The impact of Large-scale Renewable Integration on Europe's Energy Corridors

Özge Özdemir[1], Karina C. Veum[1], Jeroen de Joode[1], Gianluigi Migliavacca[2], Andrea Grassi[2], Alessandro Zani[2]

Abstract-- **Due to the long-term goals to achieve a sustainable, secure, and competitive European energy system and the consequent stringent policies for climate change mitigation, renewable energy resources (RES) will necessarily dominate Europe's future power supply. New strategies for electricity network expansion will be needed as the power supply shifts towards a high share of RES generation, in particular, with intermittent nature. Due to the interaction between electricity and gas markets, large-scale RES integration together with developments in Europe's electricity corridors is likely to influence gas consumption and imports of Europe from neighboring countries and hence affect the needs for gas infrastructure expansion. In this paper, the impact of large-scale integration of RES on EU's energy corridors including both electricity and gas infrastructures up to 2050 is assessed using economic optimization and equilibrium network models of electricity and gas markets respectively. Under four different scenarios for renewable integration, future electricity and gas infrastructure needs are determined by utilizing these models while taking into account the interactions between electricity and gas markets.**

Index Terms**-- renewable, electricity and gas markets, electricity and gas infrastructures, scenario analysis, equilibrium and optimization models.**

I. Introduction

Renewable energy sources (RES) are expected to dominate the EU's energy supply in a sustainable future energy system. Large scale integration of RES means that the future power system will consist of a considerably high base-load power generation from RES most of which are of intermittent nature such as solar and wind. High variability of power generation from RES has a profound impact on the control of network flows. More diverse network situations resulting in more congestion are likely to occur, increasing the necessity of electricity network expansion both from a national and international perspective.

There is a strong interaction between the electricity and gas markets. Gas prices and, in general, fossil fuels prices affect the electricity market clearing, being the dispatching solution function of a cost-driven merit order. This dependence has become stronger since the penetration of gas in electricity generation has largely increased in the last decade throughout the EU, mainly due to its environmental advantages over other fossil fuels. Consequently, the integration of large-scale RES and electricity network development plans will in the long term have a direct impact on the gas markets such as gas consumption in power generation will decrease in some countries with high RES generation whereas it will increase in other countries which serve gas-powered electricity generation as back-up for intermittent RES supply. The change in gas consumption levels of power sector will influence gas prices and gas flows to and within Europe and consequently affect the need for expansion of the gas infrastructure. Likewise, the investments in gas infrastructure influence the availability of gas and gas prices which consequently together with CO_2 prices affect the gas powered generation in electricity markets, the level of electricity prices, transnational corridors expansion, and electricity exchange.

In this contribution, we assess the impact of large scale RES integration both on the transnational electricity and gas infrastructures by explicitly addressing the interaction between electricity and gas markets. To this aim, we adopt four different scenarios of RES integration up to 2050 as described in [1] and we utilize gas market model (GASTALE) and electricity market model (MTSIM) to simulate the long-term development of the European energy markets (2030-2050).

In the following sections we briefly describe both the methodology applied and the adopted gas and electricity market models (Section II), providing the main results (Section III).

II. Methodology

A. *Description of the Transnational Scenarios*

The SUSPLAN project (www.susplan.eu) has developed four scenarios (storylines) diversified on the basis of two main drivers: public acceptance and technological development. The details of the methodology and the assumptions for the storyline framework can be found in [1]. Regarding RES deployment and energy demand developments in electricity and gas sectors, each storyline is characterized by different assumptions:

- **Red** storyline has the lowest amount of energy provided by RES sources which reaches only up to %40 of total electricity generation in 2050. The energy demand remains to be relatively high until 2050 due to very low environmental awareness among consumers.

This work is a part of the SUSPLAN project (www.susplan.eu) which is sponsored by the European Commission, Directorate General Energy (DG ENER) under 7th Framework Programme (FP7).

1 Özge Özdemir, Karina C. Veum, and Jeroen de Joode are Scientific Researchers at Energy Research Center of the Netherlands (ECN), P.O. Box 56680, Amsterdam, The Netherlands (Contact details: özdemir@ecn.nl, veum@ecn.nl, dejoode@ecn.nl).

2 Gianluigi Migliavacca, Andrea Grassi, and Alessandro Zani are Scientific Researchers at Ricerca Sistema Energetico, via Rubattino 54, 20134, Milan, Italy (Contact details: gianluigi.migliavacca@rse-web.it, andrgra84@hotmail.it, alessandro.zani@rse-web.it)

- **Green** storyline has significant RES deployment of mainly hydro, solar, wind, and wave and reaches a RES share of 73% of electricity generation in 2050. Moreover, the energy demand is the lowest due to positive environmental awareness.
- **Blue** storyline also assumes significant RES deployment of mainly wind offshore, solar, wind onshore, and wave with 70% share of electricity generation in 2050; however, due to low environmental awareness the energy demand remains to be high as in **Red** storyline.
- **Yellow** storyline assumes moderate RES deployment with 53% share of electricity generation in 2050 which consists of mainly wind and wave. As in **Green** storyline, the environmental awareness among consumers is high, thus energy demand is lower than **Red** and **Blue** storylines.

B. *Electricity Market Model: MTSIM*

MTSIM is an electricity market simulator which is able to determine the hourly clearing of a zonal market over an annual time horizon and calculate the zonal prices, taking primarily into account variable fuel costs of thermal power plants and other variable costs that affect power plants (such as O&M, CO_2 emissions, etc.) and bidding strategies by producers (in terms of price mark-ups in addition to production costs). Non-dispatchable power plants operation (typically RES such as wind, photovoltaic, run-of-river hydro, etc.) is modeled exogenously and hourly generation profiles have to be provided as input to the model. Reservoir hydro stations are modeled by means of their typical hourly balance which takes into account the stored amount of water, intake, and off take as well as a pre-defined amount of natural precipitation which is defined for each month of the year.

