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Renewable Energy Sources and Electricity Supply Chain: an Overview of new Structures, Planning and operational Challenges, and enabling Technologies

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INTRODUCTION

Electricity represents a service with unique characteristics that necessarily impact the competitive dynamics that rule electricity production and the supply chain. In fact, the current technological state of the art is not enabling to store huge amount of energy in an efficient way because of the high costs of storing devices, consequently, generally speaking, electricity supply and demand must be constantly kept in equilibrium in real time, managing dispatch and provisions through complex processes and systems, and coordinating a multitude of players in all the phases[1].

Real time balance between supply and demand is fundamental since an imbalance in any given point of the network has the potential to cause disruptive effects on the entire system. System operators must consequently warrant the balance at any time and in any location of the transmission and distribution network, satisfying customer needs in terms of electricity provision and service continuity

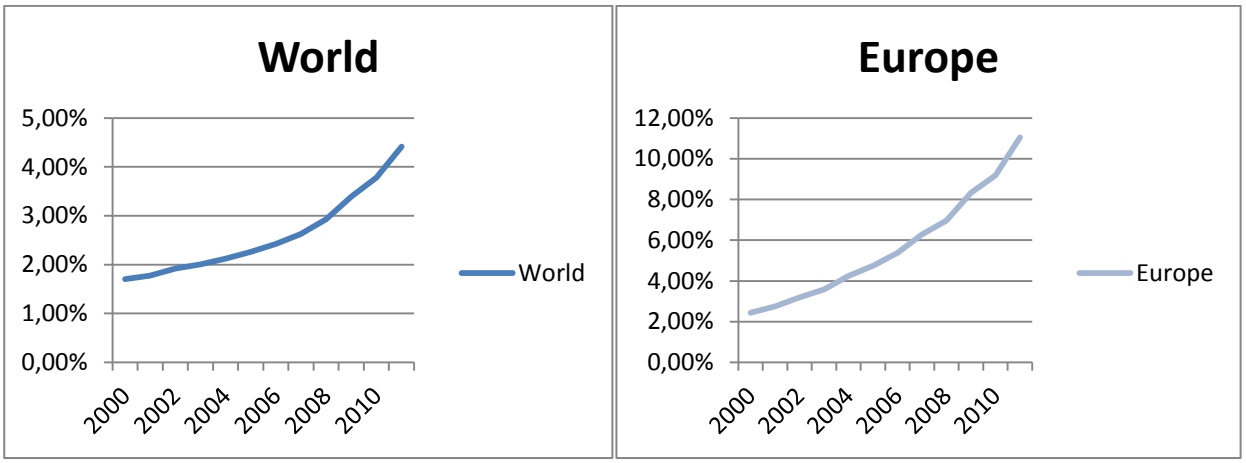
The *research problem* of this work is concentrated on investigating how the electricity supply chain is evolving in order to ensure a reliable and efficient power system, despite of the radical changes that the electricity industry is knowing because of the progressive large deployment of non-programmable renewable energy sources. In fact, a highly dynamic real-time operating environment with an international scope has been set up by policies aimed to foster renewable energy sources deployment and the "decarbonization" of the generation plants portfolio. Moreover, the core features of non-programmable renewable energy sources, that is to say volatility and uncertainty, combined with less predictable consumption patterns due to distributed generation and demand response, are deeply changing both infrastructures and network design, on the one hand, and planning and operational procedures on the other hand.

The deployment of renewable energy sources in the electricity supply chain is growing continuously on a global scale, as the graph concerning the world trend shows (*Graph 1*). However, the rise of renewables on a global level tends to be slow because it is constrained by certain regions that are not investing significantly in these new energy sources for several reasons, mainly their degree of economic development and their energetic endowment[2].

As a result, the topic concerning the integration of non-programmable renewable energy sources gains much more relevance with regard to specific areas of the world, that is to say mainly Europe and USA, as the comparison with the world trend emphasizes (*Graph 2*).

[1] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp. 21
[2] INTERNATIONAL ENERGY AGENCY, *Electricity in a Climate-Constrained World*, Paris, 2012, pp. 33

Graphs 1 and 2: comparison between World and European shares of renewable electricity over the total net electricity generation



Source: International Energy Agency Database[3]

The importance and urgency of this topic, however, is effectively pointed out especially by the forecasts concerning the role that renewables are going to play in the next four decades. Considering Europe as a reference point, according to the results of the Susplan Project promoted by the European Commission, we notice how renewable energy sources are going to become more and more crucial. *Graph 3* describes the expected growth of the renewable electricity share over the total final electricity demand in Europe according to four scenarios, elaborated on the basis of several variables[4].

As we can observe looking at *Graph 3*, in the next four decades renewable sources are supposed to reach a share comprised between 40% and 80%. This stresses the fundamental importance of effectively tackling the obstacles and barriers that are currently characterizing the integration of non-programmable renewable energy sources into the electricity supply chain, in order to create the conditions to plenty leverage their future development.

As a consequence, in the following chapters we will focus on the infrastructural and operational issues that are requiring attention, trying to understand which tools and resources can facilitate the transition to an ever more sustainable electricity generation.

More in details, *Chapter 1* describes the effects of the vertical and horizontal unbundling of the electricity supply chain and the structure of the market.

[3] INTERNATIONAL ENERGY AGENCY DATABASE: http://www.iea.org/statistics/statisticssearch/

[4] BJORN BAKKEN, INGEBORG GRAABAK, *Development of regional and Pan-European guidelines for more efficient integration of renewable energy into future infrastructures*, SINTEF Energy AS, 2012, pp. 1

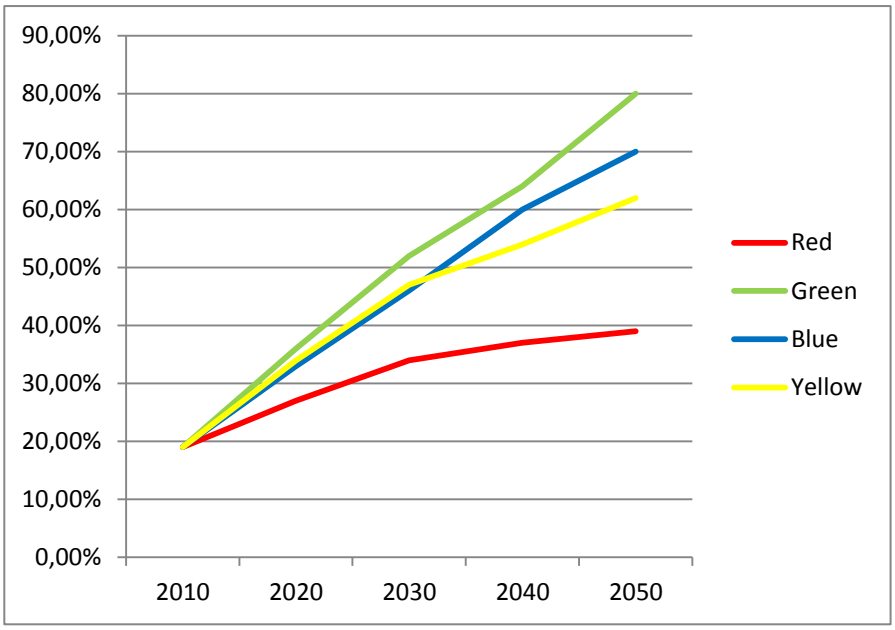
Chapter 2 defines the concept of planning process and the relative planning horizons, which will compose a fundamental frame to analyze the electricity supply chain.

Chapter 3 focuses the attention on the five phases characterizing the supply chain and on the challenges concerning the strategic long-term planning.

Chapter 4 deals with mid-term planning, concentrating on demand and supply forecasting, whereas *Chapter 5* is related to short-term planning and to the planning and operational challenges determined by the variability and unpredictability of non-programmable renewable energy sources.

Finally, *Chapters 6* and *7* concern respectively the development of a common network code among national supply chains to facilitate their interaction, and the fundamental importance of adequate information systems and information procedures along the entire electricity supply chain.

Graph 3: forecast of the share of renewable electricity over the total final electricity demand in Europe according to the Susplan Project findings



Source: B.Bakken, I.Graabak[5]

The graph emphasizes the role that renewables are going to play in few decades according to the forecasts belonging to the Susplan Project. Looking at the worst scenario (Red scenario), renewables are expected to reach a share of the 40% of the final electricity demand, stressing the urgency of the development of an electricity supply chain able to effectively and efficiently support a large scale integration of non-programmable renewable energy sources.

[5] BJORN BAKKEN, INGEBORG GRAABAK, *Development of regional and Pan-European guidelines for more efficient integration of renewable energy into future infrastructures*, SINTEF Energy AS, 2012, p. 11

1) ELECTRICITY INDUSTRY LIBERALIZATION AND MARKET STRUCTURE

1.1 From a State-owned vertically integrated Supply Chain to a vertically unbundled Supply Chain in a competitive market

Electricity is provided by a complex network, composed of generators, transmission and distribution wires (high, medium, low voltage) and different loads. From an economical perspective, it is more convenient to serve a geographical area through a single network and to suppose the network to be managed by a single system operator. Since competition among providers would not be able to reduce the costs to supply electricity and to develop a more efficient and effective supply chain, the sector presents the characteristics of a natural monopoly[6]. As a consequence, network services are provided by single entities. In order to avoid that the service provider takes advantage of this monopoly, revenues deriving from that service must be carefully regulated. In economies characterized by competitive markets, a clear separation occurs between network services, on the one hand, and generation and retailing on the other hand[7]. As a matter of fact, plurality of players and competition are referred to the latter phases, that is to say generation and retailing. Players plurality has been significantly allowed by the rise of renewable energy sources: the strong financial incentives provided by governments have cut the costs for establishing a generation plant and its running costs, whereas the recent liberalization of the market in many countries, the unbundling of the vertical chain and the parallel rise of distributed generation have created the profitability margins for new coming companies that focus their business only on retailing electricity[8].

[6] INTERNATIONAL ENERGY AGENCY, *Secure and Efficient Electricity Supply During the Transition to Low Carbon Power Systems*, Paris, 2013, pp.5

[7] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, pp.12

[8] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, pp.12

The electricity provision can be carried out through two general approaches, which represent two extremes of a continuum characterized by several feasible in-between alternatives[9]:

- Integrated Monopoly
- Competitive Market

A ***monopolistic provider*** has been the common industrial organizational mode in approximately all the countries worldwide. According to this structure, a unique company is called to manage the whole electricity supply chain for a given area, usually the entire country or an agglomerate of regions. Those companies were vertically integrated, that implies that they were owning and managing all the generating plants and infrastructures for all the supply chain phases: generation, transmission and distribution. Moreover, according also to the strategic relevance of the energy industry, those companies were government owned or at least government controlled.

In absence of competition, consumers are forced to interact with a single provider. This is the reason why governments and regulators must ensure that the quality standards expected by the customer base are met and that prices are maintained at a proper level. In addition, regulators have also the task to define the suitable investments to be undertaken to support and/or expand the supply chain. In fact, a misalignment between the investments realized and the investments really required by demand would have direct consequences on the price paid by consumers or on the quality of the service. For instance, in case of an investment insufficient to satisfy demand, consumers would face electricity shortages or service interruptions because of congestions or failures. On the other hand, excessive investments would raise the price paid by customers in order to pay back useless or under-used infrastructures.

Government-owned monopolistic companies are usually thought to achieve additional objectives respect to the simple efficient and effective supply of electricity. Examples may be maintaining retailing prices below generation and supply cost levels, especially during economic downturns, or managing the electricity sector as a branch of a broader national energy policy, including other energy forms[10].

The *advantages of a monopolistic structure* and, consequently, of a vertically integrated supply chain are mainly certainty and simplicity. Simplicity because a unique integrated company is not called to dispatch electricity from a plurality of providers and to manage loads and frequency in

[9] MANUEL BARITAUD, *Securing Power during the Transition: Generation Investment and Operation Issues in Electricity Markets with Low-Carbon Policies*, IEA, Paris, 2012, pp. 15

[10] MANUEL BARITAUD, *Securing Power during the Transition: Generation Investment and Operation Issues in Electricity Markets with Low-Carbon Policies*, IEA, Paris, 2012, pp. 15

presence of multiple retailers, since all the phases are carried out internally by the same company, highly simplifying planning and organizational processes. Certainty because, owning and managing the entire chain, the company has complete control over the information about customers usage and over short term and long term planning in all the phases, being able to conduct operations with the highest level of certainty and stability.

Looking at the *disadvantages of the monopolistic structure*, it is due to emphasize the weak incentives that the unique company has to renew network infrastructures and generation plants, and to improve the quality of the service and the system efficiency[11]. As a matter of fact, once the single operator has been able to comply with the general standards defined by the regulator, it obtains all the revenues from the entire customer base, independently from the quality of the service supplied. That has forced the regulator to be constantly committed in supervising the performance of the operator and in implementing incentive mechanisms to reach satisfying levels of service, often losing, however, efficiency in the overall costs of the supply chain.

In addition to this issue, even if the vertically integrated structure of the supply chain is typically characterized by a high degree of certainty, the forecasts carried out by the regulator always imply the risk of error, leading in some cases to an over- or under-estimation of the future demand and, consequently, to an excessive or lacking expansion of the supply.

In absence of competition, the negative effects of a forecasting error are charged to the customers, who can contract only with that provider. Moreover, usually, the knowledge of the regulator concerning the characteristics and the patterns of the demand is minor compared to the one of the entity supplying that demand, offering to the provider potential room to influence the decisions of the regulator[12].

The negative aspects of a monopolistic structure outlined above have driven toward a progressive liberalization of the electricity industry and the adoption of a competitive structure. The competition, which this structure is based on, generally occurs in the generation and retailing phases, since they present the features most likely to sustain a competitive paradigm, whereas it tends to be highly limited or avoided in the transmission and distribution phases, because of their profile of natural monopolies[13].

The supply chain based on a ***competitive model*** is characterized, as a result, by a plurality of companies generating electricity and a plurality of companies marketing it to final users, whereas

[11] MANUEL BARITAUD, *Securing Power during the Transition: Generation Investment and Operation Issues in Electricity Markets with Low-Carbon Policies*, IEA, Paris, 2012, pp. 16

[12] MANUEL BARITAUD, *Securing Power during the Transition: Generation Investment and Operation Issues in Electricity Markets with Low-Carbon Policies*, IEA, Paris, 2012, pp. 16

[13] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, pp.12

transmission and distribution tend to remain in the hands of a single company, supervised and (at least partially) owned by the government.

Generators offer the electricity produced in a wholesale market, specifying the volume offered and the related price. The interplay between the aggregate demand and the aggregate supply determines the overall quantity exchanged in the market; on the basis of this output of equilibrium, bids are dispatched starting with the lowest prices till the point in which the aggregate demand has been completely fulfilled, and the price of the last dispatched bid determines the market price, which the whole amount of energy exchanged in the market is sold at. Consequently, players belonging to the supply chain or willing to enter it consider the market price to assess the feasibility of new investments[14].

When an entity assesses the feasibility and potential profitability of an investment in infrastructure, it carries out demand forecasts similar to the ones performed by the regulator in the monopolistic model. In this case, however, the error associated to wrong forecasts, that is to say under- or over-estimation of future demand, cannot be charged automatically to customers by the operators.

Peculiarity of the competitive model is the entry into the market of companies that simply retail electricity without owning any infrastructure. These companies purchase electricity in the wholesale market and, splitting electricity and network services, they sell it to customers. These retailing companies try in particular to enlarge their customer base through a superior and customized service in addition to competitive prices[15].

Since the entire network is based on a constant real time balance between demand and supply and since demand response, even if rapidly developing, is not actually able to ensure a high price elasticity and responsiveness, wholesale prices can reach high values in case of a lacking supply. Since retailing companies purchase electricity on the wholesale market, price fluctuations in that market may be a convincing argument in favor of vertical integration. On the same time, a fall of the aggregate demand would determine a significant decline of the electricity price in the wholesale market because of over-production; that clearly would potentially hardly affect companies owning generating plants.

According to these arguments, along the supply chain, in many countries companies are opting for vertically integrating generation and retailing phases in order to protect themselves from price fluctuations in the wholesale market[16]. However, the articulated structure of the market and the

[14] LEONARDO MEEUS, KONRAD PURCHALA, RONNIE BELMANS, *Development of the Internal Electricity Market in Europe*, The Electricity Journal Volume 18, Issue 6, July 2005, pp. 25

[15] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, pp. 17

[16] MANUEL BARITAUD, *Securing Power during the Transition: Generation Investment and Operation Issues in Electricity Markets with Low-Carbon Policies*, IEA, Paris, 2012, pp.15

presence of power exchanges (as we will discuss later) provide a broad set of financial tools, like futures, to minimize the risk related to price volatility.

The *advantages of the competitive model* are typically considered in terms of improved efficiency, boosted innovation and lower prices in comparison to the monopolistic structure of the market.

If companies compete while generating electricity or retailing it, they must bear by their own the risk of failure of their strategies or investments. Since a wrong investment or a poor customer service have the potential to lock a company out of the market, companies have convincing incentives to undertake investments able to meet future demand, and to maximize, on the same time, their efficiency. In the same direction, a company lagging behind its competitors will be forced to improve the quality of the offer and its operational efficiency.

The concept of efficiency is absolutely central looking at renewable energy sources. The combination of the implementation of technological solutions that are still under development (for example highly performing storage technologies) and the planning and operational challenges that renewable energy sources raise, tend to prevent that the generation of electricity from large plants exploiting renewable energy sources is a profitable business without financial incentives and fiscal or market facilitations, explicitly thought to promote and foster the process of decarbonization of electricity production[17].

Along the electricity supply chain, in many cases governments take actions in the market to promote the application of technologies still under development, even if their usage has a negative impact on system efficiency because of their high costs. The purpose is to speed up the development of these technologies enabling the integration of non-programmable renewable energy sources into the electricity supply chain, through the exploitation of the learning-by-doing effects and of technological spillovers. As a matter of fact, testing and improving technologies directly on the playing field give a viable chance to speed up the development pace and to spread improvements to a broad set of devices thanks to technological spillovers.

Finally, the improved technologies have been reaching in a short time interval a degree of efficiency that enables them to become cost-efficient, even without being subsidized.

This consideration is related to the concept of energy conversion cost, that is a relevant indicator in order to assess the efficiency of a given generation solution[18]. In fact, the current costs of many renewable energy sources are not comparable to the ones of conventional sources; looking at the

[17] INTERNATIONAL ENERGY AGENCY, *Climate & Electricity Annual 2011*, Paris, 2011, pp.15

[18] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, *Renewable energy supply chains, performance, application barriers, and strategies for further development*, Renewable and Sustainable Energy Reviews volume 16, 2012, pp. 5454

table below, the efficiency coefficient of renewable energy sources is not comparable with the performances reached by conventional energy sources[19].

Table 1: Comparison of the efficiency coefficient of conventional plants and renewable energy plants

Type of Power Plant	Efficiency Coefficient (%)
Coal/Lignite	39,4
Oil	37,5
Natural Gas Turbine	39
Natural Gas Combined Cycle	54,8
Nuclear	33,5
Hydroelectric	80
Wind	35
Solar Photovoltaic	9,4
Biomass	28
Geothermal	6

Source: C. Pilavachi[20]

A poor performance in terms of conversion cost might be overcome, at least partially, through the selection of the locations for the generating plants, identifying sites where it is possible to maximize the input energy and, as a result, the energy output, and on the same time to improve the efficiency coefficient in order to increase the output energy more than proportionally respect to the energy input. As we will discuss more in details, often those locations tend to be inconsistent and inefficient with regard to the transmission and distribution infrastructures, potentially delineating a tradeoff between higher generation and conversion efficiency and, on the other side, superior transmission and distribution efficiency.

A last consideration is the fact that a lacking efficiency of renewable energy sources in the generation phase might be counterbalanced by a high efficiency in operation processes. In particular, a significant agility of the supply in responding to demand variations and a rationalization and maximization of power usage through smart grids might be winning directions.

[19] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, Renewable energy supply chains, performance, application barriers, and strategies for further development, Renewable and Sustainable Energy Reviews volume 16, 2012, pp. 5454

[20] C. PILAVACHI, Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process, Energy Policy volume 37, 2009, p. 780

1.2 Liberalization and Market Structure

Before entering in details into the phases of the supply chain and the operational and planning challenges in presence of non-programmable renewable energy sources, it is important in my opinion to focus the attention on two topics:

- the *liberalization* that is occurred in the recent years in the sector and that has made possible the birth and development of the actual supply chain in a competitive environment
- the *structure of the market*, since the core objective of the supply chain is to drive electricity from generators to end consumers, and, consequently, it is useful to have an overview of the market mechanisms which the electricity passes through before reaching its final destination.

As we have seen, the electricity industry is characterized first of all by *a good that cannot be stored* (more precisely: that cannot be stored in huge quantities and/or for long periods of time at the actual state-of-the-art of the technology) and that consequently requires a real time balance of supply and demand. Moreover, the industry presents high entry barriers in terms of significant sunk costs[21]. The electricity supply chain is characterized by four phases, that can be split into two categories: generation and retailing that present features enabling the development of a competitive model, and transmission and distribution that are natural monopolies according to the strong pressure for horizontal and vertical integration[22].

Liberalization should consequently have combined a plurality of players competing each other in the generation and retailing phases, and a single operator in charge for managing transmission and distribution phases. According to its monopolistic position, the operator is constantly monitored by the regulator in order to verify its compliance to the legal framework conceived to ensure a fair competition upstream the transmission and downstream the distribution.

[21] MANUEL BARITAUD, *Securing Power during the Transition*, International Energy Agency, Paris, 2012, p. 14
[22] MANUEL BARITAUD, *Securing Power during the Transition*, International Energy Agency, Paris, 2012, p. 14

The transition from a vertically integrated government-owned supply chain to a competitive supply chain, based on market interactions among a plurality of private players, can be articulated on four fundamental steps:[23]

- Restructuring
- Competition and Markets
- Regulation
- Ownership

The *restructuring* step is characterized by the vertical unbundling of the phases of the supply chain and, simultaneously, the reduction of the market concentration identifiable horizontally in each single phase.

The purpose of vertical unbundling consists on dividing competitive phases (generation and retailing) from the natural monopolies (transmission and distribution).

Separating generation from transmission enables to avoid that incumbent generators implement strategies thought to prevent a fair and open competition in the wholesale electricity markets.

In the same direction, the separation of transmission and distribution from retailing is crucial to ensure a fair competition in the retailing phase.

The horizontal splitting in the generation and retailing phases wants, on the other side, to reduce the market concentration in the hands of few incumbents, in order to foster competition when economies of scale allow it[24]. Horizontal splitting is effective generally on two temporal horizons: in the short term, it fosters competition among existing firms, whereas in the long term it stimulates the entry of new players.

The second step (*competition and markets*) consists on the establishment of wholesale and retailing markets. Clearly the structure of the markets must be consistent to several aspects characterizing electricity supply, aspects that range from technical elements to infrastructural issues and that comprise requirements like ensuring real time balance between demand and supply, efficient and effective management of congestions along the network and price determination mechanisms[25].

The third step, *regulation*, concerns the establishment of an independent regulator called to monitor the entire supply chain with the aim to verify the compliance to the legal framework regulating the

[23] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, p. 13

[24] MANUEL BARITAUD, *Securing Power during the Transition*, IEA, Paris, 2012, pp. 14

[25] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, pp. 14

industry. Great attention has to be paid to the management of the transmission and distribution phases, where a monopolistic regime remains. In particular, key topics are ensuring the access to the network to all the new comers and to determine a proper scheme of incentives to stimulate an effective and efficient management of the network.

The last step, *ownership*, wants to support the transition from a public-owned supply chain to a privately owned, facilitating the process of privatization of state-owned incumbents and facilitating the entry of new private players. The degree of privatization has reached different results across countries. For example, Germany and Belgium were already characterized by a preponderance of private firms, whereas the deepest privatization processes have taken place for instance in the UK and Portugal, while Italy and France have known a partial transition toward privately owned supply chains[26].

It is interesting to stress the fact that the process of horizontal splitting is still in progress and it is likely to take years because of the heritage of the public ownership, controlling the entire chain before the reform. According to this heritage, large shares of the national markets in the generation and retailing phases are still concentrated in the hands of few players.

1.3 European Directive 96/92/EC and Freedom of Entry in the Market

We have seen how modern economies have been implementing a process of liberalization of the electricity sector, with the objective of substituting the vertically integrated structure of the supply chain, characterized by a significant public ownership, with a competitive model, characterized by a market based on a plurality of private players fairly competing in the generation and retailing phases.

The process toward a multitude of generators and electricity providers is still on, and actually it has determined the development of an oligopoly, where a limited number of large private firms (often with a state participation) holds the major share of the market. In this oligopolistic context and, consequently, in absence of perfect competition, firms have the possibility to increase profits through the implementation of effective strategies in the electricity market and in the power exchanges.

[26] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, pp.14

The process of liberalization in Europe has been boosted by the European directive 96/92/EC[27], thanks to which the European Legislator aimed to establish the basis for the development of a unique European Internal Market for electricity, characterized by common rules across the whole Europe and concerning generation, transmission, distribution and retailing.

