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Abstract
The penetration rate of renewable-based electricity has a large impact on not only the electricity generation and transmission market across Europe, but also on the gas market. The price level of CO_2 emissions influences the choice of fuel in the electricity generation market in the short-term (the dispatch) and the long-term (investment). This report summarises SUSPLAN research into the implications of the interaction between electricity and gas market developments for trans-national network development. Key drivers assessed are the deployment of renewable-based electricity generation across Europe, differential load developments, and the role of gas in the electricity generation sector. The applied methodology is characterised by a scenario and simulation model based, quantitative approach. This report discusses the main results, draws some conclusions and identifies a number of recommendations for policy-makers.

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1 BACKGROUND

The EU faces a number of challenges in its quest for an affordable, sustainable and secure energy system towards 2050. One of these challenges is to ensure adequate and timely investments in new energy infrastructure. Addressing this challenge is a core objective of the SUSPLAN *(Planning for Sustainability)* project.[1] The project has focused on the need for infrastructure investments to accommodate the integration of a large share of renewable energy sources (RES) into the European energy system in the longer time frame 2030-2050.

Energy infrastructure needs and integration of renewable energy sources into the European energy markets is a key topic on the political agendas of the European Commission and its Member States. The Energy Infrastructure Package [EC, 2010], recently communicated by the European Council, highlights that Europe is still lacking the grid infrastructure to enable renewable energy sources to develop and compete on an equal footing with traditional sources in both the short and longer term. Among other factors, large scale wind parks in Northern Europe and solar facilities in Southern Europe need corresponding power lines capable of transmitting this renewable power to the areas of high consumption. A key message is that today's grid infrastructure will struggle to absorb the volumes of renewable power which the 2020 targets entail (i.e. about 33% of gross electricity generation). In the longer term, European Council has given a commitment to the de-carbonization path with a target for the EU and other industrialized countries of 80 to 95% cuts in emissions by 2050. New strategies on energy infrastructure development to encourage adequate grid investments in electricity, gas, oil and other energy sectors will be needed if emission cuts are to be achieved. Provided the supply is stable, natural gas will continue to play a key role in the EU's energy mix in the coming years due to its relative low CO_2 content compared to competing fuels and because gas can gain importance as the back-up fuel for variable electricity generation.[2] This calls for diversified imports, both pipeline gas and Liquefied Natural Gas (LNG) terminals, while domestic gas networks are required to be increasingly interconnected [EC, 2010].

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. To date, 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. The integration of large-scale RES and associated electricity network developments directly impact the gas market. In some countries, gas consumption in power sector may decrease due to renewable-based generation capacity displacing thermal capacity. In other countries, gas consumption in the power sector may increase due to a particularly high penetration of intermittent renewable-based electricity generation for which gas-based power plants can serve as back-up. The change in gas consumption levels of the power sector is expected to 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 affect the

[1] We refer to the project website, www.susplan.eu, for more details. The website contains, among other items, an elaborate project description, the project's publications, and will provide a link to a database comprising both input and output data from quantitative analyses performed within the project.

[2] Flexible gas-based electricity generation is by no means the only viable means to provide flexibility to an electricity system that experiences large deviations in the supply from for example wind-based generation units but certainly in the short to medium term it is one of the most cost-effective.

gas powered generation in electricity markets, the level of electricity prices, transnational corridors expansion, and trans-national electricity exchange.

In WP3 of the SUSLAN project, an assessment of the impact of large scale RES integration both on the transnational electricity and gas infrastructures has been carried out, explicitly addressing the interaction between electricity and gas market developments. This has been done in the context of four different storylines/futures, which include different scenarios of RES integration up to 2050. In particular, future trans-national electricity and gas infrastructure routes and capacities needed are identified for the four storylines. The assessment has included the use of both a gas market model (GASTALE) and an electricity market model (MTSIM) to simulate the long-term development of the European energy markets (2030-2050).