The model can handle the transmission bottlenecks by utilizing an equivalent transmission network and power transfer capacities on the interconnections between market zones. The equivalent transmission network is modeled using the so-called Power Transfer Distribution Factors (PTDF[3]) and active power flows are handled by calculating a DC Optimal Power Flow. The European transmission network has been modeled with an equivalent representation where each country (or aggregate of countries, such as in the Balkans) is represented by a node (i.e. market zone) and interconnected with the neighboring countries via equivalent lines characterized by a transmission capacity equal to the corresponding cross-border Net Transfer Capacity (NTC). Fig. 1 gives the equivalent representation of EU transmission grid where red color represents the DC lines. As far as the NTC values (for both flow directions) are concerned, the latest ENTSO-E available data [2] (summer 2009 /winter 2008-2009) have been used. Moreover, for each cross-border interconnection and for each month, the average hourly exchanged power has been calculated, using data from the ENTSO-E Statistical Database. In case the average hourly exchanged power in a certain month was higher than the official NTC value, the former has been taken into account as the reference interconnection transmission capacity[4].

As far as the electricity exchanges via DC interconnections are concerned, they are independent from the PTDF matrix coefficients (usually DC transits are regulated by an exchange program independent from the flow in the rest of the network). This was implemented by adding two fictitious generators, both characterized by maximum and minimum generation capacity equal to the maximum and minimum transit capacity of the HVDC link, in all the zones that the DC line connects. An additional hourly constraint imposes that the energy generated by one generator is equal to the energy absorbed by the other one in order to simulate the transit of energy from one node to the other. This modeling allows optimizing the usage of the HVDC link because the model will hour by hour take the decision of the optimal transit so as to minimize the overall yearly dispatching cost.

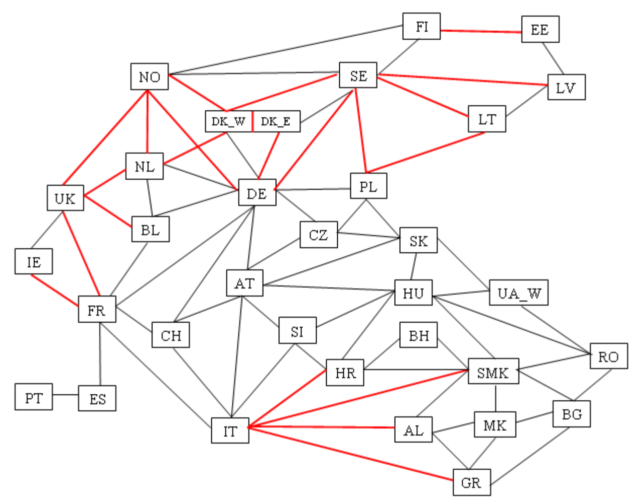

Fig. 1 Equivalent Representation of EU Transmission Network[5]

A further feature of MTSIM that has been added specifically for the SUSPLAN project is the capability to assess the AC-network expansion needs endogenously, so called "*planning modality*". In this modality, MTSIM can increase inter-zonal AC transmission capacities in case the annualized costs of such expansions are lower than the consequent reduction of generation costs due to a more efficient dispatching. As far as network expansion is concerned, we used the average cost data (the same for all

[3]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. In each of these load flows, with the slack node put in France, 100 MW of active power has been injected, in turn, into each country, while the load of all the other N-1 countries has been increased by 100/(N-1) MW. For the sake of simplicity, the presence of phase shifter transformers has been neglected. The equivalent value of the reactance of each European cross-border interconnection has been provided by ENTSO-E (see [2]).

[4] This is the case, for example, for the interconnection between Slovenia and Italy.

[5] The abbreviations used in the figure are the following:
AT: Austria, AL: Albania, BG: Bulgaria, BH: Bosnia and Herzegovina, BL: Belgium and Luxembourg, SMK: Serbia, Kosovo, and Montenegro, MK: Republic of Macedonia, CH: Switzerland, CZ: Czech Republic, DE: Germany, DK_E: Denmark East, DK_W: Denmark West, EE: Estonia, ES: Spain, FI: Finland, FR: France, GR: Greece, HR: Croatia, HU: Hungary, IE: Ireland, IT: Italy, LT: Lithuania, LV: Latvia, NL: The Netherlands, NO: Norway, PL: Poland, PT: Portugal, RO: Romania, SE: Sweden, SI: Slovenia, SK: Slovak Republic, UA_W: Ukraine West, UK: United Kingdom.

scenarios) considered within the context of the EC FP7 project REALISEGRID (http://realisegrid.erse-web.it) and based on publicly available sources and feedbacks from Transmission System Operators (TSOs) and from manufacturers.

On the other hand, the DC network in 2030-2050 is estimated in correspondence with each storyline. The expansions of HVDC lines between 2030 and 2050 have been exogenously defined, by hypothesizing their expansion program on the basis of some results of the research project REALISEGRID.

C. *Gas Market Model: GASTALE*

GASTALE is a game-theoretic equilibrium model of the European natural gas market which includes European gas consumers and gas producers supplying to Europe while taking into account the existing gas infrastructure such as transport pipelines, liquefied natural gas (LNG) shipping network, and storage. The geographical coverage and the network structure of the model are given in Fig. 2.

