure a good degree of internal competition and providing the adequate resources for the stability of the systems and security of supply, in a period characterized by the large penetration of the renewable generation. The European economic crisis, started in 2009, imposed a slowing down in the realization of important facilities (as for instance LNG terminals and tanks) aimed at reducing the cost of energy and provide final benefits to end-users. The trend of the European energy demand for the period 2001-2011 is reported in Figure 7 (electricity) and 8 (natural gas) in Appendix. The data of 2011 indicates a shrink in the electricity demand higher than 1,5% in 2011 compared to the previous year (-2,8% compared to 2008). This reduction, however, should not relax some of the issues discussed throughout the paper but, on the contrary, should reinforce the increasing need for flexible tools. In fact, in a liberalized market for electricity, power plants compete to dispatch energy according to their economic merit order. In such an order, renewables collocate usually in the first positions since they benefit from an incentivized regulation and almost null marginal costs. In other words, renewables impose a "crowding out" effect on the classical

[17] An example has been the gas crisis in February 2012 following the political tensions between Ukraine and Russia.

[18] The investments in storage technologies expected in EU in the coming years are reported in Figure 6 in Appendix

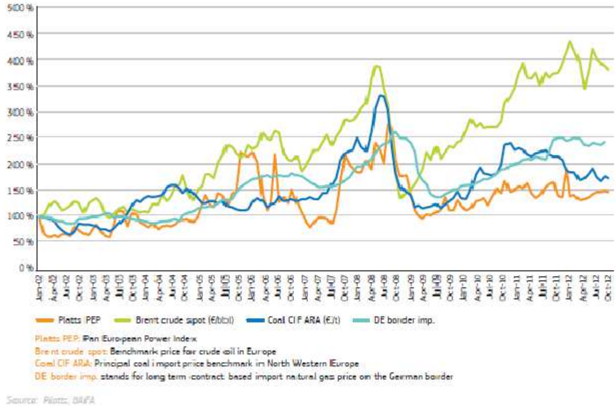
power generation, generally consisting in thermoelectric power plants. Whenever the classical power plants result to be turned off in the spot market, the TSOs have to activate them before asking for the ancillary services they can provide. This generates an additional expense for the system, since powering up a plant is costly and its utilization is uncertain. Moreover, the boost of renewable capacity may force some classic power plants to exit the market, reducing again the reserve margins for the TSOs.

Additionally, in periods where the energy demand is low, the prices for electricity and gas are declining. This may disincentive shippers to accumulate gas during the worm seasons ready to be used during the cold period. The problems related to an unexpected disruption or a critical change in demand so are exacerbate by the lack of fuel reserves for the thermoelectric production. This impacts also on the injection and withdrawal rates of the main underground storage site, i.e. depleted fields, which depends on the amount of gas in stock. When the latter is abundant in the site, the withdrawal rate is higher and the injection is lower. The inverse happens when the site is almost empty. In this case the reduction of the gas stored changes the degree of flexibility of the gas stored.

A final remark is dedicated to the leading role hoped for the demand in the next years. The development of smart meters should allow consumers to monitor the market price and permit them to modulate their consumption in real time. Such a modulation is desirable and would permit to reach higher levels of energy efficiency, indicated as a priority by the EC, both in terms of energy consumption reduction and abatement of the cost of energy to final consumers.

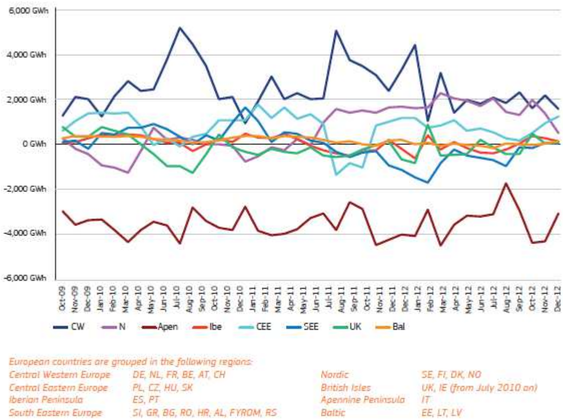
2.6 Appendix Chapter 1

Figure 4: Evolution of coal, gas, oil and European average wholesale power prices



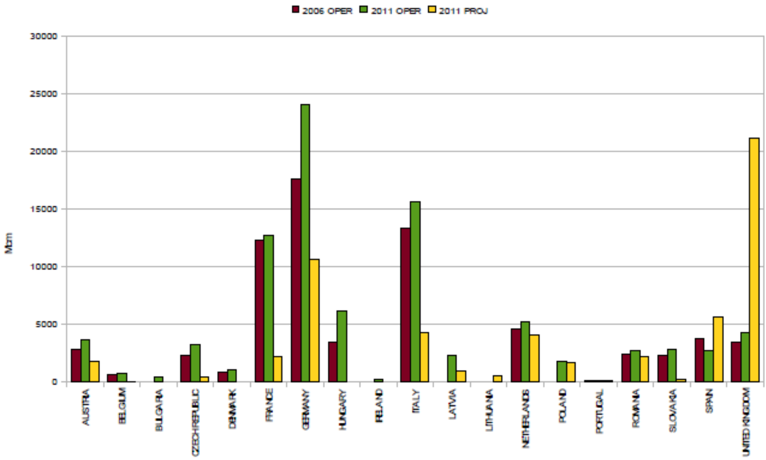
Source: EC Quarterly Report on European Electricity Market - 3rd and 4th quarters 2012.

Figure 5: EU cross border monthly physical flows by region



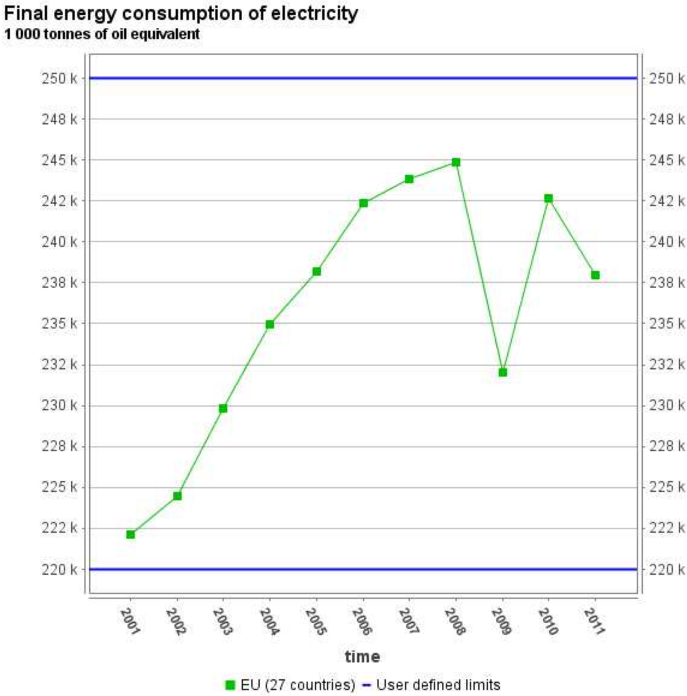
Source: EC Quarterly Report on European Electricity Market - 3rd and 4th quarters 2012.

Figure 6: Gas storage capacity per country 2006-2011 and new projects in 2011



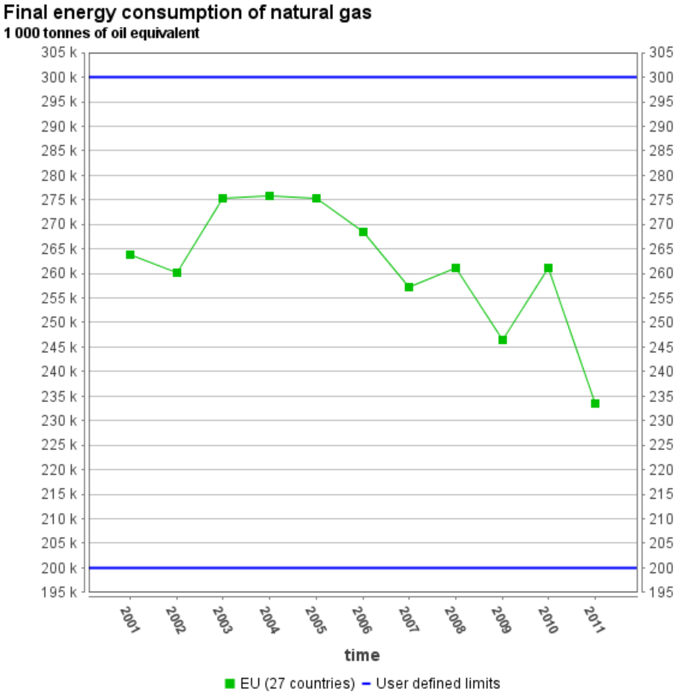
Source: Natural gas storage and its regulation, Ascari (2012) - FSR SPECIALISED TRAINING ON REGULATION OF GAS MARKETS

Figure 7: EU-27 electricity consumption in the period 2001-2011



Source: Eurostat
(http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables)

Figure 8: EU-27 gas consumption in the period 2001-2011



Source: Eurostat
(http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables)

Chapter 3

A Proposed Design for Gas Storage Services in Italy

3.1 Introduction

Storage services represent an essential part in the chain of natural gas supply. Storage gives the opportunity to accumulate gas in the periods where the demand is low (summers) in anticipation of high consumption periods (winters). This function is usually referred as *seasonal modulation*. From an economic point of view[1], the possibility to store gas in different periods of the year provides *shippers*[2] with a tool for stabilizing the prices offered to final consumers. The demand of gas is, indeed, characterized by a high seasonality. Figure 9 in Appendix shows the trend of the Italian monthly consumption of natural gas during the years 2009-2011, while Figure 10 shows that the cycle is driven principally by the domestic consumption. Absent the possibility to store gas, the prices would jump during winters and fall in summers.

The possibility of disruptions due to geopolitical risks provides a sec-

[1](23) provides a review of the economic literature on the various services provided by gas storage.

[2]A shipper is an operator that is responsible for the transmission of the natural gas from a geographic point to another, through the utilization of the transmission network (pipelines).

ond argument for gas stockpiling. The *strategic (or precautionary)* storage plays a key-role in ensuring the security of gas supply, in particular in Europe where the dependency from non-EU countries is structural[3]. The risk of facing unexpected reduction of gas importations impose to EU countries to maintain a constant amount of gas in storage sites. Such a need is exacerbated by the reduction of EU production[4] as confirmed by Figure 11 in Appendix, that reports the trend of production in Europe and, separately, in Italy during the years 2002-2011.

The third task assigned to storage is that of guaranteeing a fast response to short-term (daily or intra-daily) demand peaks and represents the argument of this paper. In this perspective, gas storage can be seen as an alternative to the spot market. In absence of a liquid market (as previous to the market liberalization[5] that took place at the end of the last century), gas furniture is principally guaranteed to the shippers by long-term supply contracts[6]. These contracts generally provide the shippers with a flat amount of gas, necessary to satisfy the baseload consumption, leaving to storage services the task of covering demand peaks[7]. In the recent years, the development of the spot market in Italy gave to the ship-

[3]According to the European Commission, Russia and Algeria provide almost 50% of European Gas Consumption.

[4]The production of gas in Europe restrains to about 8% of world production. Netherlands and Norway are the biggest producers while UK, Germany and Italy are the biggest consumers. The biggest world producer of natural gas is Russia with 17% of world production (Source: Eurostat). In the last years a greater attention has been paid to the cost and benefits related to the production of *shale gas*. For the purpose of this paper, it suffices to mention that this type of production requires, compared to conventional natural gas extraction, a deeper underground penetration – about two miles - with associated high cost of hydraulic fracturing and horizontal completions. In USA the programs of extraction on industrial-scale of shale gas started around 70's; in Europe the extraction of shale gas is still at the core of researches aimed at evaluating the costs related to environmental impact.

[5]The liberalization of gas markets in Europe has been driven by the directive 1998/30/CE and 2003/55/CE, adopted by the members states with internal regulations. In Italy the Decree 164/2000 adopted the two European directives.

[6]Generally these long-term agreements include a *Take-Or-Pay (TOP) clause*. Such a clause gives the option to the shipper to withdrawal gas up to fixed amount under the payment of a fixed price. The price must be paid independently by the decision to take or not the gas from the grid. Therefore, these contacts results to be "rigid" to demand variations and impose a big cost for the shipper for varying its supply strategy.

[7]As it will be discussed in-depth in the next section, the ability of a storage facility to meet short-term variations depends on the technology of the site.

pers an additional instrument to trade gas for short-term needs[8]. Similarly, intra-day variations of delivery and consumption programs implies the need of balancing real time injections and withdrawals and avoid congestions on the grid. In the European systems, balancing services are provided by independent TSOs (Transmission System Operators), unbundled with the production activity[9]. While the discussion on the organization of the balancing services is further the scope of this paper, it suffices to mention that in Italy, according to the current regulation[10], physical unbalances - the difference between injections and withdrawals programs - on the grid are corrected by using the gas present in storage sites.

The regulatory debate related to the utilization of gas storage for *short-term modulation* is centered, essentially, on two issues. The first is the attraction of investments in the infrastructures that increase the quick "responsiveness" (or *flexibility)* of the system. The second argument is related, instead, to the optimal allocation of these resources among the operators and how this influences the stability of the system. The Italian market is particularly interesting for two reasons. *First*, given the strong dependence from thermoelectric production (see Figure 12 in Appendix), Italy represents the third consumer of natural gas in Europe. This generates a larger exposition of the country to the risk of supply shocks, both in the long and, importantly for this analysis, in the short term. *Second*, the strong increase of *renewable sources* in the electricity industry (Photo-

[8]The Italian over-the-counter (OTC) spot market for gas takes place at the virtual hub PSV (*Punto di Scambio Virtuale*), while the regulated market has been introduced in 2010 and is run by IPEX (Italian Power Exchange). An important innovation has been the launch of the balancing market (PB-Gas) in 2011 that permits to correct shippers unbalances on daily basis. In Europe, the most liquid markets are in UK (NBP) and in North-Europe (e.g. Zeebrugge and TTF Hubs).

[9]The need of a legal unbundling originated by the recognition that *de facto* monopolies for the production and distribution of natural gas were operating in most EU countries. In order to guarantee a non-discriminatory access to the transportation networks, EU directives 1998/30/CE and 2003/55/CE asked for the creation of independent transmission system operators (TSO). In Italy, the Decree (DL) 93/2011 assigned the balancing and dispatching activities to SNAM RETE GAS Spa.

[10]According to the Regulation ARG/gas 45/11 of the AEEG (AutoritÃ per l'energia elettrica ed il gas), the TSO acquires the resources for balancing the grid in real time relying on the total storage capacity available into the system.

voltaic and Wind Turbines above all) occurring in the recent years (see Figure 13 in Appendix) is exacerbating the need of flexible storage services to cover demand peaks. Suppose, in fact, that in the real time an unexpected collapse of the renewable generation needs to be compensated by an instantaneous increase of the production from CCGT (combined cycle gas turbine), leading than to an increase of the gas demand. To manage this situation, the gas TSO relies on the reserves available into the system: the flexibility asked to the electricity industry than transfers directly to the gas market during the balancing phase.

Whereas the precautionary accumulation has been recognized as the most important purpose in the Italian and EU political debates for decades, the increasing importance of flexibility as the main characteristic of storage reserves is a quite new subject. This poses the issues of which services can be labeled as "flexible" and what should be their optimal regulation, in terms of incentives for the realization of the relevant facilities and allocation of the capacity. As it will be highlighted in the next section, the resources that are available to shippers are limited and their access represents a key element for promoting market competition and efficiency[11]. Although a market based approach for the allocation of these resources is desirable, this must occur coherently with the provision of reserves to the TSO for the balancing operations.

The paper is organized as follow: section 2 attempts to define flexibility services in terms of the performances associated to different storage technologies; section 3 describes the current Italian regulation for the realization of new facilities and their access to market operators; section 4 includes the regulatory proposals and section 5 concludes the analysis.

3.2 Flexibility Services and Storage Technologies

Generally, with the term "flexibility" it is usual to indicate all the possible instruments that give to the shippers the possibility to change their

[11]This result has been stressed by *(16)* and *(17)*.

injection or withdrawal positions in the short-term. Despite this can be considered an easy concept, the definition of a market for flexible services it is not. The reason is implicit in the definition of any market: the *substitutability* of the products that are included in the market must be high. For instance, the resources adapt to the scope of seasonal modulation can be less efficient (or useless) to meet daily peaks. Such an issue has been studied for the Italian case by (12). In this paper the authors apply a Delphi Analysis[12] to conclude that *"[...]unsurprisingly, the most suitable tool for both seasonal and peak flexibility is storage"*. This work affirms that storage provides higher flexibility compared to other possible instruments as, for instance, interruptible contracts[13], production or resorting to the spot market. However, the technology of storage is not uniform and sites are characterized by different sets of parameters that determine the degree of flexibility of the services provided. These parameters include the volume of Working Gas (WG) measured in GSmc[14], injection and withdrawal rates (MSmc/day). The substitutability of storage services and, accordingly, the individuation of the investments that increase the short term modulation of the system than must be evaluated according to these technical characteristics. A possible classification of the technologies - sorted according to the ascending degree of flexibility - is proposed in sections 2.1-2.3, while section 2.4 describes the current available capacity for the Italian market.

[12]The Delphi methodology has been developed in the 1950s by the RAND Corporation and it has been applied to numerous research fields such as health care, transportation, etc... This consists in a series of questionnaires addressed to experts and coordinated by a facilitator. A description of the methodology is provided directly in Section 3 of (12).

[13]There are several forms of interruptible contracts. In general an interruptible contract permits to reduce the load to consumers.

[14]The *Standard Cubic Meter* is the measurement unit of the volume of gas and indicates the gas volume at the atmospheric pressure and temperature of 15° C). A GScm corresponds to one billion of Smc. The Working Gas is the amount of gas that is available to the market and can be reintegrated in the site. It divides in *Cushion Gas* (necessary to provide peak performance) and (proper) *Working Gas* (ready to be used by market operators).

3.2.1 Underground Sites for Seasonal Modulation (Low Flexibility)

This category includes the usual *Depleted Gas Fields*, which corresponds to production fields where natural gas has already been extracted and, for their nature, are suitable to storage. The working capacity of this sites can be estimated around 1.000-2.000 MScm, the withdrawal (or send-out) rate between 20-50 MScm/day and the injection rate around 10 Mscm/day[15]. Depleted Gas fields have a large working capacity but a relatively low rate of injection and it takes about 3 to 6 months in order to fill the storage to its maximum WG. It is important to notice that the send-out capacity of this storage site reduces[16] as the stored volume reduces limiting, thus, the ability of the field to cover extended demand peaks. The investment cost of a depleted fields could be estimated around 700 M/Â€ and the lead-time of investment is from 5 to 8 years[17]. The characteristics of a depleted field makes this storage site an adequate tool for seasonal modulation purposes.

