A scenario analysis of a pan-European electricity market: effects of a gas shortage in Italy

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Abstract--In the last decade, energy security has gained importance due to the high dependence of industrialized economies on energy consumption and to the increased risks of disruption in supply. In order to provide quantitative inputs to decision makers, a pan-European scenario analysis for the year 2015 has been carried out concerning the effects of a winter gas supply shortage in Italy, where a large share of electricity generation is based on natural gas as primary fuel. The objective of the analysis is a quantitative assessment of the impact of the considered Italian gas shortage on the European power system, from the point of view of security of supply, competitiveness and sustainability, i.e. the three "pillars" of the EU energy policy. The results of the study show that the availability of a significant national gas storage capacity, together with fuel switching capability and greater cross-border transmission capacity in the power sector are fundamental in order to assure security of electricity supply.

***Index Terms*--European electricity market, gas shortage, power system simulation, security of supply.**

I. Introduction

Electricity security of supply remarkably depends on fuel security of supply. It is widely recognized that the role of gas in power generation in the EU Member States is growing today and will significantly increase in the future, determining risks of insecure electricity supply in case of gas supply shortages.

Within this context, this paper quantifies the impact on the overall European power system of a possible gas supply shortage occurring in a country whose power generation is largely based on natural gas, namely Italy. The reference year considered for the shortage scenario is 2015.

The impact assessment, carried out using a model of the European power system built using the MTSIM electricity market simulator (described in part II), is focused on the security of electricity supply, as well as on the impact on electricity production costs and on the environmental impact (in terms of CO_2 emissions) deriving from the redispatching of power generation (with possible fuel substitution) necessary to face the gas shortage, taking into account cross-border electricity exchanges.

In the following, the gas supply shortage scenario is described in part III and its impact assessment is reported in part IV. Then, part V shows the main results of the simulations, while the role of cross-border transmission capacity is discussed in part VI.

II. Medium Term SIMulator

MTSIM (*Medium Term SIMulator*), developed by ERSE (see [1]), is a zonal electricity market simulator able to determine the hourly clearing of the market over an annual time horizon, calculating the zonal prices and taking primarily into account:

- variable fuel costs of thermal power plants;
- other variable costs that affect power plants (such as O&M, CO_2 emissions, etc.);
- bidding strategies put in practice by producers, in terms of mark-ups over production costs.

The main results provided by the simulator are:

- hourly marginal price for each market zone;
- hourly dispatching of all dispatchable power plants;
- fuel consumption and cost for each thermal power plant;
- emissions of CO_2 (and of other pollutants) and related costs for emission allowances;
- power flows on the interconnections between market zones;
- revenues, variable profits and market shares of the modeled generation companies.

The model can handle several types of constraints, such as:

- power transfer capacity on the interconnections between market zones; the equivalent transmission network is modeled using the so-called *Power Transfer Distribution Factors* (PTDF[4]) and MTSIM can model active power flows by calculating a DC Optimal Power Flow; in this way, transmission bottlenecks can be identified and the needs for network reinforcement can be quantified;
- power plants forced and scheduled unavailability, as well as start-up and shut-down flexibility;

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[4] Power Transfer Distribution Factors, commonly referred to as PTDFs, express the percentage of a power transfer from source A to sink B that flows on each transmission facility that is part of the interconnection between A and B.

- constraints on plant operation (e.g. "must-run") and on fuel consumption over a certain time period (this feature has been used to model the gas shortage);
- emission constraints and related trading of emission allowances at exogenous prices set in the relevant international markets (e.g. ETS, CDM, JI).

Non-dispatchable power plants operation (typically RES sources such as wind, photovoltaic, run-of-river hydro, etc.) is not modeled endogenously: hourly generation profiles have to be provided as input to the simulator.

In the present study, MTSIM has been used to simulate the optimal behavior of the modeled European power system, having as objective function the cost (fuel and CO_2 allowances) minimization. No market power exercise has been simulated, in order to focus on the "natural" best response of the power system to the considered gas shortage.

A. The model of the European power system

The European AC transmission network has been modeled with an equivalent representation (see Fig. 1[5]) where each country (or aggregate of countries, such as in the Balkans) is represented by a node (i.e. market zone), interconnected with the neighboring countries via equivalent lines characterized by a transmission capacity equal to the corresponding cross-border Net Transfer Capacity (NTC).