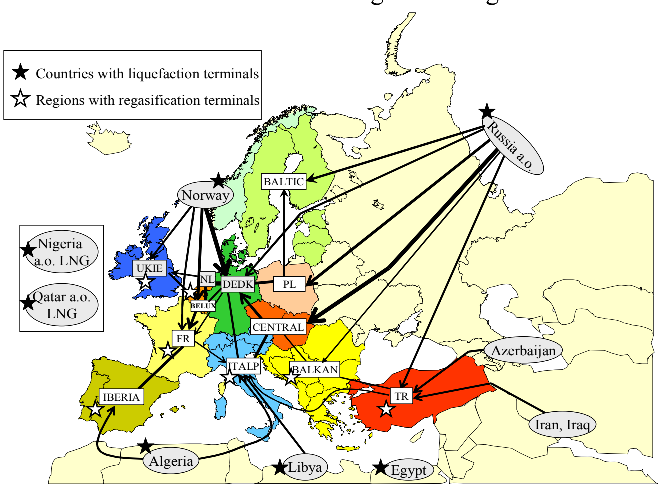

Fig. 2 Geographical Coverage of the GASTALE Model

GASTALE distinguishes among the following market players striving for different optimization goals:

- *Producers* decide on production and transport to the region of consumption, earning a wholesale price;
- *Consumers* consist of three different market sectors, namely the power generation sector, the industrial sector, and the residential sector. In addition, consumption is divided over three seasons within a year: low, shoulder, and high demand periods representing (i) April-September; (ii) February, March, October, November; and (iii) December-January of each calendar year respectively;
- *TSOs* provide transport through on- and offshore pipelines and LNG shipping;
- *Storage System Operators (SSOs)* regulate injection into storage during the low-demand warm season and withdrawals for consumption during the medium- and high-demand cold season.

Producers are the only strategic players and pay TSOs and LNG shippers to transport gas to the market. Storage owners buy gas in the low demand period for sale in the other periods. As in other gas market models (i.e., [3]) a type of congestion pricing is assumed in transport and storage. In particular, transporters and storage operators are assumed to charge their long-run variable cost (including capital costs) unless capacity constraints bind; if the latter occurs, then the price charged for transport increases until the demand for transport services equals the supply.

The GASTALE model is formulated as a mixed complementarity problem. This implies that optimality conditions of market players' maximization problems together with market clearing conditions give rise to a Nash-type of equilibrium outcomes. Market clearing conditions mainly consist of energy balances between market players (supply equals demand) which determine the wholesale gas prices and the prices for the use of gas infrastructure. For given gas supply and consumption levels at a given time period, the solution of the complementary problem includes wholesale gas prices per season in each consumption region as well as the investment levels for additional transport and storage capacity. The detailed description of the model and its underlying mathematical formulation is given in [4].

An important feature of the GASTALE model is endogenous investment decision-making with respect to expansion of gas infrastructure. This includes gas pipelines, LNG facilities, and gas storage facilities but excludes gas production assets. For this study, economically optimal expansion of gas infrastructure is determined for every decade (e.g., 2030-2040, 2040-2050) from a short-sighted point of view. Decision for the economically optimal expansion is mainly based on the following rule: if the average yearly congestion price of an infrastructure asset (pipeline, LNG, or storage) over the next ten-year period equals or exceeds X% more of its annualized marginal cost of investment (accounting for depreciation) and operation , then additional capacity will be invested in.

D. *Interactions between Gas and Electricity Market Models*

The strong interaction existing between gas and electricity markets implies that different developments in RES share in four storylines will have impact on both future electricity and gas infrastructure. Cross-border infrastructure requirements for electricity and gas are modeled using the MTSIM and GASTALE models respectively. In our approach, we simulate the interactions between electricity and gas markets for three separate key years (2030, 2040, and 2050). Investment levels determined for the year i are used as an initial point for the year i+10. For each scenario, our methodology can be summarized as follows:

1) For a given RES development and expected WEO gas price, run MTSIM in *"planning modality"* and determine the corresponding economically optimal electricity transmission corridors expansion.
2) By imposing the optimal grid expansion defined in Step 1, run MTSIM in *"traditional modality"*(no grid expansions allowed) to obtain the corresponding gas consumption level from power sector in each EU country in the year i.
3) Run GASTALE with the gas consumption level of power sector provided by MTSIM at Step 2 to obtain the economically optimal gas infrastructure in the year i (as explained in Section II.C) with the corresponding gas prices for each region in Fig. 2.

4) The new gas prices are fed into MTSIM and Steps 2 and 3 are repeated until gas prices and gas consumption levels in power sector converge. If convergence is achieved, move to the next period. With the term "convergence" we intend that, in two subsequent iterations, all gas prices and consumption data exchanged between MTSIM and GASTALE differ of a negligible quantity.

The input/output interactions between MTSIM and GASTALE models can be summarized as illustrated in Fig. 3. In all the scenario runs, it has been observed that convergence is achieved in at most four iterations.

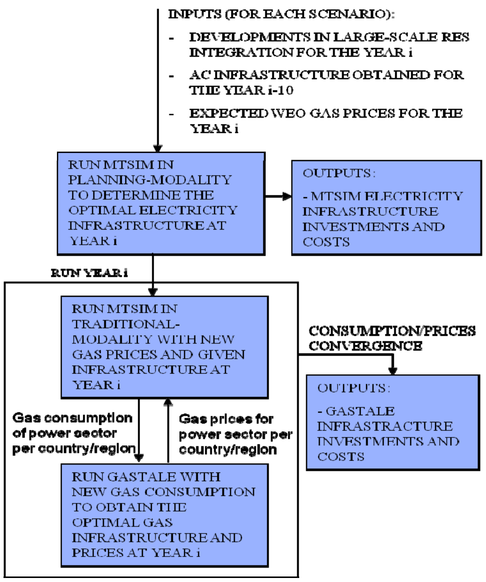

Fig. 3 Methodology for establishing interactions between electricity and gas markets

III. The Results

The main focus of the study is on the period 2030-2050. In order to bridge the gap from 2010 to 2030, the publicly available infrastructure investment plans ([5]-[13]) together with the results of some existing studies (e.g., REALISEGRID [14]-[18]) are used up to 2030. Hence, the methodology presented in this paper for identification of the key infrastructure developments is implemented for the period 2030-2050.

In order to understand the key drivers of infrastructure development, an overview of differences in implications of assumptions between storylines are first summarized and then a comparison of the results are presented. All the other assumptions of the MTSIM and GASTALE models are fixed across all storylines and for the sake of brevity are not reported here. Please refer to [19]-[22] for the details of the assumptions used in these models.