An alternative to depleted gas fields are the *Aquifers*. An Aquifer is an underground layer of water-bearing permeable rock, where the gas is injected and a natural *gas shift reaction* occurs. The technical parameters characterizing an acquifer are similar to those of a depleted field, but the costs associated to this technology and the lead-time of investment are higher. Indeed, it can be estimated an investment cost of around 800 M/Â€ and 10-12 years to make the site working[18]. The reason for this is that, contrarily to a depleted field, the geological features of the acquifer reservoir are not known at the time the reservoir is discovered and large investment must be done in investigation of field's characteristics. Moreover this kind of site requires a large amount of cushion gas, with higher associated costs, since no natural gas is already present in the field. This makes this kind of reservoir the more costly facility to store gas.

[15]Sources: Italian Ministry of Economic Development, Stogit S.p.a. (www.stogit.it).
[16]The reduction of the volume implies a reduction of the pressure of gas stored.
[17]Source: (24).
[18]See supra note 47.

3.2.2 Underground Sites for Short-Term Peaks (Medium Flexibility)

This category includes the *Salt Caverns*. Through the process of solution mining the salt is dissolved by pumping the water in the cavern. This process leaves void and continues until the cavern is the desired size. The working capacity of the site is low compared to previous sites but generates high deliverability and lower investment costs. The send-out capacity can be determined between 2-4 MScm/day against a working capacity around 30-70 MScm. The costs reduce to around 40 M/Â€[19] and the investment lasts 1-5 years. Given its relatively high send-out rate, this type of facility is generally used to satisfy peaks in demand. This is confirmed by the fact that, in order to fill in the reservoir, it takes around 20-40 days, a time sensibly lower compared to the 200-250 days necessary to fill in depleted fields and aquifers.

3.2.3 Other Storage Techniques (High Flexibility)

This category includes *LNG Storage* and *Line-packing*. The storage of natural gas can be realized through artificial infrastructure containing LNG (liquefied natural gas) and reintroduced into the market through a regasification terminal. Through the process of liquefaction, natural gas can be easier stored on-shore (LNG Storage Tank) and marine transported (LNG carriers)[20]. The advantages of this technology are clear. First, LNG carriers by maritime transportation permit long distance importation and a positioning close to the market, assuring the highest flexibility to the system. Second, liquefied gas occupies a lower space than underground storage (around 600 times less space). Finally, LNG reservoir do not need cushion gas to work and consequently the efficiency of the artificial site is increased[21]. For their nature, LNG reservoirs adapt

[19] The source is (24). (27) estimates different costs for the realization of the facilities.

[20] Natural gas is liquefied and conserved approximately at a temperature of -163 °C. The reservoirs connect the LNG tanks to a regasification terminal (on-shore or off-shore) which brings LNG back to its gaseous state before delivering it to the pipeline.

[21] In other words, all the capacity that can be stored represents the working capacity of the site.

perfectly to deliver the absolute peak demand for a small number of hours or days a year. The disadvantage are related to the higher cost of investment and maintenance.

Line-packing indicates the possibility of temporarily store gas directly into the pipeline through an increase of the internal pressure. This possibility is exploited for short term variations where, generally, accumulation occurs in off-peak periods for next days' peaking demand. In the current design of the Italian market, this resource is used for balancing purpose by the TSO.

Whereas LNG storage industry can be analyzed independently from gas transmission, line-packing depends directly on the development of the grid. The latter is further the scope of this paper and the attention will be concentrated mainly on LNG and the other storage facilities. A summary of the different technology characteristics is provided in Table 2 in Appendix.

3.2.4 The Italian Gas Storage System

At the end of 2012 the total storage capacity in Italy was 16.430 MScm[22], offered by 10 working sites, all of them corresponding to depleted gas fields. One new concession has been granted by the Ministry of Economic Development (hereafter: MED) and for seven new sites the administrative license release procedure started. The sites, the capacity (base and peak) and the storage operators are indicated in Table 3 in Appendix. In order to receive the license for storing gas in an underground site a complex administrative procedure must be passed. This involves a detailed analysis, spanning from the characteristics of the operators to the environmental impact analysis and implies a stream of informative obligation from the applicants towards the local government and the Ministry. This procedure plays a key role in the timing of the investment. In particular, the excessive delay from the presentation of the project and the license release has been accused of depressing entry

[22]Source: MED, available on http://unmig.sviluppoeconomico.gov.it/unmig/stoccaggio/info/cosa.a

into the sector[23]. What concerns to this work is not the administrative procedure *per se* but, instead, the regulation on who is entitled to present a project for a license and what happens when more operators are interested to the same storage site. These arguments will be discussed more in detail in the next section.

LNG terminals are subject to an administrative authorization by the MED and the Ministry of Environment and, as for underground sites, the license release is the result of a joint work of national and regional administrations. Currently in Italy there are 3 working LNG terminals: one On-shore (Panigaglia- SP) with a re-gasification capacity of 3,4 GSmc/year and two off-shore with a capacity of 8 GSmc/year (Porto Tolle – RO) and 3,75 GSmc/year (Livorno)[24]. Additional projects have been presented and are currently under administrative scrutiny.

3.3 The Current Regulation of Storage Facilities and Capacity Allocation.

This section is intended to introduce the current regulation of storage services in Italy. In particular the next paragraphs focused on the key points and criticalities related to the procedure for the release of a storage license, the remuneration for the realization of the infrastructures, the access to storage services and the rules for the allocation of the capacity.

[23]In some cases, this has been more than one year. In particular, longer delay are attributed to the interventions of local governments on the occasion of the evaluation of the project's environmental impact. For a detailed description of the procedure the reader can see (3).

[24]LNG terminal can be *on-shore* or *off-shore*. On shore technology consists in storage tanks located, generally, close to a harbor and connected to a terminal carrier. Off-Shore technologies can be *Gravity Based Structure* (GBS) or *Floating Storage Regassification Unit* (FSRU). In the first case the terminal is submerged with a stabilizing mass on the bottom of the sea, while in the second case the terminal is anchored permanently to the seabed. Recently, a new technology, the *Offshore Regasification Gateway*, permits to combine the transportation and regasification process on the same carrier, increasing so the flexibility of the LNG (see Figure 14 in Appendix).

3.3.1 The procedure for the Storage License

Prior to the Legislative Decree (LD)164/00 the right to use storage sites were exclusively assigned to the state monopolist company ENI Spa. The LD 164/00 liberalized the entire gas sector but opted for an administrative concession for the utilization of storage sites (underground on-shore and off-shore). The concession is grant by the MED for a period of 20 years, and is eventually renewed for two periods of 10 years each, for a total duration at most of 40 years[25]. LD 164/00 defined also the way the concession must be granted. In particular, who is entitled of a concession for the *production* of gas may successively ask the conversion of the field in a storage site. In this case the concession is granted automatically - that is without a competition - by the MED.

Informative obligations are instead imposed on the owners of a gas field with an initial reserve of 0.5 GSmc and with 80% of the gas already extracted. These have to communicate to the MED the characteristics of the field and provide information about the adequacy of the site for storage purposes. After the receipt of all the information from the producers, the MED indicates which fields are feasible for storing gas and accept requests for the concession of storage. The MED evaluates each project according to a set of indicators varying from the completeness of the project to the expected environmental and occupational impact. The same occurs when a concession expires or for those sites where no concession has been previously granted. According to the current law, therefore, the owners of a concession for the production of gas are dispense from competing with potential entrants for storage sites, to the extent that the production fields are not close to fully depletion. The selection of a candidate is only the first step towards the beginning of the storage operations. In fact, before the launch of a new site, the operator needs to obtain the environmental certificates by the regional government. The long lasting procedure has been the cause of delays in the launch of new sites. In some cases the final authorization has been awarded one year after the concession.

[25] The concessions granted before the entering into force of the Decree 164/00 are instead preserved for their entire scheduled period.

Regarding LNG terminals, the authorization procedure for their construction is more complex. Indeed, according to the location of the terminal and whether there is the presence or not of the *national strategic interest*, the license is granted by the MED together with the Ministry of Environment or, alternatively, by the local government. Moreover, the authorizations may require the achievement of environmental certificates and/or other obligations. So far, all the procedures for the release of new licenses included an environmental impact analysis.

3.3.2 The Remuneration of the Investments

According to the DL 93/11, the MED indicates the minimal requirements that any facility (LNG terminals, underground storage sites, interconnectors etc...) must have to be considered *essential* for the development of the internal (and EU) market and the security of supply. This characteristic gives the right to the investors to receive the incentives defined by the national Authority (*AutoritÃ per l'energia elettrica e il gas* – AEEG) and be remunerated for the realization of new infrastructures. With regard to underground storage sites, the Authority individuated three different types of investments: *(i)* with no impact on the total amount of capacity (no incentive is recognized); *(ii)* finalized to increase the total storage capacity and *(iii)* for the realization of new sites or *peak-shaving* facilities (highest level of remuneration). Referring to LNG infrastructures, two types of investments are instead considered: *(i)* for the maintenance of existing infrastructures (no additional incentives are recognized); *(ii)* for increasing the regasification capacity or the construction of new terminals (subject to higher remuneration).

3.3.3 The Third Party Access to Storage (TPA)

The European Directive 98/30/CE[26] and the DL 164/00 introduced the obligation for storage operators to provide services to the shippers on non-discriminatory basis, under a *Third Party Access* (TPA) regime. Nevertheless, the directive did not impose a specific guide to legislators

[26]This directive has successively been substituted by the directive 2003/55/CE.

on the implementation of the TPA, but let national jurisdictions free to choose among a *negotiated* or *regulated* TPA. The Italian legislator opted for a fully regulated TPA, entitling the national regulator to decree on the services that can be supplied and the constraints that storage operators have to fulfill. Importantly, the authority is also empowered to determine and regularly update the *tariffs* for the access to gas storage facilities[27]. The Directive 2003/55/CE included also the possibility for storage operators to ask for an *exemption* from TPA. This opportunity may occur in presence of some conditions. In particular, TPA exemptions can be awarded if *(i)* the investment is considered pro-competitive and improves the security of supply; *(ii)* the risks associated with the investments are so high that without TPA exemption the project would not be made; *(iii)* at least a legal unbundling between the infrastructure and a final user must hold; *(iv)* the exemption is not detrimental for the competition and internal-market efficiency. According to the Italian law 239/04 the exemption is granted on a case-by-case basis at least for 20 years and (at least for) 80% of the new capacity.

Like underground storage, LNG terminals have the same TPA imposition. It is important to mention that TPA can be denied only for two reasons: *(i)* absence of residual capacity that can be offered by the facility and *(ii)* objective difficulty for a shipper to operate in the market, due to the take-or-pay contracts that have been signed before the introduction of the directive 98/30/CE. From a theoretical point of view, the challenge for the regulator is the right quantification of the incentives in order to promote new investments (assuring a "normal" return to the investors) without creating distortions in the market. This trade-off has been tackled by the Authority with a capital remuneration linked to the type of the investment (increasing peak capacity, increasing the "uniform" capacity or new investments) and with the introduction of a uniform set of tariffs. On the other hand, new shareholders may consider the remuneration of the capital not sufficient to bear the initial costs. In these cases the investment can be undertaken only if a TPA exemption is granted. Con-

[27]For example, Table 4 in Appendix reports the tariffs applying in 2014 for different storage services

sequently, the adoption of tariffs that are not cost-reflective and/or the regulatory uncertainty about the TPA exemption may discourage entry.

3.3.4 The Allocation of Storage Capacity

The AEEG defines the capacities under TPA regime and the services that storage operators must offer to the market. AEEG defines also the order or priorities for the allocation of the capacity, currently given by: *(i)* Strategic Storage Capacity, *(ii)* Balancing Service Capacity, *(iii)* Mineral Capacity and *(iv)* Peak (ex-Modulation) and Uniform Capacity.

The stockpiling of *Strategic Gas* is under the responsibility of shippers that import gas from non-EU countries. The MED imposed to these shippers to store a capacity equals to 10% of the amount of gas imported from non-EU countries and oblige storage operators to make available enough space for strategic reserves. The intention of the legislation is to guarantee enough capacity in cases of gas crisis and disruption of furniture[28]. The amount of space for this service may be redefined by the MED[29].

The *Balancing Service Capacity* is used by the TSO in order to maintain the equilibrium of total injection and withdrawal flows. The storage operators allocate this capacity on-request to the shippers, while the physical balancing of the grid is managed by the TSO through both off-line (underground storage) and on-line (line-pack) reserves.

The *Mineral Capacity* has been introduced by DL 164/00 and is formally defined as the storage capacity needed to *"assure to the national production the same flexibility of importation contracts"*. The rationality for the institution of this service is that, contrarily to other European countries (for instance UK and Netherlands) where national production represents an instrument also for the short-term modulation, the production is Italy (for reasons related to the technical characteristics of production field) results to be very rigid. The total amount of mineral storage capacity is

[28] An important example of gas crises occurred in 2009, following the decision of Russia to reduce the amount of gas towards Ukraine, on the route towards Europe.

[29] For the thermal year 2013-2014 the Strategic Reserves reduced from around 5.2 to 4.6 GSmc. The potential beneficial effects of a reduction of strategic reserves in the Italian market have been studied by (26). According to this analysis, the costs of the strategic stock are around 16% of the value of storage market.

decided by the MED, while injection and withdrawal rates are computed in such a way to take into account potential production disruptions[30].

The *Uniform and Peak capacitie*s are the amount of underground storage left to the shippers to cover baseload demand and daily and seasonal fluctuations. These services, introduced in 2013[31], represent an important innovation with respect to the previous regulation. In particular, the distinction between Uniform and Peak capacity, not included in the previous norms, permit to storage operators to offer two different products to the shippers. The uniform capacity provides the shipper with a constant withdrawal profile during all the year[32], while the peak capacity (indicated in the previous regulation as the modulation capacity) is associated with a dynamic performance as a function of the emptying[33]. For his nature, this last service is used by the shippers to cover daily and seasonal peaks. Most importantly, with regard to the allocation of the capacity, the decree of 2013 introduced a combination of pro-quota and *auction mechanisms*. Specifically, the entire uniform capacity is allocated through a pay-as-bid auction, while part of the peak capacity is allocated through a marginal price auction. The remaining peak capacity is allocated with a pro-quota mechanism[34] with a priority of access to the shippers that directly or indirectly have in their portfolio domestic final consumers[35]. The total amount of capacity offered for uniform and peak services is residual to the capacity served for strategic, balancing and mineral purposes. In the case a shipper does not respect the obligation for the utilization of the capacity to the purpose it refers (for instance a selling of strategic storage) than a penalty - indicated by the AEEG - is imposed on him. The scope of the regulation is discouraging the arbitrary utilization of storage that may reveal to be harmful for the

[30]It must be noted that the greatest part of national production is made by ENI Spa, which corresponds to the main user of this type of capacity.

[31]These services have been introduced by the DL 15/02/2013.

[32]The storage "thermal year" is defined as the period from the 1st April to 31st March.

[33]In particular, the withdrawal rate is decreasing with respect to the emptying of the gas in stock.

[34]The capacity subjects to the pro-quota allocation is determined by the MED.

[35]Final consumers are identified with those users with a consumption lower than 200.000 Scm per year.

system. With regard to the LNG storage capacity, the allocation is defined by the MED and particular attention is paid to the LNG importers for industrial uses. As an example, for the thermal year 2013-2014 the storage space available and differentiated per service is reported in Table 5 in Appendix.

The introduction of a market based mechanism (auctions) for the allocation of the flexible storage capacity represents an important step to promote competition among shippers and is expected to extrapolate the real willingness to pay for the utilization of the resources, provided that the auction is well designed and cannot be manipulated by the participants. At the same time, the market approach may enter in conflict with the security of supply to end-users if shippers are not able to make accurate predictions on the demand and, consequently, on market prices. In these cases the market allocation can differ from the "social optimal" allocation, requiring the need of a regulatory intervention to align shippers incentives and social benefits.

3.4 The Proposed Design

The previous sections highlighted the criticalities of the current Italian gas market. These can be summarized in the following points:

1. The Italian market structure is characterized by an important network of storage infrastructures but with few *peak-shaving* facilities[36];

2. The slowness of the bureaucratic machine and the uncertainty about the regulatory regime related to the TPA may reduce entry-attractiveness;

3. III. The allocation of the Peak and Uniform services may undermine the stability of the system if market prices are highly volatile and shippers are not able to make accurate predictions: in this case

[36]It is worth to mention that the document of the MED of 8th march 2013, indicating the *National Energy Strategy* (SEN), quantified in at least 8 MSmc/year the additional LNG capacity required for the development of the internal (and EU) gas market.

the accumulation of gas reserves may be lower than the social optimum.

The scarcity of peak capacity imposes a limit on the amount of gas that is available on the grid for daily (or hourly) modulation. In presence of a shock on the demand side, such a limit may generate situations characterized by shortage of gas for consumers (*gas crises*). In these cases, the balancing of the grid made by the TSO is complex and alternative solutions must be found for reducing demand. Moreover, the technical difficulties related to gas supply interruptions for domestic consumption impose an additional constraint to the TSO. This problem is aggravated by the massive penetration of renewables in the electricity generation and the absence of abounding electricity storage capacity.

The uncertainties related to the thermoelectric production reduces the ability of shippers to predict demand, with unclear effects on the accumulation of reserves. For instance, shippers may consider the price spread between peak and off peak hours too low or, alternatively, undervalue the number of peak hours, with the effect of discouraging the accumulation of reserves. It must be noted that a peak scarcity event, resulting from an intermittent renewable generation, does not follow necessarily seasonal modulation and peaks. In other words, short periods with high demand may occur beside classical seasonal variations. This in turn reduces the margins available to the TSO for balancing operations and increases price volatility not only during the winter season, but also during the rest of the year. The analysis developed so far indicates a room for a regulatory intervention aimed at increasing the peak-capacity available to the shippers and encouraging the accumulation of reserves to the optimal social level. In particular, with regard to the first issue, section 4.1 individuates the public direct intervention as a solution to the capacity scarcity. Section 4.2, instead, proposes the introduction of a complementary market-based mechanism to improve the design on capacity allocation.

3.4.1 Direct Public Intervention for the Realization of the New Infrastructure(s).

The current configuration of storage services in Italy is, as section 2 showed, based on depleted fields, while no aquifers or salt caverns are currently operating, not even projects have been presented for their installation. This aspect denotes the lack of suitable fields or the non profitability of the projects for the realization of these kind of facilities. The absence of salt caverns, in particular, limits the capacity available to the system for daily and, partially, intra-daily modulation. *LNG infrastructures* (terminals and reservoir), on the other hand, fit well to these purposes and permit to "catch up" the short-term volatility of gas demand. The main obstacles for their realization are deeply related to the regulatory uncertainty governing the remuneration of the investment and the access to the facility. In the same vein, a change of the market conditions after the approval of the project may lead the investors to abandon the construction and this is more likely the more the license release procedure extends over time.

The disincentives to invest related to the just mentioned issues have been studied by several authors[37]. In particular, the regulatory uncertainty about the exemption from TPA (the "regulatory holiday") fall into the classical *hold-up* problem. In fact, gas storage facilities are capital intensive and have very limited alternatives once the investment is done but, at the same time, the returns of the investments protracts over long time, exposing investors to a large regulatory risk.