Purpose and structure of this report

The results and findings from the trans-national infrastructure analysis in WP3 of the SUSPLAN project are presented in deliverable D3.1 [De Joode *et al.*, 2011], available at the SUSPLAN website. The purpose of this report is to present a more condensed summary of key results and findings as well as policy recommendations for ensuring necessary energy infrastructure needs in the time frame to 2050.

The structure of this synthesis report is as follows. Section 2 briefly describes the methodology adopted. Thereafter sections 3 and 4 discuss results for developments on the electricity and gas market, respectively. Section 5 highlights the results from the impact assessment that integrates electricity and gas market developments. Finally, section 6 presents conclusions and recommendations.

2 METHODOLOGY

A quantitative scenario and model-based approach is adopted in assessing the future developments on European electricity and gas in general and the impact of large-scale RES integration on trans-national developments in particular. This section describes the basic scenario framework and the quantitative simulation models deployed in the assessment.

2.1 Four storylines for future developments on European electricity and gas markets in 2030 to 2050

Future energy market developments are difficult to predict and typically dependent on a range of important but uncertain factors. Key factors can for example relate to macro-economic developments, rate of technological progress or social values (i.e. public acceptance). Within the SUSPLAN project a thoroughly constructed storyline framework has been developed to function as a common basis for the key assessments regarding the impact of RES integration in electricity and gas market developments. These key assessments concern the analysis of developments on a (European) regional level [Auer *et al.*, 2010] as well as developments on the trans-national level of which this report synthesizes the results. Below follows a brief description of the storyline framework with a focus on the key elements for the assessment of developments on the trans-national level.

Figure 2-1 presents the four SUSPLAN storylines. The 'coloured' names of the storylines are based on the following principles [Auer et al., 2009]: (i) easy to remember, (ii) having a meaning / logical interpretation, (iii) consistency and similarity among the names for the four different storylines.

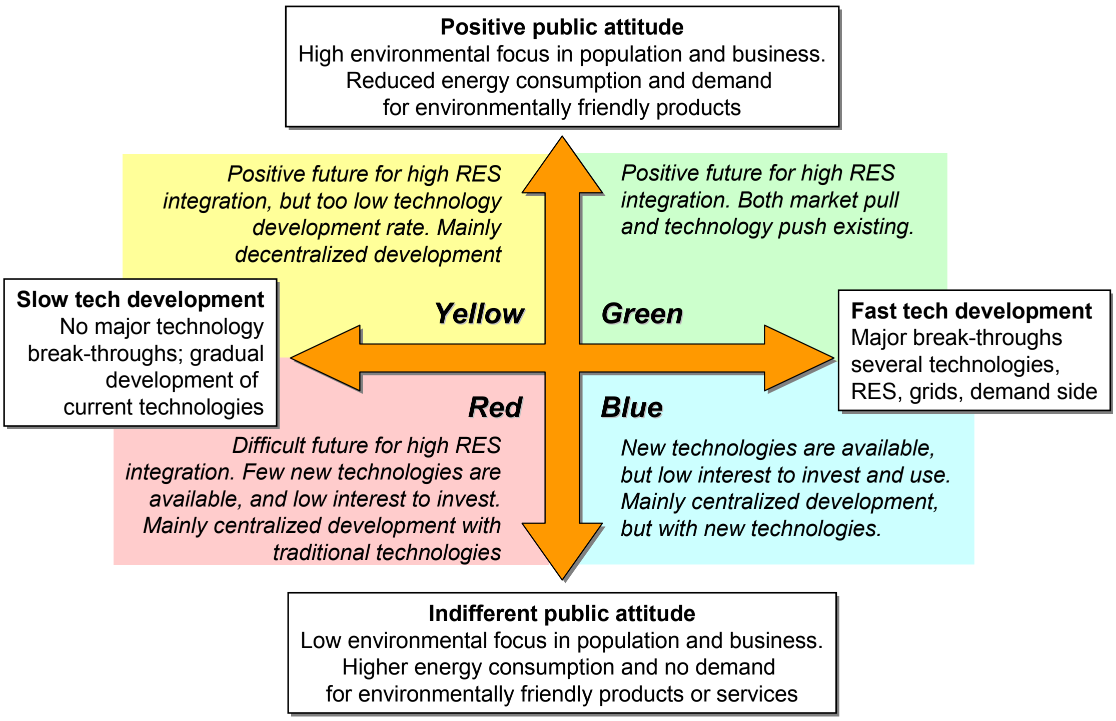


Figure 2-1 Overview of SUSPLAN storylines [Auer et al., 2009]