The directive, as a matter of fact, regulates the complete electricity chain, from generation to consumption activities, focusing the attention not simply on the modalities and freedom of access to the market, but shaping also the overall organization and functioning of the electricity sector and its supply chain.

Concerning generation, the European regulator recognizes different entry modes with the aim to support the national regulator to maintain the efficiency and effectiveness of the sector and, eventually, to take actions in case of deviation from the intended competitive structure and/or the sector performance. These market entry modes are respectively the authorization granted by the national regulator to a company willing to enter the generation segment of the supply chain, authorization that it is granted only once specific requirements are fulfilled, and tenders organized by the national regulator[28].

Later on, the directive concentrates on the transmission and distribution phases, recognizing the subsistence of the conditions that qualify them as natural monopolies. Consequently, the directive is aimed to consolidate the network management by a unique operator in the framework of a regulated monopoly. In fact, a first concern of the regulator, in order to ensure the fairness and the efficiency of the entire supply chain, consists on guaranteeing a non-discriminatory access to the network to all the entities having the right to enter it[29].

The national regulator has the task to designate an operator able to manage the network ensuring fair competition, stability, efficiency and an adequate maintenance and expansion of the infrastructures. The freedom of entry and the strict regulation concerning network management are fundamental in the context of a large penetration of non-programmable renewable energy sources.

Thanks to the aggressive financial incentive programs and taxation facilitations provided by governments in favor of renewable energy plants, the increase in the production of green electricity has been fostered by the entrance in the market of new large private producers with a highly diversified portfolio of generating plants, both in terms of type of energy sources exploited and the relative technology applied, and in terms of location, and by the entrance of a multitude of small

[27] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, pp.14

[28] TOORAJ JAMASB, MICHAEL POLLITT, *Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration*, Sloan School of Management, 24 March 2005, pp. 17

[29] MANUEL BARITAUD, *Securing Power during the Transition*, IEA, Paris, 2012, p.10

producers, accounting together for a market share highly varying from country to country, but generally significant. Each of these small producers is usually concentrated on the exploitation of a single type of energy source, for instance solar energy, and usually on a single location[30].
Natural development of this trend toward dispersed small producers has been the rise of distributed generation, through which consumers have been progressively becoming also producers.
It appears immediately clear the fundamental role played by an active and careful warranty of the freedom of entry in the market in the development of the usage of renewable energy from non-programmable sources.
Moreover, as we will discuss later, the presence of a neutral system operator, able to ensure the stability of the system and its efficient functioning, is a second fundamental condition, condition that cannot be taken for granted because of the impact on the network of the uncertainty and volatility associated to non-programmable energy sources.

1.4 Market Structure

Moving to the electricity market itself, we distinguish between power exchanges and electricity markets (intraday, market, day-ahead market..), that are both thought to facilitate transactions, even presenting different mechanisms and structures[31].
Concerning power exchanges, there are two broad categories[32]:

- Cost-of-service regulated power exchanges
- Merchant power exchanges

Cost-of-service regulated power exchanges (for example the Italian Ipex) refer to the medium and long term planning process of the generating plants and the dispatch of the energy they produce. These power exchanges are characterized by a day-ahead market and a precise mechanisms to solve congestions and to manage the reserves to ensure the ancillary services. These exchanges are generally managed by entities linked to the system operator and they account for a large share of the total volume of the electricity flowing in the network.

[30] INTERNATIONAL ENERGY AGENCY, *Climate & Electricity Annual 2011*, Paris, 2011, pp. 18
[31] M. BENINI, M. GALLANTI, S. BARSALI, P. PELACCHI, D. POLI, *Il sistema elettrico in Norvegia e Svezia, struttura e procedure di gestione*, L'Energia Elettrica, volume 77, n. 3, May-June 2000, pp.2
[32] LEONARDO MEEUS, KONRAD PURCHALA, RONNIE BELMANS, *Development of the Internal Electricity Market in Europe*, The Electricity Journal Volume 18, Issue 6, July 2005, pp. 25

Merchant power exchanges, like the German Eex, are characterized by financial contracts referred to electricity provision in regime of base demand and peak demand, and they are referred to the balance market. These contracts are futures and, according to what we have already discussed, they may have an important role in protecting from price volatility not vertically integrated companies operating in the generation phase or retailing phase[33].

Looking at the structure of the market, generally speaking it is based on three sub-markets with different temporal horizons and tasks: *day-ahead market*, *intraday market* and *balance market*.

1.4.1 Day-ahead Market, Intraday Market, Balance Market

In the ***day-ahead market***, generators propose to the market their bids, specifying the volume of energy made available for each time interval and the relative price. On the same way, retailers submit their demands per time interval with the associated price. According to these data and following a price-merit criterion (from the bid with the lowest price on), aggregate supply and demand are built and matched, defining the total amount of electricity that is planned to be exchanged the following day and the relative market price.

In the ***intraday market***, generators and retailers have the possibility to modify the selling or purchasing plans defined in the day-ahead market. Concretely, as generators and retailers refine their forecasts along the day, because of the higher temporal proximity to the considered time interval, they are in the position to adjust the volume of energy they are going to inject in the network or to extract from it. Since closer to the intended time interval the forecast error decreases drastically, the intraday market provides several negotiation sections in order to enable players to operate as close as possible to the deadline[34].

The implementation of these adjustments will depend clearly also on the availability of the transmission lines in each time interval. This is the reason why the requests of modification of the selling or purchasing plans submitted by generators and retailers are matched with the information provided by the system operator. These information concern the volume that can transit in each portion of the network in any time interval, the available capacity of the interconnections between regions and the available capacity of cross-borders interconnections[35].

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[33] LEONARDO MEEUS, KONRAD PURCHALA, RONNIE BELMANS, *Development of the Internal Electricity Market in Europe*, The Electricity Journal Volume 18, Issue 6, July 2005, pp. 25

[34] TERNA RETE ITALIA website: http://www.terna.it/default/Home/SISTEMA_ELETTRICO/mercato_elettrico.aspx

[35] ENTSOE, *Supporting Document for the Network Code on Operational Planning and Scheduling*, Belgium, 24 September 2013, pp.30

Finally there is the ***balance market***, that is to say the market where the system operator acquires the resources necessary to manage the system, ensuring its stability and the constant matching of supply and demand.

Given the fact that the balance between supply and demand must be constantly ensured in real time, this market works on the basis of a time horizon approximated to the real time. The determination of the amount of energy that the operator needs is very complex because based on a variety of variables difficult to be forecasted, even close to the real time. The two main variables are customer demand and the output deriving from non-programmable renewable energy sources.

On the basis of this two values and, in addition, the required volume for the ancillary services (primary, secondary, tertiary reserves), the system operator acquires energy from the entities participating to the balance market. Concerning non-programmable renewable energy sources, it is interesting to stress the fact that generators exploiting these sources, because of their variability and uncertainty, cannot participate to the balance market[36].

1.4.2 Territorial repartition of market

Electricity market is characterized also by an organization at geographical level. Market is articulated in regions, each of them presenting a portion of the overall network, portion that is affected by physical constraints concerning interconnections capacity with the adjacent areas. The borders of each region are updated periodically on the basis of the expansion plan of the transmission network elaborated by the system operator[37].

The identification of these regions is aimed to spot bottlenecks in the transmission network and, as a result, to avoid the occurrence of congestions by effectively managing the balance of loads and the electricity flow at local level, that is to say within each region, and across regions through the interconnections.

Interconnection between regions are a topic that is gaining greater importance in the planning process of the transmission phase in the electricity supply chain characterized by a large penetration of renewable energy sources. In fact, facilities generating energy from renewable sources, especially wind and solar energy, cannot be arbitrary located in any region and close to the major consumption areas, but they require to be established in location with a notable endowment of that

[36] TERNA RETE ITALIA, *Partecipazione alla Regolazione di Frequenza e Frequenza-Potenza*, May 2000, pp.6

[37] TERNA RETE ITALIA, *Individuazione Zone della Rete Rilevante*, elaborated by Martire F., September 2008, pp.4

renewable energy source[38]. Since this endowment is highly variable across regions, there are regions that, especially in certain periods of the year, have a relevant overproduction compared to the internal demand, whereas other regions have a demand exceeding the supply.

It appears clear how an effective management of the interconnections capacity among regions (and their expansion) has a crucial role to avoid curtailments in the generation of renewable energy, buffering production peaks through the balance of demand and supply across regions borders.

Within the framework of this geographical organization of the surface served by the electricity market, that facilitates the task of being locally effective in fulfilling demand, while keeping stable and efficient the overall supply chain and smoothing transactions in the day-ahead market , intraday market and balance market.

[38] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, *Renewable energy supply chains, performance, application barriers, and strategies for further development*, Renewable and Sustainable Energy Reviews 16, 2012, p.5457

2) INTRODUCTION TO THE ANALYSIS OF THE ELECTRICITY SUPPLY CHAIN

As we have seen, the electricity industry is experiencing a phase of transformation because of the integration of a fast growing share of power produced by non-programmable renewable energy sources. The pace at which these sources are integrated into the conventional supply chain varies from country to country, according to several factors referred to sources endowment, infrastructure and, generally speaking, stakeholders alignment[39].

Because of this process characterized by different speeds and also different starting scenarios, it is difficult to provide a precise and static picture of the actual configuration and state of the art of the electricity supply chain. This is the reason why the following overview of the supply chain phases and the main planning and operational challenges will be focus on the transformation process that is actually taking place in modern economies. As a consequence, the time horizon applied in the analysis is not "today", meaning a precise point in time, but it is the present, meaning a range of few years according to the evolutionary nature of the topic we are dealing with.

Defined the temporal dimension which the overview develops through, we proceed entering in details into the phases characterizing the electricity supply chain. Our priority is to try to understand what are the effects, changes and problems determined by the integration of non-programmable renewable energy sources. Attention will be focused especially on the technologies that are currently being developed and implemented and on the forecasting and planning challenges, arising in particular in the transmission and distribution phases.

After having dealt with the four phases of the supply chain, in fact, we try to better understand how forecasts and planning process are carried out by the system operator and which are the likely solutions to the operational and infrastructural constraints that are still slowing down renewable energy as a core source for electricity.

[39] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, *Renewable energy supply chains, performance, application barriers, and strategies for further development*, Renewable and Sustainable Energy Reviews 16, 2012, pp.5457

2.1 Planning Process and Planning Horizons

During the description and analysis of the electricity supply chain structure, according to the growing deployment of non-programmable renewable energy sources, we will pay significant attention to the planning process underlying the supply chain and to its role in enabling an effective and efficient integration of the new energy sources, despite of their high variability and uncertainty. As a consequence, before proceeding with the analysis of the supply chain, it is suitable to explain form a theoretical perspective what a planning process entails.

A supply chain is characterized by a huge number of decisions that have to be taken continuously and in a consistent and coordinated way. The planning process is aimed to support the decision-making process concerning all those decisions, pointing out per each decision the feasible alternatives and identifying among them the suitable or the optimal ones.

Planning is consequently based on defining the objectives underlying a decision problem previously identified, on elaborating forecasts concerning the future developments, on identifying and assessing the possible solutions and, finally, on selecting the optimal or suitable solution to the problem[40].

The planning process, as a result, implies forecasting and simulation models to identify the future developments and the possible solutions, and optimization models thought to select within the panel of possible solutions the optimal ones, according to specific criteria set in advance[41].

Plans are elaborated with regard to different planning horizons, which, according to their length can be organized in three different categories:

- long-term planning
- mid-term planning
- short-term planning.

Long-term planning entails decisions which effects develop in the long run, usually multiple years, and those decisions are related to the structure of the supply chain itself. *Mid-term planning*, consistently to the directions given in the long-term planning, wants to provide a rough plan for the resources allocation and flows management within the supply chain, according to a horizon usually

[40] HARTMUT STADTLER, CHRISTOPH KILGER, *Supply Chain Management and Advanced Planning*, Springer, third edition, 2005, p.81

[41] HARTMUT STADTLER, CHRISTOPH KILGER, *Supply Chain Management and Advanced Planning*, Springer, third edition, 2005, p.81

comprised between 6 and 24 months. Finally, *short-term planning* is aimed to organize, drive and monitor the execution of operations that have to be carried out within a very close temporal horizon, ranging normally between one 1 day and 3 months.

Clearly, decisions underlying short-term planning have to be consistent to the instructions deriving from the long-term and mid-term planning levels[42].

An important dimension characterizing the planning process is, indeed, the *degree of aggregation/disaggregation* underlying the decisions that are taken. Generally speaking, aggregation is referred to four objects, that are *resources*, *time*, *product* and *place*, and the degree of aggregation progressively decreases in the planning process proceeding from the long-term planning to the short-term planning horizons[43]. The degree of aggregation has a crucial impact on the accuracy of the forecasts, forecasts that are a building block of the entire process: according to the four objects, the higher is the degree of disaggregation and the higher is the likelihood and potential scope of forecast errors.

Referring to the analysis of the electricity supply chain, we will focus the attention on the challenges raised by the large deployment of non-programmable renewable energy sources with regard to the three planning horizons. We will discuss how different degrees of aggregation concerning time, resources and place impact on the accuracy of the forecasts and on the planning process.

Along the description of the generation, transmission, distribution and retailing phases we will concentrate our attention on the long-term planning , adopting a planning horizon of several years. We will focus especially on the definition of *energy sources and technological portfolio* of generators, on the *development of network infrastructures* and on the *development of new business models* in the retailing phase.

After the analysis of those phases, we will proceed with the mid-term planning process, briefly discussing the different approaches applied for the definition of the planning horizon, and, finally, we will deal with the short-term planning process, embracing a planning horizon comprised between 48 hours (day-ahead market) and the real-time.

[42] HARTMUT STADTLER, CHRISTOPH KILGER, *Supply Chain Management and Advanced Planning*, Springer, third edition, 2005, p.82

[43] HARTMUT STADTLER, CHRISTOPH KILGER, *Supply Chain Management and Advanced Planning*, Springer, third edition, 2005, p.85

3) ELECTRICITY SUPPLY CHAIN STRUCTURE AND LONG-TERM PLANNING CHALLENGES DERIVING FROM RENEWABLE ENERGY SOURCES

3.1 Electricity Generation

Generation is the first phase of the electricity supply chain and it is composed of all the plants and medium or small scale devices that produce the energy injected into the network.

This phase has known, recently, deep fundamental changes deriving, on the one hand, from the vertical unbundling and liberalization of the industry and, on the other hand, from the large scale deployment of renewable energy sources.

The combination of these two factors has completely transformed the portfolio of the devices participating to the electricity generation, according to the new energy sources and the new competitive environment.

Before proceeding with an overview of the renewable energy sources that have been progressively integrated into the system, we focus the attention on the *evolution of the competitive structure* that the generation phase has experienced in the transition from a vertically integrated state-owned supply chain to a vertically and horizontally unbundled chain with a significant participation of private companies.

It is important to stress the fact that the market liberalization and the integration of renewable energy sources are not independent but they have been mutually enhancing each other. Market liberalization, increasing the competitive pressure over the incumbent firms, has improved industry responsiveness to new technologies and new energy sources, enabling also small players to enter the market. Their entry and the consequent horizontal unbundling of the market have been allowed also by the rise of renewable energy sources, since in many case they present lower starting investments and lower operating costs than plants exploiting traditional energy sources[44].

Before the occurrence of the market liberalization and the renewable energy sources integration, the generation phase was performed by a state-owned or state-controlled entity that was in charge for managing the entire national supply chain. All the plants were owned and run by the same player

[44] IAN RUTLEDGE, *Who owns the UK Electricity Generating Industry – and does it matter?*, SERIS, UK, November 2012, p.11

and they were exploiting conventional energy sources, like oil, coal and nuclear energy[45]. Liberalization has led firstly to the development of an oligopoly and, then, significantly thanks to the rise of renewable energy sources, to a combination of few large players and a multitude of small generators exploiting low cost generating devices. The large players usually are not committed only to generate electricity, but they often downstream integrate into retailing activities. This vertical integration may protect the company from electricity price fluctuations in the wholesale market.

The ownership structure of the players belonging to this phase is currently highly heterogeneous, varying from country to country. As a matter of fact, in some countries the main generators are still partially state-owned, whereas in other countries public ownership is not particularly relevant.

In many cases national supply chains have seen the entry of large foreign players, especially through the acquisition of national incumbents. A trend identifiable for example at European level is the growth of few large international players, which enter the generation and retailing phases in multiple countries, acquiring existing plants or building new ones[46].

This process has been accelerated also by the deployment of renewable energy sources and the incentives and subsidies provided for their exploitation. In fact, many national supply chains are characterized by a significant share of their conventional plants that is reaching the end of the lifecycle. Since these conventional plants require high initial investments and also high operating costs, many of them are going to be replaced by green-field projects concerning the exploitation of renewable energy sources. These new projects are actually important opportunities for international players to enter a new national market or for strengthening their competitive position there.

The *proportion between conventional and renewable energy plants* and their sizes depend on several factors, determining a high degree of heterogeneity across countries. The main factors are *resources endowment, socioeconomic aspects, the alignment of stakeholders interests, transmission and distribution infrastructure availability and the availability of flexibility resources*[47]. A significant share of plants based on renewable energy sources is consequently achievable in presence of adequate transmission and distribution facilities and of flexibility resources able to counteract the main features of these new sources, that is to say their intermittency, variability and uncertainty.

Besides large plants owned by few international entities, renewable energy sources have supported the development also of a significant number of small and medium scale privately owned plants or

[45] IAN RUTLEDGE, *Who owns the UK Electricity Generating Industry – and does it matter?*, SERIS, UK, November 2012, pp.22

[46] IAN RUTLEDGE, *Who owns the UK Electricity Generating Industry – and does it matter?*, SERIS, UK, November 2012, pp.12

[47] MANUEL BARITAUD, *Securing Power during the Transition: Generation Investment and Operation Issues in Electricity Markets with Low-Carbon Policies*, IEA, Paris, 2012, pp.8

generating devices, directly connected to the grid. Their proliferation has been possible thanks to limited required starting investments, the important program of incentives addressed toward renewable energy and the low operating costs[48]. This phenomenon has significantly increased the number of players in this segment of the supply chain, having a crucial impact on the organization and the management of the downstream phases.

The last important topic concerning generation is the *distributed generation*. Distributed generation is an evolution of the competitive, infrastructural and technological environment created by the synergies between the rise of renewable energy sources and the market liberalization. It consists on the complex of a huge number of very small generating devices installed at demand side and directly connected to the network[49].

These devices are thought to support consumers in reducing their dependency from the electricity supply chain, leveraging auto-consumption and, on the same time, they can provide an additional flexibility resource to the system. Because of the tight interconnections with transmission and distribution plans and operations, and of the important challenges rising, we will analyze better the impact of distributed generation after having presented transmission and distribution phases.

3.1.1 Forms of Renewable Energy exploited in the Generation Phase

Once defined the competitive and ownership structure of the generation phase, it is interesting to have a brief overview of the renewable energy sources that have been fostering the transformation of the electricity sector.

First of all it is due to emphasize the distinction between *programmable* and *non-programmable sources*; programmability can be defined as the possibility to set in advance the output timing of a given plant (or system of plants) exploiting a precise energy source. *Non-programmability* entails di opposite situation, that is to say the output timing depends on the variability of the energy source, since it cannot be defined in advance.

Generally speaking, renewable energy sources tend to be non-programmable. In fact, since they depend on exogenous variables, that is to say weather conditions or geothermal potential of a site, they cannot be programmed and they are characterized by a high degree of variability and

[48] ANGEL A.BAYOD-RUJULA, *Future development of the electricity systems with distributed generation*, Energy volume n. 34, issue n. 3, March 2009, pp. 377

[49] ANGEL A.BAYOD-RUJULA, *Future development of the electricity systems with distributed generation*, Energy volume n. 34, issue n. 3, March 2009, pp. 377

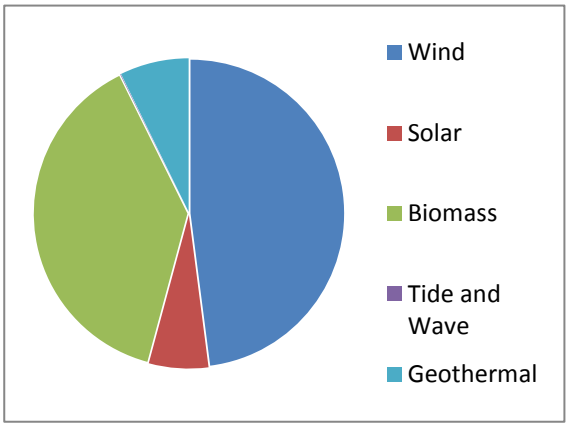
uncertainty. However, geothermal energy, even if it cannot be programmed, it presents a stable output that can be, consequently, forecasted with a certain accuracy. This leads to consider geothermal energy differently from wind, solar and hydro energy, that are purely non-programmable (except for traditional forms of hydro-power). Bioenergy represents an exception as renewable energy source, as a matter of fact its output can be modulated, making it easy to be integrated into the electricity system, being de facto programmable as the conventional sources[50].

After this distinction, we proceed with a very brief presentation of the following renewable energy forms: *wind energy*, *solar energy*, *new forms of hydropower energy*, *biomass energy* and *geothermal energy*. In addition, the following diagrams (*Graphs 4 and 5*) want to support the description of the renewable energy sources pointing out their degree of diffusion on a global scale and with a special focus on Europe.

Graph 4: World renewable sources electricity output (year 2011) distribution over the different sources

Type of Energy Source	Volume	Percentage
Wind	446,33366	47,95%
Solar	58,1853	6,25%
Biomass	358,196	38,48%
Tide and Wave	0,557	0,06%
Geothermal	67,53235	7,26%
Total Renewable Sources	930,8043	100,00%

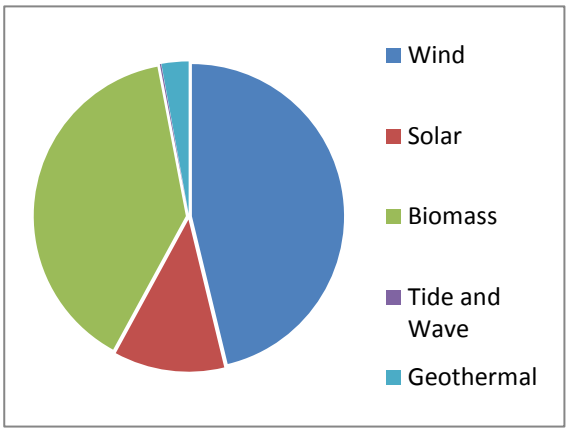
Source: International Energy Agency database



Graph 5: European (EU 27) renewable sources electricity output (year 2011) distribution over the different sources

Type of Energy Source	Volume	Percentage
Wind	181,739	46,22%
Solar	46,0779	11,72%
Biomass	153,6036	39,06%
Tide and Wave	0,527	0,13%
Geothermal	11,27	2,87%
Total Renewable Sources	393,2175	100,00%

Source: International Energy Agency database



[50] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, *Renewable energy supply chains, performance, application barriers, and strategies for further development*, Renewable and Sustainable Energy Reviews 16, 2012, pp. 5451

Wind power: concerning the exploitation of wind as energy source, it is convenient to distinguish between two types of plants that are implemented: *onshore plants* and *offshore plants*[51].

Onshore plants are a solution that has already reached a significant diffusion and degree of technological development. Nowadays, efforts are focused on maximizing the output and efficiency of those plants, by optimizing methods that concentrate on three issues: *optimal location*, *optimal plant layout and optimal size of the turbine*[52]. The combination of these three factors enables to reach the highest generation volume and, on the same time, the highest efficiency. In particular, if data are available, the optimal location is identified through time-series analysis of historical data concerning the wind speed in that location, or through the analysis of the wind speed data of close locations, and the consequent elaboration of forecasts through a precise methodology[53]. The definition of the optimal layout of a wind park is given by the optimization of the location of the turbines over the surface of the park in order to increase the volume of energy generated and, on the same time, to minimize the number of devices implemented and the extension of the surface committed to generate energy[54].

Finally, concerning the size of the turbine, recently great efforts have been addressed to the customization of the turbines according to the maximum wind speed and the extent and frequency of wind speed fluctuations that are registered over time in the location. The purpose is not only to maximize energy production, avoiding for example energy curtailments because wind speed exceeds the technical limits of the device, but also to maximize the lifecycle of the turbine and of all the underlying components[55].