Another source of uncertainty for investor is described by the *missing market* argument, that defines the scarcity of price signals as a major market failure for the attraction of new investments. The impossibility to recover the willingness to pay of consumers in the events of scarcity of gas furniture does not provide the right incentives to the operators to bring new investments into the sector. Practically this happens because the interruption of gas furniture to domestic consumers is technical complex and alternative solutions to limit consumption are adopted.

[37] For instance, a reader can refer to (24; 25).

To deal with these issues (hold up and missing market) the economic literature generally proposes several solutions: long-terms contracts, vertical integration and natural monopoly regulation. *Long-term contracts* represent a way to spread the risk associated with the investment among more players. Given the high cost of the investment, it is unlikely that an operator alone is willing to bear the total cost and be subject to the variability of demand modulation. In these situations, a third party can construct the necessary infrastructure and, subsequently, subcontracting capacity to the shippers. Therefore, the risk is not mitigated but is spread-out among more players through long term agreements. These contracts, however, suffer from two main limitations. First, they usually do not include flexibility clause (or they do at very high costs). Second, a system based on long-term contracts reduce spot competition. In other words, the reduction of the risk for the investors may occur at the expense of spot market efficiency.

A *vertical integrated* firm which is the owner of the infrastructure and, at the same time, is the shipper in the retail market would be interested in making large investments if the access to the infrastructure can be denied to competitors. That is, the bundling of the storage site within the retailer provides the right incentive for entry the market and invest in LNG facilities. Practically, this solution coincides with the abolition of TPA clause, which instead laid its foundation on characteristics of the facility: high investment cost and limited number of feasible projects. The conclusion is that the only market structure compatible with the vertical integration is the oligopoly. These arguments led the regulator in the EU to the assessment that an infrastructure indicated as *essential facility* should be regulated with a non-discriminatory TPA.

A *public regulated monopoly* may well combine the incentive to invest and guarantee a non discriminatory access to the infrastructure under a TPA regulation. A regulated *Storage System Operator* (SSO) can bear the cost for LNG investments in terminals and tanks. The introduction of a System Operator, already adopted in the transmission sector, can turn out to be extremely important to expand market flexibility when there is a relevant uncertainty about market prices (missing money arguments, high price volatility, etc...). The reasoning is similar to the introduction of capacity markets for sustaining investments in the electricity sector. The difference with respect to a market approach is that LNG infrastructures can be labeled as *essential facilities* and therefore be limited in their remuneration by a TPA. This last observation justifies the public direct intervention for the realization of new projects. The investments made by the SSO would be "automatically" recognized as essential, leaving to the Authority the definition of the optimal tariffs for their remuneration. The latter should be based on a mechanism aimed at rewarding the progresses in the realization of the infrastructures and penalize delays. The SSO remuneration is than spread among all the actors that receive advantages from the realization of the infrastructure: final consumers, that are hedged from the risks of disruptions during the peaks, and the shippers, that can use storage to arbitrate on the spot market. The higher cost for the system will be distributed over a determined number of years and reversed on consumers bills and shippers, according to the volume of gas injected and withdrawn or through a fixed contribution. In particular, the competitive allocation of storage capacity is expected to contribute to the cost recovery.

The concentration of the activities in the hand of a single subject reduces the problem related to the coordination of the investments among more players, which can lead to a "precautionary" total capital expenditure below the optimal social level. Finally, the SSO can be thought to operate for a limited period of time, necessary to make the relevant investments, after which its assets can be allocated to the market.

3.4.2 Improving the Capacity Allocation: *Supply Options* for Balancing Security.

Auctions represents a powerful tool to detect the willingness to pay of the buyers (or sellers) when there is scarcity of a good or service, provided that the auction is well designed and cannot be manipulated by the subject involved. Auction mechanisms have been applied for the allocation of the peak and uniform capacity described in Section 3.4. The theory in support of the use of auctions for the allocation of gas storage capacity has been provided by *(16; 17)*. The main idea is that auctions improve social welfare whenever the final allocation is output maximizing. In particular, the paper indicates the conditions under which an administrative allocation must be preferred to an auction mechanism and viceversa, in a market characterized by a dominant firm and a *fringe* of competitors. The strategy of introducing imperfect competition has the intent of capture some of the real features of the current European gas markets, where big players are at stake and new entrants are appearing[38].

If the advantages deriving from the adoption of market mechanism for the allocation of the capacity are clear, the drawbacks linked to the security and stability of the system have not been widely discussed. In fact, it can occur that shippers are not able to predict price peaks due to the excessive volatility of consumption and accumulate an amount of gas lower than the social optimal level. Whenever this happens, the market design approach enters in conflict with the target of assuring the security of supply to end users. An example can be represented by a low seasonal price differential expected by the shippers. This may reduce the attractiveness of gas stockpiling, with the risk of generating scarcity for limited periods in time, causing prices to jump up. Again, the price peaks may reflect not necessary the lack of an adequate amount of gas for seasonal modulation but, rather, the lack of flexible resources for daily or intra-daily instantaneous variations. The risks of extreme revenues fluctuations may than generate instability on the spot market and constrict TSOs to adopt emergency operations. As such concern is expected to become more serious due to renewable penetration and the relegation of CCGT to a “back-up” role, the spot market design should be accompanied with additional instruments.

[38]The work leaves an open discussion regarding the interaction between the allocation and productive efficiency of the shippers and the effect of introducing a secondary markets where renegotiation of storage capacities can occur. If renegotiation is allowed than it is essential to guarantee enough liquidity to the system and avoid attempts of monopolization and market foreclosure behaviors. This issue is more relevant the more the market is concentrated.

The introduction of *supply option* may serve to this scope. This instrument would provide the TSO with the additional amount of capacity for managing the daily modulation. This is achieved by purchasing from the shippers an *obligation* to supply, on TSO request and in the real time, the spot market with a certain amount of stored gas. This amount is determined by the TSO as the result of the maximization of a social function that includes, among the others, the reduction of the probability of scarcity events as a function of the total stock available[39].

The shippers commit themselves[40] to provide resources at a price that cannot exceed a given cap, predetermined when the option is bought by the TSO. The remuneration for the gas offered in the real time follows the balancing price up to the cap. If the balancing price exceeds the latter, the shippers is required to pay back the extra-revenue he received. Therefore, the cap acts for limiting the earnings of the shippers and controlling market power in the case of scarcity of reserves for short-term modulation.

To conclude the design, the shippers offer the options in a non discriminatory way through auctions and the TSO selects the offers according to the price ascending order. Practically, this may be conducted with a *Descending Uniform Price* auction, where the TSO (or the SSO as defined in the previous section) starts the auction calling a very high price and keep reducing it at each step as far as the demand equalizes the offer and a single *option price* (the "premium") comes out[41].

The advantages of this approach reveals to be manifold. *First*, the TSO is endowed, in the fullness of time, with the additional storage capacity for the real-time balancing of the grid. *Second*, the price of this additional capacity is "capped" at some determined level in the event of scarcity, permitting to control shippers market power. *Third,* the market approach gives to the shippers the possibility to diversify the risk associ-

[39] This mechanism can be thought as an adaptation of the capacity market from the electricity sector to the gas industry. The elicitation of additional capacity, diversely from electricity, is not based on the increase of gas production but, instead, on its accumulation.

[40] A penalty should be inflicted to the shipper who do not respect the obligation.

[41] The auction may include also a reservation price (lower bound) to cover part of shippers fixed costs.

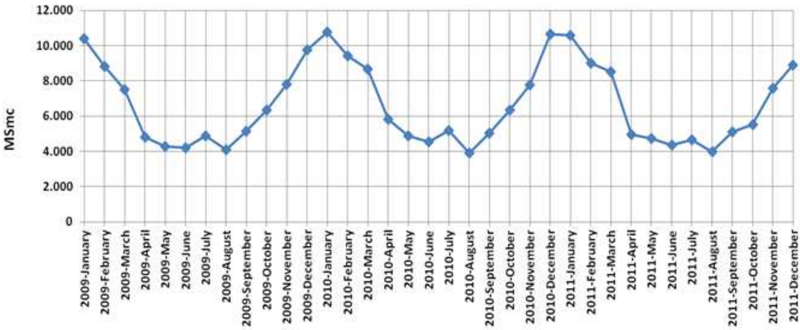
ated with price volatility. Indeed, those shippers who are more risk adverse towards future prices may stabilize the supply of their reserves by receiving a premium in exchange of gas accumulation. On the other side, the shippers who expects prices to raise up in the long term would prefer accumulate gas when prices are lower and exploit consumption peaks. Finally, the incentive to stabilize gas storage furniture for seasonal and daily modulation comes at a cost for the system represented, in the mechanism just described, by the premium paid by the TSO for the acquisition of the options. Accordingly, the difference between the revenues for the selling of storage (uniform and peak) capacity and the premium is reversed on final users, according to consumption. The timetable of the new market design is summarized in the Appendix.

3.5 Conclusion

This work is intended to contribute to the discussion on the optimal regulation of gas storage services. The main regulatory debates focus on the promotion of new facilities and the definition of products aimed at increasing system flexibility coherently with the security of supply to end users. The institution of a public storage system operators (SSO), responsible for the realization on new infrastructures, and the introduction of supply options propose a solution to the risk of scarcity of flexible resources in the Italian market. These innovations are discussed into a context of deep transformation of the energy industry. In particular, the massive penetration of *renewables* increases the uncertainty related to the modulation of storage reserves, moving the attention on the peak performances of the system rather than its overall storage capacity. This is particularly important in Italy, where the thermoelectric production based on CCGT satisfies the baseload consumption and generates the operating reserves for the electricity balancing operations. The establishment of a SSO may be necessary for sharing the high costs and the risks for the launch of new facilities. The design of a new product, complementary to the services offered with the uniform and peak capacities, reveals to be useful for assuring adequate resources for daily (and intra-daily) modulation to the TSO. The higher costs for the system can be more than compensated by a reduction of the risk of disruptions and scarcity events in the long-term.

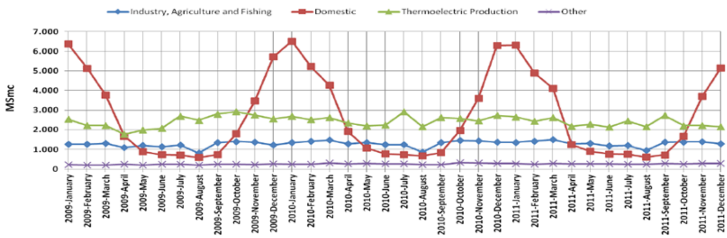
3.6 Appendix Chapter 2

Figure 9: Italian National Monthly Consumption during the period 2009-2011



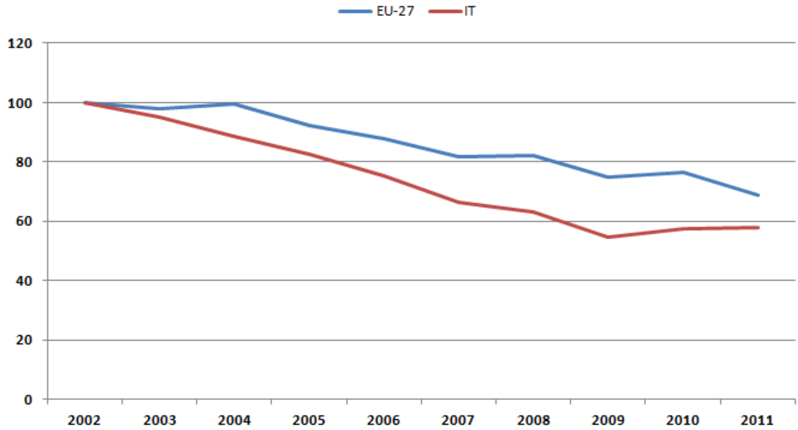
Source: Italian Ministry of Economic Development

Figure 10: Sector Decomposition of Italian National Monthly Consumption for the period 2009-2011



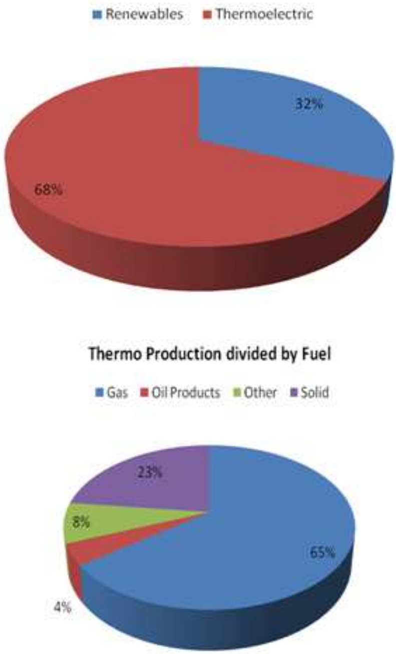
Source: Italian Ministry of Economic Development

Figure 11: Indexes of EU-27 and Italian Gas Productions in the period 2002-2011 (Base Year: 2002)



Source: Eurostat

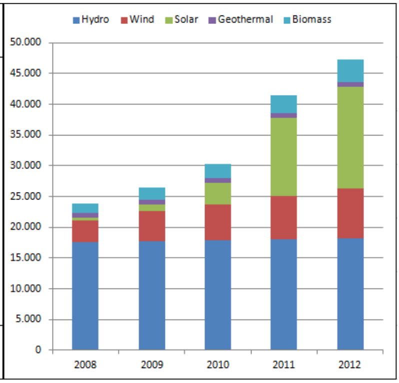
Figure 12: Electricity Generation in Italy in 2012 divided by Sources



Source: AEEG – Annual Report 2012

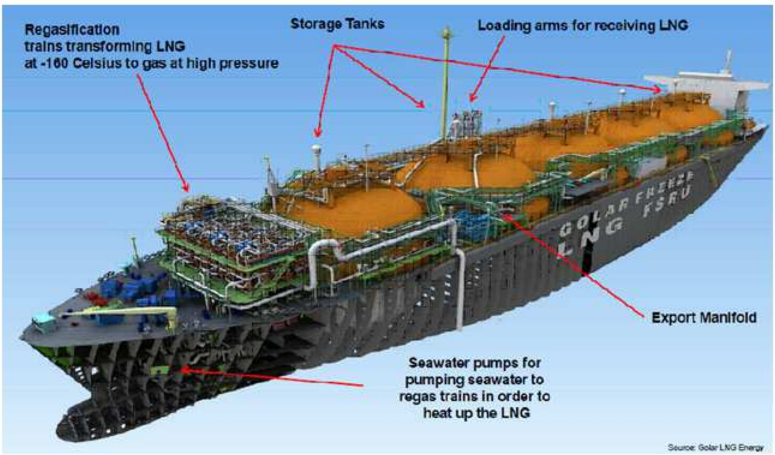
Figure 13: Renewable penetration in Italy (and technologies) from 2008 to 2012

Capacity Installed (MW)	2008	2009	2010	2011	2012
Hydro	*17.623*	*17.721*	*17.876*	*18.092*	*18.232*
Wind	*3.538*	*4.898*	*5.814*	*6.936*	*8.119*
Solar	*432*	*1.144*	*3.470*	*12.773*	*16.420*
Geothermal	*711*	*737*	*772*	*772*	*772*
Biomass	*1.555*	*2.019*	*2.352*	*2.825*	*3.802*
Total	***23.859***	***26.519***	***30.284***	***41.399***	***47.345***



Source: GSE (Statistical Reports)

Figure 14: An LNG Floating Storage and Regasification Unit



Source: Golar LNG
(http://www.golarlng.com/index.php?name=Our_Business%2FFloating_Storage_.html)

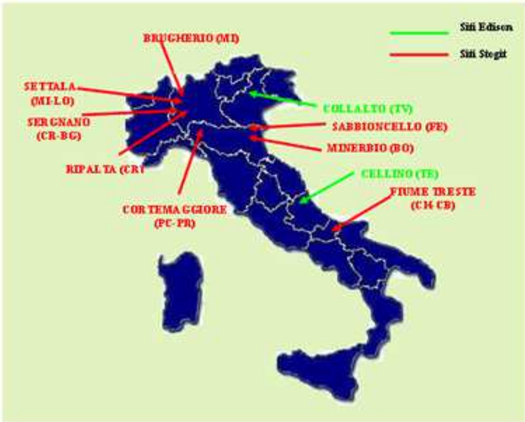
Table 2: Typical characteristics of different natural gas storage technologies

Type of storage facility	Working capacity [mcm[5]]	Send-out capacity [mcm / day]	Injection Capacity [mcm / day]	Investment cost [m€]	Lead-time of investment [years]
Depleted gas field	2,500	30	10	700	5 - 8
Aquifer	2,500	30	10	800	10 - 12
Cavern	30 - 70	2 - 4	1 - 7	40	1 - 5
LNG tank	50	50	0.25	200	5 - 7

Source: de Joode (2009) on data by (CIEP 2006)

Table 3: Storage Sites, WG and Send-Out Capacity in Italy at the end of 2012

Site	Storage Operator	Technology	WG (Mscm)	Send-Out Capacity (Mscm/day)
Brugherio	Stogit	Depleted Fields	330	8,0
Cellino	Edison	Depleted Fields	118	0,8
Collalto	Edison	Depleted Fields	440	2,8
Cortemaggiore	Stogit	Depleted Fields	960	15,0
Fiume Treste	Stogit	Depleted Fields	4.005	66,0
Minerbio	Stogit	Depleted Fields	3.078	57,0
Ripalta	Stogit	Depleted Fields	1.686	12,0
Sabbioncello	Stogit	Depleted Fields	939	20,0
Sergnano	Stogit	Depleted Fields	2.244	55,5
Settala	Stogit	Depleted Fields	1.820	37,5
	Total		*15.620*	*274,6*



Source: AEEG, Annual Report 2013

Table 4: Regulated Tariffs for Storage Services in the period from 1st January to 31st December 2014

Regulated Tariffs for Storage Services	
Service	**Unit Cost**
Space charge	0.233713 €/GJ/year
Injection charge	19.008101 €/GJ/day
Withdrawal charge	20.561702 €/GJ/day
Commodity charge	0.088123 €/GJ
Unitary charge to cover strategic storage burdens	0,000967 €/Smc

Source: Stogit Spa (http://www.stogit.it/en/business_area/storage_tariffs/index.html)

Table 5: Storage capacity allocation for the thermal year 2013-2014 differentiated per service.

Allocation of Capacity for the Thermal Year 2013-2014		
Service	**Allocation Rule**	**Capacity Available (MScm)**
Decree 130/10	Available Capacity	2.596
Mineral Capacity	Defined by the Ministry of Industry	258
Balancing	On Demand	202
LNG terminal Users	Defined by the Ministry of Industry	50
Industrial LNG Importers	Defined by the Ministry of Industry	450
Peak Capacity	Quotas	4.200
	Uniform Price Auction	2.500
Uniform Capacity	Pay-as-Bid Auction	1.740
Strategic Storage	Defined by the Ministry of Industry	4.600
Total		**16.596**

Source: AEEG, Annual Report 2013

The Market Design Timetable with Supply Options

Step 1: The TSO defines and make public the optimal amount of storage reserves for all the thermal year. This is computed by the maximization of a social function that includes, among the others, the expected level of demand and the probability of supply disruption as a function of the overall capacity available into the system. The regulator defines three products that have to be allocated on the spot market: Peak Service, Uniform Service and Supply Option.