None of the four storylines is explicitly considered to reflect a business as usual scenario: each of the storylines is considered to sketch a plausible and realistic future regarding developments important for RES integration in Europe. The key dimensions that identify the four storylines are the rate of technological development on the one hand, and the public attitude towards environmental issues on the other hand. A brief description of the basic storyline characteristics relevant for the assessment on trans-national developments due to large-scale RES integration is provided in Figure 2-1. For a detailed description of the storyline framework we refer to [Auer et al., 2009].

The key development across the storylines with large impact on trans-national developments on electricity and gas markets is the rate of RES integration within the considered timeframe of 2030 to 2050. Figure 2-2 presents the deployment rate of RES share of total final energy demand, which is a key input for the model-based assessment that is reported in this document. The different RES penetration trajectories, and their position towards each other, reflect the differences you may expect in RES penetration based on the definition of storylines. The source of these figures are Green-X modelling results up to 2030 in combination with assumptions according to the long-term RES/RES-Electricity potentials and ambitions in energy efficiency implementation up to 2050 in the different European counties [Auer et al., 2009].

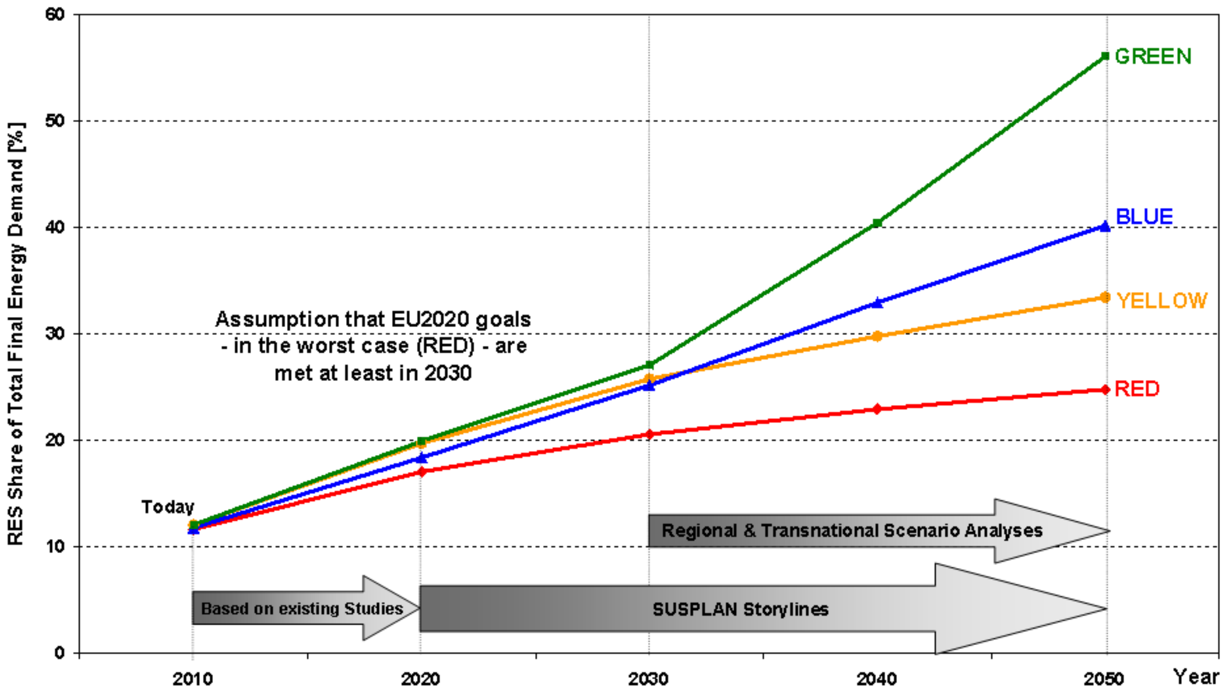
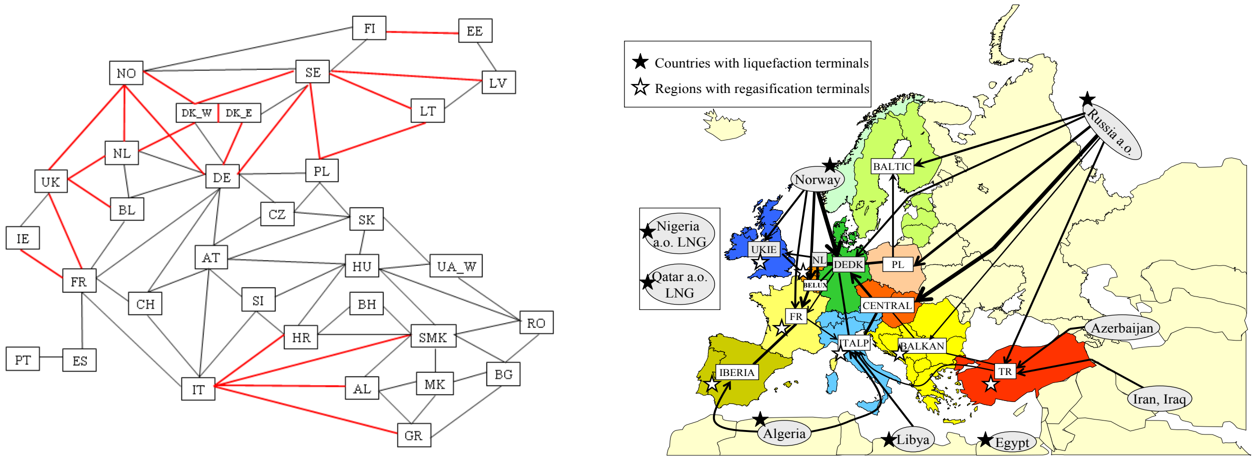