The second type of plant consists on ***offshore plants***. Compared to onshore plants, offshore ones present two main advantages: higher generation potential, because wind is not constrained by obstacles like mountains or hills and because, being offshore, they have a lower impact on the landscape and on other activities like tourism and agriculture, facilitating the approval of the stakeholders involved. However, offshore plants are characterized also by some problems that are slowing down their adoption in comparison to onshore plants. These problems are mainly the need

[51] DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, *Wind Energy Report 2012*, Politecnico of Milan, July 2012, pp.24

[52] R.BANOS, F.MANZANO-AGUGLIARO, F.C.MONTOYA, C.GIL, A.ALCAYDE, J.GOMEZ, *Optimization methods applied to renewable and sustainable energy: A review*, Renewable and Sustainable Energy Reviews 15, 2011, 1757-1758

[53] A.KUSIAK, H.ZHENG, Z.SONG, *Power optimization of wind turbines with data mining and evolutionary computation*, Renewable Energy 35, 2010, pp. 695

[54] A.EMAMI, P.NOGHREH, *New approach on optimization in placement of wind turbines within wind farm by genetic algorithms*, Renewable Energy 35, 2010, pp. 1559

[55] DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, *Wind Energy Report 2012*, Politecnico of Milan, July 2012, p.26

for ad-hoc basements for the installation in open water and the development of transmission infrastructures able to connect those plants with the mainland network[56].

In particular the transmission lines must be able to minimize power losses during transportation in order not to compromise the higher generation potential of offshore plants respect to the onshore ones. Moreover, because of the high fixed costs of offshore plants, in order to exploit economies of scale they tend to be large and far from the coast, entailing significant loads on the transmission lines and requiring, as a consequence, notable investments in long distance high voltage cables, raising investments and operational costs to a great extent. In fact, substantial investment costs are actually the main obstacle to their adoption.

Looking at the installed capacity and considering both onshore and offshore plants, in Europe the main producers of wind energy are Germany, Spain, United Kingdom and Italy. At global level, the main players are China and USA, with China not far from retaining half of the total world installed capacity[57].

Solar energy: the exploitation of solar energy implies two different designs of the technology, that is to say *passive design* and *active design*[58]. *Passive solutions* are generally based on optimizing the layout and structure of buildings in order to maximize their capacity to capture sun energy, reducing their consumption of energy. *Active design* consists on using solar panels and cells for the conversion of the solar radiations into electricity, that is made available to the network[59].

Active design is the most interesting according to our perspective, since active solutions include large and small scale plants that are used to produce and sell electricity to the market. Similarly to the wind energy, optimization methods are required with regard to the identification of suitable locations and to the definition of the distribution and inclination of the devices over the surface. These optimization models are based on time-series analysis to obtain forecasts as accurate as possible.

Solar energy has also been widely applied at demand side, both through industrial and residential applications, especially as a result of the financial incentives granted by governments. This has supported the development of the distributed generation, which, as we will discuss later, is having a crucial impact on the electricity supply chain. Residential and industrial applications, in fact, not

[56] DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, *Wind Energy Report 2012*, Politecnico of Milan, July 2012, pp.24

[57] DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, *Wind Energy Report 2012*, Politecnico of Milan, July 2012, pp.24

[58] R.BANOS, F.MANZANO-AGUGLIARO, F.C.MONTOYA, C.GIL, A.ALCAYDE, J.GOMEZ, *Optimization methods applied to renewable and sustainable energy: A review*, Renewable and Sustainable Energy Reviews 15, 2011, p.1758

[59] R.BANOS, F.MANZANO-AGUGLIARO, F.C.MONTOYA, C.GIL, A.ALCAYDE, J.GOMEZ, *Optimization methods applied to renewable and sustainable energy: A review*, Renewable and Sustainable Energy Reviews 15, 2011, p.1758

only allow to reduce the consumption of energy absorbed from the network, increasing variability and uncertainty, but they also inject energy into the network causing important operational and planning challenges.

The main markets at global level are Germany and China, which account alone for more than half of the total world installed capacity, and important growth trends have been identified in the South Europe and in developing countries like India and Mexico[60].

New hydropower energy forms: the new forms of energy that are increasingly exploited are ***wave energy*** and ***tide energy***. These two sources combine a significant advantage in terms of predictability, compared to wind and solar energy, with infrastructural problems and technological difficulties that are actually slowing their adoption. In fact, tides and waves present cyclical patterns that allow to forecast them with a certain degree of accuracy; this enables clearly to lower the degree of uncertainty associated to those types of energy sources, potentially facilitating their integration into the electricity supply chain.

However they are subject to two main obstacles that are constraining their deployment[61]. The first consists on the reliability of the technologies implemented; as a matter of fact, since these technologies are at the beginning of their development cycle, several doubts arise concerning their resistance to the stress exerted over time by the overall ocean environment. The second problem, similar to the one affecting wind energy exploitation, consists on the lack of transmission infrastructures from the sites where the generating devices are located to the network.

Biomass energy: this renewable energy source is based on burning organic materials, deriving from both plants and animals, in order to produce electricity or, alternatively, for heating residential or working environments[62].

Biomass energy has a great potential in terms of efficiency along its integration into the electricity system because, differently from the other renewable energy sources, it is programmable.

The possibility to modulate the output of biomass plants avoids to raise the planning and operational challenges for the system operator that are caused by the variability and uncertainty of the other sources of renewable energy. However, despite of this advantage, biomass energy is

[60] DAVIDE CHIARONI, FEDERICO FRATTINI, GIOVANNI TOLETTI, LORENZO COLASANTI, *Solar Energy Report 2013*, Politecnico of Milan, April 2013, pp.53

[61] OCEAN ENERGY ASSOCIATION, *Industry Vision Paper 2013*, Brussels, Belgium, 2013, pp.11

[62] R.BANOS, F.MANZANO-AGUGLIARO, F.C.MONTOYA, C.GIL, A.ALCAYDE, J.GOMEZ, *Optimization methods applied to renewable and sustainable energy: A review*, Renewable and Sustainable Energy Reviews 15, 2011, p.1760

knowing a slow adoption. In Europe, for example, the main producers are Germany, Finland and Austria[63].

The slow adoption is given by several factors that we briefly present. First of all, biomass energy is a *land intensive energy source*, that is to say it requires the commitment of large surfaces to produce the bio-materials to be burned. This represents a critical aspect especially in highly populated countries or in countries with a highly developed agricultural sector. Another relevant aspect is the *social impact* of these plants; as a matter of fact, they face often a strong opposition from the local population because they are perceived as a possible threat to their health.

Finally, a factor that in many cases obstacles the deployment of this energy form on a large scale is the *weak supply of the bio-materials*. In fact, usually there isn't a structured supply chain able to provide sufficient amounts of bio-materials and at a sustainable price[64]; the supply is usually based on of many small independent suppliers that negatively affect the efficiency of the process, inevitably increasing the costs.

Geothermal energy: geothermal energy is based on the exploitation of the heat coming from the earth. An important characteristic and, on the same time, advantage of this form of energy is its low variability. In fact the output of geothermal energy plants tends be highly constant and it provides energy 24 hours a day without interruptions[65]. Consequently, differently from wind and solar energy, geothermal energy output can be forecasted with a high accuracy, ensuring stability and continuity of provision to the system. Moreover, the running costs of these plants are lower than traditional plants, with, however, a comparable stability of output.

Main obstacles are the high investments costs required to establish new plants and the challenging locations of suitable sites for their geothermal energy potential[66]. As a matter of fact, the sites with the highest potential tend to be in remote locations, posing significant problems concerning transmission infrastructure and dispatchability of the plants.

Finally, in my opinion, it is interesting to combine this brief description of the renewable energy sources with the identification of the countries playing a key role on a global scale in terms of production of electricity deriving from renewable energy sources:

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[63] DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, *Biomass Energy Executive Report 2012*, Politecnico of Milan, June 2012

[64] DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, *Biomass Energy Executive Report 2012*, Politecnico of Milan, June 2012

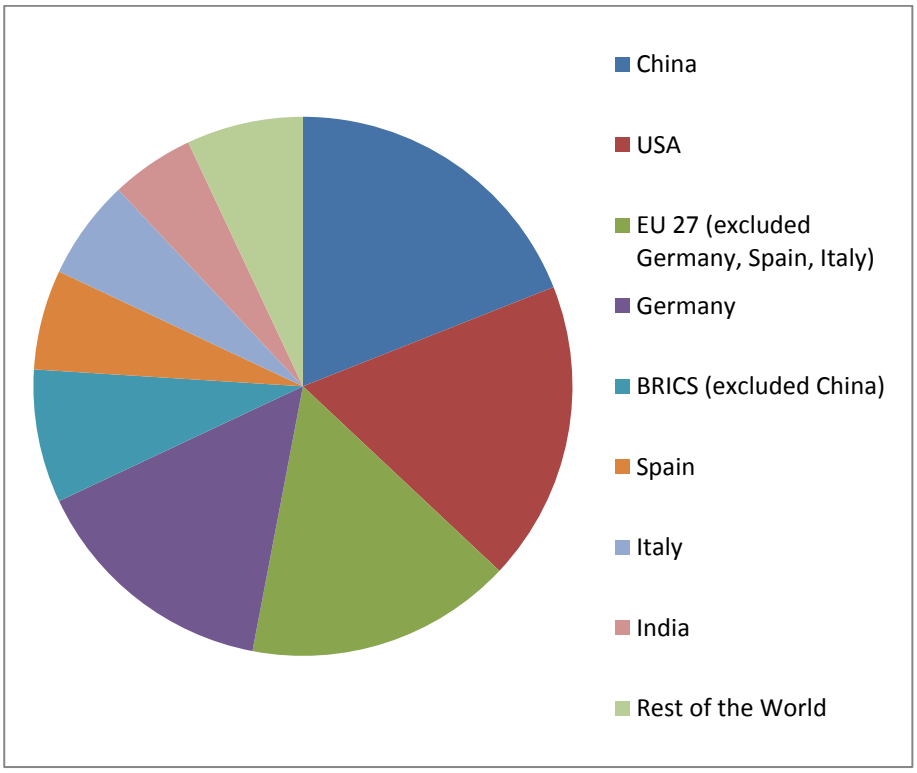
[65] R.BANOS, F.MANZANO-AGUGLIARO, F.C.MONTOYA, C.GIL, A.ALCAYDE, J.GOMEZ, *Optimization methods applied to renewable and sustainable energy: A review*, Renewable and Sustainable Energy Reviews 15, 2011, p.1761

[66] DOMITILLA CHICCHI, *Le Principali Fonti di Energia Rinnovabile*, Bollettino Ingegneri n. 6, 2010, p.7

Graph 6: Geographical Repartition of the total world installed generating power devices

Geographic Area	Percentage
China	19,00%
USA	18,00%
EU 27 (excluded Germany, Spain, Italy)	16,00%
Germany	15,00%
BRICS (excluded China)	8,00%
Spain	6,00%
Italy	6,00%
India	5,00%
Rest of the World	7,00%

Source: REN 21



Source: REN 21[67]

[67] REN 21 STEERING COMMITTEE, *Renewables 2013, Global Status Report*, REN 21, 2013, pp.17

3.2 Electricity Transmission

Transmission, together with distribution, has the role not simply to carry electricity from the generation sites to the end consumers, but it has also the fundamental role to manage the functioning of the system, ensuring its stability, security and reliability.

The integration of a significant share of electricity deriving from renewable energy sources is asking for important investments in infrastructures, not only within the national borders of each country, but also related to cross-borders operations.

Not in a far future, cross-national circulation of electricity, also for long distances, may enable to provide enormous stimulus to the establishment of renewable energy as the major source of electricity. It is sufficient to think about the potential that a cross-national circulation would have for instance in feeding the European market, as a whole, using the solar energy carried from the South-Europe and wind energy from large scale offshore and onshore plants located in the Northern countries[68].

The drivers that lead to the expansion of transmission infrastructures are mainly ensuring its security and reliability and, on the same time, its adequacy and flexibility to welcome a fast growing share of energy from renewable energy sources. Generally speaking, those investments are addressed toward two main routes, on the one hand the *retrofitting and expansion of the existing infrastructures* using new technologies in order to increase their capacity, resistance and compliance to the new patterns of supply and demand, and, on the other hand, investments thought to establish *new network infrastructures through green-field projects*, with a special attention to long distance lines.

According to the Susplan project promoted by the European Commission[69], the great majority of the bottlenecks that the transmission network would suffer in the next few years, in absence of adequate structural interventions, is referred to the integration of renewable energy sources. Therefore, system operators and national and supranational regulators need an accurate forecast of the scale, the pace of development and the geographical distribution of the main renewable energy generation facilities.

As we have seen before, wind energy has already reached an important diffusion and installed generation power, especially in the form of onshore facilities, whereas offshore technologies are

[68] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy volume n. 67, 2014, p. 170

[69] BJORN BAKKEN, INGEBORG GRAABAK, *Development of regional and Pan-European guidelines for more efficient integration of renewable energy into future infrastructures*, SINTEF Energy AS, 2012, pp.53

going to spread rapidly thanks to their high potential, in particular in countries like Norway and Ireland[70]. Concerning the solar energy, technologies have recently known notable improvements in terms of performance and efficiency, making this kind of renewable energy highly appealing in the present and in the next future.

In opposition to wind energy, most interesting areas are located in the South Europe; great interest is addressed to all the desert areas in the North Africa and Middle East[71]. This last scenario clearly has to be located farther in the future because of its technological requirements and, not less important, geo-political factors that may prevent a cost-effective exploitation of those areas.

However, from a supply chain perspective, technologies (mostly HDVC lines) that are actually starting to be implemented may fill, within the 2050, the technological gap to connect those areas with European networks and consumption areas[72].

Biomass is knowing a slower development mainly because of two factors. On the one hand a poor supply chain that is not able to support efficiently the development of this energy source, in particular because of the difficulties concerning the procurement and transportation of the biomaterials that raise the operating costs. On the other hand, a delay in the development of the technologies necessary to exploit this energy source is compromising its economic appeal.

Finally, geothermal energy and the energy deriving from waves and tides are forecasted to reach a low level of penetration in the next few years[73]. The first obstacle preventing their diffusion is their abundance in locations not easily accessible for the installation of generating plants and, especially, far from the closest network available for the transmission of the electricity produced.

As mentioned before, the *two drivers* that are leading network expansion are the *increasing penetration of renewable energy sources* and *the location of the sites* where energy is produced in relation to the actual coverage and capacity of the network. In particular significant investments are in progress in order to support energy transmission from the area with the highest generating potential, that is to say the Mediterranean countries like Spain and Italy and the Northern countries like Sweden and Norway, to the large consumption areas in Central Europe.

It is important to emphasize that the scale of these investments is progressively reduced by a more effective and, on the same time, efficient integration of the distributed generation, of a higher

[70] DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, *Wind Energy Report 2012*, Politecnico of Milan, July 2012, pp.30

[71] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy volume n. 67, 2014, p. 173

[72] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, p.26

[73] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, *Renewable energy supply chains, performance, application barriers, and strategies for further development*, Renewable and Sustainable Energy Reviews 16, 2012, pp.5451

demand response and by the continuous improvements of the technologies. As already discussed, the development of renewable energy generating technologies has made affordable the installation on demand side of medium and small generating systems connected to the grid.

These systems have experienced a huge diffusion thanks to the limited installing and maintenance costs and thanks to the financial incentives and facilitations provided by governments to increase the attention of the mass addressed toward green energy sources. The integration into the network of these small devices in the framework of smart grids is having a great impact on the management of the transmission. The main problem relies on forecasting the volume of energy injected into the network by the multitude of dispersed small and medium size devices, in order to balance supply and demand and to ensure the stability of the system. Accurate forecasts are highly challenging because of the uncertainty and variability of non-programmable renewable energy sources and because it is necessary to forecast the net quantity generated by the devices, that is to say the overall generated volume minus the volume consumed directly in site by the consumers, quantity that obviously is subjected to the variability of demand (even if precise restrictions and limits are enforced to reduce volatility).

Managing the whole electricity system can be summarized in three fundamental phases from the perspective of the system operator[74]:

- forecasting and planning
- real time monitoring of the network
- performance analysis

During the *forecasting and planning phase*, the system operator forecasts the future energy demand with regard to different time buckets (days, week, year), using algorithms consolidated over time mainly through ex-post simulations[75]. The information necessary to elaborate accurate forecasts are the forecasts provided by retailers concerning their future demand, time-series concerning the demand per region and per calendar profile of the day, expected weather conditions, socio-economic events. All these aspects have to be matched with the available transmission capacity, the operating limits of the infrastructures and with the electricity that must be available for the system operator in the form of operating reserves.

Concerning the second phase, the *real time monitoring*, its purpose consists on ensuring at any time the fulfillment of demand and, simultaneously, the continuity of service and at a predefined quality

[74] TERNA RETE ITALIA, *Criteri di Telecontrollo e Acquisizione Dati*, November 2002, p.5
[75] TERNA RETE ITALIA, *Criteri di Telecontrollo e Acquisizione Dati*, November 2002, p.5

level. In particular, the system operator focuses the attention firstly on the availability of the components of the system, for example verifying whether the generators are supplying the amount of energy required by the agreed production plan or optimizing the transmission capacity allocation in case of failure of components. Moreover, the system operator has to monitor and, eventually, adjust frequency and voltage along the network, and it has to manage all the interconnections with other national networks. This aspect is becoming more and more important since, as already discussed, the electricity sector is characterized by a progressive convergence of stand-alone national supply chains toward a system of connected and actively interacting supply chains, within the frame of a common supranational market. Finally, the system operator has to verify the effectiveness and readiness of all the recovery actions and systems, like, for instance, the black-start recovery mechanism in case of failure of the entire system[76].

Thirdly, *performance analysis* consists on assessing the performance of the system both during the normal functioning conditions and after the occurrence of a failure. Relevant aspects are for example the consistency of the energy generated with the amount planned, the demand forecasts accuracy, the forecasts accuracy with regard to the energy produced by renewable energy sources (also with the aim to adjust the model parameters through ex-post simulations in case of poor accuracy), and the ability of the system to implement measures to ensure an effective and quick recovery.

The management of the network is accomplished through the interaction of the centralized control unit with several decentralized units that have competence in precise regions[77]. All the functions of the system operator are supported by the monitoring system, which covers the entire network, and the weather forecasting system, in charge for providing the most accurate forecasts, which are fundamental for forecasting both demand and supply. The monitoring system has a complete coverage over the network, controlling in real time all the entities that can have an influence on the network, and transmitting real time data to the central system unit.

3.2.1 Barriers against Network Infrastructures Expansion

The expansion of network infrastructure is slowed down by *technical* and *non-technical* barriers, where non-technical barriers are related, generally speaking, to all the stakeholders interacting with the electricity supply chain.

[76] TERNA RETE ITALIA, *Criteri di Telecontrollo e Acquisizione Dati*, November 2002, pp.5
[77] TERNA RETE ITALIA, *Criteri di Telecontrollo e Acquisizione Dati*, November 2002, pp.5

These barriers can be divided into three broad categories, that is to say[78]:

- barriers referred to long-term planning and authorization
- barriers related to investments financing
- barriers related to the management of transmission infrastructures

Planning a new investment in infrastructures is highly difficult because it has to deal with a plurality of aspects that implies a certain degree of uncertainty, like for example how generation capacity will evolve, which technology is going to be the most convenient in the medium and long run and the variation of demand.

Trying to have a closer perspective on the concrete obstacles referred to *planning a new infrastructural investment*, it is convenient for instance to consider the interplay occurring between energy infrastructures planning and many other interests and related planning dimensions, like for example new investments in the transportation infrastructures, the priority given in certain locations to agricultural activities or the negative impact of some infrastructures on tourism. The sum of all these aspects inevitably increases the uncertainty underlying a plan.

In fact, many parties take part to the planning process and the development of a new energy infrastructure. The operator is clearly in charge for elaborating the plan and the project for the investment, but, after that, several institutions, non-governmental organizations and authorities have the power to influence the progress of the plan, delaying it or, in extreme cases, preventing its realization[79]. As a matter of fact, the intervention of many entities and the fulfillment of all their requirements may determine leading times and costs able to compromise the convenience of the investment itself.

The situation may be worse in the case of plans concerning cross-national interconnections. In fact, many transmission operators have been facing severe difficulties in improving the transmission capacity and, consequently, the capacity and security of the entire national supply chain because of the lack of homogeneity of the planning and administrative procedures enforced in the states interested by the project.

In order to facilitate and support large scale projects, which strategic relevance in the continental electricity supply chain is unquestionable, European member states are converging toward a

[78] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, pp. 175

[79] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions,* Energy Policy 67, 2014, pp. 175

harmonization of regulations and procedures[80]. This represents a viable step in the process of integration of renewable energy sources, since a poor available capacity at the interconnections between national networks would hardly affect the expansion of the potential of these energy sources.

As we have seen, many parties are involved in the development, approval, and realization of a plan concerning energy infrastructure expansion; each of those parties may represent an obstacle and negatively impact on the progress of the project. A force that is having a relevant strength is the public opposition, which has been being able to cause significant delays or, even, in some case, project rejections[81].

A first reason that explains the public opposition is the fact that a large deployment of non-programmable renewable energy sources, together with the implementation of distributed generation and smart grids technologies, is requiring deep changes in the behaviors and habits of consumers. The departure from habits and behaviors that have been applied for many years is commonly perceived by the society as an event with negative disruptive effects. The resistance against new renewable energy sources infrastructure plans can be associated with the "not in my back Yard syndrome"[82], which implies a general acceptance of these projects but, however, under the condition that they are not planned in a close location. One of the main drivers of this syndrome is the fear of negative health implications or of a worsening life quality. In addition we identify for sure an economic reason, mainly based on the potential reduction of the revenues deriving from activities carried out in the area, like for example agriculture and tourism, and the decrease of the value of the real estate properties located in the proximity[83]. Finally, environment and landscape protection may exert a significant opposition, especially in certain territories.

The second broad category of barriers consist on *financing infrastructure investments*. It is a crucial aspect, since these investments require substantial capitals. Moreover, since their lifetime and payback periods take many years, they necessitate a stable regulatory framework and a long term industrial plan.

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[80] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, pp.180

[81] BJORN BAKKEN, INGEBORG GRAABAK, *Development of regional and Pan-European guidelines for more efficient integration of renewable energy into future infrastructures*, SINTEF Energy AS, 2012, pp.53

[82] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, p. 176

[83] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, p. 176

The main difficulty related to a large penetration of renewable energy sources in Europe is determined by the need of a mechanism able to efficiently allocate the costs of new infrastructural investments among all the parties interested by the project. As a matter of fact, a biased costs allocation mechanism may penalize the countries investing in the development of renewable energy generation and transmission, since they would bear alone all the costs related to the investments even if the electricity produced and, consequently, also its benefits, are largely transferred to adjacent countries. This unbalanced repartition of the financial efforts underlying a new investment may, consequently, obstacle its progress.

The last category of barriers concerns infrastructures management and, especially, the procedures to allocate transmission capacity and to solve congestions. This topic, as we know, is crucial in a context characterized by a large deployment of non-programmable renewable energy sources, raising great challenges in terms of optimization of capacity allocation, both within the national borders and through cross-borders interconnections, and in terms of the mechanisms implemented to counteract to network congestions, in particular reactive actions implying a balancing of demand and supply between adjacent countries. In fact, balancing demand and supply across national borders to fully exploit the potential of renewable energy is still constrained by the different prices charged at the two extremes of the cross-borders interconnections[84]. In fact, the price difference may suggest to the system operator to maintain the equilibrium between the national aggregate demand and the national aggregate supply not thanks to a balancing energy flow through the interconnections, but taking action directly on the national demand or supply, for example curtailing the internal energy generation. This action would harm directly the production of renewable energy.

Production curtailments to ensure the stability of the system are taken with regard to renewable energy sources because of their flexibility, instead of modifying the output of conventional plants, which provide inertia to the system and which present flat ramp curves.

This is a very important aspect in the electricity supply chain after the rise of renewable energy sources. The supply chain delivers electricity produced by two types of plants: ***conventional plants*** (thermal and nuclear plants) and ***plants exploiting renewable energy sources*** (wind, sun, waves..).

The combination of the intermittency of renewable energy generation and the increased demand unpredictability and volatility (because of the effects of distributed generation) has been requiring an extremely high degree of flexibility of the generation system. In fact, even if supported by storage devices located along the supply chain and by smart grid technologies that enhance demand

[84] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, pp. 177

response, the system operator requires the ability of generators to quickly adjust their output according to the sudden variations of demand.

However, conventional plants based on nuclear or thermal technologies present very flat upward or downward ramp curves, being able to provide a stable base-load output, but presenting very low response times in case of requests of significant variations of production[85].

As a consequence, given the limited cross-border balancing energy flow because of the obstacles seen before, the alignment between demand and supply is achieved by increasing and decreasing renewable energy production. This is an issue that requires great attention according to the aim to obtain in few years that the majority of electricity derives from renewable sources; it emphasizes the need to combine the flexibility of renewable sources in matching demand fluctuations with the system ability to ensure a stable and constant base-load in absence of conventional plants. In this sense, further developments of cross-regional and cross-border interconnections are a potential solution that has to be associated with a large scale usage of storage technologies at all the phases and with the rationalization of electricity consumption enhanced by demand response. This solution enables to stabilize supply and demand and to ensure adequate reserves.

A last barrier related to infrastructures management is referred to the poorly harmonized network codes among countries[86]. In fact, the large penetration of renewable energy sources into the traditional electricity supply chain has requested many adaptations of the grid codes and of the operational processes. However these adjustments have been taken mainly at local level without international coordination, causing sever difficulties in interconnecting national supply chains.