Apart from the different RES share developments explained in Section II. A. the main implications of the storyline assumptions in both electricity and gas markets can be summarized as follows (see [22] for details):

- **Yellow** and **Green** storylines have in common:
  - Low electricity and gas demand,
  - Low fuel and CO2 emissions costs,
  - 6000MW maximum additional electricity transmission capacity at each border (per decade) due to higher public acceptance.
- **Red** and **Blue** storylines have in common:
  - High electricity and gas demand,
  - High fuel and CO2 emissions costs,
  - 3000MW maximum additional electricity transmission capacity at each border (per decade) due to lower public acceptance.

Moreover, the technology development factor to transmit RES generation in each storyline is characterized by utilizing different costs of new electricity transmission capacity installation. The higher the RES share is, the faster the technology developments are, leading to lower installation costs:

- **Red** storyline has very high installation costs (about 6200 €/MW for AC lines and about 30000 €/MW for DC lines);
- **Yellow** storyline has high installation costs, a little bit lower than the **Red** storyline (about 6000 €/MW for AC lines and about 26000 €/MW for DC lines);
- **Blue** storyline has medium installation costs (about 5800 €/MW for AC lines and about 24000 €/MW for DC lines);
- **Green** storyline has the lowest installation costs (about 5500 €/MW for AC lines and about 22000 €/MW for DC lines).

A. *General Overview of the Electricity Market Results*

As regards to the operational costs (i.e. total EU CO_2 emissions and fuel costs), it can be observed (see Fig. 4) that the 2030 **Green** storyline is the most advantageous one, mainly because demand, CO_2 costs, and fuel costs are lower and RES penetration is the highest. **Yellow** storyline has also low operative costs due to low demand and moderate availability of energy from RES. The **Blue** and **Red** storylines show a different behavior: the 2030 **Blue** storyline is 129.5% more expensive than 2030 **Green** storyline, while the 2030 **Red** storyline is the "worst", being by 321% more expensive. These two storylines has higher operative costs mainly because electricity demand, CO_2, and fuel costs are high. Moreover, the costs in **Blue** storyline decreases and becomes much lower than **Red** in 2050 due to high RES penetration until 2050. The operational costs are also reflected in yearly average prices (TABLE I): The prices in **Green** decrease and are the lowest in 2050 whereas the prices in **Red** are the highest. The prices in **Yellow** are also low due to low demand. In **Blue** storyline, the prices are at high levels in 2030 and decrease until 2050 to moderate levels due to high RES penetration.

As regards to electricity transmission capacity expansion, AC transmission network expands a lot in **Green** and **Blue** Storylines, improving the possibility to dispatch less costly RES generation more efficiently (see Fig. 5). **Yellow** and **Red** Storylines are the ones in which the installation of new AC capacity is lower. In the **Yellow** storyline, high installation costs combined with low prices does not make new transmission capacity installations attractive. In **Red** storyline, installation costs are also very high and there is very low amount of energy available from RES which does not justify the necessity of major installations.

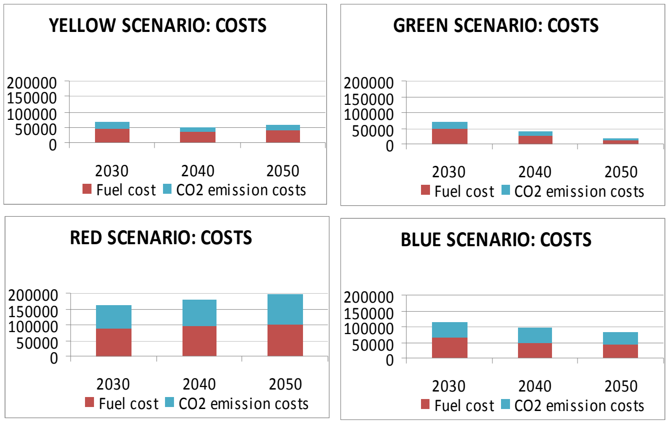

Fig. 4 Overview of Operational Costs across Four Storylines (in M€)

TABLE I
OVERVIEW OF AVERAGE ELECTRICITY PRICES PER STORYLINE

[€/MWh]	**2030**	**2040**	**2050**
Yellow	50	50	55
Green	58	48	39
Red	107	115	124
Blue	83	70	65

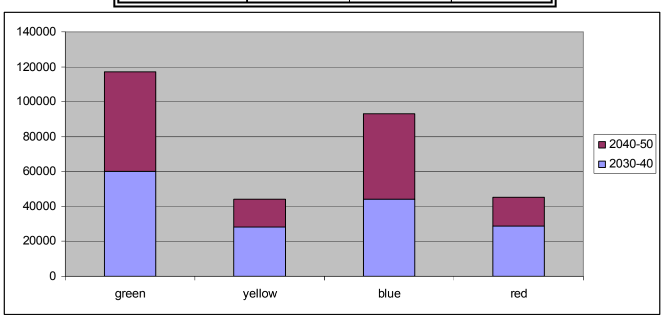

Fig. 5 Electricity Transmission Capacity Expansions (in MW)

Fig. 6 and Fig. 7 show an overview of the main electricity corridors which require grid expansions in all the storylines. For each interconnection there are two numbers that indicate the maximum and the minimum expansion (in percentage) among all the scenarios. By analyzing the results of MTSIM for the required European transmission corridors in future, it can be observed that some expansions are common to all the storylines and they seem to be fundamental for a better exploitation of the network potentiality whatsoever the future system scenarios. In particular, the corridors that connect the Central Europe with the Iberian Peninsula (ES-FR, FR-DE, FR-BL, FR-IT, DE-PL) are expanded in order to exploit all the potential RES generation and feed the consumption centers (e.g. those placed in central Europe) at minimum marginal cost. Some corridors placed in Eastern and South-Eastern Europe (AL-GR, RO-UA_W and SK-UA) are significantly expanded in all the storylines too.