Figure 2-2 RES deployment as a share of total final energy demand on aggregated European level in the four different storylines in SUSPLAN [Auer *et al.*, 2009]

The results that are presented in this report provide an answer to the question 'what if a certain combination of developments as reflected in each of the four storylines occurs?' This implies that none of the storylines can be considered to provide an optimal development given a set of input parameters. It is also important to note that we do not consider any of the storylines more likely to happen than the others.

2.2 Assessment of trans-national developments using simulation models

In analysing the impact of RES penetration in the European electricity and gas market a simulation modelling approach was adopted that successfully incorporated the basic interaction between electricity and gas markets. This involved the methodological combination of two market simulation models – one for the European electricity market, called MTSIM, and one for the European gas market, called GASTALE.[3] Communication between the two simulation models on two key variables (being gas prices throughout Europe on the one hand, and the gas demand in the electricity sector on the other) led to simulation results for both markets on aspects such as short-term market allocation, infrastructure utilization and infrastructure expansion that are consistent with the common storyline background and consistent with each other. A simplified geographic representation of the two models is provided by Figure 2-3.



(a) Electricity market (MTSIM) **(b) Gas market (GASTALE)**

Figure 2-3 Simplified geographic representation of the adopted simulation models for the European electricity and gas market [De Joode *et al.*, 2011]

As holds for simulation models in general, the simulation models applied for this assessment are an abstraction from real world markets and infrastructures in several ways. The main abstractions concern the following elements:

- A limited number of so-called demand centres or hubs, with each representing (part of) a country or a set of countries is identified in order to reduce computational requirements related to the type of integrated modelling (covering investment and operational aspects).
- Both models aggregate trans-national connections between two neighbouring regions.
- Only the transmission infrastructure is incorporated in both models, while distribution infrastructure is not, due to the focus on trans-national developments. SUSPLAN deliverable [Auer *et al.*, 2010] separately assesses distribution infrastructure issues in 9 regions across Europe.