Step 2: The regulator defines the capacity to be allocated for Peak and Uniform Services and the SSO run the auctions. At the end of the procedure, the SSO knows the difference between the optimal amount of storage defined in Step 1 and the total amount of gas allocated for the Peak and Uniform services.

Step 3: In the case the difference indicated in Step 2 is positive, this becomes the demand of Supply Options made by the SSO. Shippers compete to supply options in an auction mechanism that concludes with a single equilibrium price (the premium).

Chapter 4

Strategic Congestion in a Day-Ahead Electricity Market based on Zonal Pricing

4.1 Introduction

A deregulated market for electricity gives to the buyers the opportunity to purchase electricity from firms (generators) that charge a lower unit price for MWh. Network capacity constraints, on the other hand, limit the power that flow over the transmission lines and, consequently, reduce the amount of electricity that can be exchanged between distinct geographic areas. Whenever such limitations arise, market internal competition cannot be understood regardless of firms' response to the incentives that the network configuration may yield.

The wholesale electricity markets are designed to cope with transmission physical and contingency limits[1]. Exceeding the latter may cause a power line to collapse and, in severe cases, a domino effect can produce

[1] A clear coverage of the functioning and the issues concerning the design of power markets can be found in (67) and(64).

a black-out of the entire system.

The complexity of the network is directly transferred to the market and affects participants' supply (or demand) strategies and the formation of spot prices. In absence of transmission constraints, the power would be transferred from generating units to the buyers, located anywhere on the national territory, according to the economic merit order defined in the day-ahead market [2].

The existence of network constraints reduces this possibility. If the power required by some consumption units exceeds the capacity of the connection between the consumption and the generation nodes, the power line(s) will be congested. Following *(64)*, all limits, both physical and based on contingency, can always be expressed as a simple megawatt limit on the power flow that is allowed over the line. Therefore, a line is congested when the amount of power flowing on it reaches such limit.

To provide the right price signal to market participants, Transmission System Operators (TSOs) design the day-ahead market in a way to reflect the configuration of the grid. The partition of the national market into distinct geographic zones provides a (simplified) representation of network constraints. In particular, regions inside each zone are characterized by a low frequency of congestion[3]. This method, generally referred as *zonal pricing*, generates for any couple of zones, different prices if the power lines connecting the two zones are congested (i.e. the network constraints are binding). If no congestion on the grid occurs the price is, instead, unique on the national territory and the zones do not "separate" [4].

The immediate effect is that line capacity determines the internal degree of competition by connecting potentially isolated markets. Small

[2]The description of the economic merit order is reported in Appendix 1.

[3]The identifcation of zones usually relies upon historical data regarding transmission flow and congestion patterns. Some critical issues related to the zonal partition of the national market, can be found in (9) for the Norway case, and in (8) for the Italian case. Congestion management led, for instance, the Italian TSO (Terna S.p.A). to "divide" Italy into six geographic zones (North-Central, South-Central, North, South, Sicily and Sardinia), and six virtual zones for connections with foreign countries.

[4]An alternative format is the *"nodal pricing"* adopted, for instance, by PJM in the east cost of USA market. In a nodal configuration, the degree of disaggregation is the highest and the price is computed for each bus on the grid.

improvements in the transmission capacity may than reveal highly beneficial in terms of competition and reduction of the market power inside a zone. On the contrary, a limited capacity of the cable may induce market operators to strategic behaviors that generate a strategic congestion of the power lines. This concept is brightly illustrated in *(13)*:

> *"[...] A profit maximizing firm, however, may find it quite profitable to induce congestion into its area, thereby becoming a monopolist on any residual demand left unserved by imports from other regions [...]".*

This article introduces a model of competition aimed at study firms' market strategies in a day-ahead electricity market based on zonal pricing. The day-ahead market is run by a Power Exchange which collects, in any hour, the aggregate demand and supply and returns equilibrium quantity and price(s) determined through a uniform price auction. The model assumes that the TSO splits the national territory into two disjoint market zones, linked together with a limited capacity (the same both in import and export from a zone) transmission line. Generators compete to inject electricity by submitting a supply schedule to the power exchange, while the total demand is assumed to be the result of a stochastic process, independent from price. The presence of transmission constraints impose, in case of congestion, the determination of two prices, one per each zone, given by the corresponding marginal bids of the generators.

The model originates on the approach proposed first by *(65)*, and successively enriched by *(34)* and *(22)*, that studies the equilibrium strategies of suppliers in a multi-unit uniform price auction without network constraints. The model captures some of the essential features of the competition in the day-ahead market with "short-lived" bids[5]. In the discrete version of the game, generators are asked to submit a finite number of pairs of price and quantity. This is coherent with the bidding rule set by the power exchanges in several day-ahead market and reflects the discreteness of the marginal cost function of the firms. In fact, in order to cover daily demand, generators run first "baseload" plants that have low

[5]See Appendix 1.

operating costs, and switch on more costly plants to satisfy peaks of the demand. Nuclear power plants are classical examples of baseload units and run constantly during the day, while plants that make use of hard coal or oil have generally high cost and consequently form the market peakload capacity. Despite public information about generation costs and per period demand are far to be realistic, these are common assumptions in the literature and will be maintained here. Nevertheless, the model introduced in the next sections can be generalized to allow uncertainty on costs and demand side. Yet this is expected to complicate the analysis, the incentives to play strategically should again be preserved.

The results show that, even when transmission constraints are not binding, firms may coordinate their strategies in order to increase the market clearing price. When this happens, a firm produces a higher quantity in equilibrium ("price-taker") while the other clears the market with its marginal bid ("price-setter"). The asymmetric behaviors of the (symmetric) firms have already been described in (22) and the model of the next section generalizes this result, allowing for a greater variety of parameters related to generation costs and units size. In terms of social welfare, asymmetric equilibria are inefficient since total production costs are not minimized. Moreover, the social inefficiency increases as the asymmetry of the equilibrium allocation increases.

The introduction of binding transmission constraints generates an additional *gaming* between the firms. In particular, when the capacity of the transmission line is very low, suppliers attempt to congest the line and charge a higher price to the residual demand in their zone. For a firm, this strategy is conducted by offering its marginal unit at a price higher that of the competitor, forcing consumers located in its zone to import electricity up to the point where the cable reaches its capacity limit. In this situation, when the final allocation is more asymmetric than the expected equilibrium with no transmission constraints, investments aimed at increase the capacity of the power line improve the social welfare and reduce the market power.

The paper is organized as follow: section 2 presents a review of the literature and the main contributions of this work; section 3 introduces the model and derives the equilibrium strategies of power generators; section 4 discusses the policy implications and section 5 concludes.

4.2 Related Literature and Contributions

The interactions between network constraints and competition in the power sector have been studied in *(13)*. The model proposed by the authors considers two competing firms located into two distinct but symmetric markets. Inside each market the firm faces the same (downward sloping) demand function[6]. The two zones are connected each other by a transmission line with limited capacity and firms compete on quantities (Cournot). When the transmission capacity is very small, firms act as profit maximizing monopolists inside their zones. The introduction of a greater connection induces the firms to adopt mixed strategies on the support of their best response functions. The randomization varies between what the authors define an "optimal aggressive output", where the quantity produced is high and the price is low with the intent to export to the contiguous area, and the "optimal passive output", where higher prices are charged to a residual share of the demand. Whenever the prices differ in the two zones the line will be congested, since customers located in the area that charges a higher price will prefer to import power up to line's capacity. When the capacity is high enough, however, a unique pure strategy equilibrium exists and it is given by the unconstrained Cournot equilibrium. Any additional capacity improvement has no social value, since firms would not deviate from this equilibrium.

Even though the analysis gives clear predictions on the strategies adopted by the generators, the classic Cournot model appears to be not particularly appropriate to describe the functioning of the day-ahead market[7]. The main reason is that, in electricity markets, firms do not commit to produce a given quantity but rather submit a more complex

[6]The model, as the authors argue, was a realistic representation of the market splitting in California, where North and South correspond to two geographical interconnected areas.

[7]However, as the authors point out, there is *"[...] no reason why the basic effect we identify here wouldn't also obtain using other analytical approaches such as supply curve equilibria or multiunit auctions"*.

supply function. The commitment of a firm to a supply function has been first recognized and studied, in a generalized context, by *(50)*. This work introduces SFE (supply function equilibrium) for the analysis of situations where firms compete in presence of some type of uncertainty [8]. When a firm commits to a continuous supply function than it can better adapt to market contingencies and, after the uncertainty is vanished, it achieves its ex-post profit-maximizing outcome, a goal hardly attainable instead by fixing only prices or quantities. *(36)* applied SFE to study competition in the British electricity market[9]. The authors show how supply schedule are considerably above the marginal costs and the theoretical results seem confirmed by the empirical simulations proposed: even without collusion firms can exert a strong market power.

The main criticisms of the SFE approach are related to its applicability to real market situations. The reason is that SFE is based on the continuity of the supply function submitted by the generators. This technical condition, required to reach an equilibrium, is difficult to justify in practice. For example, in most EU markets, power exchanges ask to participant to submit a schedule indicating a finite number of pair price-quantity. In other words, generators have to submit a "step supply function"[10]. A different approach, proposed first by (65), deals with this issue by modeling competition in the power market as a multi-unit (uniform price) discrete auction. In the original model, generators have a constant marginal cost and face an inelastic demand. (34) and (22) generalize this model to allow for increasing step cost function, asymmetric firms and downward sloping demand function and show why asymmetric strategies may emerge

[8]In the work proposed by (50), the source of uncertainty were attributed to the demand. The authors also show that, if no uncertainty is present into the market, there is a multiplicity of Nash equilibria. However, as they pointed out, in the absence of uncertainty a firm knows exactly its equilibrium residual demand and this makes the supply function strategy not compelling, since this causes only an increase in the number of equilibria.

[9]Contrarily to the basic Klemperer and Meyer, no uncertainty on the demand side is included and the number of supply function equilibria is reduced by introducing supply constraints for the firms.

[10]A non technical discussion about the differences between the continuous and the discrete auction format is provided in (31). An important contribution, aimed at understanding under which conditions the discrete representation of supply functions can be approximated by the continuous representation, has been provided by *(43).*

in equilibrium.

Built on this last approach, this paper introduces transmission network constraints for studying the equilibrium strategies of the firms in an electricity market based on zonal pricing. In particular, two symmetric firms are located into two distinct geographic areas connected by a limited power line. The supplies submitted to the Power Exchange determine the dispatch merit order of the generating units of the firms and the MW amount of import/export from one zone to the other. In the case the amount flowing on the transmission line exceeds its MW limit, the zones separate and the prices (one per each zone) are determined by the (intra-zonal) marginal market clearing offer. To my knowledge, this is the first attempt to study the effects of network constraints on competition in the power sector within the multi-unit auction framework.

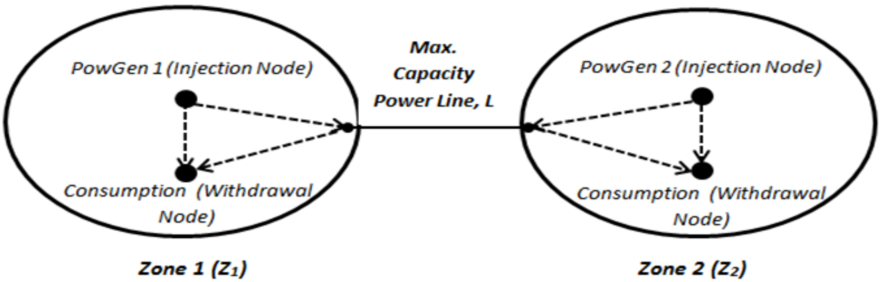
If on the one hand, the model is able to replicate the conclusions of the works of (34) and (22), on the other it considers an additional variable, the power line capacity, that can be exploit to derive policy suggestions aimed at mitigate market power on the supply-side. Under certain conditions, the model reconciles with the findings of (13) and indicates a precise target for investments in transmission capacity, above which additional development of the grid will not result in any further price reduction since generators have no incentives to deviate from the reached equilibrium.

4.3 The Model

Consider two risk-neutral symmetric power generators (indexed by $i = 1, 2$) located in two distinct geographic areas, $Z_1$and Z_2, connected through a power line with a limited transmission capacity, L. Each zone is characterized by an injection node (generation) and a withdrawal node (consumption)[11]. The demand in each zone is met by the internal production or through importation from the contiguous zone, up to the maximal capacity of interconnection (see Figure 15).

[11] Alternatively one can consider additional nodes grouped under a “hub”.

Figure 15: Physical Grid Representation



The following assumptions regarding production costs and market demand will be maintained throughout the paper:

Assumption1 (Production Costs): *Firms produce electricity employing a fixed number U of generating units with start-up costs normalized to zero*[12]*. In particular indicate with* $\mathscr{U} = \{1, 2, ..., u, ...U\}$ *the set representing the generating units of each firm. Each production unit* $'u'$ *has a constant unit cost of production indicated by* c_u *and a maximum generating capacity indicated by* k_u*. The current output of a unit is instead indicated by* q_u *with* $q_u \leq k_u$[13]*. Generators rank the units in the cost-ascending order, and so the set* $\mathscr{U}$ *can be reshuffled so that* $\mathscr{U} = \{1, 2, ..., u, ..., U : c_u \leq c_{u+1}\}$*. Costs are common knowledge in the market.*

Let $u(q)$ be the marginal unit necessary to produce the quantity q, that is $u(q) = \left\{\min u : \sum_{u=1}^{q} k_u \geq q\right\}$. The marginal cost function will so be given by $c(q) = c_{u(q)}$, while the total cost function is $C(s) = \sum_{u=1}^{u(q)} c_u q_u$ where

[12]Alternatively one may consider plants already running in the Day-Ahead Market.

[13]Note that this notation can also be used to represent "packages" of quantities that are produced by the same plant. For instance, the same plant can produces from 0 to 100 MWh at a unit (marginal) cost lower than the production in the range [100-200] MWh. The two packages can so be treated as two different units.

$q_u = k_u$ *for all* $u < u(q)$. The total capacity of a firm is given instead by $K = \sum_{u=1}^{U} k_u$.

Assumption 1 summarizes the discreteness of the production cost function of a firm. The model is general enough to include cases where a firm owns a single power plant with increasing costs associated with higher production or, alternatively, different generation technologies (for instance "baseload" and "peakload")[14] or a mix of both. Importantly, the information about the costs of the firms are known to market participants. This last hypothesis can be justified by the communications about the technical characteristics of the generating units that firms, generally, provide to grid operators for reasons related to the security and stability of the system during real time operations.

Assumption2. (Market Demand)*: The internal demands in* $Z_{1,2}$ *are indicated by* $D_{1,2}$ *and are independent from prices. Let* $D_1 + D_2 = D_T$ *and* $Prob(D_T) : [0, 2K] \to [0, 1]$.

Assumption 2 identifies the total demand as the result of a simple stochastic process limited by the total generation capacity available in the market[15]. As it will be clear further on, the introduction of a price-sensitive demand does not eliminate the incentive on the bidding strategies of generators but only their magnitude that, in these situations, would vary with the elasticity of the demand. Therefore, the market demand considered here still provides useful insights without complicating the equilibrium strategy computation. For the same reason and without loss of generality set $D_1 = D_2 = D$.

Firms compete to supply electricity in a Day-Ahead market, run by a Power Exchange through hourly auction, subject to a zonal pricing regulation. In particular, the following business rules (BR) apply:

[14]In this case one can consider additional injection points corrisponding to each of the power plant owned by a firm.

[15]The model does not include the possibility of scarcity events (total demand higher than total generation capacity).

1. For any hour of the day the generators are asked to submit a step supply function to the Power Exchange containing, for any production unit, a single price (Â€/MWh) at which the generators are willing to sell all unit's capacity. A strategy for the generator is given by a step supply function $\beta_i(u) : \mathscr{U} \rightarrow P$ where $P = \{0, \bar{P}\} \subset R$ and $\overline{P}$ is an arbitrary price ceiling (maximum price accepted by the pool). Withouth loss of generality assume that $\bar{P} > c_U$[16].

2. For each hour of the day, the Power Exchange receives the market demand in each zone and forwards them to the firms before the beginning of the market. The Power Exchange collects the supply of the generators and gives back the equilibrium quantity of each firm, $s_i^{z_i}$, and the price, p_i, in each zone. Formally indicate the function *Outcome* as $\mathcal{O}(\beta_1(u), \beta_2(u), D_t) : [0, \overline{P}]^{2U} \times [0, 2K] \rightarrow [0, K]^2 \times [0, K]^2 \times [0, \bar{P}]^2$.

3. The pricing rule adopted by the Power Exchange is the *Zonal Transmission Marginal Pricing*. This works as follow: in any hourly auction, the price in each zone is determined by the *clearing condition* $D = s_1^{Z_i}(\beta_1(u), \beta_2(u)) + s_2^{Z_i}(\beta_1(u), \beta_2(u))$ and with $s_1^{Z_1} + s_1^{Z_2} = s_1$, trough a *Uniform Price Auction* (or *System Marginal Pricing* - SMP) mechanism. In particular, in each zone, the price submitted for the marginal generating unit[17] determines the zonal price. Each firm, independently by the zone where the quantity is consumed, will be paid the price of the zone where it injects electricity. All consumers, instead, are charged the same amount, given by a weighted average of the prices with the consumption in the two zones[18].

4. Whenever the line is not *congested*, that is the import/export of electricity from one area to the other is lower than L, there is a unique market (zone) and a unique clearing price. Formally the *equilibrium* price in the single market zone is given by $p_{NC} = max_i \beta\left(u\left(s_i\right)\right)$

[16] The Price Ceiling is higher than the highest unit marginal cost of the firms.

[17] The last generating unit necessary to satisfy the zonal demand.

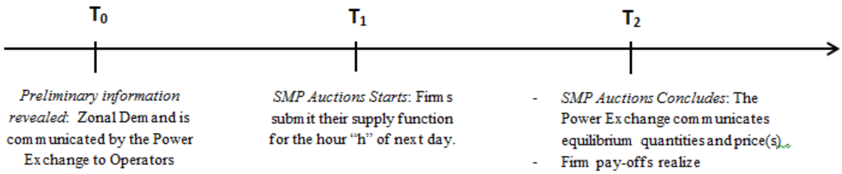
[18] Under the assumption $D_1 = D_2$, this reduces to a simple average of zonal prices.

and call i the *price-setter* and j the *price-taker*[19].