B. *General Overview of the Gas Market Results*

While public attitude directly affects the gas consumption (e.g. a highly environmental attitude, as in the **Green** storyline, implies more efficient use of energy and therefore lower demand of energy sources including gas), technology development in the electricity sector has also an influence on the gas consumption of power sector through the deployment

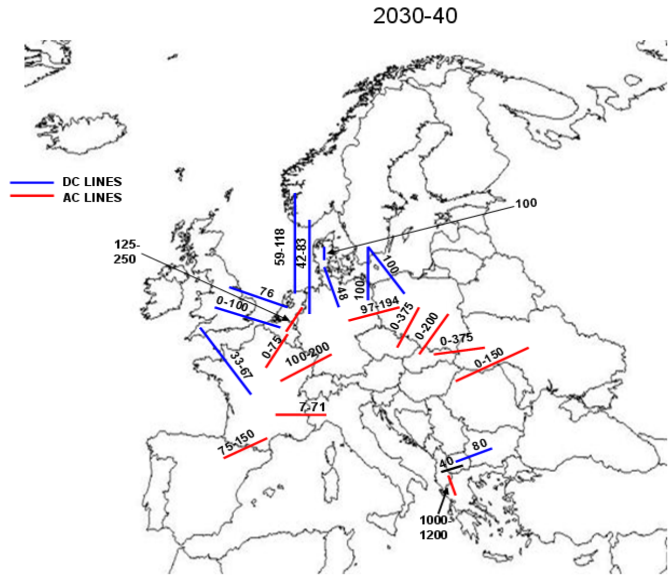

Fig. 6 Grid Expansion Overview 2030-40 in Percentage to Installed Capacity

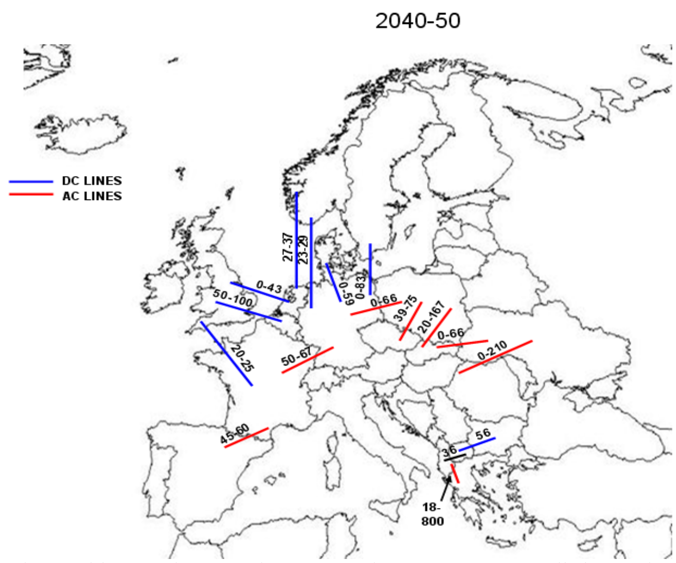

Fig. 7 Grid Expansion Overview 2040-50 in Percentage to Installed Capacity

of power generation technologies. Fig. 8 shows the demand for gas in the four storylines as well as the gas allocation of total gas demand across the three distinguished gas consuming sectors. From this figure we observe that the differences in gas demand are particularly driven by developments in the electricity sector, and to a lesser extent by developments in the residential sector. Furthermore, due to similar background regarding fossil fuel prices and energy demand, the gas prices of the **Yellow** and **Green** storyline on the one hand and the **Red** and **Blue** storylines on the other show a similar development at comparable levels. Contrasting the high gas demand storylines (**Red** & **Blue**) with the low gas demand storylines (**Yellow** & **Green**), we observe that the average EU gas price in 2050 is about €1.4 per GJ lower in the latter than the former storyline.

Regional or country-based increases or decreases in gas demand can be considered as a primary driver for gas infrastructure investment of different types. The need for total investments until 2050 in new pipelines and LNG terminals

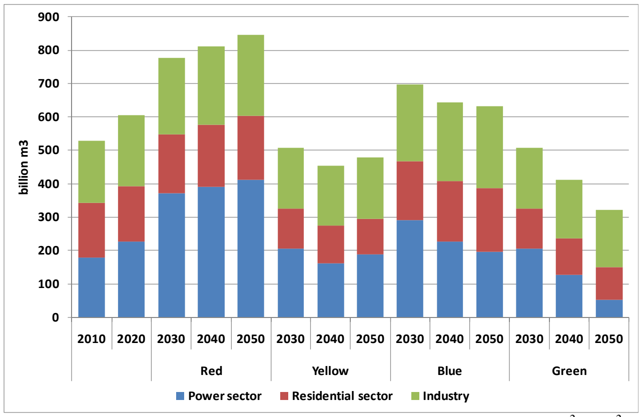

Fig. 8 EU Sectoral Gas Consumption across Storylines (in billion m^3 (bm^3))

enabling more gas imports from outside the EU is the highest in the **Red** storyline (see Fig. 9). This is explained by the high level of gas demand throughout the period, which results – given the presumed inability of the EU to increase its indigenous gas production – in a much higher gas import dependency. The **Green** storyline has the lowest total investments due to the low gas demand from all sectors. Also the total investment levels within the period 2030-2050 in both the **Blue** and **Yellow** storylines are relatively low due to stagnation in gas demand after 2030. The gas demand in **Blue** mainly decreases with increase in RES share of electricity generation while in **Yellow** gas demand decreases mainly due to high environmental awareness of consumers. The increase in LNG import capacity over time across different storylines is limited. Although investment in LNG receiving terminals continues at a rate of about 20 billion m^3 per decade in the **Red** storyline, almost no LNG investment takes place after 2030 in other storylines. This may be explained by the fact that due to the relatively lower level of gas demand in the other storylines, pipeline supplies are generally preferred over LNG supplies due to economic considerations. With LNG being a relatively more expensive gas supply option for the majority of EU countries, additional demand for EU external gas is pre-dominantly served by pipelines.