The PTDF matrix used in the MTSIM simulator has been calculated on the basis of a series of DC Load Flows executed on a detailed representation (about 4000 nodes) of the European AC network. The equivalent value of the reactance (x_{ij}) of each European cross-border interconnection has been provided by ENTSO-E [2].

As far as the NTC values (for both flow directions) are concerned, the latest ENTSO-E available data (Summer 2009 and Winter 2008-2009: see [2]) have been used. In addition, for all the interconnections for which expansions of the transmission capacity are expected before 2015 (the reference year for the simulations), the new increased NTC values have been taken into account.

As far as the electricity exchanges via DC interconnections are concerned, considering their independence from the PTDF matrix coefficients, it was decided to impose an hourly profile. The same has been done for AC interconnections with other power systems.

As shown in Fig. 1, in the model each country has been "collapsed" into a node of the equivalent AC European network, therefore, for each country, an "equivalent" power plant for each main generation technology has been defined.

5 The abbreviations used in Fig. 1 are the following: AT: Austria, BG: Bulgaria, BL: Belgium and Luxembourg, BX: Balkan countries (Albania, Bosnia and Herzegovina, Kosovo, Montenegro, Republic of Macedonia, Serbia), CH: Switzerland, CZ: Czech Republic, DE: Germany and Denmark West, ES: Spain, FR: France, GR: Greece, HR: Croatia, HU: Hungary, IT: Italy, NL: The Netherlands, PL: Poland, PT: Portugal, RO: Romania, SI: Slovenia, SK: Slovak Republic, UA_W: Ukraine West.

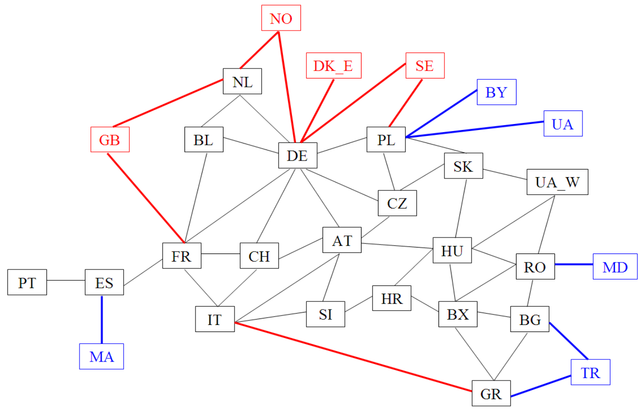

Fig. 1. Equivalent representation of the European AC transmission network (in black), cross-border DC interconnections (in red) and AC interconnections with other power systems (in blue).

In general, the net generation capacity values (for each technology/fuel and for the reference year 2015), have been taken from the "Conservative Scenario" (Scenario A) of the UCTE (now ENTSO-E) *System Adequacy Forecast (SAF) 2009-2020* (available from [2]). Such scenario takes into account the commissioning of new power plants considered as sure and the shutdown of power plants expected during the study period.

Additional information necessary for a more detailed subdivision of the UCTE data have been taken from the results of the FP6 European project ENCOURAGED (see [3]) and of the FP7 project REALISEGRID (see [4]), as well as estimated by ERSE.

B. Other scenario hypothesis

As for the other main scenario assumptions, in most cases they have been derived from the POLES scenario *"GR-FT Global Regime with Full Trade"* (see [5]) developed within the context of the FP7 European project SECURE (see [6]).

The POLES modeling system allows the simulation of world energy scenarios under environmental constraints. It is a Partial Equilibrium Model, with a dynamic recursive simulation process. From the identification of the drivers and constraints in the energy system, the model allows to describe the pathways for energy development, energy demand, fuel supply, greenhouse gas emissions, international and end-user prices, from today to 2100.

The GR-FT scenario assumes the introduction of a global cap on emissions, with abatement programs corresponding to a cost-effective program resulting from a unique carbon value, as introduced either by a global carbon market or by an international carbon tax.

For our simulations, oil, coal and gas prices have been directly taken from the GR-FT scenario, while lignite and fuel oil prices have been calculated as indexed to coal and oil prices, respectively (see TABLE II).

The nuclear fuel price has been derived from the POLES scenario's fuel costs of nuclear generation, assuming an average electrical efficiency of 34,2%.