Given the broad scope of the combined modelling approach a lot of attention has been given to the quality of different type of required input data. Input data for example include infrastructure investment costs, fuel and biomass prices for the electricity sector, costs of CO_2 emission rights, and gas transportation costs. For a full overview of input data assumptions we again refer to the background document.

[3] Both simulation models have not been developed just for SUSPLAN research but have been developed by RSE and ECN respectively and applied and reported on in numerous other studies. We refer to [De Joode *et al.*, 2011] for further links.

3 INCREASING NEED FOR TRANS-NATIONAL ELECTRICITY INFRASTRUCTURE INVESTMENTS

The push for more renewable energy gives rise to different electricity flow patterns across Europe, with the main drivers being: (i) the penetration rate of RES, (ii) the development of electricity demand, and (iii) the development of non-RES generation capacity. The region where additional RES generation is deployed does not necessarily correspond to the region where thermal generation is displaced or where electricity consumption growth is strongest. The level of 'mismatch' determines the need to expand European trans-national electricity infrastructure.

3.1 Different RES deployment across Europe

Figure 3-1 shows the penetration of RES, and particular RES-technologies across storylines. For a concise presentation country-based results are grouped into 6 European regions.[4] The figure shows the change in electricity generation (per technology) in 2050 compared to 2030 in terms of Gigawatt hour (GWh) per year.