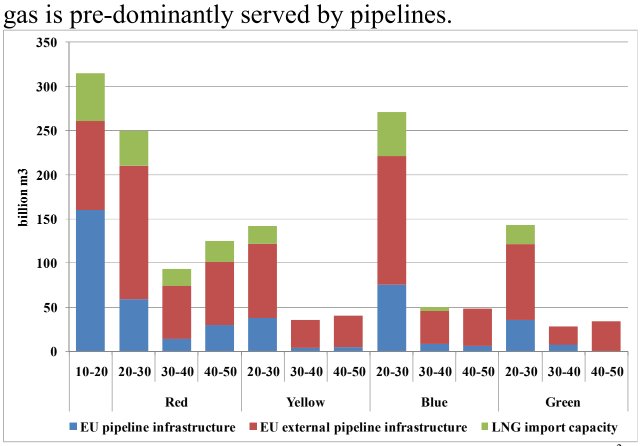

Fig. 9 Total Gas Infrastructure Expansion across Storylines (in bm^3)

Fig. 10 and Fig. 11 show the investments in EU import capacity and EU internal pipeline capacity respectively. Results concerning the upgrade of EU pipeline capacity show that some cross-border investments are robust across the different storylines whereas other cross-border investments are storyline dependent. The South-East European corridor is an important supply corridor in all storylines. Cross-border investment in the gas corridor from Turkey to Central Europe and relatively smaller investment in the Northwest European pipeline system are constant across storylines. Upgrades in the Northwest European region are, despite of possible changes in gas flow patterns, rather limited due to the already quite developed infrastructure there. The infrastructure in this part of Europe will be increasingly used to accommodate import flows whereas it has been used to accommodate Dutch and UK export flows previously. Important storyline differences can be observed especially in the Southwest and South of Europe where additional EU internal pipeline investments are required to facilitate mostly for pipeline imports from Algeria (to Italy and Spain) and LNG imports (via Italy). Since the need for additional imports from Algeria and LNG exporting countries is different across storylines, also infrastructure investments are storyline-dependent. Especially in the **Red** and **Blue** storyline Italy is, for example, an important gas hub for both LNG and pipeline imports, giving rise to significant capacity upgrades of its interconnections with Germany and Central Europe.

Based on the gas flows simulated in the analysis, additional observations can be made with respect to the relevance of particular gas corridors and cross-border interconnections in the future gas system. Although the identified infrastructure investments provide an indication of pipeline routes where gas flows are likely to increase over time, it may be informative to assess particular pipelines with a decreasing gas flow as well. In the period up to 2050, a shift in EU relevant gas corridors may take place. Comparing the 2010 and 2050 gas flows the following observations are made:

- The increasing depletion of gas reserves in the UK and the Netherlands significantly reduces the gas flows from North-western Europe to neighboring countries (i.e. Netherlands – Germany, UK – Belgium interconnections).
- A large increase in direct gas flows from Russia to Germany via the proposed North Stream corridor reduces the gas flows from Russia via the Central European corridor in all storylines.
- Italy emerges as a gas hub in all storylines although its relative importance differs across storylines. Its gas hub position gives rise to a net gas flow from Italy to Germany and Central Europe. The Italian gas imports that allow Italy to become a transit hub originate from Algeria, Libya, and various LNG exporting countries.
- Spain increases its importance as gas transit country to varying degree across storylines due to increased exports of Algeria to the EU borders.
- Across all storylines, Turkey and the Balkan region emerge as important gas hubs. Gas is sourced from Central Asia and Russia, and re-exported to South-East Europe and from there further into Central and Western Europe.

The decline in indigenous EU gas production is similar across the four storylines, decreasing from 85 billion m^3 per year in 2030 to about 30 billion m^3 per year in 2050. This implies that the depletion of own gas reserves takes place irrespective of particular future gas demand developments. The dependency on gas imports thus varies with the level of total gas demand: the higher the demand for gas over time is,

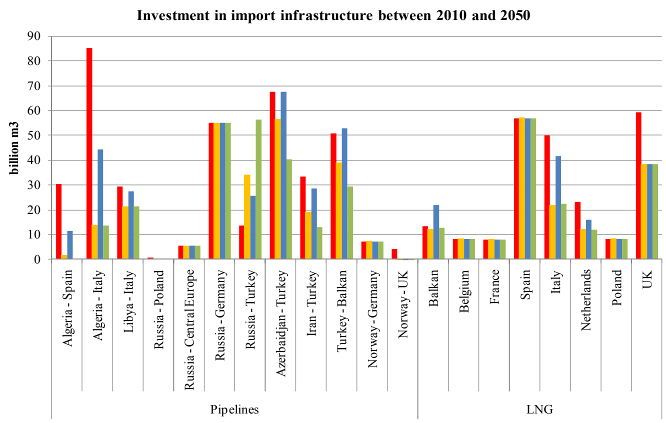

Fig. 10 Investments (in bm[3]) in gas import infrastructure across storylines in 2010-2050 represented by the corresponding storyline colors