5. The following *acceptance and priority* rules are adopted by the Power Exchange: (a) The market supply in each zone is constructed by ordering the generators' bids in the price-ascending order (the so called *merit order*); (b) Whenever some units are priced the same, that the lower cost unit is dispatched first; (c) In the case the firms submit the same unit at the same price and this results to be marginal (i.e. the *price-setting* unit), than the total quantity required for this unit will be equally splitted among the two firms.

The timing of the game is summarized in Figure 16

Figure 16: Timing of the game



The objective of firm "i" located in zone Z_i is to maximize its hourly profit function, given by $\Pi_i = p_i^{Z_i} s_i(\beta_1(u), \beta_2(u)) - C(s_i)$. The following analysis will focus solely on increasing supply functions[20], that is $\beta(u) \leq \beta(u+1)$. From the clearing condition in BR3 it is useful to derive the residual demand of player 'i' in the zone Z_i given by:

Definition1 *The demand supplied by player "i" in zone Z_i is indicated by*
$$s_i^{Z_i}(\beta_i(u), \beta_j(u)) = D - s_j^{Z_i}(\beta_i(u), \beta_j(u))$$

Note that when $D_T = 2K$ the demand is covered by the total generation capacity and the only possible equilibrium allocation is given by

[19] If $p_{NC} = max_1 \beta(u(s_1)) = max_2 \beta(u(s_2))$both players are at the same time the price taker and price setter

[20] This comes at the cost of reducing the number of equilibria available to the firms.

$\mathcal{O}(\beta_1(u), \beta_2(u), D_t) = \{(D, 0); (D, 0); (\overline{P}, \overline{P})\}$where the total demand is equally splitted between the two firms and the price (or prices in case of congestion) reaches the ceiling. This result is trivial since generators are monopolist on half of market demand. Independently by the level of the demand, such an equilibrium holds also in the case where $L = 0$. In this situation the possibility to import/export is inhibited (consider for instance a power line maintenance) and firms are monopolist inside their injection zone.

The next section is intended to derive the equilibrium solution for the basic case where the transmission constraint is not binding. This happens when $L \geq D$ since, in this situation, a firm is able to export all its capacity to cover the demand in the contiguous zone without congesting the power line. The result generalizes the "withholding" effect already described in Crawford et al. (2007), allowing for a higher choice of parameters related to costs, demand and units size.

Successively the analysis is enriched to study the case where L is limited and bounded by D, that is $0 < L < D$. In these situations the export capacity of a firm in a zone is constrained by the capacity of the transmission line and each firm conserve in its area an irreducible residual demand. As in Boreinstein et al. (2000) this generates for a firm a trade-off between asking higher prices with the possibility of a congestion event and offering lower prices with the intent of increasing exportations. The result is that the marginal production unit of each firm will be offered at a price resulting from a randomized rather than a pure equilibrium strategy.

Equilibrium Analysis when $L \geq D$.

The absence of congestion on the power line allows the delivery of any positive amount of electricity from one area to the other. This implies the existence of a single market zone with demand given by D_T and a unique price, here indicated by P_{NC}. The following propositions rules out the possibility that a firm prices some units below the marginal cost:

Proposition1 *Play some units below the unit cost is a* weakly dominated *strategy.*

Proof: See Appendix 2.

Playing some units below the marginal cost has a double negative effect for a firm since *(i)* it pushes the equilibrium price (and revenues) downward and *(ii)* with some positive probability the firm will bear losses at the margin. This result permits to focus the attention on those bidding strategies where the units are priced at least at their marginal cost. Next proposition reveals, instead, that the pricing strategy that asks to the price-taker to bid all its units at the marginal cost (*marginal cost pricing*) represents for him an optimal bidding behavior (or a 'best response' strategy).

Proposition2 *For a Price-Taker any strategy which is "outcome-equivalent" to the marginal cost pricing is a best response strategy.*

Proof: See Appendix 2.

The basic idea behind Proposition 2 is that the price-taker has an incentive to introduce more infra-marginal capacity by cutting its rival's price. This is achieved by pricing each unit at the marginal cost (or with an outcome equivalent strategy). From Proposition 2 the next corollary follows:

Corollary1 *The minimum amount of power that is produced by the price taker is given by D.*

Proof: See Appendix 2.

Propositions 2 can now be used to derive the maximization problem for the price-setter. Indicating with $i = 2$ the price taker and with $\beta^*(u)$ its best response strategy and remembering that for a price setter it must hold that $\beta\left(u(s)\right) = p_{NC}$ the objective function of player 1 becomes[21]:

[21] Notice that whenever the maximization problem admits as solution an allocation such that $p_{NC} = max_1 \beta\left(u\left(s_1\right)\right) = max_2 \beta^*\left(u\left(s_2\right)\right)$both players are, at the same time, the price taker and the price setter

$$\max_{\beta_1(u)} \Pi_1\left(\beta_1(u(s_1)), s_1(\beta_1(u), \beta_2^*(u)\right) =$$

$$\beta_1(u(s_1))s_1\left(\beta_1(u), \beta_2^*(u)\right) - C\left(s_1(\beta_1(u), \beta_2^*(u)\right) \ (PSP)$$

$$s.t.\ \beta_1(u(s_1)) \leq \overline{P}$$

The trade-off of the price setter can be explained as the choice between pricing, symmetrically with its competitor, all its units at the marginal cost (see proposition 2) or reducing its residual demand with the intent of increasing the equilibrium price. In this last case the price setter will be unique and, despite of the symmetry of the firms, asymmetric strategies will emerge. It must be noted that, given the optimal response of player 2, there exists a continuum of strategies for player 1 that gives back the same final price p_{NC} (outcome equivalent strategies) and allocation and among which player 1 is indifferent. Therefore, indicating with $\dot{B}(p_{NC}, \beta_2^*(u), D_T)$ the set of strategies that return the same final price p_{NC}, given the best response of the competitor and the total demand D_T, there exists a map $\mathscr{M}$:$\left[0, \overline{P}\right] \rightarrow \dot{B}(p, \beta_2^*(u), D_T)$ that associates to each clearing price a set of possible strategies for player 1[22]. Remembering that $\beta_1(u(s_1)) = p_{NC}$ and applyng the inverse mapping $\mathscr{M}^{-1}$ the (PSP) can be reduced to a function of the single variable p_{NC}:

$$\max_{p_{NC}} \Pi_1\left(p_{NC}, s_1(\mathscr{M}^{-1})\right) = \max_{p_{NC}} \Pi_1\left(p_{NC}, s_1(p_{NC})\right)$$

$$s.t.\ p_{NC} \leq \overline{P}$$

and if a bidding strategies that maximizes (PSP) exists there will also be a continuum of solutions. The next proposition characterizes the solution of the (PSP):

[22] In other words, the map $\mathscr{M}$ is the inverse of the outcome function $\mathcal{O}(\beta_1(u), \beta_2^*(u), D_T)$ restricted to final prices.

Proposition3 *(PSP) admits always a continuum of solutions and the price solution is a discontinuity point in the domain of the (PSP) function.*

Proof: See Appendix 2.

Given the existence of (at least) a solution to the PSP problem, now it can be possible to characterize the equilibrium of the game for the case L>D. For this purpose it is useful to define the following quantities:

Definition2 *Indicate with* $\underline{u} = \left\{ \min u : \sum_{u=1}^{u} k_u \geq D \right\}$ *and* $\overline{u} = \left\{ \min u : \sum_{u=1}^{\overline{u}} k_u \geq D_U \right\}$.

These quantities represent, for a firm, the last generating unit that must be activated to satisfy alone, respectively, its zonal demand and the total market demand. Under the initial assumption that $D_1 = D_2 = D$ and $D_T \in [0, 2K]$ than the first quantity $\underline{u}$ is always defined, while the second quantity $\overline{u}$ may be not. However this last case perfectly coincide with the case of a limited transmission capacity L described in the next section. In fact when a firm located in one zone is not able to cover completely total market demand, this means that there is an irreducible residual share for the competitor in its injection zone. For this reason, in this section, it is assumed that the quantity $\overline{u}$ exists, while the other case is integrated in the successive paragraph. The next proposition establishes the existence and the characteristic of the pure strategy equilibrium of the game for the case L>D.

Proposition4 *There exists at least a pure strategy Nash equilibria of the game when* $L = +\infty$. *Moreover any pure equilibrium, results in the allocation* $0 < D_i \leq D \leq D_{-i}$ *where player* $i = 1$ *is the price-setter and player*$-i = 2$ *the price taker and* $p_U = c_u$ *with* $u \in [\underline{u}, \overline{u}]$.

Proof: See Appendix 2.

Proposition 4 characterizes the equilibrium allocation and highlights the trade-off previously described for the price setter. A direct consequence of the equilibrium allocation is indicated by the following:

Corollary2 *Any pure strategy equilibrium of the game would result in*

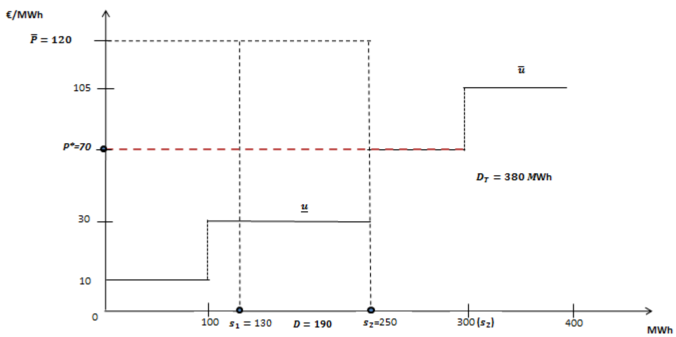
$$\Pi_2(p_{NC}, D_{-i}) \geq \Pi_2(p_{NC}, D_i).$$

Proof: This is straightforward since the price is the same for both players but $s_2 \geq s_1$.■

The detection of the equilibrium (or equilibria) of the game is a tedious work, since it requires to check for the price-setter all the possible strategies where a jump in the demand occurs in correspondence of variations of the market clearing price. In other words, also if the equilibrium price must be found in a limited number of discontinuity points of the profit function, the strategies that implies a "jump" of the residual demand of player 1 must be found among a higher number of strategies, which increases as the number of generating units U and demand D increases. A simple algorithm ("Scan Algorithm") that can be used for the equilibrium detection is showed in Appendix 3, while an equilibrium allocation is shown for instance in Figure 17 below, with the parameters of the model reported in the attached Table.

Figure 17: Asymmetric equilibrium with no transmission constraints

Generation Unit	Unit Capacity	Maximum Production	Marginal Cost	Total Cost	Price Cap (€/Mwh)
Nr.	MWh	MWh	€/MWh	€	120
1	100	100	10	1.000	
2	150	250	30	5.500	Total Demand (MWh)
3	50	300	70	9.000	
4	100	400	105	19.500	380



Proposition 4 does not rule out the possibility of multiple equilibria. These arise when, in the comparison between two discontinuity points of the PSP function, the losses for the price setter due to a demand reduction ("jump") are totally offset by the gain deriving from an increase of the market clearing price. Whenever this happens the price-setter is indifferent among multiple allocations. The uniqueness of the solution will depend on the demand, the cost function and the capacity of the generating units. In Appendix 4 are derived a set of conditions (U.C.) that involves these three variables and guarantees the uniqueness of the equilibrium. For the rest of the paper it will be assumed that the equilibrium allocation is always unique[23].

Notice that Corollary 2 generates always an incentive for both player to act as a price-taker in equilibrium. This implies the existence of a mixed strategy equilibrium of the game, which is symmetric and requires player to choose the marginal cost pricing (or an outcome equivalent strategy) with some probability p and the allocation indentified by the previous mechanism with probability $(1-p)$. In other words, generators randomize between the price-taker and the price-setter role.

With regard to the social desirability of the equilibrium, the asymmetric allocation generates always higher costs with respect to the equal division of the total demand among the firms. Indeed, the economic "withholding" of some generating units by the price-setter entails the activation of more expensive (higher marginal cost) generating units of the price-taker. This is reported in the next proposition:

Proposition5 *The total welfare is maximized when the allocation is symmetric.*

Proof: See Appendix 2.

The higher the substitution of the cheaper power units of the price-setter with the most expensive units of the price-taker, the higher is the inefficiency related to the asymmetric equilibrium. This is the direct consequence of proposition 5:

[23]Notwithstanding, there is always a continuum of bidding strategies for both players that end up with the equilibrium allocation.

Corollary3: *The inefficiency of the equilibrium increases with the asymmetry of the final allocation.*

Proof: See Appendix 2.

Equilibrium Analysis when $0 < L < D$

When the transmission capacity is limited to $L < D$, $D + L$ is the maximum amount of power that a single generator can supply to the market. In this case each operator conserves in its area an irreducible residual demand that cannot be satisfied by the other firm. Whenever the line is congested, i.e. the amount of power flowing on the transmission line is given exactly by L, the zones separate and record different clearing prices, indicated by $p_1$for the zone $Z_1$and $p_2$for the zone Z_2. In particular the net import zone will have a higher clearing price than the net export zone. Contrarily, when the line is not congested there will be a single price in the market, indicated by p_C. For a given L and D define the following quantities:

Definition3 *Indicate with* $\overleftarrow{u} = \left\{ \min u : \sum_{u=1}^{\overleftarrow{u}} k_u \geq D - L \right\}$ *and* $\overrightarrow{u} = \left\{ \min u : \sum_{u=1}^{\overrightarrow{u}} k_u \geq D + L \right\}$ *the marginal units necessary to produce respectively the quantities of power* $D + L$ *and* $D - L$*.*

As the analysis will show, the role of the quantities in definition 3 will be the same as of $\underline{u}$ e $\overline{u}$ for the case $L \geq D$. However, differently from the previous section, $\overleftarrow{u}$ and $\overrightarrow{u}$ now defines respectively the minimal and the maximal units that a power generator can activate in the net importing and net exporting zone.

Consider now player 2 adopting a strategy which is outcome equivalent to the marginal cost pricing. In other words, assign to this player the role of "price-taker" as discussed in the previous section. It is straightforward to observe that, for this player, the optimal bidding strategy up to the unit $\overrightarrow{u}$ is similar to the strategy for the case of L unlimited discussed in the previous section. This similarity is revealed in the following proposition:

Proposition6 *Any strategies which is outcome equivalent to the marginal cost pricing for all $u < \overrightarrow{u}$ is part of a best response strategy of the player i in the case that $s_i \geq D \geq s_{-i}$.*

Proof: See Appendix 5.

For the case $0 < L < D$, proposition 6 plays the same role of proposition 2 for the first $\overrightarrow{u}$ units. Any attempt of player 1 to increase the (unique) market clearing price is optimally replied with a marginal pricing by the competitor. Coherently with Corollary1, the minimum amount that will be produced by player 2 in equilibrium will be given by D. The difference with respect to the previous case is that if player 1 attemps to increase the market clearing price above $c_{\overrightarrow{u}}$ the line becomes congested and its residual demand now shrinks to $(D - L)$. In other words, by increasing further the price above $c_{\overrightarrow{u}}$, firm 1 can accomodate the exportations of the other firm and still conserve a positive market share. This results in a final allocation that awards a quantity (D-L) to player 1 (with marginal unit $\overleftarrow{u}$) and (D+L) to player 2 (with marginal unit $\overrightarrow{u}$) and, since the two zones separate, in two clearing prices with $p_1 > p_2 \geq c_{\overrightarrow{u}}$.

At a first glance it seems natural to think that, whenever this strategy is profitable, player 1 would offer its marginal unit $\overleftarrow{u}$ and set the clearing price in its zone at the highest value admitted by the pool, i.e. $\overline{P}$ the price ceiling. However this does not represent an equilibrium of the game. The reason is that player 2 now has an incentive to keep the line congested and increasing the price on its marginal unit $\overrightarrow{u}$ slightly below the marginal bid of its competitor. In fact, suppose that firm 1 is playing with probability equals to 1 a strategy that would result in the price $\overline{P}$ in its zone. Than player 2 would stay better off by pricing all its units $u < \overrightarrow{u}$ at their marginal cost and setting the price in its zone with $\beta_2(\overrightarrow{u}) = \overline{P} - \varepsilon$ with ε small enough. But now firm 1 has, in turn, an incentive to reduce the price on its marginal unit to $\beta_1(\overleftarrow{u}) = \beta_2(\overrightarrow{u})$. Given the acceptence and priority rules adopted by the power exchange (see point b), this will result in an increase of the residual demand of firm

1 to some $s_1 > (D-L)$, a "decongestion" of the power line and the determination (again) of a unique market clearing price. Therefore it is clear that, on their marginal units, the two firms will start a 'Bertrand-like' competition with the intent of capturing a higher share of the demand. This leads to the conclusion that whenever a generator attempts to clear its zonal market with a price higher than $c_{\overrightarrow{u}}$, there does not exist a pure strategy equilibrium with increasing supply function.

Like in the previous section, proposition 6 can be used to derive the optimal problem for player 1:

$$\max_{\beta_1(u)} \Pi_1\left(\beta_1(u(s_1)), s_1(\beta_1(u), \beta_2(u)\right) =$$

$$\beta_1(u(s_1)s_1\left((\beta_1(u(s_1)), \beta_2(u)\right) - C\left(s_1(\beta_1(u), \beta_2(u)\right) \;\; (PSP-L)$$

$$s.t.$$

$$(i)\ \beta_1(u(s_1)) \leq \overline{P}$$

$$(ii)\ \beta_2(u) = c_u \quad \forall u < \overrightarrow{u}$$

In order to derive the optimal strategy for both players, notice that Proposition 3 still applies here up to the point where the price for the marginal unit of palyer 1 does not exceed $c_{\overrightarrow{u}}$. Up to this point the profit function in (PSP-L) has the same form of (PSP). Indeed it is continuous but in a finite number of points and is increasing over a fnite number of intervals. Moreover, *given* the strategy of player 2 for the first $\overrightarrow{u}-1$ units, the (PSP-L) admits always at least a solution if restricted to $p_L \leq c_{\overrightarrow{u}}$. Up to this point the equilibrium behaviour of generator 2 is known and the residual demand of 1 is uniquely determined by the price he requires for its marginal unit. Consider now the following definition:

Definition4 *Let $\langle p_z, s_1(p_z)\rangle$ be the allocation that maximizes $(PSP - L)$ s.t. (i) $\beta_1(u(s_1)) \leq c_{\overrightarrow{u}}$ and (ii) $\beta_2(u) = c_u \quad \forall u < \overrightarrow{u}$.*

Definition 4 identifies the highest profit achievable by player 1 in the situation where the probability of congestion is null (i.e. PSP-L is constrained to$\beta_1(u(s_1)) \leq c_{\overrightarrow{u}}$) and player 2 is playing its best response function. In this case the residual demand of player 1 amounts to some $s_1 > D - L$ and a single price p_z clear both zones. This profit defines a pay-off threshold[24] for player 1 (*"outside option"*) that determines the type of the equilibrium solution. In particular if, for player 1, an increase of the price of the marginal offer to some value above $c_{\overrightarrow{u}}$ is profitable, we will observe both players randomize with some probability distribution their pricing strategy for their marginal unit. As a consequence, the congestion of the power line and the separation of the two zones may emerge as the result of firms price randomization and, in particular, if the clearing price in net importing zone is strictly higher than the price in the net exporting zone. Conversely, if the attempt of increasing the price above $c_{\overrightarrow{u}}$ is never profitable for player 1, the final allocation of the game is a pure strategy Nash equilibrium with outcomes indicated in Definition 4. This is the statement of the next proposition:

Proposition7 *Suppose that $(U.C.)$ holds for (PSP). The equilibrium of the game is as follow:*

- *If $\Pi_1(\overline{P}, D - L) \leq \Pi_1(p_z, s_1(p_z))$ there exist a Nash pure strategy equilibrium of the game where the pay-off of player 1 is given by $\Pi_1(p_z, s_1(p_z))$ and that of player 2 is given instead by $\Pi_2(p_z, s_2(p_z))$. The price is unique and given by p_z and the line is never congested.*

- *If $\Pi_1(\overline{P}, D - L) > \Pi_1(p_z, s_1(p_z))$there does not exist a pure strategy equilibrium. The equilibrium of the game, if exists, is in mixed strategies where the expected pay-off of player 1 is given by some $A_1 > \Pi_1(p_z, s_1(p_z))$ and that of player 2 is $A_2 > \Pi_2(p_z, s_2(p_z))$. Whenever the price is unique it is at least equal to some $\underline{P} > p_z$ and the power line*

[24]Under the validity of (U.C.) conditions in Appendix 4, this threshold is uniquely defined.

is not congested, otherwise it must be that $p_1 > p_2 \geq \underline{P}$ and the power line is congested.