The lack of harmonization determines also a poor coordination in planning an efficient infrastructure usage and expansion[87]. A key aspect, already mentioned, is the absence of mechanisms able to fairly distribute the costs of infrastructural investments among all the parties involved. In order to stimulate investments, it is necessary to ensure a balanced allocation of the costs. For example, assuming the construction of high voltage transmission lines for long distances to carry electricity from regions with a high endowment of renewable energy sources to large consumption areas with a low renewable energy potential, it is clear that the region grasping the main benefits are the consumption areas that are served by the green electricity produced elsewhere.

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[85] GIANFRANCO CHICCO, PIERLUIGI MANCARELLA, *Distributed multi-generation: A comprehensive view*, Renewable and Sustainable Energy Reviews 13, 2009, 535–551

[86] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, p. 178

[87] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, pp. 178

These benefits, however, are granted by the long distance transmission lines built in the generating regions and in the transit regions, overcoming all the obstacles previously seen concerning the realization of a new project. Consequently, in order to effectively support further expansion of the transmission lines, that are fundamental to foster a large deployment or renewable energy sources, it is necessary to define a fair mechanism of allocation of costs and revenues able to reward countries that bear the major costs, and able to ensure a financial contribution from countries having the main benefits from the investment, without having proportionally participated to its realization.

3.2.2 Long-term Strategies to overcome Barriers

The described barriers necessitate ad-hoc strategies aimed to overcome the problem underlying them, ensuring an infrastructural development consistent to the needs advanced by the large scale development of renewable energy sources.

The first category of barriers we have dealt with is related to the authorization procedures and the reactions of stakeholders. For sure, an effective way to smooth authorization procedures and to reduce the lead times consists on establishing the basis for a *large public acceptance*[88]. This is possible involving the public from the earlier steps of the planning process, ensuring transparency and open information sharing about the investment costs and the impact on health and environment. This involvement, on the other hand, must be adequate to the time granted to consultations in order to avoid an excessive duration of the planning process. Moreover, in several regions, effective mechanisms to fairly allocate compensations and revenues to the population affected by the new infrastructures are having positive results.

Concerning the second category of barriers, that is to say investments financing, the already discussed process to distribute costs and revenues deriving from a new investment is a really effective tool. This should be integrated by a mechanism at national and international level to identify priority investments for the development of the supply chain, in order to facilitate their realization.

Finally, according to the type of barriers belonging to the third category, in order to further facilitate the integration of renewable energy sources it is necessary to optimally use the existing infrastructures and to set up a coordinated approach to network and congestions management.

[88] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, p. 179

In this direction, it is worth the adaptation of the CACM (capacity allocation and congestion management) mechanisms[89]. These mechanisms enable first of all a superior network capacity management through the consideration and simultaneous coordination of both internal and international constraints, de facto reducing the barriers toward a higher integration of national electricity supply chains, ensuring all the benefits in terms of exploitation of renewable energy sources that we discussed earlier.

An additional important step consists on harmonizing network codes and technological and structural requirements among the national supply chains. The aim is to increase system security and efficiency, defining standard procedures and infrastructures, and to increase the flexibility of the system to better support the integration of renewable energy sources, for example through the adoption of control centers and new technologies.

3.2.3 Optimal Allocation of Transmission Capacity and new Transmission Technologies

In the previous chapter we have seen how the integration of renewable energy sources has made more and more fundamental the efficient transmission of electricity for long distances.

National supply chains have been investing in transmission infrastructures in order to strengthen them according to the needs and the challenges arising from the deployment of renewable energy sources. An interesting aspect of these investments is their timing, as a matter of fact the technologies and the components that are under replacement are close to the end of their lifecycle. In fact, the underground and overhead lines and all the controlling and operating components were installed approximately five decades ago and they were not conceived to work with non-programmable renewable energy sources, distributed generation and demand response. Consequently, the overlapping of the end of their lifecycle with their becoming technologically obsolete, because of the transformation in the electricity industry, represents a unique opportunity to revolutionize the network through substantial investments.

A new interesting technology for instance consists on *high temperature lines*, which enable to increase transportation capacity at high voltage without establishing new corridors through green-field investments but, simply, substituting the existing wires. The retrofitting of existing lines allows to significantly increase transmission capacity without notable investments, as in the case of

[89] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, p. 181

the construction of new infrastructures. However, they require some interventions, in particular the upgrade of some elements of the lines, like the transformers, and they require sometimes to verify whether the increased capacity of the lines may determine a rise of losses along the network.

Since overhead lines tend to face obstacles for their approval because of their visional impact, underground current cables represent an effective alternative. However they present some negative aspects that are still slowing their large scale adoption: they cannot be as long as the overhead lines, and, in case of a failure, its detection may represent a severe problem; finally, they have some complications when implemented in networks with several interconnections[90].

High voltage direct current transmission (**HVDC**) ensure lower losses than traditional alternating current lines over long distances[91]. Moreover, this kind of technology allows a superior control over the energy that circulates in the network. HVDC lines are consequently extremely interesting for the large scale deployment of renewable energy sources since they increase the efficiency of the transmission over long distances, that is fundamental for cross-border interconnections and for virtually making closer generation facilities in remote locations and major areas of consumption.

Finally, the ***flexible alternating current transmission*** (**FACTS**) significantly improves the responsiveness of the system toward sudden and unpredictable changes in the network conditions[92]. That enables to increase the system flexibility and reliability, providing a fundamental support for the integration of non-programmable renewable energy sources within the supply chain.

However, in addition to the technological improvements in transmission networks, it is viable to optimize the exploitation of the existing infrastructures.

A first important aspect consists on the rationalization and efficient allocation of the available transmission capacity[93]; the capacity factor of each generating plant varies according to different variables, like availability of the energy resource and potential technical faults or maintenance interventions. Since network lines are shared among a number of plants, conventional or renewable energy plants, it is important to efficiently allocate the entire transmission capacity among them according to their capacity factors in that moment, before, proceeding eventually with curtailments that would penalize renewable energy sources because of their higher flexibility.

[90] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, p.25
[91] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, p.26
[92] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables,* Paris, 2008, p.26
[93] INTERNATIONAL ENERGY AGENCY, *Secure and Efficient Electricity Supply During the Transition to Low Carbon Power Systems*, Paris, 2013, pp.15

3.3 Electricity Distribution

In the previous chapter we focus the attention on the transmission phase, that implies electricity circulation at high voltage over long distances, and we tried to discuss how a large scale deployment of non-programmable renewable energy sources is challenging planning and operational procedures.

However renewable energy sources have been significantly changing also the structure of electricity medium and low voltage distribution, that is to say the section of the network that works as a link between the high voltage transmission lines and all the end users connected to the grid, ensuring the maximum capillarity in terms of coverage of the territory.

The fundamental transformation has being determined by the development of a multitude of dispersed medium and small size generating devices exploiting renewable energy sources in the form of wind and solar energy. As a matter of fact, before the rise of renewable energy sources, the conventional structure of the supply chain was based on the energy generation located upstream in the chain and on the electricity flowing downstream in a single direction till the end users. Distributed generation, distributed storage devices and demand response are completely changing distribution patterns, causing a shift from the traditional passive network management to an active highly dynamic one[94]. Today, consequently, the fundamental challenge consists on the effective and efficient integration into the system of all distributed renewable energy generating devices.

Over the last years, as we have seen, the electricity sector experienced an additional fundamental transformation consisting on liberalization and vertical unbundling of the supply chain. As a result, a rapidly increasing number of companies have requested to connect to low or medium voltage network lines, forcing distribution network operators to integrate them, maintaining a high efficiency of the system to avoid costs increasing and, on the same time, without compromising the existing service quality.

The rise of renewable energy sources has been consequently changing the goals of planning processes, requiring to maximize the exploitation of existing network infrastructures, operating them just below their structural constraints. Moreover the deployment of storage devices along the whole network, the development of an active and responsive demand and the development of more

[94] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, *Renewable energy supply chains, performance, application barriers, and strategies for further development*, Renewable and Sustainable Energy Reviews 16, 2012, pp.5460

complex forecasting and planning processes have implied a switch from a load following paradigm to a new paradigm able to buffer renewable energy uncertainty and volatility[95].

Common critical aspects deriving from renewable energy sources exploitation are for example voltage fluctuations, network available capacity and its optimal usage, sources of reactive power for the system security and infrastructural components deterioration because they are not conceived to comply with the technical and operational features associated to non-programmable renewable energy sources[96].

An effective and efficient integration of renewable energy sources into the distribution network requires to deal with some important issues that have the power to significantly smooth the transition: selection of the *optimal network structure*, *enhanced information and communication technologies and systems*, *new planning* tools for renewable energy sources integration and *optimization of the management of the ageing infrastructures* of the distribution network[97].

3.3.1 Selection of optimal Network Structure

Concerning the selection of the optimal network structure, traditional networks, according to the single direction top-down structure of the supply chain, were based on ***radial structure***. However, the deployment of renewable energy sources is increasing technical and operational challenges to a great extent, like for instance maintaining stable frequency and voltage and optimizing network capacity exploitation, making radial networks no more competitive and converging toward a ***meshed network structure***[98]. As a matter of fact, a meshed network is more suitable and appropriate to develop an automated active and flexible network, able to cope with non-programmable renewable energy sources. As we have seen, flexibility of the system is a fundamental requirement to deal with the volatility of energy generation from renewable sources and their poor predictability, enabling to reduce production curtailments, energy losses and making the system more secure and stable.

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[95] DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, *Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato*, 2001, pp.6

[96] DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, *Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato*, 2001, p.5

[97] FABRIZIO PILO, GIANNI CELLI, EMILIO GHIANI, GIAN GIUSEPPE SOMA, *New electricity distribution network planning approaches for integrating renewable*, WIREs Energy Environ 2013, 2: pp.141

[98] FABRIZIO PILO, GIANNI CELLI, EMILIO GHIANI, GIAN GIUSEPPE SOMA, *New electricity distribution network planning approaches for integrating renewable*, WIREs Energy Environ 2013, 2: p.143

3.3.2 Improvement of Information and Communication Technologies Support

In order to monitor and manage in real time such a complex structure, the system operator needs a network structure able to facilitate automated processes, and information and communication technologies that provide detailed real time information concerning any single component of the network.

In order to have full control over the whole distribution network and to actively manage it from the central unit, the system operator has been promoting the integration into the network of a complex system of hardware and software, like communication tools, remote control devices and software, that must be consistent and interconnected along the entire supply chain.

The aim is to make all the players and infrastructures of the system behaving as a single body controlled and guided through a centralized control unit[99]. This topic represents a key aspect for the deployment of non-programmable renewable energy sources, because their integration without the possibility to effectively monitor and govern the entire supply chain in real time would have disruptive effects, especially for the impossibility to elaborate in advance accurate plans and to remain adherent to them, according the unpredictability and variability of renewable energy sources.

A crucial aspect, that is always important to emphasize, is that networks and systems have not been conceived and designed on the basis of the characteristics of the renewable energy sources that have entered the electricity industry. Networks and systems were thought to operate with the traditional top-down organization of the supply chain and in presence of a limited volatility and uncertainty. That has determined the need to empower the network capacity and flexibility both from an infrastructural and planning perspective.

3.3.3 Probabilistic Approach and Multi-Objective Optimization

Concerning the planning perspective, new planning methodologies have been implemented or are still under development; the new methodologies are thought to deal, clearly, with a high degree of uncertainty and they are based on a *probabilistic approach*, on *time-series analysis* and on *multi-objective optimization*.

[99] DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, *Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato*, 2001, p.5

In the following analysis we try to have a look of the most meaningful changes in the planning process and the solutions that have been implemented to cope with the deployment of renewable energy sources.

Concerning data modelling, in the traditional approach, loads data have been used to determine typologies of customer profiles on the basis of their requests in terms of loads and on the basis of the patterns of their electricity demand. Starting from a yearly base volume of demand and generation, the combination of the different profiles has been used in order to identify the worst operational conditions that could occur, and the resulting extreme scenarios have been applied in a deterministic approach to assess network adequacy and to plan network management and expansion[100].

The main problem concerning this way of approaching the planning tasks consists on the fact that the network is conceived and developed considering the occurrence of the extreme scenarios as certain, even if, in reality, the probability is very low, seriously affecting network management efficiency. As a matter of fact, assuming as certain those scenarios and planning and managing the entire system on the basis of those extremes lead to a really static model, incapable of dealing with the variability and uncertainty of renewable energy sources and incapable of allocating efficiently network capacity and resources, because anchored by the requirements of the extreme scenarios.

Integrating variability and uncertainty of non-programmable renewable energy sources into the planning process represents a fundamental step to achieve an efficient and effective management of the system[101].

A relevant aspect consists on defining in which measure operating aspects should be modeled, defining for example the level of granularity of the forecasting and planning dimensions. For instance, too small time buckets may lead to overload the planning process or, in the opposite case, a low granularity may prevent from spotting important operational details.

The solution that is often applied is based on the identification of typologies of days according to calendar position, socio-economic events and weather conditions, in order to draw approximately the patterns followed by demand and supply over the year. After that, each of these days is split into small time intervals (for example one hour) in order to identify hourly patterns of demand and supply, within their general patterns associated to that day typology. The uncertainty of their patterns is integrated in the planning process through the application of appropriate probabilistic

[100] FABRIZIO PILO, GIANNI CELLI, EMILIO GHIANI, GIAN GIUSEPPE SOMA, *New electricity distribution network planning approaches for integrating renewable*, WIREs Energy Environ 2013, 2: p.146

[101] DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, *Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato*, 2001, p.7

density functions, for instance Gaussian distribution, and the concept of acceptable risk[102]. The consideration of the concept of risk in the management of the supply chain, as required by the unpredictability of non-programmable renewable energy sources, represents a really important difference compared to the traditional approach. According to the new approach, the planning process becomes a complex of problems of *decision-making under uncertainty*, granting a key role to the concepts of *probability* and *expected value*[103].

In the case in which the probabilities associated to the values of the variables are known, clearly the operator can select the probability distribution function that best fits the specific scenario. However, if probabilities are unknown the operator can estimate them through a *subjective interpretation approach*, according to his expertise and know-how. Thanks to this probabilistic approach, the system operator, through statistical verification tests of a hypothesis and through confidence intervals, can make assumptions on the values of the variables with relative confidence.

Uncertainty is not only connected to the short term volatility of loads and generation volumes because of the integration of renewables, but it is also linked to the medium and long term development of the technologies underlying the electricity supply chain and the deployment of non-programmable renewable energy sources. Since many technologies are at the beginning of their technological development cycle and since even the supply chain structure itself is evolving, long term planning implies a high degree of uncertainty. Consequently, a probabilistic approach based on probabilities and expected values is a suitable tool also to identify possible investment solutions for the long term, for example solutions able to minimize the expected value of operating costs[104].

The vertical unbundling of the electricity supply chain has clearly increased the number of participating entities, determining an interplay (often a tradeoff) among several different interests: for example the regulator is willing to speed up a large scale deployment of renewable energy sources while keeping low the costs, generators and retailers want to maximize their profits, and consumers want to take the greatest advantage from the small generating devices they own. A *multi-objective decision making and optimization process* is necessary to combine all these clashing aims and to find a set of solutions able to provide a suitable compromise[105].

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[102] FABRIZIO PILO, GIANNI CELLI, EMILIO GHIANI, GIAN GIUSEPPE SOMA, *New electricity distribution network planning approaches for integrating renewable*, WIREs Energy Environ 2013, 2: pp.146

[103] DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, *Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato*, 2001, pp.7

[104] FABRIZIO PILO, GIANNI CELLI, EMILIO GHIANI, GIAN GIUSEPPE SOMA, *New electricity distribution network planning approaches for integrating renewable*, WIREs Energy Environ 2013, 2: pp.146

[105] DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, *Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato*, 2001, pp.7

The identification of a panel of solutions, but not a single optimal solution, may entail a problem: the selection of the solution to be implemented depends on subjective evaluations carried out by the decision maker through the incorporation of judgmental factors, potentially leading to a lack of objectivity and methods. The selection of the single solution can be reached by assigning a coefficient to each planning alternative and, then, selecting the alternative leading to the best expected value of the variable considered as priority[106].

3.3.4 Interplay between Distribution and Distributed Generation

We have seen how uncertainty has changed the planning process in the distribution phase. An important source of uncertainty is distributed generation. As a matter of fact, a huge amount of small devices, highly different among each other in terms of size, type of energy exploited and technology applied, makes extremely difficult to forecast the volume of energy that will be produced by them, the share of this volume that will be injected into the network and, finally, the resulting level of aggregate net demand.

The rise of distributed generation is posing difficult challenges in network management, and system operators not always appear willing to support an effective integration of these technologies through a revolution of the planning and operational processes. Especially in the initial phase, many national supply chains have been reluctant to modify their practices, trying to integrate renewable energy sources and distribute generation keeping unchanged the system as much as possible[107]. For example, a relevant obstacle has been the transition from radial networks to meshed networks (that is currently in progress), and, generally speaking, the retrofitting of many components of the low voltage and medium voltage lines in order to ensure their compatibility with a bi-directional flow of energy at the connections with the final users, and a flexibility of the distribution network able to cope with the variability of energy production. In fact, many system operating companies have tried to charge to the owners of the distributed generators the costs referred to the infrastructures expansion and updating, and to obtain from the regulator more strict rules and requirements in order to limit the number and the heterogeneity of the devices connected to the grid[108].

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[106] DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, *Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato*, 2001, pp.7

[107] ANGEL A.BAYOD-RUJULA, *Future development of the electricity systems with distributed generation*, Energy Volume 34, Issue 3, March 2009, pp. 378

[108] ANGEL A.BAYOD-RUJULA, *Future development of the electricity systems with distributed generation*, Energy Volume 34, Issue 3, March 2009, pp. 378

However, improvements in planning and operating models, and the high pace of development of the technologies underlying renewable energy sources exploitation have been enhancing the important role that distributed generation is going to play in increasing production capacity of the system, without requiring proportional investments in the transmission and distribution infrastructures and postponing or reducing them.

In my opinion, as a result of the last consideration, before entering more in details into the concept of flexibility of the supply chain and the solutions to the operational challenges arising because of renewable energy sources, it is appropriate to briefly describe what distributed generation is and what it implies in the context of long term and short term planning of the electricity supply chain.

3.3.5 Distributed Generation

Distributed generation can be considered the result of the combination of the improvement of technologies enabling to exploit wind and solar energy through small scale devices, making it affordable for consumers, and of the deregulation and vertical unbundling experienced by electricity sector in all the modern countries. These small scale devices present a size comprised between 1KW and 1MW, and, important characteristic, they are located in the same sites of the loads[109]. These small devices can be integrated with management system and storing technologies that enable to significantly increase the importance of the role that they are able to play, both in terms of demand fulfillment and system security.

Distributed generation is having a huge impact on the electricity supply chain, really implementing a revolution. The traditional supply chain configuration was based on a top-down stream of the electricity generated by large scale programmable plants located close to the consumption areas, and on energy transmitted at high voltage by the system operator and distributed at low voltage by passive and radial networks terminations.

Renewable energy sources and distributed generation have significantly changed the supply chain both in the generation phase and in the distribution phase[110].

In the generation segment, the transformation has implied the progressive integration, in addition to the traditional programmable plants, of large scale plants exploiting renewable energy sources, with

[109] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp.101

[110] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, *Renewable energy supply chains, performance, application barriers, and strategies for further development*, Renewable and Sustainable Energy Reviews 16, 2012, pp.5457

a size approximately comprised between 100MW and 1GW and of a huge multitude of small devices, exploiting solar and wind energy[111]. Both large plants and small devices are not programmable and they present a really heterogeneous distribution in the territory, since large plants tend to be in remote locations, where energy sources are abundant, whereas small devices are close to consumers.

Concerning the distribution phase, the network is experiencing a transition from a passive system based on a single-direction energy flow through radial networks, to an active system based a bi-direction energy flow, meshed networks and the task to coordinate the co-working of several components, like storage devices, and automated tools for real time monitoring and management of the system.

Distributed generation appears as a controversial topic in the current development of the electricity supply chain because it entails important benefits but, on the same time, it raises significant challenges and technical problems.

Long Term Planning and Short Term Operational Advantages associated to Distributed Generation:

Distributed generation facilitates the process of integration of renewable energy sources increasing production capacity, enlarging the energy portfolio and, potentially, buffering the variability of energy production of large scale plants exploiting renewable energy sources.

Moreover, distributed generation, producing electricity directly where the demand is located, significantly helps to overcome network congestions in an efficient way.

In fact, being able to partially satisfy customers demand in a direct way and without requiring energy to cover long distances over the transmission and distribution lines, it enables to reduce network capacity usage, decreasing the likelihood of congestions. That allows to reduce or postpone infrastructural investments that otherwise would be immediately required to ensure the security of the system[112].

In addition, the lower amount of energy transferred over the network allows to reduce energy losses during the circulation and to limit transmission and distribution costs, increasing the overall efficiency of the system[113]. They can play an important role also in terms of enhanced flexibility and responsiveness in expanding production capacity because, thanks to their limited size and short

[111] ANGEL A.BAYOD-RUJULA, *Future development of the electricity systems with distributed generation*, Energy Volume 34, Issue 3, March 2009, p. 377

[112] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, pp.21

[113] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, pp.21

construction times and installing costs, it is quite simple to find a suitable site, even if in highly populated areas, and they can be built in a short period of time.

Planning and Operational Problems deriving from Distributed Generation:

After having briefly discussed the main benefits provided by distributed generation, it is due to point out also the technical problems and challenges resulting from its implementation.

The first problem, already emphasized, consists on the ***inversion of energy flow***: electricity produced by consumers is injected into the low voltage network and, then, into the high voltage network to be transferred in another location. This process stresses some components of the network risking to lead them toward failures, and it makes necessary to modify planning and operational processes[114]. Moreover the electricity injected into the network in some cases determines a rising voltage, which may be positive in some areas characterized by excessive low voltage, but that, in standard situations, may represent a severe problem.

Finally an aspect the captures growing importance is the difficult integration of smart grids in the mechanisms for providing ancillary services and reactive power, and to participate to the restoration of the network in case of failure.

As seen earlier, distributed generation and the new challenges emerging in the distribution phase are tightly linked. Together they are driving the distribution phase of the supply chain toward active distribution networks with meshed networks and a constant close interaction among generators, distributors and consumers.

A last consideration is addressed to storing technologies. Storing technologies are going to play a fundamental role in accommodating the exploitation of renewable energy sources, both in terms of large plants and distributed small devices, solving many technical challenges and providing security and stability to the system. Distributed generation, as all the segments of the supply chain, is going to be notably empowered by those technologies, becoming less challenging for distribution operations.

[114] ANGEL A.BAYOD-RUJULA, *Future development of the electricity systems with distributed generation*, Energy Volume 34, Issue 3, March 2009, p. 380

3.4 Electricity Retailing

The vertical and horizontal unbundling of the electricity supply chain, as previously seen, has determined a notable reduction of the market concentration characterizing the generation phase and the retailing phase, while transmission and distribution, because of their characteristics of natural monopolies, tend to remain performed by single state-owned or state-controlled players.

According to the effects of the market liberalization reforms occurred in modern economies, the retailing phase has seen its structure evolving from a monopolistic regime to a structure characterized by the coexistence of heterogeneous players. Generally speaking, the retailing competitive environment varies significantly across countries, consistently to the different liberalization paths followed by each nation and the different requirements posed by the national authorities.

Retailing companies behave as linkers between the electricity consumers and the electricity market. As a matter of fact, those companies, according to their demand forecasts, purchase the power from the generators through the transactions completed in the electricity markets and power exchanges and/or directly from generators through bilateral agreements, retailing the power through the medium and low voltage distribution lines managed by the system operators[115].

Retailers acquire energy according to the plans elaborated with regard to both mid-term and short-term planning. Concerning mid-term planning, retailers stipulate *bilateral contracts* (which duration significantly varies across countries) with the generators in order to secure the provision of the electricity to fulfill the forecasted base-load demand, protecting themselves from the fluctuations that the electricity price experiences constantly in the wholesale market. These contracts are consequently an effective mechanism to allocate among generators and retailers the risk component associated to the variability of the wholesale price and to generate a stable and in advance known cash-flow[116].

However, due to the high demand variability, the mid-term bilateral contracts are integrated by the transactions that take place in the *day-ahead market* and in the *intraday market*, transactions that are necessary to modulate the volume of energy exchanged according to the short-term deviation of the net demand respect to the volumes forecasted in the mid-term. In fact, the rise of non-programmable renewable energy sources and of the distributed generation have significantly increase the unpredictability and variability of both electricity demand and supply, forcing

[115] LEONARDO MEEUS, KONRAD PURCHALA, RONNIE BELMANS, *Development of the Internal Electricity Market in Europe*, The Electricity Journal Volume 18, Issue 6, July 2005, p. 28

[116] LEONARDO MEEUS, KONRAD PURCHALA, RONNIE BELMANS, *Development of the Internal Electricity Market in Europe*, The Electricity Journal Volume 18, Issue 6, July 2005, p. 28-29

generators and retailers to constantly interact in transaction sections extremely close to the real time. As a matter of fact, the intermittency and unpredictability of the output of renewable energy sources plants require that the generators constantly update the volume of energy they offer in the market, while the variability of the aggregate net demand , due to the impact of the distributed generation, leads retailers to adjust continuously their purchasing volumes proceeding toward the closure of the transaction section.