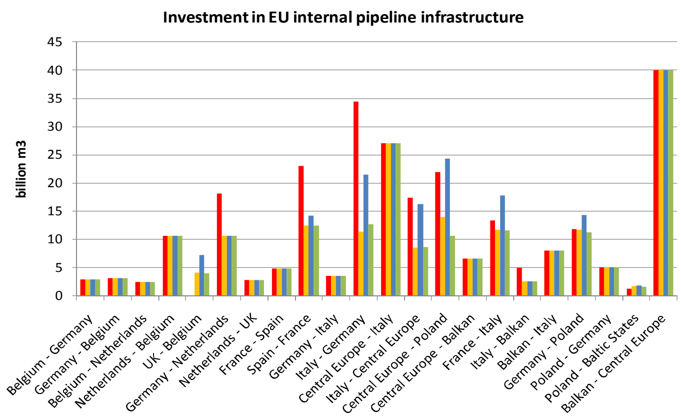

Fig. 11 Investments (in bm[3]) in EU internal pipeline capacity across storylines in 2010-2050 represented by the corresponding storyline colors

the larger the import dependency becomes. Gas import dependency (in % of total demand) increases in all storylines but at a relatively slower rate in gas-extensive storylines (i.e. **Yellow** and **Green**). Gas import dependency of the EU in 2050 varies between 91% (**Green**) and 96% (**Red**), whereas dependency is 'only' 69% in 2010. This corresponds with an import volume of gas in 2050 between 291 (**Green**) and 815 (**Red**) billion m^3 per year, compared to a total amount of EU gas imports of about 365 billion m^3 per year in 2010. The difference between the 2050 EU import volumes across the storylines signals that there is large uncertainty with respect to the future gas import level. Although there is a large difference in total EU gas import volume in 2050 across storylines, the import dependency in relative terms is not much affected. Russia is the largest supplier of gas to the EU market in all storylines until 2050. The market share of Russian supplies in total EU demand is not the highest in the gas-intensive **Red** storyline (30%) but in the gas-extensive **Green** storyline (little over 50%). The reason for this is that at relatively low gas demand levels Russian gas is the preferred source for imports: other gas suppliers are relatively more expensive and thus only come into the picture when gas demand (and gas prices) is at relatively higher levels. Hence we observe the paradox result that diversification of gas import sources increases with an increase in total gas demand. In the **Red** and **Blue** storylines, the EU dependency on Russia remains at about 30 to 25% of total demand until 2050. After Russia, Algeria is the second-largest EU gas supplier in all storylines, with an average share of about 20% in the **Red** and **Blue** storylines. Norway supplies about 10 to 15% of EU gas demand across the different storylines. The share of other gas suppliers in total EU gas demand varies from 2 to 8% across storylines in the period until 2050.

C. *Interaction between Electricity and Gas Markets*

TABLE II summarizes the joint implications of different RES penetration on various aspects of the future electricity and gas markets. In our analysis, we observed that the electricity infrastructure costs of integrating renewable electricity are higher in especially storylines with many locations (e.g., countries) having high RES penetration combined with low demand. This is caused by an increasing need to transfer large volumes of electricity through Europe to match favorable RES generation regions with existing load centers. In a high demand storyline, the need to transfer large volumes of power is observed to a lesser extent since it is easier to match demand and favorable electricity production locally. However we need to take into account gas infrastructure developments as well. A low energy demand combined with high RES power generation leads to low gas consumption in all sectors The lower the gas consumption, the less the need for additional gas infrastructure and the less the cost of gas infrastructure of different types. Lower gas consumption also improves security of supply somewhat, although at least 90% of total gas demand in 2050 needs to be imported in any case due to the depletion of EU gas reserves.

Moreover, we observed that different future energy backgrounds have different implications for the cost of generating electricity. In particular future energy systems with high penetration rates of renewable electricity, the total costs of fuel (and CO_2 emissions) is low but the capital costs of generation capacity high, whereas this is exactly the other way around in future energy systems with low penetration rates of renewable electricity.

TABLE II
SUMMARY OF IMPACT ON DIFFERENT ASPECTS (EVALUATION PER STORYLINE IS RELATIVE COMPARED WITH OTHER STORYLINES)

	Storyline			
	Red	**Yellow**	**Blue**	**Green**
Electricity generation fuel cost	High	Moderate	Moderate	Low
Electricity generation capital cost	Low	Moderate	Moderate	High
Electricity generation CO2 costs	Very High	Moderate	High	Very Low
Electricity infrastructure expansion	Low	Low	High	Very High
Gas infrastructure expansion	High	Low	Moderate	Very Low
CO2 emissions	High	Moderate	Moderate	Low
Security of gas supply	Very low	Low	Very low	Low

IV. CONCLUSIONS

From the analysis on future electricity infrastructure developments we conclude that a strong increase in the penetration rate of especially large-scale renewable electricity generating units (i.e. large-scale offshore wind parks) has large impact on the future need for electricity infrastructure upgrades, both in offshore DC and in onshore AC lines. Since most favorable wind locations generally lay in the south-western and north-western parts of Europe a substantial share of future investments need to go to strengthening of the electricity corridors from south and north-western Europe to central and Eastern Europe. Because of the insufficient geographical match between favorable RES generation and large load centers, large electricity network upgrades are required.

Future infrastructure developments on the gas market are determined by the inevitable transition towards much higher gas import dependency on the one hand and the further infrastructure needs resulting from a possibly larger role of gas consumption in the electricity sector on the other. The share of gas in the electricity sector is, among other factors, dependent on the penetration rate of centralized and decentralized renewable electricity generation. A relative gas-extensive future electricity generating mix (such as in the **Green** storyline) naturally sees a much lower gas infrastructure investment need compared to a relative gas-intensive future electricity generating mix (such as the **Red** storyline).

V. References

[1] H. Auer, K. Zach, G.Totschnig, and L. Weissensteiner, "Scenario Guidebook: Definition of a consistent scenario framework", Tech. SUSPLAN Rep, 23 Oct. 2009. http://www.susplan.eu/fileadmin/susplan/documents/publications/SUSPLAN_Guidebook_231009.pdf

[2] ENTSO-E, NTS values. https://www.entsoe.eu/resources/ntc-values/

[3] Gabriel, S. A., S. Kiet, and J. Zhuang, "A mixed complementarity-based equilibrium model of natural gas markets.", Operations Research, vol. 53 (5), pp 799-818, 2005.

[4] W. Lise and B. F. Hobbs, " A dynamic simulation of market power in the liberalized European natural gas market," The *Energy Journal,* vol. 30, pp 119-136, May 2009.