Proof: See Appendix 5.

Proposition 7 indicates how the equilibrium solution varies according to the parameters of the model. For instance, an increase of the price ceiling, as well as a reduction of the power transmission capacity, implies, ceteris paribus the other parameters, a higher likelihood of observing mixed strategies in equilibrium and market separations. Interestingly, the incentives to play asymmetric strategies is intrinsic into the model, while the capacity of the power line just affects their magnitude.

As already discussed in the previous section, the case of a limited transmission capacity can be "translated" in the case where the power line is unlimited but the level of demand implies the existence of a residual market share for the players[25]. In such situations, the higher the residual demand (the difference between total demand and the maximum capacity of the generator) the higher the likelihood of observing mixed strategies in equilibrium and higher mark-ups on the marginal units costs.

To conclude this section, it is important to note that the Proposition 5 and corollary 3 remain for the case just described. This implies that the profitability of strategies that may end up in an equilibrium with a congestion of the power line, generates, from a welfare point of view, higher level of inefficiency with respect to the optimal allocation under the constrained (PSP-L). The policy implications of the model are discussed deeper in the next section, while the equilibrium solutions and allocations of the game are derived in Appendix 6.

4.4 Policy Implications and Comparative Statics

This section discusses how the equilibrium allocation is affected by a change of the parameters of the model and the policy intervention aimed

[25]Consider the case where $D_T > K$ the total capacity of a generator.

at increasing the social welfare. In particular two parameters will be discussed in this section: the power line capacity (L) and the price ceiling ($\overline{P}$). These parameters are generally included in the set of instrument that can be directly used by policy makers for regulatory purpose. Indeed, the price ceiling is generally chosen to reflect the value of lost load (VOLL) for consumers in case of scarcity events[26]. Similarly the expansion of the power line capacity is normally included in the objectives of the TSOs and is finalized to increase the security of supply in different geographic zones.

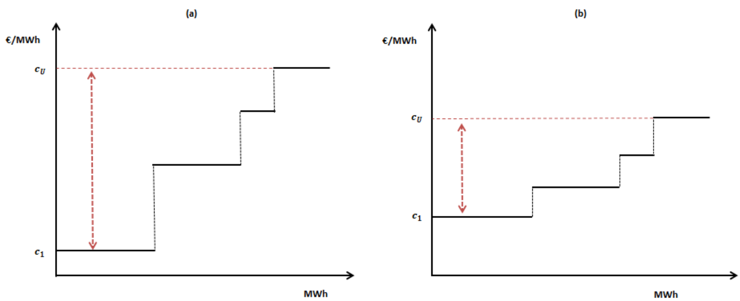
If, on the one hand, it seems normal to think investments in transmission capacity as always beneficial for total welfare, the model indicates that this may not be the case. Indeed by Corollary 3, we know that the social benefits are inversely related to the asymmetry of the equilibrium allocation. For this reason, the perfect monopoly case (L=0) implies always the highest social efficiency. This is due to the fact that both firms will always play symmetric strategies that result in a clearing price in each zone equals to the price ceiling: the symmetry is always guaranteed but the total surplus is entirely captured by the firms. Similarly, whenever the level of asymmetry reached by the equilibrium allocation when the line has unlimited capacity is higher that in a congestion case, having a reduced capacity in transmission may be socially preferred. The reason is that an unlimited transmission may allow for a higher variety of asymmetric equilibrium with some of those resulting in a firm producing a quantity less than $(D-L)$ - the minimum quantity in case of congestion - and the other firm $(D+L)$ - the maximum quantity under congestion. In these cases, having a limited capacity of transmission forces a generator to produce in its zone a higher quantity in equilibrium with a resulting reduction of the asymmetry.

In term of the model, this happens when $\Pi_1\left(p_z, s_1(p_z)\right)$ is different from the allocation that maximizes (PSP), since the latter must occur at some $s_1 \leq (D-L)$ and $s_2 \geq (D+L)$. Note that the condition $\Pi_1\left(\bar{P}, D-L\right) = \Pi_1\left(\underline{P}, s_1(c_{\overrightarrow{u}})\right)$ implies that as L increases $\underline{P}$, the lower bound of the price randomization support, is driven down. For policy

[26]Leading, for instance, to a disruption of the forniture to final consumers.

maker than there might be a trade-off between a reduction of the social welfare and the control of market power. Indeed if an increase of the capacity of the power line may, on one hand, coordinate firms on highly asymmetric equilibria, on the other hand, lower prices are included into the support of mixed strategies that may occur in equilibrium. These situations are more likely to occur the higher the price ceiling and the variance of firm's marginal costs (See Figure 18):

Figure 18: Asymmetric equilibrium is more likely in case *(a)* where the variance of firms marginal costs is higher



Contrarily, in the cases where the capacity of the transmission line just creates an artificial monopoly for one of the two firms, the development of additional transmission capacity improves the social welfare and reduces market power. This is true when $\Pi_1\left(p_z, s_1(p_z)\right)$coincides with the allocation that maximizes (PSP). To see these results, consider first that the equilibrium of the game generates, with some positive probability, a congestion of the power line whenever firms play mixed strategies. The condition under which the adoption of mixed strategies is profitable for both firm is indicated in proposition 7 by $\Pi_1(\overline{P}, D-L) > \Pi_1\left(p_z, s_1(p_z)\right)$. For a given D, this condition defines a threshold value $\underline{L}$ such that for any $L \geq \underline{L}$ any attempt to congest the power line is never profitable for the price setter. The value of $\underline{L}$ is the solution to the condition:

$$\underline{L} - \left(\frac{C(\underline{L})}{\overline{P}}\right) = D - \left(\frac{1}{\overline{\overline{P}}}\right)[p_z s_1(p_z) - C(s_1(p_z)) + C(D)]$$

and the additional investment from the current level of capacity is given by $L - \underline{L}$. When transmission capacity reaches $\underline{L}$ players have no more incentive to deviate (unilaterally) from the equilibrium allocation $\langle s_1^*(p_z^*); s_2^*(p_z^*), p_z^*\rangle$and additional investments do not have any impact on final outcomes. With $\underline{P}$ defined in proposition 7, the equilibrium prices as function of $\underline{L}$ can be here summarized:

$$(p_1, p_2) = \begin{cases} p_1 = p_2 = \overline{P} & L = 0 \\ \overline{P} \geq p_1 \geq p_2 \geq \underline{P} > p_z & L < \underline{L} \\ \underline{P} > p_1 = p_2 = p_z & L \geq \underline{L} \end{cases}$$

In terms of total welfare, by Corollary 3, the equilibrium $\langle s_1^*(p_z^*); s_2^*(p_z^*), p_z^*\rangle$ weakly dominates the result of the mixed strategies, since $s_1(p_z) \geq s_1(p_1)$ and $s_2(p_z) \leq s_2(p_2)$. When the transmission capacity reaches $\underline{L}$ thus the incentives for players to switch to mixed strategies are removed, the clearing price reduces and the total welfare is driven up.

Given the probability distribution of D, it is possible to define a capacity target for policy makers $L*$ given by the solution to the equation:

$$L^* - \left(\frac{C(L^*)}{\overline{P}}\right) = E(D) - \left(\frac{1}{\overline{\overline{P}}}\right)\{p_z s_1^*(p_z) - C(s_1^*(p_z)) + E[C(D)]\}$$

and the additional investment from the current level of capacity is given by $L - L^*$. The capacity target depends positively on the price cap and on the expected level of the demand. Consequently, policy makers may control market power and increase the social welfare by mixing additional investments in capacity with a reduction of the maximum price accepted by the power exchange.

4.5 Conclusion

This paper introduces a basic model to study firm strategic behaviors in a day-ahead market based on zonal pricing with grid transmission constraints. The results show that, in equilibrium, asymmetric strategies may be adopted by the firms even with an unlimited transmission capacity. The incentives to play asymmetrically induce the economic withholding of some power units with the intent of increasing the market clearing prices. From a social point of view asymmetric allocations are inefficient, since they impose the activation of more expensive generation units to cover total demand. A limited capacity of the power line on the one hand preserves the incentive to play asymmetric strategies and, on the other hand, increases the market power of the firms. The latter have an additional incentive given by the possibility to induce a congestion of the power line and further increase the price in their zone. However, in order to be marginal in its own zone, a firm must not mimic, with its marginal unit, the price strategy of its competitor and decongesting the power line. This results in firms playing asymmetric mixed strategies in equilibrium. In terms of social welfare, interventions aimed at increasing the capacity of the power line may lead to different conclusions according to the parameters that characterize the cost function of the firms. In particular, players may reach an equilibrium allocation which is more asymmetric when the transmission capacity is unlimited with respect to the case where transmission constraints are binding. The intuition is that a limited transmission capacity reduces the possibility of economic withholding of power units. In these situations, investing in transmission capacity may reduce market power but, at the same time, increase the inefficiency of the final allocation. Alternatively, when the constraints on the transmission capacity creates a mere monopolistic position on a residual demand, policy-makers may reduce market power and increase social welfare by intervening both on the transmission limits and regulating the maximum price accepted by the pool.

Well away from being exhaustive, the framework introduced in the previous sections offers a starting point for studying firms' strategies in the context of a multi-unit auction model. The paper can be enriched in several directions to take into account a number of complexities of the current electricity markets. Among these, the introduction of more players inside one or both zones, a more complex network configuration[27] or allowing for real-time uncertainty of the demand.

[27] Consider for instance 3 or more zones

4.6 Appendix Chapter 3

Appendix 1: The Economic Merit Order in the Day-Ahead Electricity Market

The day-ahead market is run by a Power Exchange through an auction mechanism. Generators submit a finite number of bids, each containing the minimum unit-price at which they are willing to sell power, and the maximum quantity offered at that price, for any relevant time of the next day[28]. The pool collects the bids and establishes a merit order based on the price-ascending ranking, constructing so an aggregate supply of electricity at any time interval.

On the other side of the market, purchasers submit a pair of numbers containing the maximum price they are willing to pay for power, and the maximum quantity they are willing to buy at that price. Analogously, the bids are collected in a price-descending order by the pool, and an aggregate demand is created. In each period, demand and supply determine the equilibrium quantity that will be dispatched and the generating units that will be called to operate, while the price paid to the generators instead will depend on the particular format adopted for the auction. A discriminatory or "pay-as-bid" auction results, in case of acceptance, in the supplier be paid the price he submitted for supply that amount of electricity. A uniform or SMP - system marginal pricing - auction will instead generate a unique price for all suppliers, given by the price submitted by the marginal (generating) unit accepted by the power exchange[29].

[28]It must be noted that there is no a standard organization of the market that remains valid worldwide. Every jurisdiction indeed, regulates the wholesale market in a different way. For instance, in the IPEX (the Italian Power Exchange) generators are allowed to bid up to four pairs price-quantity for each hour of the day and for each generating unit, while in the PJM the maximum number of pairs admitted is ten (per genset). Electricity auctions differ also in the duration of suppliers' bids. While in Australia and Argentina these remain valid for a given period of time during which demand changes ("long-lived" bids), in the case of the Italian, Spanish and Nordic markets, demand and supply are constructed by collecting the bids in any relevant period ("short-lived" bids), generally any 24 hours. A reader can find an overview of the different approaches commonly used in the electricity market in (31).

[29]The pay-as-bid format has been adopted in England and Wales since March 2001,

Appendix 2: Proofs for the case L>D

Proof of Proposition 1. Let $(\beta_i(u), \beta_{-i}(u))$ be a profile of strategies such that for player $i = 1$ $\beta_1(u) = b_u < c_u$ for some u's. Let the resulting allocation be $\mathcal{O}(\beta_1(u), \beta_2(u), D) = (s_1, s_2, p_{NC})$ where $p_{NC} = \max_i \beta(u(s_i))$. Now for player 1 any u's for which $b_u < c_u$ must be positioned in one of this two subsets:

1. If $u > u(s_1)$, the unit will not be called to dispatch power and will not affect the profit function of the firm. Consequently increasing the bid for this unit up to its marginal cost will not change the payoff.

2. If $u \leq u(s_1)$, this unit will be called to dispatch power. Let $\Pi_0(p_{NC}, s_1) = p_{NC}s_1 - C(s_1)$ be the profit of generator 1 under the strategy $\beta_1(u)$. Suppose now that player 1 were to switch to the strategy $\beta'_1(u) = c_u$ for all u's initially priced below the marginal cost and $\beta'_1(u) = \beta_1(u)$ for all other u's. Since generator 1 is increasing the price of some units and the bidding function is increasing for both players, than the new allocation will give an equilibrium price not lower than p_{NC}. So indicating the price under the new allocation with p'_{NC} we have that $p'_{NC} \geq p_{NC}$. Because of the price increase the quantity produced by generator 1 and 2 would become $s'_1 = s_1 - \triangle$ and $s'_2 = s_2 + \triangle$, with $\triangle \geq 0$. In particular, if $p_{NC} > c_{u(s_1)}$ (the cost of the marginal unit of generator 1) than all units that were initially priced lower than p_{NC} were already called to dispatch power at full capacity and adopting the marginal cost strategy would not change the previous final allocation, i.e $\triangle = 0$ and $p'_{NC} = p_{NC}$. If $p_{NC} \leq c_{u(s_1)}$ the new allocation may change the final quantities of the firms, given now by the pair $\left(s'_1, s'_2\right)$. In this case the new price would be bounded above by the unit cost of the marginal unit of player 1, that is it must be valid that $c_{u(s_1)} \geq p'_{NC} \geq p_{NC}$. The profit of generator 1 after the

while SMP is currently run, among the others, in Italy, Spain and New England (NEPOOL). A theoretical comparison, in terms of efficiency, between Pay-as-bid and SMP can be found in (32).

reallocation would be so given by $\Pi_1(p'_{NC}, s'_1) = p'_{NC}s'_1 - C(s'_1)$. The difference in payoffs under the two strategies is $\Pi_1 - \Pi_0 = s_1(p'_{NC} - p_{NC}) - p'_{NC}\triangle + (C(s_1) - C(s'_1))$. If $p_U \leq c_{u(D_1)}$ notice that, by construction of the cost function, and since under the new strategy all the units priced below p'_{NC} would always be called to dispatch at their full capacity, the following equality must hold $C(s_1) - C(s'_1) = c_{u(s_1)}\triangle$. So finally we have:

$$\Pi_1 - \Pi_0 = \underbrace{s_1(p'_{NC} - p_{NC})}_{\geq 0} + \underbrace{\triangle(c_{u(s_1)} - p'_{NC})}_{\geq 0} \geq 0$$

which leads to a contradiction. The first term is the gain due to the fact that the price under the new strategy is higher for all the units, while the second term is the gain due to the fact that the firm is no more selling some units at a price lower than the cost. ■

Proof of Proposition 2. Suppose not and let $(\beta_1(u), \beta_2(u))$ be a pair of strategies of the game, where player 2 is the price taker and $\beta_2(u) \neq c_u$ for some u. From Proposition 1, bidding some unit below the marginal cost is a weakly dominated strategy so it would never be played. If player 1 is the only price-setter it must be that $\max_i \beta(u(s_i)) = \beta_1(u(s_1))$. So consider first the case where $\beta_1(u) > c_u$ for some u's. Under this strategies profile the pay-off of player 2 is given by $\Pi_0(\beta_1(u(s_1), s_2)$. Now suppose that for player 2 there is a u such that $\beta_1(u(s_1)) > \beta_2(u) > c_u$, thus in this case pricing u to its marginal cost would not change the equilibrium price and allocations. Suppose now that $\beta_2(u) > \beta_1(u(s_1)) > c_u$ for some u's and let $\widetilde{u}$ be the first among these $u's$. In this case let player 2 playing a strategy $\beta'_2(u)$ where $\beta'_2(\widetilde{u}) = c_{\widetilde{u}}$. Notice that in this case the demand of player 1 must reduce to some $s'_1 < s_1$. Since player 1 is the price setter than in equilibrium it must still be $\beta_1(u(s'_1) = \beta_2\left(u\left(s_1\right)\right) = p_{NC}$. Given that the units priced below this equilibrium price will be accepted, with the new strategy the quantity produced by player 2 increases to $s'_2 = \sum_{u=1}^{\widetilde{u}} k_u$. The payoff of player 2 with the new strategy is given by $\Pi_1(p_{NC}, s'_2)$. So finally we have

$$\Pi_1 - \Pi_0 = \beta_1(u(s_1))[s_2^{'} - s_2] - (C(s_2^{'}) - C(s_2)) > 0$$

since by construction of the cost function $c(s_2^{'}) = c_{\widetilde{u}}$, $c_{\widetilde{u}}(s_2^{'} - s_2) \geq (C(s_2^{'}) - C(s_2))$ and $p_{NC} > c_{\widetilde{u}}$.■

Proof of Corollary 1. From proposition 2 the price-taker will play a strategy which is outcome equivalent to the marginal cost pricing and from proposition 1 the price-setter will never bid its units below their marginal cost. By playing the marginal cost stategy (or an outcome equivalent strategy), the price-setter will be sure to dispatch a quantity equals to D. If the price-setter increases the prices of some units its reasidual demand falls to $s_1 \leq D$. Finally, the market clearing condition $D_T = s_1 + s_2$ implies that $s_2 \geq D$.■