It is important to pay attention also to the pressure that the rise of renewable energy sources and distributed generation are exerting on retailing companies, forcing them to go beyond a business model purely based on electricity retailing. The large deployment of renewable energy sources, the increasing distributed generation, the development of the smart grid paradigm and the intense competition are requiring retailing companies to develop ***new business models*** able to enhance the new market opportunities that the electricity sector transformation is creating[117]. Because of the high competition intensity in the retailing phase and the decreased electricity demand because of the growing share of demand fulfilled directly by the distributed generation, the scope and profitability of the pure retailing market are shrinking. This is the reason why the new business opportunities that are arising are fundamental for retailing companies in order to diversify their business portfolio and to keep on growing. The emerging opportunities are referred mainly to storage devices, distributed generation devices and to the provision of more tailored customer services[118]. In particular, current and future efforts are going to be concentrated in developing tailored energy management packages and consulting services for a higher energy efficiency of commercial and residential spaces.

[117] EURELECTRIC, *Utilities: Powerhouses of Innovation, Full Report*, 8 May 2013, pp.35
[118] EURELECTRIC, *Utilities: Powerhouses of Innovation, Full Report*, 8 May 2013, pp.35

3.5 Electricity Consumption

The demand of electricity has been significantly modified by the rise of non-programmable renewable energy sources and the contextual development of the smart grid and the distributed generation paradigm. As a matter of fact, the traditional vertically integrated electricity supply chain was characterized by a passive demand and by the energy flowing from the generators downstream through a unique direction toward the end users. That demand was clearly presenting a certain degree of variability, but its passivity, associated with its cyclical patterns identified for different time buckets (day, week, season), was ensuring the possibility to forecast it with a significant level of accuracy. In fact, through the assessment of the impact of socioeconomic events, day profile and weather conditions, the error referred to the forecasts was limited, enabling to allocate a notable share of the generation capacity and transmission capacity both in the mid-term and in the day-ahead planning horizons, requiring small adjustments while proceeding toward the real-time[119].
Moreover, demand variability was counteracted using traditional programmable power plants, which programmability clearly was reducing the degree of complexity of the challenges referred to the power system management and to the constant balance of the electricity demand and supply.
However, the large development of non-programmable renewable energy sources, the development of small low-cost generating devices exploiting wind and solar energy and the consequent development of the distributed generation paradigm have had a crucial impact on demand and on its variability and unpredictability[120]. In fact, domestic and industrial consumers are progressively also producers, even if clearly on a small scale, reducing their dependency from the electricity system and injecting energy into the grid, consequently revolutionizing the top-down energy flow characterizing the traditional structure of the supply chain[121].
The generation of electricity at demand side has requested the development of the concept of ***net demand***: as a matter of fact, the volume of energy required by each end user is equal to his electricity need minus the eventual amount of electricity he has produced. This mechanism significantly distorts the cyclical patterns followed by demand, adding a notable source of uncertainty. In fact, the intermittency and non-programmability of the energy sources exploited by the distributed devices and the consequent very low predictability of their outcome make extremely

[119] TERNA RETE ITALIA, *Previsione della Domanda Elettrica in Italia e del Fabbisogno di Potenza necessario*, 12 November 2013, pp.75
[120] ANGEL A.BAYOD-RUJULA, *Future development of the electricity systems with distributed generation*, Energy Volume 34, Issue 3, March 2009, pp.381
[121] RUGGERO SCHLEICHER-TAPPESER, *How renewables will change electricity markets in the next five years*, Energy Policy 48, 2012, pp. 64

difficult to forecast the amount of energy that will be demanded to the network and, in addition, the volume of energy that consumers will inject into the grid as output of their small generators. Moreover, the progressive diffusion of storage devices is going to enable consumers to behave more strategically, for example increasing their demand during low-price hours, that, instead, should be characterized by low demand according to the traditional cyclical patterns, storing it and releasing it during high-price hours, increasing even more the degree of complexity of demand fluctuations[122].

Finally an interesting aspect, deriving from the vertical unbundling of the supply chain and the liberalization of the retailing market, consists on the possibility for electricity consumers to select and eventually change the power supplier. This is an important topic concerning electricity demand because, in a context characterized by a high intra-sector competition and by a decreasing demand due to a growing energy efficiency of buildings and appliances and to the distributed generation, it is exerting a great pressure on retailers, forcing them to better understand consumer needs and preferences to retain them[123].

In particular the profile of consumers is changing because of a higher attention to the concept of environmental sustainability, a higher availability of information and a lower dependency from the network thanks to the small generators devices that individuals can install. This evolution of the consumer profile is consequently forcing retailers, as we have seen, to change their product offer and to enter new business models in order to increase the switching costs for the customers.

[122] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report,* Politecnico of Milan, July 2013, pp.33
[123] EURELECTRIC, Utilities: Powerhouses of Innovation, Full Report, 8 May 2013, pp.31

4) RENEWABLE ENERGY SOURCES AND MID-TERM PLANNING

In the previous section of the analysis we have focused the attention on the structure of the electricity supply chain, pointing out its phases and the tasks of the long-term planning process that are associated to them. Long-term planning process, as we have seen, concerns projects that refer to a period of several years, being aimed for example to strengthen transmission capacity, to redesign distribution network structure according to the needs posed by the rise of renewable energy sources and distributed generation, and to improve cross-border transmission infrastructures[124].

In this chapter, instead, we want to focus our attention on the mid-term planning process underlying the electricity supply chain, trying to emphasize its core objectives.

Before entering in details into the tasks that mid-term planning aims to accomplish, it is necessary to define the *temporal horizon* which it refers to. According to the literature available on the topic, this is an aspect that has to be carefully considered. As a matter of fact, compared to long-term planning and short-term planning, authors have defined over time highly heterogeneous temporal horizons referred to mid-term planning[125]. For instance, in some cases authors identify a planning horizon of some years[126], structuring a mid-term planning process that is close to the long-term planning, other authors propose a planning horizon of 12 months, based on time intervals of one month[127], or finally they opt for a mid-term planning process closer to the short-term one, adopting a planning horizon of one month and analyzing loads variations on a daily basis[128].

However the increasing deployment of renewable energy sources is progressively moving the attention toward planning horizons close to the short-term planning process, due to the high degree of variability and unpredictability associated to these energy sources.

The core objectives of mid-term planning consist on elaborating the *power plants commitment plan* for the considered temporal horizon, and to allocate transmission capacity on the basis of the

[124] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, pp. 172

[125] N.AMJADY, F.KEYNIA, *Mid-term load forecasting of power systems by a new prediction method*, Volume 49, Issue 10, October 2008, p. 2678

[126] N.AMJADY, F.KEYNIA, *Mid-term load forecasting of power systems by a new prediction method*, Volume 49, Issue 10, October 2008, p. 2678

[127] M.GHIASSI, DAVID K.ZIMBRA, H.SAIDANE, *Medium term system load forecasting with a dynamic artificial neural network model*, Electric Power Systems Research 76, 2006, pp. 302

[128] N.AMJADY, F.KEYNIA, *Mid-term load forecasting of power systems by a new prediction method*, Volume 49, Issue 10, October 2008, p. 2678

forecasted demand, the forecasted supply and the volume of energy underlying the forward contracts stipulated in the power exchanges or through bilateral agreements[129].

Concerning the power plants commitment plan, the system operator defines, according to the customers demand and the distributed generation output forecasted for each period of the planning horizon, a draft identifying the operating regime of every generating plant. This plan is only a temporary draft because based on forecasts carried out for a long horizon and consequently not enough reliable; as a consequence, it will be updated during the operational short-term planning according to the needs emerging while proceeding close to the real time. However, the mid-term commitment plan is viable since it allocates the forecasted demanded power assigning the priority to the programmable plants with the lowest responsiveness, creating a frame suitable for short-term planning because it maintains available the plants with the highest responsiveness for the adjustments that are performed close to the real time to counteract the variability and unpredictability of demand and non-programmable renewable energy sources.

The allocation of the transmission capacity is the second core objective of mid-term planning. It is thought to allocate infrastructural capacity on the basis of forward contracts stipulated on the power exchanges or of bilateral agreements between members of the supply chain and on the basis of the electricity demand and supply that are forecasted for the whole planning horizon, with the aim to schedule maintenance interventions without compromising the quality of the service provided to the end users and with the fundamental objective of maximizing the transmission capacity available after the mid-term plan. An important aim consists on ensuring to the short-term planning process significant manoeuvring margins to enhance network flexibility[130].

According to these two tasks and taking in consideration that the mid-term commitment plan is elaborated considering the needs of the mid-term transmission capacity allocation, it appears clear how mid-term planning requires accurate forecasts concerning the volumes of electricity demand and the volume and structure (territorial repartition, type of energy source) of the electricity supply for the planning horizon considered. Accurate forecasts are extremely difficult to be elaborated because of the length of the planning horizon which mid-term planning is based on, and according to this length the variables taken into consideration change. In the following two paragraphs we try to identify the main approaches that are followed to perform these forecasts.

[129] LEONARDO MEEUS, KONRAD PURCHALA, RONNIE BELMANS, *Development of the Internal Electricity Market in Europe*, The Electricity Journal Volume 18, Issue 6, July 2005, pp. 28

[130] N.AMJADY, F.KEYNIA, *Mid-term load forecasting of power systems by a new prediction method*, Volume 49, Issue 10, October 2008, pp. 2678

4.1 Mid-Term Demand Forecasting

The security of the electricity supply chain is based, generally speaking, on the real time balance between demand and supply, since any misalignment would have disruptive effects on the functioning of the system. The crucial phases to warrant the constant balance are transmission and distribution, because of their role of linkers between the large scale generators and small distributed generators on the one hand, and the aggregate demand on the other hand. The system operator, consequently, has the responsibility to modulate the volume of energy injected into the market in order to maintain a stable and secure situation.

To perform this task, the transmission operator applies different types of information, that is to say its forecasts concerning the amount of renewable energy produced and injected into the network by the dispersed medium and small scale generators belonging to the distributed generation, its assessment about the volume of energy required for the operating reserves, the plans deriving from the transactions completed in the power exchanges and electricity wholesale markets and the eventual bilateral contracts between producers and users.

The forecasts about the aggregate demand are developed according to the *geographical repartition of the network* into regions, *expected socio-economic conditions* relevant for the planning process and to the *calendar profile of days*[131].

According to the length of the temporal horizon that is considered in mid-term planning, different variables and factors and considered in the literature with the goal to elaborate accurate forecasts. Generally speaking, we can define three categories of planning horizons in order to point out the variables associated to each of them and consequently applied in the forecasting process.

The first category is based on a temporal horizon of few years, underlying as a consequence a mid-term planning process that tends toward the long-term planning process, focusing on the analysis of the annual power peaks. According to the length of this planning horizon, planning models are usually based on economic variables that reflect the evolution of the macroeconomic context in which the electricity supply chain operates. Those economic variables are for example gross domestic product (GDP), consumer price index (CPI), and average salary earnings (ASE), usually combined with indicators related to the supply chain structure itself, like the number of connections to the transmission network[132].

[131] TERNA RETE ITALIA, *Previsione della Domanda Elettrica in Italia e del Fabbisogno di Potenza necessario*, 12 November 2013, pp.22

[132] N.AMJADY, F.KEYNIA, *Mid-term load forecasting of power systems by a new prediction method*, Volume 49, Issue 10, October 2008, p. 2679

The use of this economic variables is justified by the fact that, given the length of the planning horizon and the degree of aggregation of the forecasts, taking into account indicators concerning the calendar profiles of the days or the weather conditions would be not feasible. However, this kind of approach appears immediately not consistent with the mid-term planning objectives described in the previous paragraph, being more suitable for the evaluation of infrastructural adequacy of the supply chain and for planning eventual expansion projects and investments.

The second category is referred to a planning horizon of one month or multiple months (usually 12), concentrating on the analysis of daily power peaks. According to this planning horizon, forecasts are elaborated on the basis of socioeconomic events, calendar profiles of the days and weather conditions[133]. Weather conditions in this case are not explicitly considered in the model, since they should be forecasted at least one month in advance, having consequently a not acceptable reliability. In order to solve this obstacle, the impact of weather conditions on the electricity demand is included in the model by considering them already embedded in the loads trend emerging from the historical data used for the time-series analysis which the forecasts are based on. As a result, the electricity demand forecasts are given by a base forecast deriving from the time-series analysis thought to identify the impact of socioeconomic events and of the profile of the days; after that, the base forecast is corrected by a trend coefficient resulting from the time-series analysis thought to consider the impact of weather conditions.

Finally, the last category concerns a planning horizon of one or two weeks, consequently tending toward the temporal horizon applied for short-term planning. In this context, the calendar profile of the days and the socioeconomic events are still relevant, but it is necessary also to explicitly include the weather conditions in the planning process, since, due to temporal closeness, weather forecasts present a high accuracy.

According to this approach, the final forecast of the demand is a combination of a *time-series analysis* model and a *causal model*. In fact, base forecasts are determined concentrating the attention on a sequence of days with a similar calendar profile and considering similar socio-economic events; these forecasts are then integrated by a causal model estimating the dependency between demand volumes and weather conditions, precisely air temperature and sky conditions[134].

It is important to stress the fact that the large scale deployment of renewable energy sources and the parallel and consequent development of distributed generation have had a crucial impact on the

[133] N.AMJADY, F.KEYNIA, *Mid-term load forecasting of power systems by a new prediction method*, Volume 49, Issue 10, October 2008, pp. 2678

[134] DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, *Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato*, 2001, pp.7

dependency between demand and weather conditions. As a matter of fact, the system operator is required to consider the net aggregate demand, that is to say the overall demand of electricity minus the amount of energy produced by consumers and used directly at the generation location, without being injected into the market. Since the renewable energy sources exploited by the devices belonging to the distributed generation are wind and solar energy, it appears clear the connection between weather conditions, energy generated and directly consumed by demand, and the aggregate net demand[135]. Just to provide a very simple example, we consider a very hot day with sunshine during the summer. According to the causal forecasting model based on the dependency between aggregate demand and weather conditions, the high air temperature and the sunshine should determine a very high electricity consumption, caused by the peak of air-conditioning usage. However, the spread of small renewable energy generating devices has recently required to consider an additional variable in the forecasting process. As a matter of fact, during a sunny day, at the demand side we register a high volume of energy produced by the dispersed small photovoltaic devices and directly consumed in site by consumers, without being injected into the network. That determines a level of aggregate net demand (the volume really requested to the network) that is significantly lower than the demand that would have been forecasted applying only the forecasting causal model based on weather conditions, as done before the rise of non-programmable renewable energy sources.

An additional aspect that must be carefully kept in mind and that derives from renewable energy sources deployment and smart grids development consists on the impact of demand response. In fact, the components belonging to the smart grids enhance consumers responsiveness, directly impacting on the net aggregate demand[136]. Considering again the previous example of the sunny day, during the central hours the price of the electricity increases because of the consumption peak due to the air conditioning; consumers receive a signal emphasizing the high price and, consequently, they reduce the amount of energy absorbed by the network, consuming instead the energy produced by their small photovoltaic systems or, eventually, also the energy stored in small devices during hours characterized by a lower price. Consequently, that may reduce to a greater extent the aggregate net demand during periods in which, according to the weather conditions, there should be an extremely high demand, whereas it may significantly increase demand during the night in order to recharge storage devices taking advantage of the low price electricity, conflicting with what would have been expected by the weather forecast model.

[135] TERNA RETE ITALIA, *Previsione della Domanda Elettrica in Italia e del Fabbisogno di Potenza necessario*, 12 November 2013, pp.22

[136] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.47

As a conclusion, it is important to stress a problem referred to those models concerning mid-term planning and that has been accentuated by the rise of renewable energy sources. This problem consists on the lacking availability of data to carry out the time-series analysis which models are based on, especially because of the large deployment of renewable energy sources and distributed generation that have taken place only in the recent years and, as a consequence, the historical data related to them are limited[137].

4.2 Mid-Term Supply Forecasting

Besides the forecasts concerning demand, clearly the system operator has to elaborate accurate forecasts concerning the amount of energy generated and supplied, with special attention to non-programmable renewable energy sources, since conventional thermal or nuclear plants present stable and in advance programmable behavioral patterns. Consequently, in order to ensure the balance between demand and supply, the system operator needs to forecast the amount of energy that will be delivered to the network, in addition to the traditional plants output, by large scale plants and dispersed medium and small scale generating devices based on renewable energy sources.

The attention is concentrated in particular on wind and solar energy, since they are characterized by the highest degree of uncertainty and volatility. In fact, geothermal energy, tide energy and biomass energy are much more constant and stable in their contribution[138].

According to the distinction of the three categories of planning horizons described in the previous paragraph, electricity supply forecasts for the mid-term are carried with regard to a planning horizon usually comprised between one month and few months, eventually adopting shorter planning horizons to counteract the high variability and unpredictability of renewable energy sources.

Concerning large scale generation facilities for wind and solar energy, usually forecasts are carried out on the basis of the regions which the territory is divided in. These regions are defined according to similar weather conditions, geographical distribution of the plants and according to the historical

[137] N.AMJADY, F.KEYNIA, *Mid-term load forecasting of power systems by a new prediction method*, Volume 49, Issue 10, October 2008, p. 2679

[138] HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, *Renewable energy supply chains, performance, application barriers, and strategies for further development*, Renewable and Sustainable Energy Reviews 16, 2012, pp.5451

data available. After that, the forecasts of the regions are integrated through a linear combination, determining the expected output of the whole territory.

Finally, accurate forecasts of the volume of energy supplied at each time interval play an important role to ensure an adequate flexibility of the system and, on the same time, the efficient allocation of network resources. As we will see later dealing with the concept of system flexibility, different methods are applied to maximize supply forecasts accuracy, like for example considering the aggregate supply of plants located in the same region but exploiting different types of energy, or pooling similar plants but located in different regions, since aggregate variability tends to be lower than the variability of every single plant.

5) RENEWABLE ENERGY SOURCES AND SHORT-TERM PLANNING

5.1 Variability and Uncertainty

It is possible to identify two categories of technologies implemented to produce electricity from renewable energy sources: *firm technologies* and *variable technologies*[139].

Firm technologies are able to ensure a stable and programmable volume of electricity, consequently they do not raise particular challenges in the planning process of the supply chain and, afterward, during operations. With regard to these technologies, the main sources of uncertainty are referred to the occurrence of components failure able to affect the appropriate functioning of the power system. Renewable energy sources for firm technologies are biomass, geothermal and hydropower energy[140]. The very low variability of the output of these sources and the degree to which they can be programmed or forecasted minimize the problems related to their integration into the traditional supply chain and existing network. In fact, they allow to maintain unchanged many planning and operational processes and they are compatible with incumbent network technologies and infrastructures and with the common radial structure of distribution networks.

Variable technologies are related to the exploitation of renewable energy sources which output varies significantly in a very short period of time and in an unpredictable way. The output of these plants cannot be programmed but only forecasted and the system has to be able to deal with sudden upward and downward fluctuations of the volume of electricity produced. The variability and unpredictability clearly cause a high degree of uncertainty affecting the planning and operational processes[141]. The renewable energy sources belonging to this category are solar, wind, wave and tide energy. However tide and wave energy present, generally speaking, a lower degree of uncertainty because their output can be forecasted to a higher extent. As a matter of fact, for example, tides follow cyclical patterns that are known in advance.

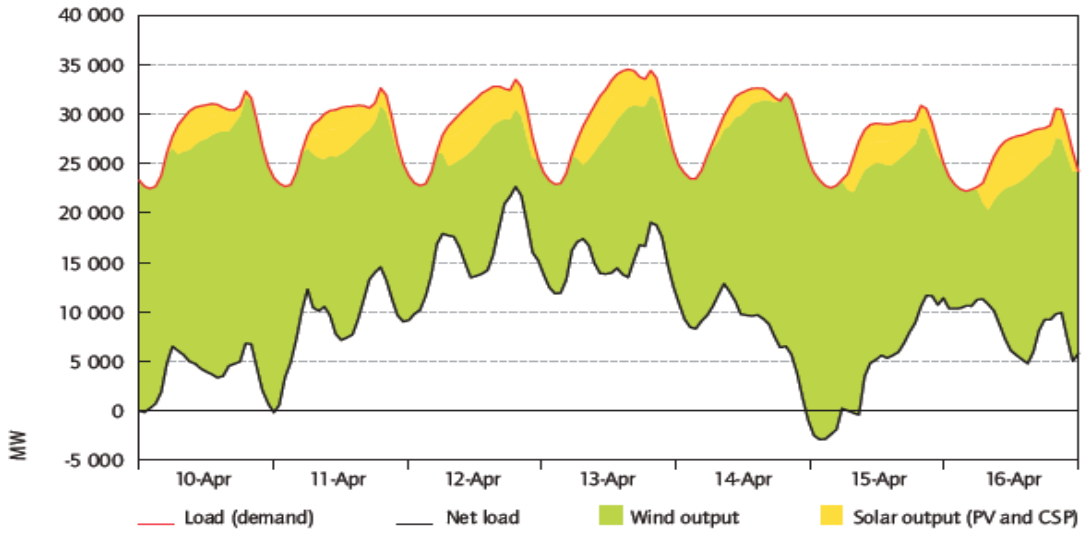
The key challenge referred to a large deployment of renewable energy sources (with special attention on variable and not firm technologies) is not simply the variability of the output, but the

[139] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables,* Paris, 2008, pp.9
[140] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013
[141] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, pp.9

unpredictability associated to the variability[142]. A highly variable output but easily predictable with an appropriate notice would not pose particular challenges for the power system; as a matter of fact, knowing in advance the fluctuations that the output will follow, it is possible to effectively plan operations to ensure an efficient and secure functioning of the system.

Problems are consequently generated by the unpredictability underlying some renewable energy sources. The planning process is indeed based on forecasting models contemplating several variables and aiming to provide forecasts as accurate as possible. However, forecasts by definition entail errors, and their accuracy increases getting closer and closer to the time interval considered, leading the system to work with a certain degree of certainty only approximately in real time.

Graph 7: Electricity demand variability and electricity net demand variability over a period of one week



Source: GE Energy 2010[143]

The red curve describes the fluctuations of the overall week electricity demand, emphasizing how it follows cyclical patterns that make it predictable.

The grey curve, instead, describes the fluctuations of the net demand, that is to say the demand resulting after provision in the network of the electricity produced by wind and solar power plants.

As we notice, net demand is characterized by sudden and unpredictable fluctuations, making it extremely difficult to be forecasted. This is consequently an example of how renewables and significantly increasing the degree of complexity associated to short-term planning and operations[144].

[142] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.31

[143] GE ENERGY, Western Wind and Solar Integration Study, May 2010, p. 31

[144] GE ENERGY, Western Wind and Solar Integration Study, May 2010, pp.31

Tackling variability through improved forecasting models and technological or geographical system integration:

The fundamental aim of the electricity supply chain in a context characterized by a large deployment of non-programmable renewable energy sources consists on being able to ensure a secure, stable and high quality service, despite of the challenges raised by this kind of energy sources. In particular, national supply chains are trying to leverage three crucial points: *increase of the output predictability* through improved forecasting models, *implementation of factors reducing output variability* and, finally, *adoption of actions to significantly increase supply chain and system flexibility*, enabling them to be effective and efficient also in presence of variability and uncertainty[145].

Concerning the *improvements of forecasting methods*, we have seen how system operators are switching to a probabilistic approach, instead of a deterministic one, accepting to constantly deal with the concepts of probability and expected value. As a result, the planning process is becoming a sequence of decisions taken under uncertainty or risk: under risk in case of known probabilities of events and scenarios, under uncertainty when these probabilities are unknown.

The application of this decision-theory approach refers to both short term and long term scenarios, that is to say predicting the generated output and the aggregate demand to manage and balance the whole system in the short-term, and in the long term, with the aim to forecast the pace and scope of the deployment of renewable energy sources and the relative technologies in order to undertake appropriate investments.

The accuracy of the forecasts and the consequent decisions depend on the probabilities and parameters used in the models. A great attention is consequently paid to maximize the precision of probabilities and parameters, defining them through time-series analysis or a subjective interpretation approach based on the know-how and experience of the decision maker in the case in which insufficient data are available. The parameters are then adjusted through ex-post simulations and constantly tested and eventually updated, if the performance is not assessed as satisfying[146].

The second objective aims to *reduce variability* in order to simplify planning and operating processes and to reduce the technical and operational requirements that renewable energy sources are demanding to the supply chain. We identify three main smoothing factors, concerning *storage technologies, systems aggregation and the aggregation of the output coming from different technologies*[147].