TABLE I
PRICES ASSUMED FOR YEAR 2015 IN THE SIMULATIONS

Fuel	Price [€/GJ]
Coal	**1.936**
Lignite	**0.871**
Gas	**5.076**
Fuel Oil	**8.358**
Nuclear	**0.428**

The CO_2 emissions value for year 2015 is 13.25 €/tCO_2 and it has been taken from the GR-FT scenario, as well as data concerning electricity demand in the considered countries.

III. GAS SUPPLY SHORTAGE SCENARIO

The gas shortage scenario for the reference year 2015 in Italy entails an interruption of supply from the *TransMed "Enrico Mattei"* pipeline connecting Algeria to Italy (entry point at Mazara del Vallo, Sicily) via Tunisia.

This pipeline has an annual maximum capacity of 33.5 bcm, and the interruption is assumed for the 5 months between November and March, i.e. the most critical ones in terms of gas consumption in Italy, due to heating demand.

It must be noticed that the probability of occurrence of such a severe event is not so remote as it would seem at a first glance. In fact, on December 19, 2008, one of the five lines composing *TransMed* was damaged by the anchor of an oil tanker in the Channel of Sicily. In mid-2009, repair operations of the damaged line were still ongoing.

IV. IMPACT ASSESSMENT

In the following, the monthly balance between gas supply and demand in Italy in the reference year 2015 is reported, in order to calculate the amount of gas available for power generation in case the gas supply shortage occurs.

The values shown in TABLE III have been obtained as described in the following:

- *National production*: the Italian national gas production is rapidly declining and the trend is not foreseen to change; last years' data show a linearly decreasing trend that, if extrapolated, leads to a value of **1.34 bcm/year** in 2015, that is **0.11 bcm/month**.
- *Import pipelines*: together with all of the existing pipelines, we take into account also the new *IGI Poseidon* pipeline (8 bcm/year), connecting Greece to Italy (entry point at Otranto), completing the natural gas corridor through Turkey, Greece and Italy and allowing Italy and the rest of Europe to import natural gas from the Caspian Sea and the Middle East. IGI is expected to start operation from late 2012 (see [8]). Considering out of order the *TransMed* pipeline, the maximum effective monthly import capacity is therefore around **6.34 bcm/month**. In fact, there are other projects for new import pipelines (see [9]) in Italy, but none of them can be assumed for sure to be in operation by 2015.
- *LNG terminals*: in Italy there are currently two LNG terminals: Panigaglia (ENI) and Porto Levante (Adriatic LNG). Several projects for new LNG terminals have been proposed (see [10]), but only Livorno (OLT Offshore LNG, 3.75 bcm/year) is at an advanced stage and it is foreseen to be in operation in 2011. The maximum effective monthly import capacity assumed for 2015 is therefore around **1.21 bcm/month**.
- *Storage*: in Italy gas storage capacity for the modulation service is currently about **8.72 bcm**. In addition, strategic storage capacity of about **5.17 bcm** is available. There are several projects (see [11]) for new storage facilities but, since none of them was in the construction phase when the study was carried out, we did not take them into account. We assume that storage is full at the end of October (end of the injection phase) and that all the capacity available for modulation is used till the end of March (end of the withdrawal phase). Moreover, we assume that withdrawal is carried out according to the optimal profiles defined by the companies operating the storage facilities.

TABLE II
MONTHLY AMOUNT OF GAS AVAILABLE FOR POWER GENERATION IN THE CONSIDERED ITALIAN SHORTAGE SCENARIO (BCM)

		Nov.	Dec.	Jan.	Feb.	Mar.
SUPPLY	National production	0.11	0.11	0.11	0.11	0.11
	Import pipelines	6.34	6.34	6.34	6.34	6.34
	LNG terminals	1.21	1.21	1.21	1.21	1.21
	Storage	0.95	2.01	2.94	2.34	0.47
	TOTAL	8.61	9.67	10.60	10.00	8.13
DEMAND	Distribution networks	-4.57	-6.30	-6.68	-5.47	-4.49
	Industry	-1.7	-1.7	-1.7	-1.7	-1.7
	Network consumptions and losses	-0.125	-0.125	-0.125	-0.125	-0.125
	TOTAL	-6.40	-8.12	-8.51	-7.29	-6.32
Gas available for power generation		2.21	1.54	2.09	2.71	1.82

- *Distribution networks*: consumption on gas distribution networks is mainly due to heating demand. In this study we calculated the heating demand in a cold winter whose probability to occur is once every 20 years, that is the reference winter defined by the Italian law regulating the gas sector (Legislative Decree nr. 164 of May 23, 2000).
- *Industry*: we assume that in 2015 gas consumption of the industrial sector will recover to the pre-economic crisis levels, corresponding to about **1.7 bcm/month**. Assuming this value, we implicitly give priority to industry gas consumption over power generation, even if, at least to a small extent, the industrial sector can perform some fuel switching in case of gas shortage.