Proof of Proposition 3. For the existence of the solution notice tha p_N varies over $\left[0, \bar{P}\right]$ and than the profit function varies over a compact space. Now notice that the profit function is always continuous with respect to the clearing price but in a finite number of points, that is, it is continuous on intervals. Moreover in any interval the function is strictly increasing with respect to the clearing price. To see this, let p_{NC} and $p_{NC}^{'}$be the result of two different allocations with $p_{NC}^{'} = p_{NC} + \varepsilon$, with $\varepsilon \to 0$. The profit of the price setter will be $\Pi\left(p_{NC}^{'}, s_1(p_{NC}^{'})\right) > \Pi\left(p_{NC}, s_1(p_{NC})\right)$ as long as $s_1(p_{NC}) = s_1(p_{NC}^{'})$ and continuosly increasing the clearing price the price-setter can assure itself a higher profit up to the point where his demand reduces. Now let p_{NC} be a price such that there is a jump in the demand to $s_1(p_{NC}) > s_1(p_{NC}^{'})$, than for ε small enough $\lim_{p_{NC^+}} \Pi(p_{NC}, s_1(p_{NC})) \neq \lim_{p_{NC^-}} \Pi(p_{NC}, s_1(p_{NC}))$ and p_{NC} is a discontinuity point. So in any discontinuity point but the last, where $s_1(p_{NC}) = 0$, the profit function *jumps* and increases continuously up to a new point where the residual demand of the price setter reduces and that of the price-taker increases. As long as U is finite, the number of discontinuity point is also finite. Moreover since the function is increasing on any continuos interval, the discontinuity point must be the maximizer over that interval. Let $\overline{\Pi}_1 = \Pi_1 (p*, s_1(p*))$ be the highets profit computed among all the possible discontinuity points, thus any strategy which results in a clearing price $\beta_1 (u (s_1)) = p*$ represent a solution of the (PSP). ■

Proof of Proposition 4 By Proposition 2 the price-taker will play a strategy which is outcome equivalent to the marginal cost pricing, so consider that $\beta_2(u) = c_u \forall u \in \mathscr{U}$. This implies that the profit function in (PSP) is characterized by U discontinuity points, each corresponding to a market clearing price $p_{NC} = c_u$. By proposition 3 the maximum of the (PSP) must be evaluated among the U discontinuity points. Note that any allocation resulting in a price $p_{NC} < c_{\underline{u}}$is not optimal. To see this, suppose that this is the case and so it must be that $\beta_1(u(s_1)) = p_{NC} < c_{\underline{u}}$, and necessarily $s_1 > D > s_2$. By Corollary 1 this allocation cannot result to be an equilibrium since generator 1 is pricing some units below their marginal cost and $u(s_1) \geq \underline{u}$ implies that on the marginal unit the price-setter is making losses. So in equilibrium it must be that $p_{NC} \geq c_{\underline{u}}$ and $s_2 \geq D \geq s_1$. It is straightforward to see that $p_{NC} > c_{\overline{u}}$ cannot be an equilibrium neither. Indeed under the assumption $D_T < K$ there must be so a unit $\bar{u}$ with which each generator is able to satisfy all the market demand. For the price-setter pricing some unit above $c_{\overline{u}}$ would just imply a reduction of his demand without resulting in a higher clearing-price, since its marginal unit would be some $u \leq \overline{u}$. To see this, let $\beta_1(u)$, $\beta_2^*(u)$ an allocation such that $\beta_1(u(s_1)) = c_{\overline{u}}$ and the demand of 1 is $s_1(c_{\overline{u}})$. The profit of 1 than is given by $\Pi (c_{\overline{u}}, s_1(c_{\overline{u}}))$. Let now generator 1 to increase the price on the marginal unit to $p' = c_{\overline{u}} + \varepsilon$. The new marginal unit that clears the market so would be some $\widetilde{u} \leq \overline{u}$ and the resulting price is some $p_{NC} \leq c_{\bar{u}}$. The demand of player 1 shrinks to some $s_1 < D(c_{\overline{u}})$ since he is loosing a potential production on the marginal unit, and clearly $\Pi (c_{\overline{u}}, s_1(c_{\overline{u}})) > \Pi \left(p^{'}, s_1(p^{'})\right)$. So the equilibrium strategies must maximize the profit function of 1 in (PSP) in some discontinuity points where the clearing price assumes value $p_{NC} \in \left[c_{\underline{u}}, c_{\overline{u}}\right]$ (See Figure 19) ■

Figure 19: Graphical representation of the PSP function

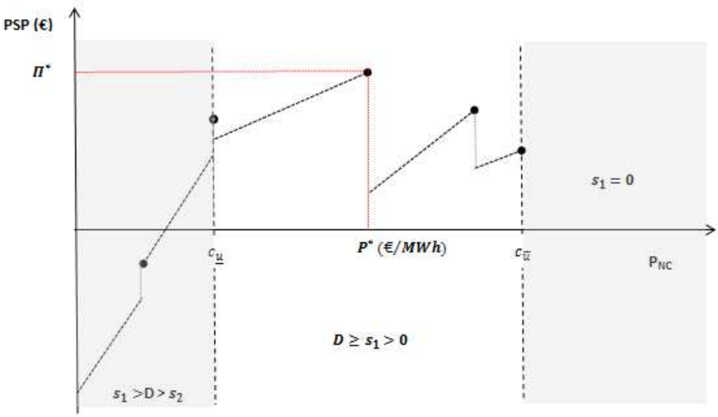


Figure 19 shows a graphical representation of the PSP function. As one can observe, any allocation resulting in a price $p^* < c_{\underline{u}}$ is not optimal since, at the margin, player 1 is bearing losses. Conversely, any allocation resulting in a market clearing price higher than $c_{\overline{u}}$ leads to zero the residual demand of player 1. When the price is equal to $c_{\underline{u}}$ BR3 applies and players equally share the total market demand. For the range of prices included in the set $\left[c_{\underline{u}}, c_{\overline{u}}\right]$, the solution of the PSP must be find among the discontinuity points, in the upper bounds of the intervals. Contrarily to the locus where $s_1 > D$, in this range the PSP jumps to a lower value after an infinitesimal increase of the price in correspondence of a discontinuity point.

Proof of Proposition 5 The welfare function is given by $W = (\overline{P} - p_{NC})D_T + p_{NC}s_1 + p_{NC}s_2 - (C(s_1) + C(s_2))$. Employing the clearing condition, the maximization problem with respect to p_{NC} can be written as

$$\max_{p_{NC}} W = \overline{P}D_T - \left[C\left(s_1(p_{NC})\right) + C\left(D_T - s_1(p_{NC})\right)\right]$$

The F.O.C defines the condition $C'(s_1(pz)) = C'\left(D_T - s_1(p_z)\right)$which is verified when the marginal unit is the same. ∎

Proof of Corollary 3 Let s_1 and s_2 be an allocation of the game. The welfare distortion from the optimal allocation is given by $C(s_1)+C(s_2)-2C(D)$. From the clearing condition the allocation can be rewritten as

$$C(s_1) + C(D_T - s_1) - 2C(D) \geq 0$$

with a maximum equal to $C(D)$ when $s_1 = 0$ and $s_2 = D_T$ (or viceversa). ■

Appendix 3: The "Scan" Algorithm for the Equilibrium Detection.

The pseudo algorithm is constructed as:

- For the price-taker let $\beta_2(u) = c_u \ \forall u \in \mathscr{U}$.
- For the price setter, follow these steps:
  1. Let $\beta_1(u) = \begin{cases} c_{\underline{u}} & \forall u \leq \underline{u} \\ c_u & \forall u > \underline{u} \end{cases}$
     In this case the allocation for both player is the same and is given by the pair$\langle c_{\underline{u}}, D \rangle$. The marginal unit is $u(s_1) = u(s_2) = u(D) = \underline{u}$ and $p_{NC} = c_{\underline{u}}$.
  2. Increase the prices of all units below $\underline{u}$ up to the unit cost of the next to the marginal unit of player 2. That is play:
     $\beta_1(u) = \begin{cases} c_{\underline{u}+1} & \forall u \leq \underline{u}+1 \\ c_u & \forall u > \underline{u}+1 \end{cases}$
     In this case the demand of player 1 reduces while the demand of the price-taker increases with respect to the previous step, that is $s_1 < D < s_2$. Consequently the marginal units are ranked $u(s_1) \leq \underline{u} \leq u(s_2)$. Business Rule b) ensures that player 1 is the price setter and the clearing price is $\beta_1(u(s_1)) = c_{(\underline{u}+1)}$. Record the new allocation pair of player 1with $\langle c_{(\underline{u}+1)}, s_1 \rangle$.
  3. For any $c_{(\underline{u}+j)}$ such that $c_{(\underline{u}+1)} < c_{(\underline{u}+j)} \leq c_{\bar{u}}$ repeat Step 2 and increase the price of all units up to the $(\underline{u}+j)$ unit:

$$\beta_1(u) = \begin{cases} c_{\underline{u}+j} & \forall u \leq \underline{u}+j \\ c_u & \forall u > \underline{u}+j \end{cases}$$

In any of these steps the demand of player 1 shrinks in behalf of player 2. Any allocation so results in $s_1 < D < s_2$ and $u(s_1) < \underline{u} < u(s_2)$ and a clearing price given by $\beta_1(u(s_1)) = c_{(\underline{u}+j)}$. Record the new allocations $\left\langle c_{(\underline{u}+j)}, s_1 \right\rangle \forall c_{(\underline{u}+j)}$

4. Any further increase that occur beyond $c_{\bar{u}}$ would result in $s_1 = 0$ and a profit null for player 1. Evaluate the profit function $\Pi(p_{NC}, s_1)$ in all the allocations previously recorded and find the maximum (or maxima if the allocation is not unique).

The pair of bidding functions (β_1^*, β_1^*):

$$\beta_1^*(u) = c_u \forall u$$

$$\beta_1^*(u) = \begin{cases} c_{\underline{u}+j} & \forall u \leq \underline{u}+j \\ c_u & \forall u > \underline{u}+j \end{cases} \; for\, some\, j \in \{0, ..., [\overline{u} - \underline{u}]\}$$

represents a Nash pure strategy equilibrium of the game.

Appendix 4: Conditions for the uniqueness of the equilibrium allocation.

This Appendix discusses the conditions that guarantee the uniqueness of the equilibrium solution. First note that any final allocation requires a different set of operating units called to dispatch power, each of them characterized by specific parameters (capacity and size). Since the model impose no restrictions on the number and/or the technical characteristics of the units, a general condition for the uniqueness of the solution cannot be derived. Therefore, what is here proposed is a condition that must be valid in any pairwise comparison of the discontinuity points in the domain of the (PSP) function. Notice that, given the best response strategy of player 2, the discontinuity points coincide with the number of steps characterizing the cost curve of the firms. In particular, proposition 4 restricts the comparison to a number of $(\overline{u} - \underline{u})$discontinuity points, among which the (PSP) reaches its maximum.

Consider than two different allocations given by (p_a, s_a) and (p_b, s_b) where $p_b > p_a$ and $s_b < s_a$ and let the profit of player 1 be given by $\Pi(p_a, s_a)$ and $\Pi(p_b, s_b)$. The difference between the latter produces:

$$\Pi(p_a, s_a) - \Pi(p_b, s_b) = c_a s_a - c_b s_b - [C(s_a) - C(s_b)]$$

where c_a and c_b are the marginal costs of some units a and b with $b > a$ since $p_b > p_a$. Given the strategy of the price taker, the residual demands of the price setter can be written as $s_a = D_T - \sum_{u=1}^{a-1} k_u$ and $s_b = D_T - \sum_{u=1}^{b-1} k_u$ and by construction of the cost function $[C(s_a) - C(s_b)] = \sum_{u=a}^{b-1} c_u k_u$. The uniqueness of the equilibrium solution is than provided by the condition:

$$D_T \neq \frac{\left(c_b \sum_{u=1}^{b-1} k_u - c_a \sum_{u=1}^{a-1}\right) - \sum_{u=a}^{b-1} c_u k_u}{c_b - c_a} \quad (U.C.)$$

which must hold in any pairwise comparison of the units included in the interval $(\overline{u} - \underline{u})$.

Appendix 5: Proofs for the case 0<L<D

Proof of Proposition 6. Suppose not and let $(\beta_1(u), \beta_2(u))$ be a couple of strategies resulting in a final allocation where player 2 has a residual demand given by $s_2 \geq D \geq s_1$. By Proposition 1 both players will never price their units lower than the marginal cost and than $\beta_2(u) \geq c_u$ for all $u's$. Notice that if the line is congested, there will be two prices in equilibrium and the price in zone 2 is given by $p_2 = \beta_2(\overrightarrow{u})$. In this case, since the supply functions are increasing, all units below $\overrightarrow{u}$ will be called to dispatch power and so bidding all of them at their marginal cost has no impact on profits.

In the case where there is a single market price the unit $\overrightarrow{u}$ of player 2 will not be called to dispatch power. Suppose, in this case, that the clearing price is given by $\beta_2(u(s_2)) = p_C \neq \beta_1(u(s_1))$ for some $u(s_2) < \overrightarrow{u}$ and let $p_L > c_{u(s_2)}$. Notice that if player 2 is the only price setter than $u(s_1) \neq u(s_2)$ and necessarily the only possible allocation implies $s_2 > D > s_1$ and $u(s_2) > u(s_1)$. Therefore $p_C > c_u$ for all $u \in [1, u(s_2)]$ and so player 1 by deviating to

$$\beta_1^{'}(u) = \begin{cases} \beta_1(u) & \forall u \leq u(s_1) \\ \max\{p_C, c_u\} & u > u(s_1) \end{cases}$$

will increase its pay-off (and reducing that of player 2) since he increases his residual demand without reducing the equilibrium price. But this strategy is always feasible for player1 as long as $p_L > c_{u(s_2)}$, which leads to a contradiction for $\beta_2(u)$ as a best response strategy of player 2.

Finally, consider the case$\beta_1(u(s_1)) = p_C$[30]. Now for player 2 those u's which are priced above their marginal cost, and have been accepted to dispatch power under this equilibrium price, will continue to dispatch power also if the price bid for them reduces to the marginal cost. In this case lowering the bidding price does not change the final allocation. On the contrary suppose that there are some units priced above the marginal costs that are initially not called to dispatch. In the case $\beta_2(u) > \beta_1(u(s_1)) > c_u$ for some u's consider the following deviation for player 2:

$$\beta_2^{'}(u) = \begin{cases} \beta_2(u) & \forall u \leq u(s_2) \\ \max\{p_L - \varepsilon, c_u\} & u > u(s_2) \end{cases}$$

For ε small enough, the pay-off of player 2 under this new srategies is never lower than under the strategy $\beta_2(u)$ since with some positive probability player 2 is going to increase its residual demand, which leads to a contradiction for $\beta_2(u)$ as a best response strategy of player 2. ■

Proof of Proposition 7. Consider the following cases:

Case 1: $\Pi_1(\overline{P}, D - L) \leq \Pi_1\left(p_z, s_1(p_z)\right)$

Suppose player 1 wants to increase the clearing price in its zone by offering its marginal unit at a price higher than $c_{\overrightarrow{u}}$. Depending on the

[30]This does not exclude the case $\beta_1(u(s_1)) = \beta_2(u(s_2)) = p_C$

behavior of player 2 two possible allocations for player 1 may occur: (1) the residual demand of player 1 shrinks to $s_1 = (D - L) > s_1(p_z)$ and $\beta_1(\overleftarrow{u}){>}\beta_2(\overrightarrow{u})$ resulting than in a congestion of the power line or (2) the demand of player is $s_1(p = c_{\overrightarrow{u}})$ and $\beta_1(\overleftarrow{u}) \leq \beta_2(\overrightarrow{u})$. In the former allocation, the highest profit achievable by player 1 is given by $\Pi_1(\overline{P}, D - L)$ with a bid for the marginal unit $\overleftarrow{u}$ $\beta(\overleftarrow{u}) = \overline{P} = p_1$(price in zone 1). Given the initial condition, a deviation that concludes in this allocation is never preferable than the allocation $\Pi_1\left(p_z, s_1(p_z)\right)$. Indeed even if $\Pi_1(\overline{P}, D - L)$=$\Pi_1\left(p_z, s_1(p_z)\right)$ the outcome $\left\langle\overline{P}, D - L\right\rangle$ for player 1 cannot be part of an equilibrium since player 2 has an incentive to cut its rival price. To see this notice that since $s_1(p_z) \geq s_1(c_{\overrightarrow{u}})$ (the residual demand of player 1 when the price is equal $c_{\overrightarrow{u}}$) and since $\Pi_1(\overline{P}, s_1(c_{\overrightarrow{u}})) > \Pi_1(\overline{P}, D - L)$ than there exists a P_0 with $\overline{P} > P_0 > c_{\overrightarrow{u}}$ such that $\Pi_1\left(P_0, s_1(c_{\overrightarrow{u}})\right) = \Pi_1\left(p_z, s_1(p_z)\right)$. Therefore by lowering the marginal unit offer below P_0 player 2 can still get a profit higher than $\Pi_2\left(c_{\overrightarrow{u},}, s_2(c_{\overrightarrow{u}})\right)$, but player 1 now has an incentive to play again a strategy resulting in the allocation $\langle p_z, s_1(p_z)\rangle$.

In the second allocation, the highest profit reachable by player 1 is $\Pi_1\left(\overline{P}, s_1(c_{\overrightarrow{u}})\right)$ with no congestion and a single market price given by $p_C = \overline{P}$. Note that even if this profit is higher than $\Pi_1\left(p_z, s_1(p_z)\right)$the strategy $\beta_1(\overleftarrow{u}) = \beta_2(\overrightarrow{u}) > c_{\overrightarrow{u}}$ can never turns out to be part of a pure strategy equilibrium of the game. Indeed, player 2 has an incentive to reduce slightly the price below $\beta_1(\overleftarrow{u})$ and supply a residual demand $(D + L) > s_2(c_{\overrightarrow{u}})$, that result in a profit $\Pi_2\left(\beta_1(\overleftarrow{u}) - \varepsilon, D + L\right) > \Pi_2\left(\beta_1(\overleftarrow{u}), c_{\overrightarrow{u}}\right)$ with ε small enough. Such a deviation is profitable for firm 2 as long as $\beta_1(\overleftarrow{u}) > c_{\overrightarrow{u}}$. The result is that no pure strategy equilibria exist with a market clearing price in one or both zones higher than $c_{\overrightarrow{u}}$. Therefore, the only pure strategy equilibrium of the game ends with a line never congested and a market clearing price at most $c_{\overrightarrow{u}}$. Under the assumption of the validity of *U.C.* condition, the equilibrium allocation is unique and given by $\langle s_1^*(p_z^*); s_2^*(p_z^*); p_z^*\rangle$in definition 4.