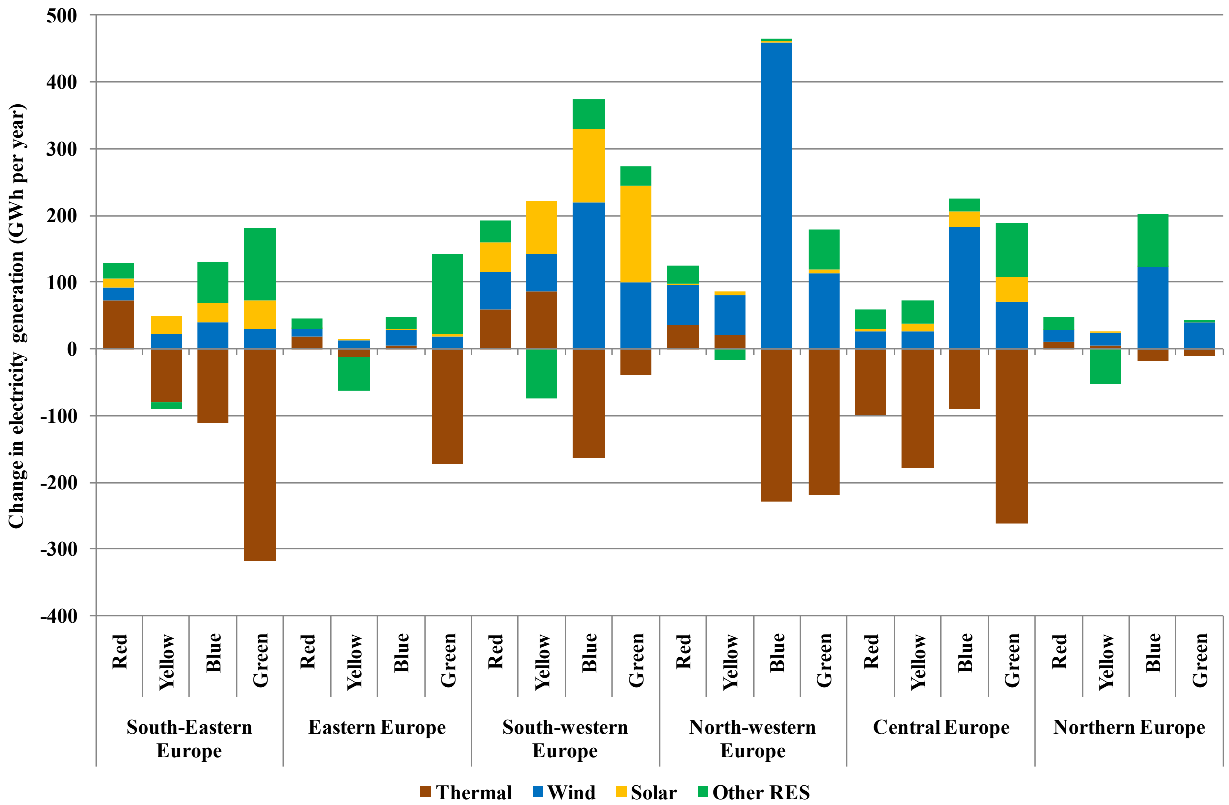


Figure 3-1 Overview of changes in the 2030 to 2050 timeframe in electricity generation per generation technology across Europe and across storylines (Source: MTSIM)

[4] **South-Eastern Europe** consists of Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Greece, Italy, Macedonia, Romania, Serbia, Montenegro, Kosovo, and Slovenia. **Eastern Europe** consists of the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, and Slovakia. **South-western Europe** consists of France, Portugal and Spain. **North-western Europe** consists of Belgium, Ireland, Luxembourg, the Netherlands, and the UK. **Central Europe** consists of Austria, Germany and Switzerland. **Northern Europe** consists of Denmark, Finland, Norway and Sweden.

An uneven deployment of RES-based electricity generation technologies arises throughout Europe, which is for example illustrated by the significant concentration of solar-based electricity generation in South-Western and South-Eastern Europe across storylines, and the large share of wind-based electricity generation in North-Western and South-Western Europe. The regions of Northern Europe, Eastern-Europe and, to a lesser extent, South-Eastern Europe show a moderate increase in RES-based electricity generation across storylines in comparison. Changes in the amount of RES-based electricity generated explain changes in the amount of thermal-based electricity generated in only a limited number of cases. South-Western Europe, for example, increases its total electricity generation in all storylines, whereas South-Eastern Europe and Central Europe decrease its total electricity generation in most of the storylines.

3.2 Different electricity demand and supply developments across Europe

The need for developing trans-national electricity infrastructure can be assessed when, apart from changes in electricity generation, electricity consumption is included. Figure 3-2 presents the changes in regional electricity consumption, regional electricity generation (which is the sum of the changes per region and per storyline depicted in Figure 3-1), and the net impact of the changes for these variables for the period between 2030 and 2050. Substantial changes in regional electricity consumption only occur in the **Red** and **Blue** storylines. The regions of South-Eastern Europe, Eastern Europe, and Central Europe develop a negative electricity balance over the 2030-2050 timeframe, which means that these regions are required to import electricity generated in other regions. The required imports may be sources from regions that develop a positive electricity balance within the same timeframe. South-Western and North-Western Europe are regions that are expected to provide export of electricity.