[5] ENTSO-E, "Ten year network development plan 2010-2020", March 1, 2010. Available: www.entsoe.eu/index.php?id=232

[6] ENTSO-E, " UCTE transmission development plan: Development of interconnections ", April 2009. Available: www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/otherreports/tdp09_report_ucte.pdf

[7] Secure gas supplies will empower Balkan integration, 25 March, accessed on 5th of May 2010. Available: www.balkaninsight.com

[8] BEMIP, "Baltic Energy Market Interconnection Plan- final report of the High Level Group", 2009.

[9] European Commission (EC), "Economic Recovery: Second batch of 4-billion-euro package goes to 43 pipeline and electricity projects", IP/10/231, 4 March, Brussels.

[10] MED-EMIP, "MEDRING update study: Mediterranean electricity interconnections", April 2010. Available: http://ec.europa.eu/energy/international/studies/external_dimension_en.htm

[11] Inter-RAO, "Project Baltic NPP – Kaliningrad region", 2010. http://www.interrao.ru/eng/

[12] GTE+, "Reverse Flow Study TF, Technical Solutions", 21 July 2009.

[13] UCTE-IPS/UPS, "Feasibility Study: Synchronous Interconnection of the Power Systems of IPS/UPS with UCTE", December 2008, http://www.ucte-ipsups.org/

[14] L'Abbate, A., G. Migliavacca, A. R. Ciupuliga, and M. Gibescu, "Interim Report Preliminary results on streamlining planning and approval procedures of electricity transmission infrastructures", FP7 Realisegrid project, 2010. Available: http://realisegrid.rse-web.it

[15] L'Abbate, A., Migliavacca G., "Review of costs of transmission infrastructures, including cross border connections", Report D3.3.2 FP7 Realisegrid project, 2010. Available: http://realisegrid.rse-web.it

[16] Migliavacca, G., L'Abbate, A., Cazzol, M.V., Calisti,R., Losa,I., Vergine,C., Sallati A., "Application of the REALISEGRID framework to assess technical-economic and strategic benefits of specific transmission projects", Report D3.5.1 FP7 Realisegrid project, 2010.

[17] Loulou, R., Kanudia, A., Gargiulo M.,Tosato G., "Final report of WP2 on results of long term scenario analysis for European power systems", Report D2.3.2 FP7 Realisegrid project, 2010.

[18] EC FP7 project REALISEGRID: "Research methodologies and technologies for the effective development of pan-European key grid infrastructures to support the achievement of a reliable, competitive and sustainable supply", Available: http://realisegrid.rse-web.it

[19] SECURE deliverable 5.6.1 rev. 1, "Optimization of transmission infrastructure investments in the EU power sector", July 2010. Available: www.feem-project.net/secure/plastore/Deliverables/SECURE_Deliverable%205.6.1_REV.pdf

[20] EC FP7 project SECURE, "Security of Energy Considering its Uncertainty, Risks and Economic implications", www.secure-ec.eu

[21] SECURE deliverable 3.2a, "Long-term storylines for energy scenarios in Europe", July 2010. Available: www.feem-project.net/secure/plastore/Deliverables/SECURE%20Additional%20Deliverable%203.2a.pdf

[22] J. de Joode, O. Ozdemir, K. Veum, G. Migliavacca, and A. Zani, " Development of regional and Pan-European guidelines for more efficient integration of renewable energy into future infrastructure", Tech. SUSPLAN Rep., Forthcoming in 2011, http://www.susplan.eu

VI. Biographies

Özge Özdemir received her MSc degree in Operations Research and Management in 2003 at Faculty of Economics and Business Administration, University of Tilburg, the Netherlands. Since 2008 she works as a scientific researcher at ECN Policy Studies and has been involved in various research projects for private and public sector in the field of competition in liberalized gas and electricity markets and electricity and gas infrastructure issues. She is also a PhD candidate in Operations Research at University of Tilburg and her research interests are deterministic and stochastic optimization problems and equilibrium models, stochastic modelling techniques and simulation: applications in energy and environment.

Karina Veum holds an MSc in Economics from the University of Oslo, Norway. She works as Senior Researcher at ECN Policy Studies. She has over ten years experience in developing renewable energy policy and measures both at EU level and for the Norwegian government. Her work at ECN mainly focuses on renewable energy policy issues. She specializes in renewable energy support schemes, offshore wind energy development as well as issues related to large scale integration of renewable energy into the electricity market.

Jeroen de Joode graduated in Economics at Tilburg University, The Netherlands in 2003. He has been working as a researcher in the field of energy economics at the Dutch Bureau for Economic Policy Analysis and the Energy Research Centre of the Netherlands (ECN). He is currently topic coordinator of natural gas at ECN. He has been involved in a large number of studies for private and public clients in the field of gas market liberalization, security of supply, and gas infrastructure issues. He is currently finalizing his PhD dissertation on the regulation of gas infrastructure investment at the Delft University of Technology, The Netherlands.

Gianluigi Migliavacca graduated in Electronic Engineering at the Polytechnic University of Milan in 1991 and joined the Automation Research Center of ENEL in 1994, working on mathematical modeling and dynamic simulation of thermal power plants. In 2000, he joined CESI (now: RSE), where he is head of the transmission network planning research group. Focus of his research activities is on mathematical modeling and regulatory issues concerning deregulated electricity markets, cross border trade issues, and transmission planning. During 2005 he was consultant at the Italian Regulator about the development of a common energy market in South-East Europe and about congestion management in Central-South Europe. He is the coordinator of the European FP7 research project REALISEGRID.

Alessandro Zani received a M.Sc. in Informatics Engineering (2006) and a PhD in "Computational methods for forecasting and decision in Economics and Finance" (2010) from the University of Bergamo. 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 working as junior researcher with the Transmission Network Planning Research Group at RSE.

Andrea Grassi graduated in Electrical Engineering at Politecnico di Milano, Italy (2009). In 2009, he joined RSE, where he has worked in the field of power system development and simulation.