[145] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, pp.10
[146] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, pp.12
[147] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, p.10

Storage technologies have a great potential in limiting the variability associated to the output of renewable energy sources. Those technologies are in fact able to buffer upwards and downwards peaks of generation, storing electricity when the output produced suddenly increases and releasing electricity when the output falls out of the blue. Storage technologies are consequently able to stabilize over time the volume of energy injected into the market by renewable energy generators, reducing short-term power fluctuations. The main limits of these technologies are the storing capacity and the duration of the storage, suggesting their application especially for small generators[148].

System aggregation is an important potential large scale solution for short-term planning. The volume of electricity produced in a given time interval varies significantly according to the type of energy source exploited, the scale and technology of the plant and its location. These variables imply that the output of every plant changes continuously because of the variability and intermittency of the energy source. Within a given time interval, the outputs of plants located in different sites and exploiting different energy sources are highly different among each other, both in terms of absolute values reached and in terms of the scope, sequence and velocity of the fluctuations[149]. The huge heterogeneity among plants belonging to the same system and the asynchronous variations of the outputs of the plants taken individually determine extremely hard planning challenges for the supply chain in managing short-term operations.

However, if we consider the joint output of the multiple plants located within a wide area, the variability of the output as a whole is much lower than the variability of the output of each single plant[150].

This effect emphasizes the importance of cross-borders interconnections in the transmission network and the crucial support that electricity cross-national exchanges are going to have for the development and stability of the electricity supply chain[151]. In fact, the low variability of the joint production of the plants within a wide area enables to plan in advance cross-borders electricity exchanges and to enlarge supply-demand balancing areas further than the national borders, with a huge benefit for the entire system in terms of efficiency, security and avoidance of curtailments of production from renewable energy sources.

[148] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp.33
[149] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.58
[150] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, pp.10
[151] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.58

The aggregation of the output produced by different technologies works similarly to the aggregation of plants distributed over a wide area[152]. If we locate in the same site different technologies exploiting different energy sources, the output of each single technology will vary significantly over the period of time considered, whereas the joint output of all the technologies located in that site will be more stable. As a result, the diversification of the technology portfolio can have an interesting role in smoothing short-term renewable energy sources variability. A higher predictability of the output thanks to improved forecasting models and a lower variability of the output thanks to the discussed smoothing actions for sure partially simplify the large scale integration of non-programmable renewable energy sources. However, uncertainty and variability in the generation phase still persist and their combination with the increasing distributed generation and demand response urgently require the electricity system to reach a sufficient flexibility[153].
Flexibility is, in fact, the third point enabling a large scale deployment of renewable energy and it represents the key tool to overcome the challenges deriving from uncertainty and variability both at demand and supply side.

5.2 Demand for Electricity System Flexibility in the Short-Term

A large scale integration of non-programmable renewable energy sources is raising significant challenges in the planning and management phases of the entire supply chain, mainly because of the high degree of variability and uncertainty that are associated to this kind of energy sources.
Variability is a factor that has been always present in the electricity supply chain, because of the volatility of demand. As a matter of fact, the demand of electricity is always fluctuated according to several factors, making more complex planning and operational activities and requiring effective forecasting mechanisms.
However, in presence of conventional generating plants, variability and uncertainty were referred only to demand side and, consequently, the system operator was supposed simply to ensure the constant short-term alignment of demand and supply, acting on the generated output, by optimally modulating the volume of energy provided by programmable sources. The impact of renewable energy sources is so crucial because it affects both demand and supply side. Concerning demand side, variations of demand are no more linked exclusively to the patterns spotted within the frame of

[152] INTERNATIONAL ENERGY AGENCY, *Empowering Variable Renewables*, Paris, 2008, pp.10
[153] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.69

the traditional supply chain, that is to say patterns depending on the calendar, on socio-economic events and on weather conditions, but, according to distributed generation and demand response , they depend also on the quantity of energy produced and consumed directly at demand sites, on the price signals that make demand more price sensitive and elastic and on the technologies installed.[154].

Concerning the supply side, the integration of large and small scale renewable energy generating devices has deeply changed the dynamics of this phase; in fact, energy generation is carried out simultaneously by large concentrated plants and by a huge number of dispersed small devices, making extremely difficult to forecast and manage the volume of production because of the non-programmability of the energy sources and because of the high number of producers. As a result, the integration of renewable energy sources significantly increases the degree of uncertainty associated to the supply chain, forcing the system operator to interact with highly volatile demand and supply, which require notable efforts to ensure their constant balance.

In particular the attention of the system operator is focused on the frequency and extent of oscillations and on the points in time when they occur. An additional aspect that requires attention is the potential asynchrony between demand and supply peaks. As a matter of fact, a positive peak of the electricity supply due to the abundance of generated renewable energy may not coincide with a positive peak of the aggregate demand as well. That may cause a negative value of the aggregate net demand, stressing the presence of a demand not able to absorb the whole supply. This is a critical point since, to balance the system, the system operator has to curtail the production of electricity from renewable energy sources, because they are more flexible in the short term than conventional plants. However, electricity curtailments clearly reduce significantly the efficiency of the overall system and penalize renewable energy sources, that, instead, are supposed to be boosted. As already mentioned, this conflicting solution is going to be solved through the installation of storage devices on the different phases of the supply chain, with the aim to enable the system to maximize the reception of energy from renewable sources[155].

The second element challenging the system operator and the supply chain as a whole consists on the uncertainty deriving from the unpredictability of the volume of energy that renewable energy sources are able to produce in a given time interval, especially considering limited territorial surfaces. The degree of unpredictability clearly changes according to the type of renewable energy source. Generally speaking, waves, photovoltaic and solar energies are the least predictable because

[154] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.47-48

[155] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.52

tightly related to weather conditions. On the other hand, tide, geothermal and biomass energies can be forecasted more easily or programmed in the case of the biomass energy. However, analyzing the world volume of energy produced, wind and solar energies are the most relevant and to a great extent[156]. This uncertainty concerning both the volume of energy provided and its timing stresses the importance that forecasting is acquiring in the management of the supply chain. Accurate forecasts are fundamental, however, because of the number of factors involved, accurate forecasts are available only close to the time period considered. This forces the entire system to be extremely responsive and agile, requiring a significant flexibility to be able to be effective in any operational context characterized the need to act close to the real time.

5.3 Sources of Flexibility of the Electricity System

The term ***flexibility*** refers to the ability of the system to react to sudden and unpredictable variations of the demand or of the electricity generation and to failures of components along the infrastructures. The flexibility of the supply chain has, consequently, a fundamental role at operating level, enabling the system to counteract any occurrence in real time, and giving important tools to support short term operational planning. However the degree of flexibility of the system depends on several factors tied to the strategic long term planning of the supply chain, that is to say all the plans concerning the infrastructures and technologies implemented. As a matter of fact, in order to better understand how strategic planning is able to influence the system flexibility, it is necessary to focus the attention on the sources of flexibility.
We identify four main sources[157]:

- the types and sizes of dispatchable electricity generating plants
- the storage devices integrated into the system
- the cross-borders electricity transactions
- the responsiveness of demand

Those are the factors able to provide to the system the flexibility required to integrate effectively and efficiently non-programmable renewable energy sources, without compromising the system

[156] INTERNATIONAL ENERGY AGENCY, *Electricity in a Climate-Constrained World*, Paris, 2012
[157] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.51

security and the service quality. In order to better understand how they boost system flexibility, it is convenient to enter more in details into each of these sources.

Renewable Energy Sources and Generating Plants Dispatchability:

Dispatchable plants are a fundamental aspect in structuring the supply chain: with the concept of *dispatchability* we mean the ability of the generating plants to ramp up and down according to the instructions sent by the system operator; clearly the ramping up or down must be performed within certain operational and technical requirements and the capacity to ramp must be available at any time. The assessment of the power plants dispatchability has to be carried out carefully considering the velocity at which their outputs vary, as a consequence of the type of energy exploited and the technology implemented. In this sense, we distinguish three categories of plants: *peaking power plants, intermediate power plants, base-load power plants*[158].

Peaking power plants are able to modify their output in the lowest period of time compared to the other plant types, being able in some cases to reach lead times close to the real time. It means that they can ramp up or down close to the real time, enabling the system operator to adjust immediately the volume of production according to the supply chain needs. This ability of the peaking power plants represents consequently a fundamental characteristic to counteract the effects of a high demand and supply variability and to ensure the instruments necessary to deal with forecasting errors. Peaking power plants are become so crucial with the rise of non-programmable renewable energy sources, since wind, solar and wave energies are simultaneously key sources of variability and uncertainty on the one hand, and key energy sources for peaking power plants on the other hand, especially in ramping down. In fact, plants exploiting solar, wind and wave energy have very short set up times and the ability to ramp up quickly (in case of availability of the energy source) and to ramp down or to be shut down in a while at very low cost[159].

Base-load power plants have the lowest responsiveness and they are able to significantly modify their output in several hours (usually not less than six hours). Because of the long lead times necessary to ramp up or down, they are addressed to satisfy the base load demand, that is to say the minimum value of energy that from hour to hour must be available in the system[160]. Considering renewable energy sources, geothermal energy plants constitute a perfect example of a base load

[158] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.43

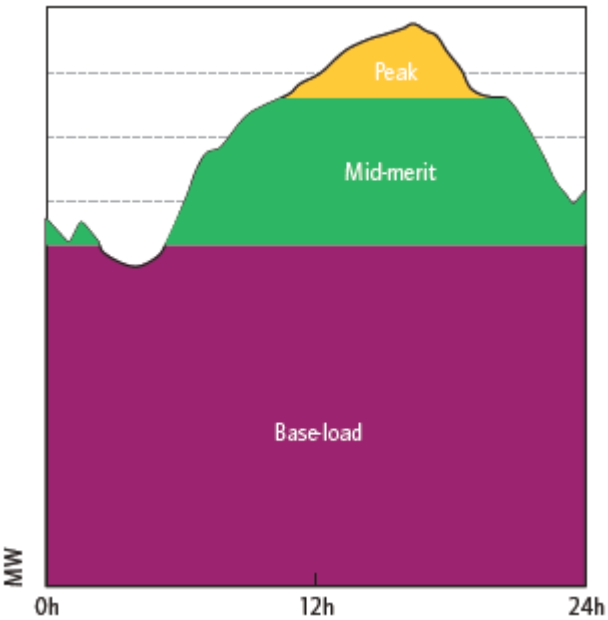
[159] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.43

[160] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.43

power plant energy source; as a matter of fact, it presents very long lead times combined with a stable energy output, making them suitable to provide a constant base load.

Intermediate power plants have lower response times than peaking power plants but they are important to support the supply chain flexibility, being able to significantly modify their output in a time interval of one hour. In particular they present the ability to ramp up and down from/to a certain minimum operating level, contributing to ensure a constant base load with their minimum operating output, and to counteract demand peaks ramping up or down[161]. Biomass and tide are renewable energy sources that can be classified as intermediate power plants energy sources.

Graph 8: Load repartition among power plants types



Source: International Energy Agency[162]

This graph aims to show the load of a period of 24h is distributed among the three types of plants. As we can notice, peaking-power plants play usually a marginal role; in fact, they are required simply to fulfill peaks of the load, exploiting their ability to ramp up and down in a very short period of time and at a low cost[163].

The previous overview shows how generating plants can be categorized according to their dispatchability potential and how renewable energy sources have been integrated in order to support

[161] INTERNATIONAL ENERGY AGENCY, Harnessing Variable Renewables, a Guide to the Balancing Challenge, Paris, 2011, pp.43
[162] INTERNATIONAL ENERGY AGENCY, Harnessing Variable Renewables, a Guide to the Balancing Challenge, Paris, 2011, p. 43
[163] INTERNATIONAL ENERGY AGENCY, Harnessing Variable Renewables, a Guide to the Balancing Challenge, Paris, 2011, pp.43

the short-term flexibility of the system. After this description, it is however necessary to analyze the major constraints that may limit plants dispatchability. The fundamental limit to the availability of a disptchable plant consists on its actual operating regime. In fact, the availability of a plant to ramp up or down and the extent to which it can modify its output clearly depend on its current operating regime, that is to say the volume of energy it is producing in that time compared to its operational maximum.

The likely operating regime depends on the category of generating plants. Generally speaking, power peaking plants, according to their ramping potential, tend to be operating only during the short periods in which demand reaches its highest values; intermediate power plants, instead, tend to operate during phases characterized by high demand but not by peaks requiring quick and large scale increases of the quantity of electricity generated. In fact, their ability to ramp up or down from/to a minimum operating level makes them suitable for balancing not extreme deviations from the base load. Finally, base load plants, being characterized by long set up times usually combined with high set up costs, run constantly, enabling to exploit them efficiently[164].

As a result, the demand level (for instance high demand or demand peak) is determinant to define which plants are running and, consequently, which dispatchable plants are available and to which extent.

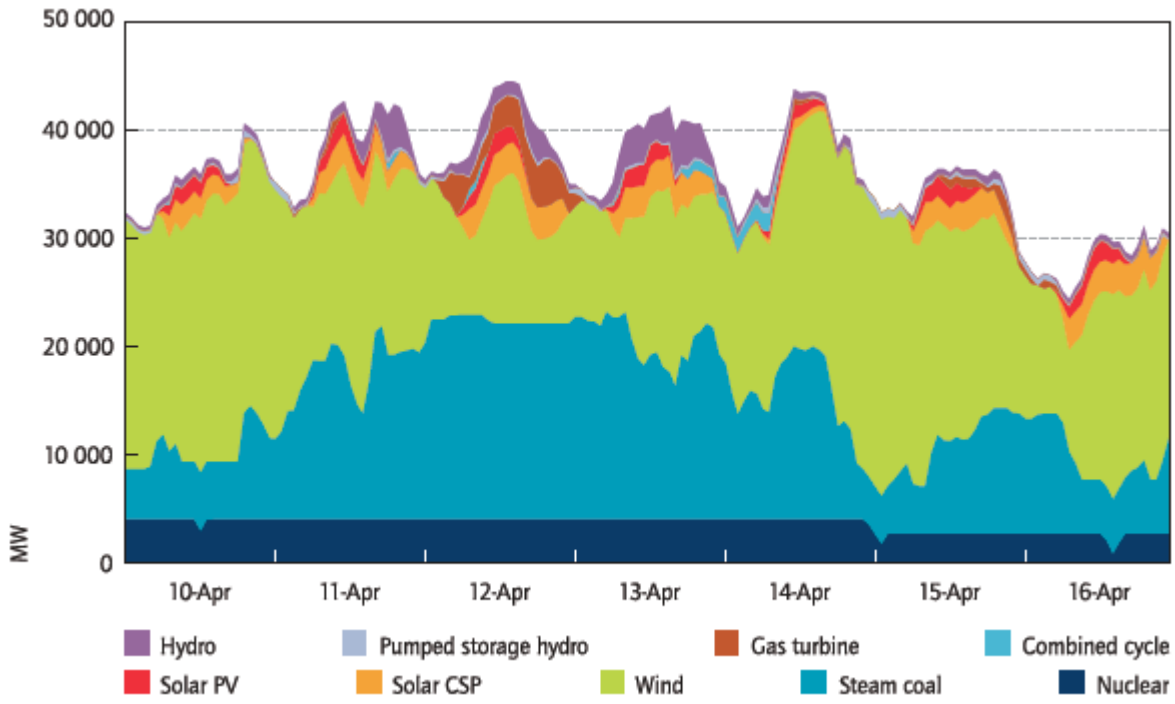
Dispatchable power plants availability, as said before, is becoming more and more important because of the rise of non-programmable renewable energy sources and the explicit aim of governments and policy makers to maximize the exploitation of renewable sources instead of traditional ones. It represents a key point because the characteristics of the most spread renewable sources, wind and sun, qualify them as suitable sources for peaking power plants, consequently making them strategically relevant in terms of enhanced system capacity in balancing demand peaks. However the likely regime of use of this type of plants recognizes to them a marginal role in terms of volume of energy concretely provided to the system compared to the traditional plants. As a matter of fact, not only they present a notable capability to ramp up or down, but their operating regime can be changed with costs that are extremely lower compared to the other plant types. The problem is, indeed, the fact that the deployment of renewable energy sources mainly as peaking power plants would significantly reduce their potential exploitation. This is the reason why many strategies have been implemented or are going to be implemented to enlarge their usage[165]. While maintaining their role of peaking power plants leveraging their ramping potential, changes in the

[164] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.43

[165] INTERNATIONAL ENERGY AGENCY, Harnessing Variable Renewables, a Guide to the Balancing Challenge, Paris, 2011, pp.61

planning and management processes of the system (for example aggregation of different types of technologies to reduce the overall combined variability) and the implementation of new technologies, like storage devices and improved transmission facilities, are enabling their progressive contribution to the supply chain also as intermediate power plants, and, in the future, as base load power plants, displacing conventional ones. As a matter of fact, the aggregation of renewable energy plants using different energy sources and located in different sites, in combination with adequate technologies, allows to arbitrarily assign to renewable energy plants the operating profile characterizing conventional plants.

Graph 9: Repartition of electricity demand among power plant types over an interval of one week



Source: GE Energy 2010[166]

The Graph emphasizes how renewable energy plants tend to act as peaking-power plants, consequently having a marginal role in fulfilling electricity demand. In this case, only wind plants are working as intermediate power plants, having a greater impact on the total electricity generation. As already discussed, being classified only as peaking-power plants represent a severe obstacle to a large deployment of renewable energy sources.

[166] GE ENERGY, Western Wind and Solar Integration Study, May 2010, p. 15

Renewable Energy Sources and Storage Technologies:

Energy storage is the second fundamental source of system flexibility, and, on the same time, it represents an important evolution respect to the traditional past configuration of the supply chain; in fact, that configuration was considering electricity as a good not storable and, consequently, strictly requiring that the volume of energy demanded in a precise point in time was exactly the same than the volume produced in that point in time. Thanks to the development of storage technologies, the real time balance between demand and supply is still a binding requirement, but the way in which supply is managed is different. Supply is no longer simply the volume of energy produced in a precise moment, but that volume plus the amount of energy that storage devices can make available in that moment.

Storage technologies provide a great flexibility to the power system since short term planning is no longer strictly depending on the volume of production provided by generators in a precise instant, volume of production the clearly is highly affected by the variability and uncertainty associated to non-programmable renewable energy sources. In fact, storage devices help to stabilize the volume of energy available, enabling the system operator to carry out the planning tasks on the basis of less volatile quantities.

A key advantage deriving from these technologies is the fact that they are highly different, providing diversified operational requirements and performances, and making them able to adapt to both energy intensive and power intensive applications. This ensures to the system an adequate support both in terms of security of electricity provision (*energy intensive applications*) and security of the provisions of the resources for the ancillary services (mainly *power intensive applications*)[167].

The relevance of storage technologies in the supply chain depends on the way in which those technologies are used in all its phases. The versatility, the variable size and low initial costs of these technologies are facilitating their diffusion not only at the generation sites or along the transmission and distribution infrastructures, but also at the demand side. Concerning this last issue, in order to reach the maximum exploitation of the potential of these technologies, it is necessary to make sure that also consumers are using them to smooth the variability and uncertainty of the aggregate net load, and not simply to store energy during low price hours with the aim to use it and sell it during the high price hours. That is possible only if the use of storage technologies for the purpose to contribute to the stability of the system is economically convenient also for consumers owning generating and storing devices[168].

[167] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp.33
[168] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp.33

The first fundamental aspect concerning their functions is the distinction between *energy intensive application* and *power intensive application*[169].

Power intensive application are characterized by the release of a high volume of energy in a very short period of time, usually lower than sixty seconds. For instance, two extremely important power intensive applications are recovery or restart actions and real time balancing of demand and supply.

Energy intensive applications are characterized instead by the provision of a high volume of energy through a slow and constant release that lasts hours. Examples of energy intensive applications are the stabilization of the supply of generators based on non-programmable sources or the compensation of a reduction of the available generation capacity.

In order to understand how storage technologies are able to facilitate the process of integration of these energy sources, it is suitable to have an overview of their functions.

Concerning *energy intensive applications*, their functions are mainly *time-shift*, *non-programmable renewable energy sources integration support* and *system security support*[170].

Time shift function consists on postponing energy consumption respect to its generation and accumulation. This function is particularly important in presence of renewable energy sources that cannot be programmed. As a matter of fact, their production is characterized by a high variability and uncertainty, reaching suddenly peaks of energy production that cannot be injected into the network because a simultaneous and equivalent increase of demand to balance the system would not be feasible. This obstacle would determine frequent curtailments of the production of energy from renewable sources, compromising system efficiency and an optimal integration of the new energy sources. Storage technologies, thanks to their time-shift function, allow to store energy when production exceeds demand, avoiding curtailments, and releasing the accumulated energy when demand is able to receive it.

Time-shift function has stimulated also the development of distributed generation, increasing the volume of energy that is consumed directly by producers and reducing fluctuations and uncertainty associated to the net demand. As a matter of fact, thanks to the storing technologies installed at the demand side, the injection of electricity into the network from consumers generating devices is less variable and uncertain: the storage technologies, releasing energy gradually and according to precise signals, enable the system operator to remotely managed distributed generation, aligning it to its operational plans and schedules, and consequently having a notable beneficial impact on short-term planning.

[169] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp.33
[170] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp.33

Storage technologies increase the hosting capacity with regard to renewable energy sources minimizing the risk of congestions along transmission and distribution lines. In fact they accumulate energy when the available network capacity is scarce, avoiding any overloading, and they release electricity when high and low voltage lines have enough spare capacity. This is crucial especially in the cases in which the plants exploiting renewable sources are located in remote sites, where energy sources are abundant but the transmission infrastructures connecting those plants to the consumption areas are poor.

The transmission capacity of these lines is often insufficient and that would force to curtail energy production whenever it exceeds the capacity constraint of the transmission lines. Storage devices consequently allow to avoid that network capacity imposes production constraints to renewable energy plants. On the same time, they allow to fully exploit the potential of generating plants without necessarily undertaking new investments to expand the network.

Storage technologies with regard to non-programmable renewable energy sources ensure over time a stable injection of electricity into the network, smoothing the intermittency of these sources. That, combined with the increased hosting capacity of the network, allows the system operator to elaborate operational plans facing a lower degree of uncertainty, increasing as a result the overall system efficiency[171].

Security is a fundamental requirement for the electricity system and the main concern for the system operator and the regulator; consequently, the system reactivity after a failure is an aspect that is crucial while structuring the network. Storage technologies, for example, can have an important role in enhancing the black-start capacity of the network in case of black out. In fact, large scale storage devices have the energy capacity and the responsiveness to recover the system. Moreover, they can be used also to provide the resources for ancillary services and to reduce the volume of reserves required for the stability of the system.

Storage technologies potentially impact also the quality of the service provided to customers, especially in terms of continuity of service. In fact, installing storage devices at the connections between the user and the low voltage line enables to ensure uninterruptible power supply. The customers connected to the portion of the distribution network affected by the failure would not suffer the interruptions and that would significantly increase the service quality.

[171] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp.33

Another important aspect concerning storage technologies is referred to their *location* along the supply chain[172]. Decisions about where to locate storing devices are related to the strategic long term planning but obviously they have a crucial impact on the operational short term planning.

Generally speaking, storage devices can be located in three different phases of the supply chain, that is to say at the generation phase, along the transmission and distribution infrastructures and at demand side. Locating them *close to the generators* enables to store directly the energy produced that cannot be received by the network, avoiding generation curtailments even if non-programmable renewable energy sources reach positive peaks. In fact, since energy, in order to be stored, doesn't need to be transferred along a portion of the network, the volume of production and the quantity that can be stored are not limited by transmission constraints, but by the storing capacity available at generation sites. Once stored, the energy then would be released into the network according to the needs of the system operator and to its request of energy intensive or power intensive actions.

At operating level, storing devices close to the generators simplify the short term operating tasks of the system operator, since it is called to allocate network capacity on the basis of two variables that are the amount of energy necessary to balance in real time the supply and the capacity that must be available for the provision of ancillary services. In fact, in this case the system operator doesn't need to allocate network capacity also considering the quantity of energy that would circulate along the network just with the aim of being stored and, consequently, reducing the capacity available for demand balancing and for the security of the system.

However, since renewable energy plants are usually located in remote sites where these sources are abundant, the current capacity of the infrastructures connecting those plants to the main transmission and distribution lines tend to be insufficient to support this organizational solution. As a matter of fact, the lines from the plants in remote locations to the main infrastructures usually do not have a maximum capacity able to carry the sum of the electricity produced in that moment and the electricity previously stored and required in that moment, for example because an unexpected demand peak[173]. This problem arises especially when storage devices are used to provide power intensive functions, since the release of high volume of energy in a short period of time (15 seconds) would cause the collapse of those lines[174].

A solution sustainable from an infrastructural perspective consists on *locating the storage technologies close to the transmission and distribution hubs*. In these sites, in fact, the network

[172] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.52-53

[173] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.52-53

[174] DAVIDE CHIARONI, FEDERICO FRATTINI, SIMONE FRANZÒ, *Smart Grid Report*, Politecnico of Milan, July 2013, pp.33

presents its maximum capacity, which is able to support storage technologies in providing their services for the flexibility of the whole system, including both power intensive and energy intensive functions. This solution enables to avoid a collapse of the lines linking generating plants with the core of the network, but, on the other hand, it poses to the supply chain notable short term operational planning challenges; the system operator, as a matter of fact, in this case has to allocate network capacity considering also the capacity required by electricity flowing from generators toward the storage technologies , with the aim to maximize the ability of the network to receive the electricity in excess and ready to be stored (consequently reducing curtailments of production from renewable energy sources), minimizing on the same time the risk of congestions.