- *Network consumption and losses*: on average, network consumptions and losses are **0.125 bcm/month**.

V. Results of the Simulations

The impact and cost quantitative assessment of the gas supply shortage taken into account have been focused on the following main aspects:

- security of supply (i.e. electric energy not supplied);
- competitiveness (i.e. electricity production costs);
- sustainability (i.e. CO_2 emissions).

Two simulations have been carried out, in which the modeled European power system has been dispatched to cover the load foreseen for the reference year 2015:

- the "base case", without any gas shortage,
- the "shortage case", with the assumed gas supply shortage.

Then, the results of the simulations of the two cases have been compared in order to draw conclusions, as reported in the following (all the reported data refer to the five months November ÷ March, when the gas supply shortage occurs).

In the following TABLE III, a comparison between gas consumption for power generation in the "base case" and the estimated amount of available gas (see TABLE II) without resorting to strategic storage is reported.

TABLE III
Comparison between gas consumption for power generation in the "base case" and the estimated amount of available gas (in case of shortage), without resorting to strategic storage (bcm)

	Nov.	Dec.	Jan.	Feb.	Mar.	Nov ÷ Mar
Gas available for power generation	**2.21**	**1.54**	**2.09**	**2.71**	**1.82**	**10.37**
Consumption of CHP power plants	**-1.58**	**-1.63**	**-1.63**	**-1.48**	**-1.60**	**-7.92**
Consumption of non-CHP power plants	**-1.04**	**-1.13**	**-1.58**	**-1.83**	**-1.17**	**-6.75**
Balance	**-0.41**	**-1.22**	**-1.12**	**-0.6**	**-0.95**	**-4.3**

It is quite clear that there is no gas enough to allow for a "normal" operation of the Italian generation system, that would require an additional consumption of about **4.3 bcm** out of the 5.17 bcm strategic storage capacity. Moreover, it must be taken into account that the more strategic storage is depleted, the less the daily peak flowrate of the extracted gas, so that, in case of cold days in the last part of the winter, supply can be at risk even if gas reserves are not exhausted.

As for the "shortage case", we impose the amount of gas available for power generation (see TABLE II) as a constraint to the MTSIM simulator. In such a case, the modeled European power system is redispatched to provide more energy to Italy, in order to compensate for its reduced generation. Moreover, in Italy the available fuel oil-fired generation capacity is dispatched to face the gas shortage. Finally, a constant import of 500 MW (the NTC value) from the Italy-Greece DC interconnector is assumed.

In the following TABLE IV a comparison between gas consumption of non-CHP thermal power plants in the "base case" and in the "shortage case" is reported.

TABLE IV
Comparison between gas consumption of non-CHP thermal power plants in the "base case" and in the "shortage case"

Month	Gas consumption [TJ]		Gas consumption [Mcm]		Δ%
	Base	Shortage	Base	Shortage	
Nov.	35.78	22.32	1036	646	-37.6
Dec.	39.10	0	1132	0	-100
Jan.	54.47	15.71	1577	455	-71.2
Feb.	63.26	42.60	1832	1234	-32.7
Mar.	40.34	7.44	1168	215	-81.6
Nov ÷ Mar	**232.95**	**88.07**	**6745**	**2551**	**-62.2**

Under these conditions and assuming not to use the strategic gas storage for non-CHP thermal power plants (**92 Mcm** of strategic gas storage are necessary in December to keep all CHP gas-fired power plants in operation), a criticality shows up only in December (the month with the greatest lack of gas: see TABLE III), when the modeled power system is not able to supply **349.5 GWh**, i.e. about 1.38% of the monthly load.

In particular, the most of such energy not supplied (ENS) occurs in the first part of the month, characterized by a higher load, as shown in the following TABLE V.

TABLE V
Energy not supplied in December, in the "shortage case"

Week	Maximum load value [MW]	ENS [GWh]
Mon 1 – Sun 7	49426	117.3
Mon 8 – Sun 14	50674	152.9
Mon 15 – Sun 21	48909	77.7
Mon 22 – Sun 28	42936	0
Mon 29 – Wed 31	44922	1.6
Total		**349.5**

Assuming to produce such energy with a Combined Cycle Gas Turbine power plant with a 55% efficiency, it would correspond to a gas consumption of about **66 Mcm**, that could be easily provided by the strategic storage.