Case 2: $\Pi_1(\overline{P}, D-L) > \Pi_1\left(p_z, s_1(p_z)\right)$

First notice that in this situation no pure strategy equilibrium exists. In fact suppose player 1 wants to increase the clearing price in its zone by offering its marginal unit at a price higher than $c_{\overrightarrow{u}}$. In this case, the highest profit achievable by player 1 is given by $\Pi_1(\overline{P}, D-L)$ if $\beta_1(\overleftarrow{u}) = \overline{P}(=p_1) > \beta_2(\overrightarrow{u})(=p_2)$ and the zone separates or alternatively, since $s_1(c_{\overrightarrow{u}}) > (D-L)$, $\Pi_1\left(\overline{P}, s_1(c_{\overrightarrow{u}})\right) > \Pi_1(\overline{P}, D-L)$ if $\beta_1(\overleftarrow{u}) = \beta_2(\overrightarrow{u}) = \overline{P} = p_C$. Therefore, given the initial condition, a deviation to a strategy that prices the marginal unit at the price ceiling is always profitable for player1 and, moreover, the optimal response stated in proposition 6 shows that any attempts of player 1 to increase the price above $c_{\overrightarrow{u}}$ increase also the profit for player 2, that is $\Pi_2\left(a, s_2(a)\right) > \Pi_2\left(p_z, s_2(p_z)\right)$ for any $a > p_z$ since $s_2(a) \geq s_2(p_z)$. However, any strategy that asks player 1 and player 2 to offer the price of their marginal unit at $\overline{P}$ with probability 1 cannot be part of an equilibrium allocation. In fact both players have always an incentive to cut (or, for player 1, to equalize) rival's price to increase the market share. To see this, let the marginal units of 1 and 2 offered at $\beta_1 = \beta_1 = \overline{P}$. The outcome function of the power exchange assigns $s_1(c_{\overrightarrow{u}})$ to player 1, $s_2(c_{\overrightarrow{u}})$ to player 2 and clear the market with the unique equilibrium price $\overline{P}$. Now player 2 has an incentive to set $\beta_2 = \beta_1 - \varepsilon$ to increase its market share to $(D+L)$ and, consequently, congesting the line. In turn, now player 1 has an incentive to offer its marginal unit at the same price of player 2 and decongesting the line (remember priority rule 3 of the Power Exchange). This deviation is profitable for player 2 as long as the market clearing price $p_C$is higher than $c_{\overrightarrow{u}}$. But at this last price $\Pi_1\left(c_{\overrightarrow{u}}, s_1(c_{\overrightarrow{u}})\right) \leq \Pi_1\left(p_z, s_1(p_z)\right)$ and firm 1 has an incentive to price again its last unit at the price ceiling. The result is that no pure strategy equilibrium exists for this case.

Second, if a mixed strategy equilibrium exists, this gives an expected pay-off to player 1 equals to $A_1 > \Pi_1\left(p_z, s_1(p_z)\right)$ and to player 2 equals to $A_2 > \Pi_1\left(p_z, s_2(p_z)\right)$. To see this notice that player 1 can assure itself a profit at least equals to $\Pi_1(\overline{P}, D-L)$ by pricing its marginal unit at $\overline{P}$ with probability equals to 1. The same profit is achievable by player 1 with a price $\underline{P} < \overline{P}$ in the event that $\beta_1(u^{'}) = \underline{P} \leq \beta_2(u^{''})$, where $u^{'}$ and $u^{''}$ are the marginal units of players 1 and 2, and the line is never congested. In particular defines $\underline{P}$ the price such that $\Pi_1(\overline{P}, D - L) = \Pi_1\left(\underline{P}, s_1(c_{\overrightarrow{u}})\right)$. By elimination of dominated strategy player 1 is never going to price its marginal unit at a price lower that $\underline{P}$. Moreover notice that the allocation $s_1(p_z) \geq s_1(c_{\overrightarrow{u}})$ implies that $\Pi_1\left(\overline{P}, D - L\right) = \Pi\left(P_0, s_1(p_z)\right)$ for a $(c_{\overrightarrow{u}} \leq)\, P_0 < \underline{P}$. The result is that any strategy that asks to player 1 to assign randomly a price to its marginal unit included in the interval $\left[\underline{P}, \overline{P}\right]$ gives it an expected payoff higher than $\Pi_1\left(p_z, s_1(p_z)\right)$. Equally, player 2 cannot gain from a randomization of its marginal offer at a value lower than $\underline{P}$. Therefore any strategy that asks to player 2 to assign randomly a price to its marginal unit included in the interval$\left[\underline{P}, \overline{P}\right]$ gives it an expected pay-off higher than $\Pi_2\left(p_z, s_2(p_z)\right)$. Finally the result of the randomization implies one of the following situations: if $\beta_1(u^{'}) > \beta_2(u^{''})$ the final allocation ends up with a congestion of the power lines and zonal prices $p_1 > p_2 \geq \underline{P}$, otherwise, if $\beta_1(u^{'}) \leq \beta_2(u^{''})$ the line will not be congested and the unique price is some $p_C \geq \underline{P}$.$\blacksquare$

Appendix 6: Equilibrium Strategies and Allocations for the case 0<L<D

In this Appendix the equilibrium solution and allocations of the game are derived. Coherently with the characterization indicated in Proposition 7, the solutions are reported for the two cases:

Case 1: $\Pi_1(\overline{P}, D - L) \leq \Pi_1\left(p_z, s_1(p_z)\right)$

In this situation it is never optimal for generator 1 to increase the price on its marginal unit beyond $c_{\overrightarrow{u}}$.The application of the Algorithm proposed in Appendix 3 shows that the best allocation for 1 is indicated by the couple $(p_z, s_1(p_z))$ with $p_z = c_u$ for some (given proposition 6) $u \in [\underline{u}, \overrightarrow{u}]$. Any outcome equivalent strategy which result in this allocation is an equilibrium strategy for player 1. On the other hand, for player 2 any strategy which constraints the first $(\overrightarrow{u} - 1)$ units to the marginal cost represents part of an equilibrium strategy. The unit $\overrightarrow{u}$ of generator

2 must be priced in order to eliminate the incentive of player 1 to deviate from his strategy. In fact if generator 2 sets a price for its marginal unit $\overrightarrow{u}$ too high, generator 1 may find profitable to price its last unit the same of its competitor. In this case, the demand of generator 1 would be given by $s_1(c_{\overrightarrow{u}})$, the line will not be congested and the unique clearing price in both zone would be higher than $c_{\overrightarrow{u}}$. So let $P_0 \in \left[c_{\overrightarrow{u}}, \overline{P}\right]$be a price, if exists, such that $\Pi_1(P_0, s_1(c_{\overrightarrow{u}})) = \Pi_1\left(p_z, s_1(p_z)\right)$ and consider the following strategies:

For generator $i = 1$ let

$$\beta_1^*(u) = \begin{cases} p_z & \forall u \leq \overrightarrow{u} \\ c_u & \forall u > \overrightarrow{u} \end{cases}$$

For generator 2 let

$$\beta_2^*(u) = \begin{cases} c_u & \forall u < \overrightarrow{u} \\ \in [c_u, P_0] & u = \overrightarrow{u} \\ \overline{P} & \forall u > \overrightarrow{u} \end{cases}$$

if P_0 exists, otherwise

$$\beta_2^*(u) = c_u \, \forall u$$

It is easy to check that these strategies represent a couple of pure strategy Nash equilibrium of the game, and the final allocation is unique when (U.C.) holds. It is important to remind that there is also a mixed strategy symmetric equilibrium of the game where both players randomize between $\beta_1^*(u)$ with probability p and $\beta_2^*$with probability $(1 - p)$.

The only equilibrium allocation results in no congestion on the grid and equilibrium quantities and price given by $\mathcal{O}(\beta_1^*(u), \beta_2^*(u), D_t) = \{s_1^*(p_z^*); s_2^*(p_z^*); p_z^*\}$.

Case 2: $\Pi_1(\overline{P}, D - L) > \Pi_1\left(p_z, s_1(p_z)\right)$

From Proposition 7 there does not exist a pure strategy Nash equilibrium of the game and the equilibrium, if exists, must be found in mized strategy. The first step is the determination of the equillibrium strategy for the marginal units of the two players.

Consider first the equilibrium condition for player 2, and let $\underline{P}$ be the price such that $\Pi_1 \left(\underline{P}, s_1(c_{\overrightarrow{u}})\right) = \Pi_1 \left(\overline{P}, D - L\right)$. This value is given by

$$\underline{P} = \frac{\overline{P}(D-L) + [C(\bar{s_1}) - C(D-L)]}{\bar{s_1}}.$$

where $\bar{s_1} \equiv s_1(c_{\overrightarrow{u}})$. From proposition 7,$\underline{P}$ represents the lower bound of the randomization support for the two players. Player 2 will than randomize the marginal price of its unit on $\left[\underline{P}, \overline{P}\right]$in order to make player 1 indifferent between any pure marginal price strategy in the support. The condition for player 2's mixed strategy is obtained from the expected pay-off of player 1:

$$\underbrace{\Pr\left[p_2 < p\right]\left[p(D-L) - C(D-L)\right]}_{Congestion} + \underbrace{\Pr[p_2 \geq p]\left[p\bar{s_1} - C\left(\bar{s_1}\right)\right]}_{NoCongestion}$$

Again, from proposition 7, the expected pay-off of player 1 must be equal to some $A_1 > \Pi_1\left(p_z, s_1(p_z)\right)$which gives the condition for player 2:

$$F_2(p)\left[p(D-L) - C(D-L)\right] + (1 - F_2(p))\left[pD_1 - C(\bar{s_1})\right] = A_1$$

and, after some rearrangement, to the probabilistic distribution:

$$F_2(p) = \frac{A_1 - [p\bar{s_1} - C(\bar{s_1})]}{p[(D-L) - \bar{s_1}] + [C(\bar{s_1}) - C(D-L)]} \quad with\ \ p \in [\underline{P}, \overline{P}]$$

Now it must be that $F_2^*(\overline{P}) = 1$, which implies that $A_1 = \overline{P}(D-L) - C(D-L)$. The distribution $F_2(p)$ can than be rewritten as:

$$F_2(p) = \frac{\overline{P}(D-L) - p\bar{s_1} + [C(\bar{s_1}) - C(D-L)]}{p\left[(D-L) - \bar{s_1}\right] + [C(\bar{s_1}) - C(D-L)]}\ with\, p \in [\underline{P}, \overline{P}] \quad (PD.2)$$

In order to generate an equilibrium, it must be verified that

$$f_2(p)=\frac{\left[\overline{P}\left(\bar{s_1}-(D-L)\right)-\left[C\left(\bar{s_1}\right)-C\left(D-L\right)\right]\right]}{\left[p\left[(D-L)-\bar{s_1}\right]+\left[C\left(\bar{s_1}\right)-C\left(D-L\right)\right]\right]^2}\geq 0$$

for any $p\in\left[\underline{P},\overline{P}\right]$ which happens when

$$\overline{P}\geq\frac{C\left(\bar{s_1}\right)-C\left(D-L\right)}{\bar{s_1}-(D-L)}\ (T.C.-1)$$

At the limit

$$F_2(\underline{P})=0\quad as\quad \underline{P}=\tfrac{\overline{P}(D-L)+\left[C(\bar{s_1})-C(D-L)\right]}{\bar{s_1}}.$$

consistently with the lower boundary of the randomization support. Consider now the equilibrium condition for player 1. The latter will randomize in order to let player 2 indifferent between any strategy $\beta_u(c_{\overrightarrow{u}})$ included in the support $\left[\underline{P},\overline{P}\right]$. By proposition 7, the play-off of player 2 resulting from any pure strategy must be equal to some $A_2>\Pi_2\left(p_z,s_2(p_z)\right)$, providing a condition for player 1:

$$\underbrace{\Pr\left[p_1>p\right]\left[p(D+L)-C(D+L)\right]}_{Congestion}+$$

$$+\underbrace{\Pr[p_1\leq p]\left[E(p_1|p_1\leq p)\left(\bar{s_2}\right)-C\left(\bar{s_2}\right)\right]}_{NoCongestion}$$

where $\sum\limits_{u=1}^{\overrightarrow{u}-1}k_u=D_T-\bar{s_1}\equiv\overline{s_2}$ is the residual demand of generator 2 in the case the line is not congested and player 1 offer its last unit at a price lower than the marginal unit of player 2. The condition for player 1 is than given by:

$$\left[1-F_1(p)\right]\left[p(D+L)-C(D+L)\right]+F_1(p)\left[E(p_1|p_1\leq p)\bar{s_2}-C\left(\bar{s_2}\right)\right]=A_2$$

that deriving for p can be written as

$$f_1(p)=\frac{\left[1-F_1(p)\right](D+L)}{p\left[(D+L)-\bar{s_2}\right]-\left[C(D+L)-C(\bar{s_2})\right]}$$

This differential equation can be solved by using a separation of variables. Call $F_1(p) = y$ and $f_1(p) = \frac{dy}{dp}$. The above equation can be rewritten as:

$$\left(\frac{1}{D+L}\right)\frac{dy}{[1-y]} = \frac{dp}{p\left[(D+L)-\bar{s_2}\right]-\left[C(D+L)-C(\bar{s_2})\right]}$$

taking the integral of both sides from the lower bound $\underline{P}$ to p yields:

$$\left(\frac{1}{D+L}\right)\int\limits_{y(\underline{P})}^{y(p)}\frac{1}{1-y}dy = \int\limits_{\underline{P}}^{p}\frac{1}{p\left[(D+L)-\bar{s_2}\right]-\left[C(D+L)-C(\bar{s_2})\right]}dp$$

$$\iff -\left(\tfrac{1}{D+L}\right)\ln\left(1-y\right)|_{y(\underline{P})}^{y(p)} =$$

$$= \left(\tfrac{1}{(D+L)-\bar{s_2}}\right)\ln\left[p\left[(D+L)-\bar{s_2}\right]-\left[C(D+L)-C(\bar{s_2})\right]\right]|_{\underline{P}}^{p}$$

which after some rearrangements produces finally:

$$y(p) = F_1(p) = 1 - \left[\frac{p\left[(D+L)-\bar{s_2}\right]-\left[C(D+L)-C(\bar{s_2})\right]}{\underline{P}\left[(D+L)-\bar{s_2}\right]-\left[C(D+L)-C(\bar{s_2})\right]}\right]^{\left(\frac{D+L}{\bar{s_2}-(D+L)}\right)}$$

$$with\, p \in [\underline{P}, \overline{P}] \quad (PD.1)$$

Note that the value in brackets is always positive since $(D+L) > \bar{s_2}$ and $p \geq \underline{P} > c_{\overrightarrow{u}}$. At the lower bound of $(PD.1)$ it holds that $F_1(\underline{P}) = 0$ and the function is always increasing if

$$\underline{P} > \frac{C(D+L)-C(\bar{s_2})}{(D+L)-\bar{s}_2} \;\; (T.C.-2)$$

Note that at the upper bound there must $F_1(\overline{P}) \to 1 \quad as \quad \overline{P} \to +\infty$. This requires a truncation of the density function in order to reconduct all the probabilities inside the support of randomization. The probability of player 1 to offer the marginal unit at a price included in the support $\left[\underline{P}, \overline{P}\right]$ so must be given by

$f_1(p) =$

$$\begin{cases} -\left(\frac{(D+L)-\bar{s_2}}{F(\overline{P})}\right)\left(\frac{D+L}{\bar{s_2}-(D+L)}\right)\times \\ \times\left[\frac{p[(D+L)-\bar{s_2}]-[C(D+L)-C(\bar{s_2})]}{\underline{P}[(D+L)-\bar{s_2}]-[C(D+L)-C(\bar{s_2})]}\right]^{\left(\frac{D+L}{\bar{s_2}-(D+L)}-1\right)} & for\, p\in[\underline{P},\overline{P}] \\ \\ 0 & otherwise \end{cases}$$

To summarize the mixed strategy equilibrium for the marginal unit of the two players is given by the following distributions and conditions:

$$F_1^*(p) = 1-\left[\frac{p[(D+L)-\bar{s_2}]-[C(D+L)-C(\bar{s_2})]}{\underline{P}[(D+L)-\bar{s_2}]-[C(D+L)-C(\bar{s_2})]}\right]^{\left(\frac{D+L}{\bar{s_2}-(D+L)}\right)} \quad (PD.1)$$

$$F_2^*(p) = \frac{\overline{P}(D-L)-p\bar{s_1}+[C(\bar{s_1})-C(D-L)]}{p[(D-L)-\bar{s_1}]+[C(\bar{s_1})-C(D-L)]} \quad (PD.2)$$

$$\overline{P} \geq \frac{C(\bar{s_1})-C(D-L)}{\bar{s_1}-(D-L)} \quad (T.C.-1)$$

$$\underline{P} > \frac{C(D+L)-C(\bar{s_2})}{(D+L)-\bar{s}_2} \quad (T.C.-2)$$

The above distributions generate an *expected pay-off* higher than the constrained equilibrium of (PSP-L) in Definition 4. It is easy to see that, for player 1 it is verified that

$$E(\pi_1) = \int_{\underline{P}}^{\overline{P}} \left[F_2^*(p)\pi_1(p,D-L) + (1-F_2^*(p))\,\pi_1\left(p,\bar{s_1}\right)\right] f_1^*(p)dp =$$

$$\overline{P}(D-L) - C(D-L) = A_1 > \Pi_1\left(p_z, s_1(p_z)\right)$$

and for player 2

$$E(\pi_2) = \int_{\underline{P}}^{\overline{P}} \left[F_1^*(p)E\left[\pi_2(p,\bar{s_2})|p_1\leq p\right] + (1-F_1^*(p))\,\pi_2\left(p,D+L\right)\right] f_2^*(p)dp =$$

$$A_2 > \Pi_2(p_z, s_2(p_z))$$

since $(D+L) > \bar{s_2} \geq s_2(p_z)$ and $\underline{P} > p_z$.This is the straightforward result of the generalization of *Corollary2* to the case of randomization.

After having derived the equilibrium distributions for the marginal prices submitted by the two players, similarly to the solution of the "Scan Algorithm" for the case $L > D$, a pair of equilibrium strategies is given by the following:

1. Player 1 will keep randomly a price p_1 upon the support $\left[\underline{P}, \overline{P}\right]$ according to the probability distribution $F_1^*(p)$ and will play $\beta_1^*(u) = p_u$ for any $u \in U$

2. Player 2 will keep randomly a price p_2 upon the suport $\left[\underline{P}, \overline{P}\right]$ according to the probability distribution $F_2^*(p)$. An equilibrium strategy is given by $\beta_2^*(u) = \begin{cases} c_u & \forall u < \overrightarrow{u} \\ p_2 & u = \overrightarrow{u} \\ \overline{P} & \forall u > \overrightarrow{u} \end{cases}$

Whenever $p_1 > p_2$ than the line will be congested and the equilibrium outcome in this case is given by

$$\mathcal{O}(\beta_1^*(u), \beta_2^*(u), D) = \{(D-L, 0)\,; (D, L)\,; (p_{1,}p_2)\}$$

On the contrary if $p_1 \leq p_2$ the zones do not separate and a unique price indicated by p_C will result in equilibrium. The final allocation in this case is given by

$$\mathcal{O}(\beta_1^*(u), \beta_2^*(u), D) = \{\bar{s_1}; \bar{s_2}; p_C\}$$

Equally to the previous case, it is important to remind the existence of a mixed strategy symmetric equilibrium of the game where both players randomize between $\beta_1^*(u)$ with probability p and β_2^* with probability $(1-p)$.

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