Renewable Energy Sources and Cross-border Electricity Transactions:

Cross-border electricity transactions have an important role in ensuring to the electricity system a sufficient degree of flexibility. In a very general way, this kind of transactions enables to increase the flexibility of a given region, because its flexibility no longer depends only on its own resources, like dispatchable plants and storage devices, but it is also enhanced by the flexibility sources of adjacent regions. The extent to which cross-borders electricity exchanges occur depends clearly on historical socio-economic factors characterizing the relationship among regions and on economic constraints. For example, the benefits deriving from linking an island network to the mainland network may be not sufficient to justify all the investments that are necessary[175].

The contribution of these cross-borders transactions is not determined exclusively by the capacity underlying the interconnections, but also, and especially, by the *coincidence of the needs of the adjacent regions* and their *availability to provide flexibility*.

The coincidence of needs is a crucial point since the incentives of regions to cooperate derive from the opportunity to mutually fulfill their needs. Considering a couple of adjacent regions, it means that if a region is experiencing a demand peak exceeding the available supply, the balancing mechanism across regions is possible only if the counterpart has a consistent excess of energy supply. This stresses the importance of interconnections with a plurality of regions instead of just a unique counterpart[176]: as a matter of fact, in presence of multiple partners, it is more likely to find a counterpart presenting suitable complementary needs. Moreover, in order to fully exploit the balancing potential among regions, it is important the availability of multiple connections points

[175] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.53-54

[176] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.53-54

between each couple of regions, in order to prevent congestions or to prevent the consequences of the failure of a connection point.

The availability of a plurality of connection points is relevant both for short term planning and strategic long term planning. Concerning operational planning, clearly the system operator is allowed to manage the circulation of the balancing electricity through many lines, reducing the incidence of the action on the load of each single line, leaving them largely available for common daily operations and avoiding congestions.

The plurality of interconnections allows the system operator also to prevent the interruption of cross-borders balancing mechanisms due to a failure of an interconnection or due to the overloading of a portion of the network, since it can guide the flow through alternative routes[177].

At operational level, a fundamental requirement is the real time coordination that takes place among the involved system operators, especially when cross-borders connections are used frequently. In this sense, homogeneous rules and procedures enable system operators of different regions to be always aligned and to manage cross-borders operations in a way that is effective and efficient for the whole system[178].

However, the current extent of interconnections usage is an aspect that must be carefully considered because of its implications for short term and long term planning. In fact, if in the daily routine interconnections are already used close to their maximum capacity they provide little additional flexibility in case of unexpected fluctuations, reducing the room for actions of the system operator and forcing it to focus, on the short term, on the flexibility sources within the region borders.

In the long term planning cross-borders transactions have a possible double effect. On the one hand the possibility to share resources with adjacent regions postpone or reduce the need for infrastructural investments within the network of each region. On the other hand, if interconnections facilities are already largely used, it may be necessary to expand them.

Demand Response and Demand Management:

Dispatchable plants, energy storage devices and cross-borders electricity transactions are all sources of flexibility that are located at the electricity system supply side. However the role of renewable energy sources has caused a transition from a supply chain characterized by a passive demand to a supply chain based on a highly active demand, active demand that is simultaneously source of flexibility for the system and a cause of the increase need of flexibility along the chain.

[177] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.53

[178] ENTSOE, *Supporting Document for the Network Code on Operational Planning and Scheduling*, Belgium, 24 September 2013, pp.43

Within this context, *demand management* and *demand response* ensure a notable degree of flexibility of the system and the ability to quickly adapt in real time to the arising needs. That makes these flexibility resources viable for the efficiency and effectiveness of the operational short term planning.

Before analyzing how they support the planning process and the advantages and disadvantages they provide, it is convenient to point out what demand management and demand response entail.

Demand management is a mechanism based on contracts signed between the system operator and consumers, according to which the latter agree and contract in advance to decrease the amount of energy they demand with regard to specific time intervals, postponing the consumption[179].

Demand response is a mechanism based on the real time reaction of consumers to electricity excess or scarcity and consequent price variations[180]. Consumers immediately adapt their consumption according to the price signals they receive as the system experiences a surplus or shortage of electricity; these adjustments are, as a result, not previously planned and contracted with the system operator.

Demand response is provided by all the categories of customers that are connected to the network and have the necessary devices, from industrial customers to individual consumers. The ability of demand to respond can be enhanced by aggregating different end users into groups, in order to increase the scope of the total adjustments.

The scope of the adjustments isn't the only relevant dimension; as a matter of fact it is necessary to consider the speed at which demand responds to the stimulus and how long the adjustment lasts. Both the speed and the duration of the adjustments depend on the interplay between the quality of the incentives provided by the governments to consumers and the extent of the efforts required to customers[181].

Actually, countries are usually implementing mechanisms aimed to counteract demand peaks, leading consumers to reduce their consumption when demand and price are high. However, for the next future, a further step that has been already planned by system operators and policy makers consists on creating suitable mechanisms to incentive consumers to increase their demand when prices are low, in order to limit downward demand peaks. The overall effect is a variability reduction of demand and a reduction of the delta between the highest demand level and the lowest demand level. Benefits are clear: lower variability of the average demand allows to reduce the

[179] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.47

[180] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.47

[181] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.47-48

degree of uncertainty associated to operational planning and it allows to maximize the efficiency related to network management, for example simplifying the elaboration of plans concerning network capacity allocation.

A key point concerning demand response and demand management consists on the willingness and availability of consumers to contract in advance limitations to their consumption or to proactively adapt in real time their demand, increasing and decreasing it according to the price signals they receive. The willingness of consumers clearly depends on the incentives that are provided and, generally speaking, consumers tend to be more prone toward variations with a short duration, comprised between 15 and 60 minutes[182].

Demand management grants to the supply operator an important operating tool. In fact, consistently to the conditions defined in the contracts stipulated with customers, the system operator can manage demand, adapting it to the system needs. However, although its support to the system operator, demand management presents a severe limit: the system operator can act on demand only with a notice of at least one day, according to the day-ahead market frame. This is a significant constraint, especially after the large scale deployment of non-programmable renewable energy sources, because day-ahead forecasts still present a relevant probability of error, inevitably limiting the effectiveness of this mechanism. As a consequence, demand management is an effective tool in short term planning to reduce the potential volatility of demand, since the system operator in a day-ahead temporal horizon can increase or decrease it, reducing its extreme values. However, it is not able to provide enough flexibility to support the system in being effective in maintaining in real time its balance, that, as we have seen, represents the most important challenge in the context characterized by the rise of renewable energy sources and smart grids. This is the reason why demand response appears to be the most effective source of flexibility concerning demand side[183].

The effectiveness of demand response is based on a crucial assumption: demand responds with a sufficient degree of certainty to the stimulus sent by the system operator. Taking for certain that demand responds properly, its responsiveness constitutes an important instrument in the hands of the system operator for real time operations.

In order to incentive small consumers to be reactive, in many countries they are grouped forming collective entities that work as a single body, reducing the efforts required to each single consumer. Large customers, like companies, usually do not belong to these groups but they interact directly

[182] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.48

[183] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.47

with the system operator in order to fully exploit savings potential related to demand adjustments according to price variations.

A satisfying responsiveness of demand clearly requires the implementation of consistent technologies to ensure the real time coordination of system operators and consumers; in particular these technologies allow a continuous exchange of information enabling the system operator to monitor in real time demand, and to modulate it sending proper signals to consumers[184]. The main problem concerning this approach is the fact that operating in real time entails always an extremely high degree of uncertainty. It is true that demand response provides the tool to deal with the real time deviations of the actual electricity volumes compared to the forecasted ones, but it is also due to emphasize that such an uncertainty referred to a large share of the total electricity circulating in the network may have a significant impact on the ability of the system operator to elaborate reliable short term plans. This is the reason why demand response is always integrated by demand management. In fact, since the adjustments underlying demand management have been contracted in advance, they can be assumed as certain reducing the extent to which demand is volatile and, consequently, reducing uncertainty.

5.4 Enhancing Electricity System Flexibility Sources

Through this short discussion, we have seen which are the main sources of flexibility of the system. The common aspect of all these sources is the fact that they depend on the reliability and degree of development of the network. In fact, the effectiveness of each source of flexibility depends on the current state of the network, that is to say its capacity to dispatch energy, the availability and location of storage technologies, the availability of cross-borders interconnections and the ability to interact with demand both in terms of demand management and demand responsiveness.

The strategic long term planning, involving new infrastructural investments, is a very complex process that faces many obstacles and that presents a really uncertain outcome; in fact, the high number of stakeholders involved and the often conflicting interests tend to significantly delay the progress of the projects. Since long term strategic planning appears to be so complex and uncertain, system operators running the electricity supply chain have to compensate the potential lacks or

[184] INTERNATIONAL ENERGY AGENCY, *Secure and Efficient Electricity Supply During the Transition to Low Carbon Power Systems*, Paris, 2013, p.4

delays of long term plans with an effective and constantly improving of the short term planning, able to support the increasing integration of non-programmable renewable energy sources.

The approach to short-term and mid-term planning must be consequently based on improving efficiency and effectiveness of the existing grid, optimally managing energy supply and demand acting on operational procedures and on the retrofitting of network components implementing new technologies.

Taking the assumption that network capacity can be increased only in the mid-term or long-term (from a pair of years to a decade according to all the factors previously seen), the core aim in the short term consists on maximizing the efficiency of capacity utilization, ensuring the effectiveness and reliability of the supply chain in providing to end users the electricity generated by large centralized conventional plants and large renewable energy plants on the one hand, and, on the other side, by small generating devices dispersed among consumers, according to the distribute generation paradigm.

The two main routes followed to accomplish this goal are congestion avoidance and enhancement of demand response[185].

Whether flexibility resources are available or not depends on different aspects, which require to be briefly discussed.

A first factor is the presence of a sufficient coordination and a sufficient interconnections availability among balancing areas within a given region. In fact, poor coordination or lacking interconnections prevent an efficient sharing of the available sources for the flexibility of the system, avoiding any balancing mechanism among the areas.

Another important factor consists on the way in which electricity is traded, or, more precisely, whether the market dynamics along the vertical unbundled supply chain really enable the use of flexibility resources to ensure the security and efficiency of the system. For example, if the market is characterized mainly by long term contracts, generators, retailers and customers are bound months in advance to fixed volume of energy to be exchanged affecting the system ability to exploit the sources of flexibility. This forces the system operator to contract in advance also the provision of reserves of electricity for the ancillary services and to allocate network capacity according to the needs of these reserves, reducing the capacity available for balancing mechanisms[186].

[185] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011

[186] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.53

Power exchanges, on the other hand, work on the basis of closer time horizons, enabling to allocate network capacity and to shape demand and supply consistently to the difficulties deriving from the variability and uncertainty due to non-programmable renewable energy sources.

A topic that urges attention is the conflict rising between variable renewable energy plants, which are mainly peaking power plants, and conventional base load plants. As a matter of fact, thanks to their lower operational costs and, in most cases, lower setup costs, variable renewable energy plants are displacing not only traditional peaking load power plants, but also intermediate and base load traditional plants[187]. On one side it represents a very positive sign since it means that the decarbonization strategy is working properly, however, on the other side, it is posing significant problems in terms of planning tasks and management of the system. In fact, even if variable renewable energy plants are substituting conventional ones, they do not present the same characteristics related to output programmability and stability, that are fundamental in order to ensure along the system the vital base load. It is consequently necessary that regulators carefully define the steps and pace for the transition from conventional electricity supply chains to the new structure based on a large integration of renewable energy sources, in order to maintain a suitable equilibrium between traditional plants and variable plants, to ensure the security of the system.

Forecasting is an additional factor that plays a fundamental role in facilitating the concrete and successful exploitation of flexibility resources. The mechanism through which forecasts enhance flexibility is simple: the sooner a variation of generators output is predicted and the more this forecast is accurate, and the sooner the system operator plans the actions suitable to counteract that variation.

Accurate forecasts with a relevant notice (mainly day-ahead forecasts) enable the system operator to balance variations modifying the output of intermediate power plants, having enough time to do it thanks to the notice, maintaining available the peaking power plants for fluctuations that cannot be predicted in advance.

This is an extremely important issue for short term planning and security of the system. As a matter of fact, since non-programmable renewable energy sources are characterized in general by a high degree of uncertainty and variability, they force the system operator to constantly adjust in real time supply and demand through the available flexibility resources analyzed before. However, real time balancing requires supply and demand to adapt in an extremely short time interval, emphasizing the importance of a reliable demand response and of the availability of peaking power plants, since they

[187] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.43

are the only plants characterized by response times consistent to the requirements of real time balancing[188].

Since the availability of power peaking plants is constrained not only by their overall installed power but also by the available transmission capacity, it appears clear the need for an optimal rationalization of the utilization of this kind of plants. Accurate forecasts are viable in this direction, since, predicting in advance fluctuations, they allow to balance the system through intermediate power plants, leaving the power peaking plants available for more challenging and sudden variations.

The availability of power peaking plants is necessary also to ensure the resources to "cover" forecasts errors, since they are identified only on a time horizon close or coinciding with the real time, consequently excluding the contribution of intermediate power plants.

The uncertainty deriving from non-programmable renewable energy sources has been deeply changing the forecasting and planning models applied along the electricity supply chain. The new methods are based on a probabilistic approach, recalling decision theory methods implying decision under risk or under uncertainty. The *probabilistic unit commitment method* is an example of them, which aim is to tackle uncertainty providing different suitable plants dispatch solutions according to the scenarios that progressively occur[189]. In fact, the unit commitment method provides a plurality of scenarios, where each of them identifies, in the frame of a day-ahead plan, the plants that should operate and their output for every period of time (usually a hour). A certain probability is then associated to each scenario, enabling to determine the expected optimal volume of production and operating time periods for each unit. Clearly, in addition to the plants commitment required by the plan, some peaking power plants not contemplated in the plan must be available to ensure protection against the uncertainty inevitably associated to a probabilistic approach.

5.5 Forecasting Error and Rolling Planning Horizon

Since the planning process is based on anticipating the future in a context characterized by a high uncertainty, it necessarily has to be able to deal with potential relevant errors. These errors have obviously a notable potential impact on the final objective of the supply chain, that is to say ensuring to customers a secure provision of electricity and with a satisfying level of customer

[188] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.51

[189] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.65

service. As we have seen, the electricity supply chain is supposed to be able to overcome the challenges deriving from uncertainty leveraging its flexibility, which depends on the number and types of dispatchable plants, on the availability of storage capacity, on cross-border transactions and on demand response.

However, concentrating the attention more on the plans themselves, a method to face uncertainty consists on regularly monitoring whether the reality is deviating or not from what has been planned before and, eventually, updating the plan according to the new real data. In this sense we distinguish two main approaches for plans monitoring and updating: *rolling horizon planning* and *event-driven planning*[190].

Rolling horizon planning entails the repartition of the whole planning horizon into a number *n* of time periods. At the beginning of the planning horizon, only the plan referred to the first period is concretely implemented, and, as well as the second period starts, a new plan is elaborated according to what is happened in the first period, updating the forecasts for the following periods. The new plan overlaps with the initial plan for the *n*-1 remaining periods (period 1 excluded) and it presents a further period (period *n*). In the same way at the beginning of the third period, a new plan is elaborated for the following *n* periods according to the results of the second period and so on[191].

The alternative consists on ***event-driven planning***. In this case a plan is not adjusted cyclically at regular intervals, but it is updated only once a relevant event is occurred, that is to say an event able to compromise the effectiveness of the plan in the future[192].

Rolling horizon planning can be an important tool for operational planning in the context of the electricity supply chain characterized by a large deployment of non-programmable renewable energy sources[193].

The unit commitment plan of the system operator defines per each period of the planning horizon which plants have to be operating and which volume each of them has to generate. This plan is based on forecasts about the future output of the non-programmable renewable energy sources plants and about the net demand that has to be fulfilled. Clearly, the farther is a time period, the higher is the probability of error and the larger is the likely discrepancy with the reality.

Rolling horizon planning and, consequently, elaborating for the whole horizon a new plan at the end of each period on the basis of the previous period enables to significantly decrease the degree of

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[190] HARTMUT STADTLER, CHRISTOPH KILGER, *Supply Chain Management and Advanced Planning*, Springer, third edition, 2005, p.83

[191] HARTMUT STADTLER, CHRISTOPH KILGER, *Supply Chain Management and Advanced Planning*, Springer, third edition, 2005, p.83

[192] HARTMUT STADTLER, CHRISTOPH KILGER, *Supply Chain Management and Advanced Planning*, Springer, third edition, 2005, p.83

[193] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.64

uncertainty associated to the forecast; as a matter of fact, the closer is the interval interested by the forecast, and the more the latter tends to be accurate. As a result, a more certain plan for the following period allows to allocate more efficiently flexibility resources and to increase the overall security and efficiency of the system.

5.6 Possible Solutions to reduce Flexibility Requirements in Short-Term Planning

The flexibility of the system is become an urging and viable requirement because of the increasing integration of non-programmable renewable energy sources, the overtime variability of their output and because of their uncertainty. An important characteristic of these energy sources is the fact that each source varies over time and over space differently from the others, requiring customized forecasting models. The lower is the predictability of the source and the higher is the likelihood of extreme variations, and the higher is the requirement of flexibility of the system. However, since increasing system flexibility entails significant efforts and investments, it is preferable or less expensive to reduce flexibility requirements rather than increasing flexibility.

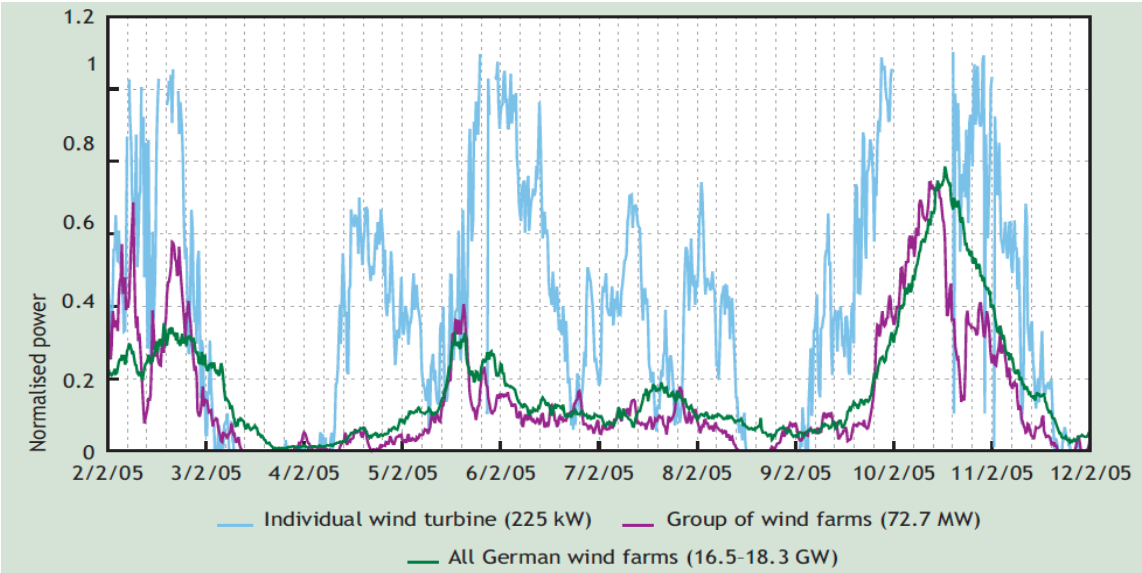
A first possible action consists on *grouping renewable energy generating plants dispersed over a wide area*[194]; in fact, we have seen that the variability of plants output changes from location to location, consequently considering together a multitude of plants from different areas tends to reduce the aggregate output volatility. A wide area tends to present also an aggregate output with a lower uncertainty, allowing more reliable forecasts. The same approach is valid also considering the technological dimension: grouping together plants with different types of technology may help to reduce the aggregate output variability.

Another possible action consists on *curtailments of the production of renewable energy plants*[195]. We have already seen that curtailments affect mainly renewable energy plants because, as peaking power plants, they have the best response times and the lowest response costs in ramping down. Generation curtailments, however, tend to be accepted only if referred to short periods of time and limited volumes, in order not to hurt generation profitability. In many cases, thanks to the fast growing storage facilities, curtailments are avoided simply storing the energy in excess instead of injecting it into the network.

[194] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.72

[195] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, p.72

Graph 10: comparison of the variability of the electricity production of a single wind power plant and the aggregate variability of a group of plants over a wide area



Source: *Wind Energy Report Germany 2006, ISET, Kassel, 2006.*

The graph wants to demonstrate how grouping renewable energy plants distributed over a wide area may represent an effective strategy to reduce the flexibility requirements of the system. In fact, as we can notice, the aggregate variability of the group of wind farms and of all the German wind farms is much lower than the variability of a single wind farm.

5.7 Balancing Costs

The overall costs for the balancing operations depend, first of all, on the extent of the contribution of renewable energy sources to the total volume of production of the electricity system. Generally speaking, the larger is the deployment of renewable energy sources and the higher are the balancing costs, because the higher is the requirement for flexibility and balancing actions[196].

The relevance of the balancing costs depends also on the availability of flexibility resources in the system. As a matter of fact, if the resources are already present and available in the system when needed, the costs associated to them tend to be low. On the other hand, in the case in which resources are not enough or they have not been optimally allocated, balancing costs may increase significantly. Balancing costs, consequently, directly depend on the dispatchability of generators, on

[196] INTERNATIONAL ENERGY AGENCY, *Harnessing Variable Renewables, a Guide to the Balancing Challenge*, Paris, 2011, pp.82

the availability of storage technologies, on the availability of cross-border transactions and on demand response. After that, flexibility is enhanced by the way in which the system is managed, recognizing great importance to forecasts accuracy, plans reliability and all the operational actions that are applied.

6) INCREASING INTERACTION AMONG NATIONAL SUPPLY CHAINS AND THE RISING NEED OF A COMMON NETWORK CODE

Electricity supply chain has experienced a radical transformation in the modern economies, switching from its static conventional structure to a highly dynamic structure. The plurality of players in the new structure, thanks to the market liberalization, the vertical and horizontal unbundling have progressively required greater interactions among national supply chains in order to optimize network capacity utilization, flexibility resources and operational reserves allocation, and to increase the overall efficiency and security of the network.

Cross-borders interactions among supply chains are consequently become a fundamental factor for system management; however, great difficulties have been encountered because of the heterogeneity of technical standards and planning and operational procedures, which have been preventing a successful cooperation among national supply chains[197].

Regulators and national supply chains, especially within the European context, are concentrated in developing the conditions for a better cooperation at international level of the several national system operators. Plans are consequently thought to accomplish several objectives which final purpose is to boost cooperation.

These objectives can be summarized in the following bullet points in order to have an immediate overview of them[198]:

- Implementing common best practices and procedures allows to create a cross-national homogeneous modus operandi to counteract the high degree of variability and uncertainty, increasing operational and planning efficiency and consistency.
- The commonality of planning procedures and horizons enables to better plan and coordinate flexibility resources sharing and balancing mechanisms.

[197] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, *Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy 67, 2014, pp. 175

[198] ENTSOE, *Supporting Document for the Network Code on Operational Planning and Scheduling*, Belgium, 24 September 2013

- Higher coordination enables also the optimization of interconnections capacity usage, minimizing the risk of congestions and, on the same time, maximizing capacity utilization, reducing or postponing new infrastructural investments to increase existing capacity.
- Superior coordination creates the basis also for more effective preventing or remedial actions, increasing the security of the system and improving its recovery time in case of failure.
- Interaction among the system operators may have also a positive effect in terms of avoidance of energy curtailments from renewable energy sources due to an insufficient internal demand, and it may increase the potential for geographical or technological aggregation of generating power plants to reduce aggregate supply variability and uncertainty
- Interaction among system operators improves data and information sharing, facilitating forecasts model verification and adjustments thanks to a higher data availability.

The core purpose of this process of harmonization is, indeed, to create a common framework that guides and helps interconnected supply chains in accomplishing their planning and operating tasks in a way that not only allows, but also facilitates a fast growing deployment of renewable energy sources.

This coordination is referred to all the entities involved in the supply chain, that is to say from the generators to the end users, going through transmission and distribution operators and retailers.

In particular, the attention is focused on the allocation of the available infrastructure capacity and of the available flexibility resources. The notable attention paid to optimize availability allocation is justified mainly by the fact that capacities and resources belong to multiple parties and an effective and efficient integration of renewable energy sources is possible only thanks to a precise coordination of all the components and resources available in the network[199].

Concerning the first point, the vertical and horizontal unbundling of the supply chain and the liberalization of the market have implied that each phase of the chain, except for the ones with the characteristics of natural monopolies, are performed by a multitude of players and that each player difficultly performs both generation and retailing activities. The high number of involved players and the need of ensuring to every single player a fair competition and a nondiscriminatory access to network compel to optimally allocate availabilities and to make sure that they are used through a careful coordination in order to fully exploit their capacities and potentials.