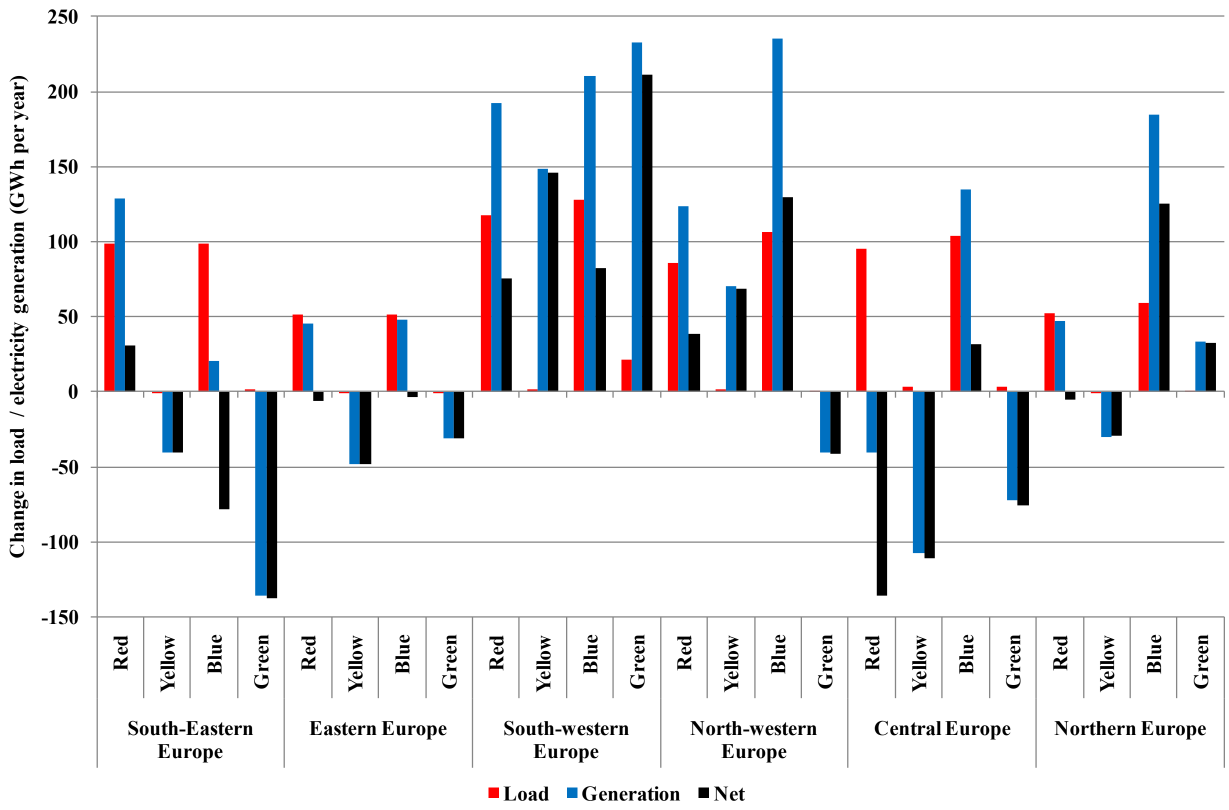
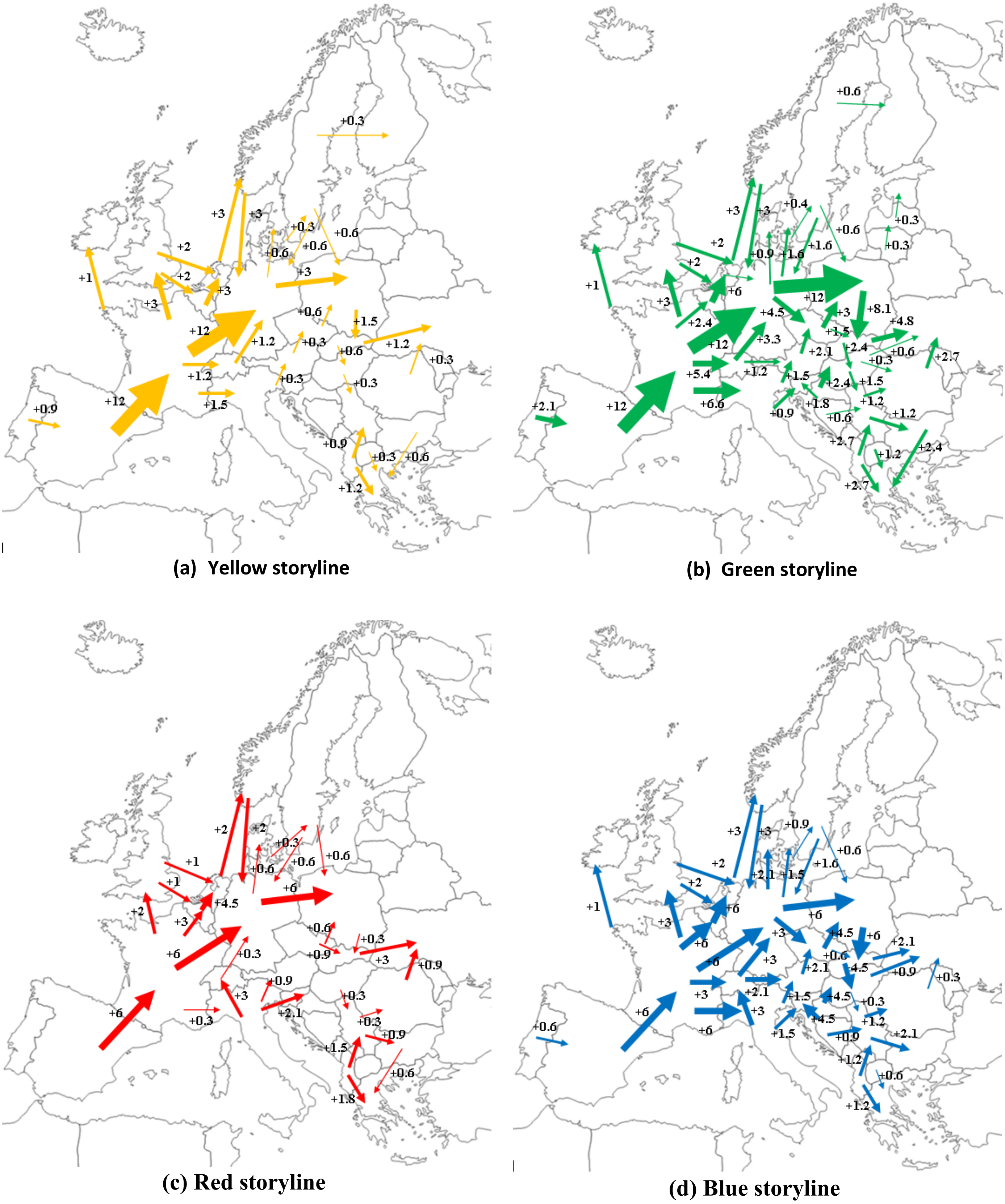