Moreover, it can be seen that the neighboring generation systems do their best to help Italy to tackle with the shortage: in fact, when there is energy not supplied in Italy, import capacity from Austria, Slovenia and Greece is saturated, while thermoelectric generation in France and in Switzerland is at its maximum capacity. It is basically not possible to increase imports through France and Switzerland from other countries due to saturation of other relevant cross-border interconnections.

Of course, in the "shortage case" CO_2 emissions of the Italian power system decrease (by 1946 ktCO_2), due to the reduced production of its power plants caused by the gas shortage.

Anyway, due to substitution of gas generation with less efficient and more emissive fuel-oil power plants, CO_2

emissions decrease much less (-5.6%) than power generation (-20.9%).
As for the entire modeled European power system, the difference is significant: CO_2 emissions in the “shortage case” are **1900 ktCO_2** greater than in the “base case”.
As above mentioned, if we make the (unrealistic) assumption not to use in any case strategic storage for non-CHP thermal power plants operation, about 349.5 GWh of energy would not be supplied in December.
With a 20 €/kWh VOLL (see [7]), this would entail the astronomical cost of about 7 billions €.
If, on the contrary, we assume to use a very small part (66 Mcm, as above mentioned) of strategic gas storage to avoid such energy not supplied, the extra-costs that the modeled European power system must bear due to the Italian gas shortage are basically due only to the change of fuel mix and to the increase of CO_2 emissions and of the related need for allowances.
As reported in TABLE VI, the resulting total extra-cost is quite high, being around **646 M€**, and is almost all due to the change of fuel mix.

TABLE VI
EXTRA-COSTS BORNE BY THE MODELED POWER SYSTEM DUE TO THE GAS SHORTAGE IN ITALY

	Extra-costs [M€]
Change of fuel mix	**619**
Increased CO_2 emissions	**27**
Total	**646**

VI. ROLE OF CROSS-BORDER TRANSMISSION CAPACITY

As above mentioned, in the “shortage” case an important contribution is provided by the increase of Italian electricity imports from the rest of Europe.
In fact, a reduction of bottlenecks in the European transmission network, especially the ones affecting cross-border trades, would make easier to transport energy where it is required, increasing security of supply, but also allowing for a more optimized operation of the generation set, with significant economic benefits.
Within this context, we have compared the results of the Italian “shortage case” with a purely theoretical ideal scenario (that we will call “unconstrained shortage case”) where all cross-border AC transmission capacity constraints are removed, in order to assess their strength in constraining the system.
In the following, the results concerning the five cold months when the shortage occurs in the two cases are reported.
First of all, in the “unconstrained shortage case” no energy not supplied occurs in Italy, since electricity imports from the northern frontier increase by 72% (see TABLE VII).

TABLE VII
INCREASE OF ELECTRICITY IMPORTS FROM THE NORTHERN FRONTIER IN THE “UNCONSTRAINED SHORTAGE CASE” W.R.T. THE “SHORTAGE CASE”

Interconnection	“shortage case” [GWh]	“unconstrained” [GWh]	Δ%
FR ⇨ IT	7203	13431	86
CH ⇨ IT	5671	8237	45
AT ⇨ IT	712	1317	85
SI ⇨ IT	1951	3750	92
Total	**15537**	**26736**	**72**

Moreover, such greater availability of “foreign” energy allows not to dispatch Italian fuel oil-fired power plants; in addition, a significant increase at the European level of cheaper coal production substitutes not only fuel oil-fired, but also gas-fired generation, as shown in TABLE VIII. The corresponding results in terms of fuel consumptions are shown in TABLE IX.