[199] ENTSOE, *Supporting Document for the Network Code on Operational Planning and Scheduling,* Belgium, 24 September 2013, pp.40

Concerning the second aspect, non-programmable renewable energy sources have the power to cause variations of the loads generated, ramping suddenly up or down and in an unpredictable way. We have seen how actions thought to reduce variability and uncertainty involve wide areas, also crossing national borders, and all the players within those areas. It appears immediately clear how coordination is a necessary requirement for the success of balancing mechanisms and security of the system.

The harmonization of planning and operational procedures and tasks among national supply chains deals with three key topics: *adequacy of generation capacity*, *cross-borders interconnection capacity*, *security of operations* in absence or in presence of failures of network components[200].

The transmission operator of the system has the responsibility to ensure an adequate generation capacity, which depends on the number and types of power plants that are not available, the volume of energy made available by the demand side and the available capacity of cross-border interconnections. The transmission operator has also the responsibility to identify with a sufficient notice potential adequacy lacks and to make aware of it the other interconnected transmission operators and all the parties involved in the chain.

Concerning cross-border interconnections capacity, the transmission operator has to optimally plan and allocate it and the capacity of the portion of network close to the interconnections in order to facilitate the energy inflow. In particular, it has to ensure the maximum exploitation of the available capacity avoiding congestions and to reduce as much as possible variations of capacity utilization, contracting in advance (at least in the day-ahead market) the allocation of a significant share of capacity and leaving the remaining capacity available for flexibility actions.

Finally, the transmission operator is called to ensure the security of the system despite of problems referred to the failure or unavailability of components of the grid or problems deriving from issues related to elements of the supply chain different from transmission and distribution network.

Since the decision of a party of the network is potentially able to influence all the other parties, all the strategies and operational plans along the supply chain must be coordinated; this provides a certain degree of stability and reciprocity among the parties, stability and reciprocity that are fundamental to ensure operations security for short term planning and to create solid and stable basis for plans and projects referred to the long-term and the mid-term[201].

[200] ENTSOE, Supporting Document for the Network Code on Operational Planning and Scheduling, Belgium, 24 September 2013, pp.29

[201] ENTSOE, Supporting Document for the Network Code on Operational Planning and Scheduling, Belgium, 24 September 2013, pp.29

The network code that is in charge for harmonizing practices and procedures among national supply chains has two main concrete objectives.

First of all, any incompatibility or misalignment of one party's plan with the plans of one or more other parties must be avoided, both in the short-term and long term; consequently, any new plan or plan modification have to be verified according to the compatibility requirements with the other parties plans. Secondly, according to the first objective, as soon as a potential incompatibility arises, an ad-hoc coordinating mechanism has to deal with it, finding a suitable solution.

The framework that is applied to define to what extent parties have to be coordinated and that provides the ideal procedures and solutions to be applied is composed of the current best practices applied in the European Union.

7) INCREASING IMPORTANCE OF ADEQUATE INFORMATION SYSTEMS AND PROCEDURES ALONG THE ELECTRICITY SUPPLY CHAIN

Mid-term planning and short-term planning require a high level of cooperation among the parties involved in the supply chain, and this implies necessarily a significant flow of information among them. The flow of information takes place especially from and to the transmission operator, since it is in charge for ensuring a secure and efficient functioning of the whole system. Information are used by the transmission operator to align the mid-term plans of all the players with the aim to ensure the avoidance of incompatibilities and, in the short term planning, to maintain the balance between demand and supply by optimally managing available network capacity and flexibility resources[202].

The flow of information doesn't occur downstream in a uniform way from the top to the bottom of the supply chain, but all the information tend to converge toward the transmission operator from the upstream members of the supply chain (generators) and from the downstream members (distributors and retailers, end users). In addition, an important share of information comes from the electricity markets and power exchanges, in particular from bilateral contracts stipulated in advance (mid-term planning) and from the transactions in the day-ahead market and intraday market (short term planning)[203].

The amount of information circulating along the supply chain is significantly increased after the large integration of non-programmable renewable energy sources. The main drivers of this increase have been the variability and uncertainty of these sources, that require constant monitoring and adjustments of plans and they require to operate close to real time for the lack of programmability; the second driver has been the market liberalization and vertical and horizontal unbundling of the supply chain. This second aspect, in particular, has had a crucial impact on the planning processes of the transmission operator.

In the traditional vertically integrated chain, it had direct access to any information of any phase of the supply chain, and it had the power to act directly on any component of the system. Nowadays, the transformation and unbundling of the supply chain entail the presence of a multitude of players, with different and sometimes conflicting strategies and interests; as a consequence, information

[202] ENTSOE, *Supporting Document for the Network Code on Operational Security*, Belgium, 24 September 2013, pp.33
[203] ENTSOE, *Supporting Document for the Network Code on Operational Security*, Belgium, 24 September 2013, pp.40

have gained a significant strategic relevance, due to the competitive environment, potentially limiting information sharing among parties. Moreover the transmission operator has no longer direct access to the sources of information along the system but it has to constantly interact with all the players in order to obtain the data and information it needs. This has been requiring a stronger cooperation among players and also a consistent and homogeneous information and communication system along the supply chain in order to ensure a proper information circulation.

In order to better describe how information circulation develops along the supply chain, it is convenient in my opinion to briefly review the objectives and tasks underlying system operator's strategy and plans.

The main objectives are, first of all, ensuring a constant fulfillment of demand and with a satisfying level of customer service, followed by the optimal allocation of network capacity and flexibility resources, maintaining the stability of the system and minimizing disturbances and, finally, ensuring effective and prompt restoring actions in case of failures or blackouts.

These objectives concretely imply constant efforts of the system operator to stabilize frequency at demand level and to monitor the voltage and power flowing along the network, to verify whether they are in compliance with the technical operating limits[204].

According to the fundamental importance of the tasks and responsibilities of the transmission operator for the proper functioning and security of the whole system, regulators grant to them the right and, on the same time, the duty to have complete access to all the sources of information that are not in-house.

The transmission operators have also the responsibility to define the quality standards of the information that must be provided and the frequency and timing of their provision[205]. This is thought to enable system operators to organize information flows consistently to their planning tasks and needs, with the aim to maximize their effectiveness and efficiency. Since it is fundamental that a system operator is properly informed, regulators compel all the parties belonging to the supply chain to provide the requested information and to do it in compliance with the quality standards and schedules defined by the system operators themselves.

The information are related to real time data, short term schedules and plans, but also infrastructural plans, since system operators have to ensure plans alignment in the short, mid and long term. More precisely, short term schedules are referred to the transactions in the day-ahead market and intraday market, which, added to the bilateral contracts set in advance in the mid-term planning, enable

[204] ENTSOE, *Supporting Document for the Network Code on Operational Security*, 2nd Edition Final, Belgium, 24 September 2013, pp.30

[205] V.AGNETTA, G.AGNUZZI, *Criteri di Telecontrollo e Acquisizione Dati*, GRTN, Allegato A6, Rev. 03, July 2010, pp.11

transmission operators to plan the allocation of a significant share of the network capacity. Real time information are, instead, the data required by the transmission operators to adjust plans previously based on forecasts. It is important to stress the relevance of also horizontal circulation of information in addition to the vertical circulation occurring along the chain. Horizontal circulation takes place among system operators and it is experiencing an increasing importance due to the central role that cross-borders transactions are acquiring[206].

We have seen how electricity flows through cross-national interconnections are determinant to avoid generation curtailments from renewable energy sources, to improve and better allocate flexibility resources, to fully exploit existing infrastructure capacity and, consequently, to reduce or postpone infrastructure investments. A proper information sharing between system operators of adjacent national supply chains is, indeed, necessary to efficiently and effectively plan in advance interconnections capacity allocation and to adjust in real time those plans, being able to comply with the sudden and unpredictable loads variations due to the large deployment of non-programmable renewable energy sources.

The integration of renewable energy sources, as a matter of fact, has stressed the impact of an open information sharing on the efficiency of the whole system. Non-programmable energy sources and distributed degeneration make extremely variable both the output of the generators connected to the grid and the net demand. The reliability of the plans that are elaborated depends clearly on the accuracy of the forecasts, accuracy that is proportional to the amount of available information and their precision.

Given the uncertainty and variability associated to renewable energy sources and the increasing integration of the latters, a poor accuracy of information would have disruptive effects in the short term planning and mid-term planning, and it would also bias long term planning, providing misleading information about the requirements in terms of expansion of infrastructure capacity.

[206] ENTSOE, *Supporting Document for the Network Code on Operational Planning and Scheduling*, Belgium, 24 September 2013, p.40

CONCLUSION

According to our theoretical overview of the deep transformation occurring in the electricity industry and supply chain, we have identified two main forces that have been driving this process, that is to say the *market liberalization*, which has enabled the vertical and horizontal unbundling of the supply chain, and *the fast growing deployment of non-programmable renewable energy sources*, which has had a crucial impact on the planning and management processes of all the phases of the supply chain, progressively displacing the incumbent structure.

The emerging new structure is consequently characterized by two phases open to market competition, the generation and retailing phases, whereas transmission and distribution remain performed by single players because of their characteristics of natural monopolies, and by the coexistence of conventional plants, exploiting traditional energy sources, and of renewable energy sources plants.

We have seen how this transformation process is raising notable challenges at all the three levels of the planning process, long-term planning, mid-term planning and short-term planning, and how it is consequently requiring significant actions to allow an effective and efficient integration of non-programmable renewable energy sources. These actions are, in fact, aimed to create the conditions for combining the fast growing development of the new sources of energy with the stability, sustainability and security of the whole power system and of electricity provision.

Concerning long-term planning, each phase of the supply chain presents precise routes of development that are in progress and that are thought to accomplish the transition. At generation level, the main concern consists on planning the replacement of traditional plants with renewable energy plants, ensuring constantly a reliable and flexible power supply, through the optimization of the power plants portfolio. The optimization takes place with regard to the types of energy sources exploited, their location according to the network infrastructures and the repartition of the installed power among power-peaking plants, intermediate plants and base-load plants, in order to combine generation inertia and responsiveness.

Looking at the transmission phase, the planning objectives can be divided into two categories: on the one hand, they aim to expand the transmission infrastructures through substantial investments in order to foster the integration of renewable energy sources, and, on the other hand, they aim to integrate those investments with a more efficient allocation of the existing transmission capacity to

reduce the demand for new expansion projects[207]. Concerning the first category, efforts are concentrated on aligning stakeholders interests, on determining a fair allocation among transit countries (or regions) and benefitting countries (or regions) of the costs underlying the new investments, and selecting the most suitable technologies to minimize power losses that would compromise the efficiency of the system. With regard to the second category, we have seen how the attention is concentrated on coordinating the planning processes of all the players of the supply chain in order to improve as much as possible transmission capacity allocation, enhancing power system efficiency and flexibility.

Concerning distribution phase, the key aspect consists on the rise of distributed degeneration and the consequent switch from a one-direction electricity flow to a bi-directional flow, which has had a huge impact on distribution both in terms of infrastructure and planning processes[208]. Consequently, efforts are concentrated on adopting a new network structure (meshed networks), on improving the information and communication systems along the supply chain, and on installing new technologies at the access points of the network in order to support the integration of distributed generation.

Finally, looking at retailers, we notice how the transformation of the electricity industry and supply chain is forcing them to go beyond the traditional business model based simply on selling electricity, and to develop new business models aimed to offer a broader variety of tailored products and services to raise customers switching costs[209].

Concerning mid-term and short-term planning, they are focused on constantly balancing electricity demand and supply, maximizing the efficiency and security of the power system. As a consequence, these two planning horizons are characterized by the crucial role played by the forecasting process and by the optimal allocation of the flexibility resources of the system, as tools to counteract the high variability and uncertainty associated to non-programmable renewable energy sources.

In particular, we have seen that an increasing attention is addressed toward cross-border electricity exchanges among national supply chains, in order to enlarge the potential of the balancing areas and mechanisms.

Before entering the analysis of the supply chain, we stressed the fact that the evolutionary process of the electricity supply chain is actually in progress, developing at a different pace in each country and making difficult the provision of a static picture of the current state of the art of the supply chain. The heart of this process is the constant innovation that is enabling to transform the

[207] INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA*, Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions*, Energy Policy volume n. 67, 2014, pp. 172

[208] FABRIZIO PILO, GIANNI CELLI, EMILIO GHIANI, GIAN GIUSEPPE SOMA, *New electricity distribution network planning approaches for integrating renewable*, *WIREs Energy Environ* n. 2, 2013, pp. 140

[209] EURELECTRIC, Utilities: Powerhouses of Innovation, Full Report, 8 May 2013, pp.26

incumbent structure, counteracting the challenges deriving from the integration of non-programmable renewable energy sources and preserving and ensuring the stability and security of the system. Farther developments of this transformation will be allowed and supported investing in innovation as broad concept, not limiting the efforts only to the technologies themselves, but innovating the power system as a whole, that is to say its products, its processes and its business models, innovating them in close interaction with all the industries located upstream and downstream the electricity supply chain, leveraging spillovers in a virtuous self-reinforcing mechanism.

INDEX OF TABLES AND GRAPHS

REFERENCES

DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, Biomass Energy Executive Report 2012, Politecnico of Milan, June 2012
Available at http://www.energystrategy.it/report/biomasse.html

DAVIDE CHIARONI, FEDERICO FRATTINI, GIOVANNI TOLETTI, LORENZO COLASANTI, Solar Energy Report 2013, Politecnico of Milan, April 2013
Available at http://www.energystrategy.it/report/solare.html

DAVIDE CHIARONI, FEDERICO FRATTINI, RICCARDO TERRUZZI, Wind Energy Report 2012, Politecnico of Milan, July 2012
Available at http://www.energystrategy.it/report/eolico.html

DAVIDE CHIARONI, FEDERICO FRATTINI, Simone Franzò, Smart Grid Report, Politecnico of Milan, July 2013
Available at http://www.energystrategy.it/report/smart-grid.html

INTERNATIONAL ENERGY AGENCY, Climate & Electricity Annual 2011, Paris, 2011
Available at
http://www.iea.org/publications/freepublications/publication/Climate_Electricity_Annual2011.pdf

INTERNATIONAL ENERGY AGENCY, Electricity in a Climate-Constrained World, Paris, 2012
Available at
http://www.iea.org/publications/freepublications/publication/ElecClimate2012_free.pdf

INTERNATIONAL ENERGY AGENCY, Empowering Variable Renewables, Paris, 2008
Available at
http://www.iea.org/publications/freepublications/publication/Empowering_Variable_Renewables.pdf

INTERNATIONAL ENERGY AGENCY, Secure and Efficient Electricity Supply During the Transition to Low Carbon Power Systems, Paris, 2013
Available at
https://www.iea.org/publications/freepublications/publication/SecureandEfficientElectricitySupply.pdf

INTERNATIONAL ENERGY AGENCY, Harnessing Variable Renewables, a Guide to the Balancing Challenge, Paris, 2011
Available at
http://www.iea.org/publications/freepublications/publication/Harnessing_Variable_Renewables2011.pdf

DOMITILLA CHICCHI, Le Principali Fonti di Energia Rinnovabile, Bollettino Ingegneri n. 6, 2010, p. 3-12
Available at http://eprints.bice.rm.cnr.it/3004/

ARSIA-SCUOLA SUPERIORE SANT'ANNA, Le Colture dedicate ad uso energetico il Progetto Bioenergy Farm, Quaderno Arsia n. 6, Tuscany, 2004
Available at
http://www.avanzi.unipi.it/ricerca/quadro_gen_ric/ricerche_concluse/bioenergy_farm/documenti_bioenery_farm/Le%20colture%20dedicate%20ad%20uso%20energetico%20il%20Progetto%20Bioenergy%20Farm_Quaderno%20ARSIA%206_2004.pdf

DINO CASTELLI, GIANNI CELLI, GIOVANNI GOLA, BRUNO COVA, FRANCESCO DI SALVATORE, FABRIZIO PILO, FRANCESCO VERTEMATI, Problematiche della pianificazione delle reti derivanti dalla liberalizzazione del mercato, 2001
Available at http://www.ricercadisistema.it:8080/site/binaries/content/assets/rse-sola-lettura/pregresso/2002/Generazione_distribuita/a0092001.pdf

FABRIZIO PILO, GIANNI CELLI, EMILIO GHIANI, GIAN GIUSEPPE SOMA, New electricity distribution network planning approaches for integrating renewable, *WIREs Energy Environ* n. 2, 2013, p. 140–157
Available at http://onlinelibrary.wiley.com/doi/10.1002/wene.70/full

HANNELE HOLTINNEN, NICOLAOS CUTULULIS, ANDREJ GUBINA, ANDREW KEANE, FRANS VAN HULLE, Ancillary services: technical specifications, system needs and costs. Deliverable 2.2, December 2012
Available at http://orbit.dtu.dk/fedora/objects/orbit:127228/datastreams/file_390101fa-0daf-49bb-b0a3-abbcade80404/content

ENTSOE, Supporting Document for the Network Code on Operational Security, 2nd Edition Final, Belgium, 24 September 2013
Available at http://networkcodes.entsoe.eu/wp-content/uploads/2013/08/130924-AS-NC-OS_Supporting_Document_2nd_Edition_final.pdf

ENTSOE, Supporting Document for the Network Code on Operational Planning and Scheduling, Belgium, 24 September 2013
Available at http://networkcodes.entsoe.eu/wp-content/uploads/2013/08/130924-AS-NC-OPS_Supporting-Document_2nd_Edition_final.pdf

INGA BOIE, CAMILA FERNANDES, PABLO FRIAS, MARIAN KLOBASA, Efficient strategies for the integration of renewable energy into future energy infrastructures in Europe – An analysis based on transnational modeling and case studies for nine European regions, Energy Policy volume n. 67, 2014, p. 170–185
Available at http://www.sciencedirect.com/science/article/pii/S030142151301121X#

ANDREW KUSIAK, HAIYANG ZHENG, ZHE SONG, Power optimization of wind turbines with data mining and
evolutionary computation, Renewable Energy volume n. 35, issue n. 3, 2010, p. 695–702
Available at http://www.sciencedirect.com/science/article/pii/S0960148109003772

V.AGNETTA, G.AGNUZZI, Criteri di Telecontrollo e Acquisizione Dati, GRTN, Allegato A6, Rev. 03, July 2010
Available at http://www.terna.it/LinkClick.aspx?fileticket=36637

TERNA RETE ITALIA, Previsione della Domanda Elettrica in Italia e del Fabbisogno di Potenza necessario Anni 2012-2022, 12 November 2013
Available at http://www.terna.it/linkclick.aspx?fileticket=103363

TERNA RETE ITALIA, Partecipazione alla Regolazione di Frequenza e Frequenza-Potenza, Allegato A15, July 2008
Available at http://www.terna.it/LinkClick.aspx?fileticket=TwRReqwHbvk=

TERNA RETE ITALIA, Individuazione Zone della Rete Rilevante, Rev. 06, elaborated by Martire F., January 2007
Available at http://www.terna.it/linkclick.aspx?FileTicket=017364

GIANFRANCO CHICCO, PIERLUIGI MANCARELLA, Distributed multi-generation: A comprehensive view, Renewable and Sustainable Energy Reviews volume n. 13, issue n. 3, 2009, p. 535–551
Available at http://www.sciencedirect.com/science/article/pii/S1364032107001578

MANUEL BARITAUD, Securing Power during the Transition:
Generation Investment and Operation Issues in Electricity Markets with Low-Carbon Policies, IEA, Paris, 2012
Available at
http://www.iea.org/publications/insights/insightpublications/SecuringPowerTransition_Secondeedition_WEB.pdf

TOORAJ JAMASB, MICHAEL POLLITT, Electricity Market Reform in the European Union:
Review of Progress toward Liberalization & Integration, Sloan School of Management, 24 March 2005
Available at http://web.mit.edu/ceepr/www/publications/workingpapers/2005-003.pdf

CINZIA PUGLISI, Modello Supply Function Equilibrium per l'Analisi delle Interazioni tra il Mercato del Giorno Prima ed il Mercato dei Servizi di Dispacciamento, MA thesis, Politecnico of Milan, 2013
Available at https://www.politesi.polimi.it/bitstream/10589/81523/1/2013_07_Puglisi.pdf

HUI-MING WEE, WEN-HSIUNG YANG, CHAO-WU CHOU, MARIVIC V.PADILAN, Renewable energy supply chains, performance, application barriers, and strategies for further development, Renewable and Sustainable Energy Reviews volume n. 16, issue n. 8, 2012, p. 5451–5465
Available at http://www.sciencedirect.com/science/article/pii/S1364032112003863

R.BANOS, F.MANZANO-AGUGLIARO, F.C.MONTOYA, C.GIL, A.ALCAYDE, J.GOMEZ, Optimization methods applied to renewable and sustainable energy: A review, Renewable and Sustainable Energy Reviews volume n. 15, issue n. 4, 2011, p. 1753–1766
Available at http://www.sciencedirect.com/science/article/pii/S1364032110004430

LEONARDO MEEUS, KONRAD PURCHALA, RONNIE BELMANS, Development of the Internal Electricity Market in Europe, The Electricity Journal volume n. 18, issue n. 6, July 2005, p. 25–35
Available at http://www.sciencedirect.com/science/article/pii/S1040619005000771

EUROPEAN OCEAN ENERGY ASSOCIATION, Industry Vision Paper 2013, Brussels, Belgium, 2013
Available at http://www.oceanenergy-europe.eu/images/Publications/European_Ocean_Energy-Industry_Vision_Paper_2013.pdf

BJORN BAKKEN, INGEBORG GRAABAK, Development of regional and Pan-European guidelines for more efficient integration of renewable energy into future infrastructures, SINTEF Energiforskning AS, 2012
Available at
http://www.susplan.eu/fileadmin/susplan/documents/downloads/WP_1/D1.1_main_report.pdf

M. BENINI, M. GALLANTI, S. BARSALI, P. PELACCHI, D. POLI, Il sistema elettrico in Norvegia e Svezia, struttura e procedure di gestione, L'Energia Elettrica, volume n. 77, issue n. 3, May-June 2000
Available at http://www.ricercadisistema.it:8080/site/binaries/content/assets/rse-sola-lettura/pregresso/2002/Studio_del_comportamento_degli_operatori_del_mercato_dell_energia_e_analisi_dei_prezzi/a0632000.doc

A.EMAMI, P.NOGHREH, New approach on optimization in placement of wind turbines within wind farm by genetic algorithms, Renewable Energy volume n. 35, 2010, p. 1559–1564
Available at http://www.sciencedirect.com/science/article/pii/S0960148109005023

N.AMJADY, F.KEYNIA, Mid-term load forecasting of power systems by a new prediction method, volume n. 49, issue n. 10, October 2008, p. 2678–2687
Available at http://www.sciencedirect.com/science/article/pii/S0196890408001441

ANGEL A.BAYOD-RUJULA, Future development of the electricity systems with distributed generation, Energy volume n. 34, issue n. 3, March 2009, p. 377–383
Available at http://www.sciencedirect.com/science/article/pii/S0360544208003174

M.GHIASSI, DAVID K.ZIMBRA, H.SAIDANE, Medium term system load forecasting with a dynamic artificial neural network model, Electric Power Systems Research volume n. 76, issue n. 5, 2006, p. 302–316
Available at http://www.sciencedirect.com/science/article/pii/S0378779605001951

RUGGERO SCHLEICHER-TAPPESER, How renewables will change electricity markets in the next five years, Energy Policy volume n. 48, 2012, p. 64–75
Available at http://www.sciencedirect.com/science/article/pii/S0301421512003473

REN 21 STEERING COMMITTEE, Renewables 2013, Global Status Report, REN 21, 2013
Available at http://www.ren21.net/Portals/0/documents/Resources/GSR/2013/GSR2013_lowres.pdf

EURELECTRIC, Utilities: Powerhouses of Innovation, Full Report, 8 May 2013
Available at
http://www.eurelectric.org/media/79178/utilties_powerhouse_of_innovation_full_report_final-2013-104-0001-01-e.pdf

GE ENERGY, Western Wind and Solar Integration Study, May 2010
Available at http://www.nrel.gov/docs/fy10osti/47781.pdf

HARTMUT STADTLER, CHRISTOPH KILGER, Supply Chain Management and Advanced Planning, Springer, third edition, 2005

C. PILAVACHI, Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process, Energy Policy volume n. 37, issue n. 3, 2009, p. 778-787
Available at http://www.sciencedirect.com/science/article/pii/S0301421508005880#

IAN RUTLEDGE, Who owns the UK Electricity Generating Industry – and does it matter?, SERIS, UK, November 2012
Available at
http://www.seris.co.uk/SERIS_(Sheffield_Energy_Resources_Information_Services/Viewpoint_files/Who_Owns_UK-Generation.pdf

TERNA RETE ITALIA website: http://www.terna.it/

INTERNATIONAL ENERGY AGENCY DATABASE:
http://www.iea.org/statistics/statisticssearch/