TABLE VIII
COMPARISON BETWEEN PRODUCTIONS BY DIFFERENT FUELS OF NON-CHP PLANTS IN THE “UNCONSTRAINED SHORTAGE CASE” W.R.T. THE “SHORTAGE CASE”

Fuel	“shortage case” [GWh]	“unconstrained” [GWh]	Δ%
Nuclear	317177	317395	0.1
Hard coal	185315	199865	7.9
Lignite	110744	111577	0.8
Natural gas	132080	127345	-3.6
Fuel oil	10510	0	-100

TABLE IX
COMPARISON BETWEEN FUEL CONSUMPTION OF NON-CHP PLANTS IN THE “UNCONSTRAINED SHORTAGE CASE” W.R.T. THE “SHORTAGE CASE”

Fuel	“shortage case” [PJ]	“unconstrained” [PJ]	Δ%
Nuclear	3297	3299	0.1
Hard coal	1905	2063	8.3
Lignite	1144	1152	0.8
Natural gas	878	800	-8.8
Fuel oil	100	0	-100

The increased coal production causes an increase of CO_2 emissions of about **3600 ktCO_2** in the “unconstrained shortage case”.
In terms of costs, as shown in TABLE X, due to a strong reduction of fuel costs, the “unconstrained shortage case” is about **900 M€** cheaper than the “shortage case”, that is **254 M€** cheaper even than the “base case”, where no gas shortage occurs.

TABLE X
DIFFERENCE OF COSTS BETWEEN THE “UNCONSTRAINED SHORTAGE CASE” AND THE “SHORTAGE CASE”

	Δ costs [M€]
Change of fuel mix	**-946**
Increased CO_2 emissions	**46**
Total	**-900**

Of course, these estimated savings do not take into account the annualized costs of network expansions, nevertheless they give an idea of the economic importance of network constraints.

VII. Conclusions

This study, carried out within the FP7 European project *SECURE – "Security of Energy Considering its Uncertainty, Risks and Economic implications"* (see [6] and [12]), quantified the impact on the overall European power system of a possible gas supply shortage in Italy in 2015.

The impact assessment, carried out using a simulation model of the European power system, has been focused on the security of electricity supply, as well as on the impact on electricity production costs and on the environmental impact (in terms of CO_2 emissions) deriving from the redispatching of power generation (with possible fuel substitution) necessary to face the gas shortage, taking into account cross-border electricity exchanges.

The results for Italy showed that a limited use of strategic gas storage can avoid electric energy not supplied; moreover, the assumption of preserving as much as possible the rest of strategic gas storage proved to be quite expensive, since the fuel switching towards fuel oil causes both an increase of CO_2 emissions and, especially, a significant cost increase of about 646 M€.

Several remedies can be envisaged to tackle with the impact of gas supply shortages on electricity security of supply, that can be put in practice both in the short and in the long term, and that can affect both the gas and the electricity sector. As for the gas sector, in a long term view, the most effective remedies are the diversification of supply sources, both in terms of suppliers and of supply infrastructures, and the increase of gas storage capacity. As for the electricity sector, the most effective long-term remedies are the diversification of generation sources, as well as the development of the transmission network to increase transfer capacity.

As for this latter remedy, we showed its importance by analyzing a purely theoretical ideal scenario where all cross-border AC transmission capacity constraints in Europe are removed, in order to assess their strength in constraining the system.

Within this context, the MTSIM simulator has been recently extended with a "network expansion" capability: it can increase inter-zonal transmission capacities in case the annualized costs of such expansions are lower than the consequent reduction of generation costs due to more efficient dispatching.

Using this new simulation capability, within the context of the FP7 SECURE project (see [6]), we will assess in different scenarios the non-optimality level of cross-border transmission capacity in the European power system.

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IX. Biographies

Alessandro Zani graduated in Informatics Engineering at Università Degli Studi di Bergamo (2006) and is now at his 3rd year of the PhD in "Computational methods for forecasting and decision in Economics and Finance". With a Master in the Electricity Sector at Universidad Pontificia Comillas of Madrid (2008), in 2007-2008 he collaborated with the Regulation Department of Endesa working on the development of a statistical model of the Spanish electricity market. Since October 2008 he has been collaborating with the Power System Scenarios and Energy Efficiency Research Group at ERSE.

Andrea Grassi graduated in Electrical Engineering at Politecnico di Milano, Italy, in 2009. In 2009, he joined ERSE, where he is currently working in the field of power system development and simulation.

Michele Benini graduated in Electronic Engineering at University of Bologna, Italy, in 1987. In 1989, he joined CISE, where he worked in the field of Artificial Intelligence and was responsible for development of expert system applications to power systems. In 1998, he joined ENEL R&D, then CESI and CESI RICERCA, where he was responsible for several research projects in the field of deregulated electricity markets. He is currently head of the Power System Scenarios and Energy Efficiency Research Group at ERSE and his main interests are in the field of power system economics, electricity market deregulation and long-term scenario simulation.