Figure 3-2 Overview of changes in the 2030 to 2050 timeframe in load and generation across Europe and across storylines (Source: MTSIM)

3.3 Investment in trans-national electricity infrastructure

Combining the results on the regional changes in the electricity generation from RES and thermal-based electricity generating technologies (Figure 3-1) with the results on the regional changes in electricity consumption (Figure 3-2), determines the need for future trans-national electricity networks. An upgrade of existing trans-national network capacity is required when existing capacity proves insufficient in accommodating the electricity flows induced by regional imbalances between generation and consumption.

Figure 3-3 shows the expansion of trans-national electricity interconnections in Europe across storylines in the period of 2030 to 2050. What stands out in all storylines is a strengthening of a trans-European corridor from Southwest Europe (Spain) via France to Central Europe (Germany) and even Eastern Europe (Poland).This results from the developments in generation capacity in the respective regions illustrated in the earlier figures. There we observed in particular a decline in generation capacity in Central and Eastern Europe and an increase in renewable-based electricity generation capacity in Southwest Europe. Furthermore, Figure 3-3 illustrates that a relatively large penetration of renewables (such as in the **Blue** and **Green** storyline) gives rise to a relatively large, and widespread, need for more electricity transmission capacity expansion. A common observation for all storylines except **Red** is that a strengthening of electricity transmission networks in Northwest Europe is required for the integration of mainly wind-based electricity generation.



(a) Yellow storyline

(b) Green storyline

(c) Red storyline

(d) Blue storyline

Figure 3-3 Overview of trans-national electricity infrastructure expansion in Europe between 2030 and 2050 in GW across storylines (Source: MTSIM)

4 TRANS-NATIONAL DEVELOPMENTS IN THE GAS MARKET

4.1 Declining production and growth in electricity sector demand as main drivers

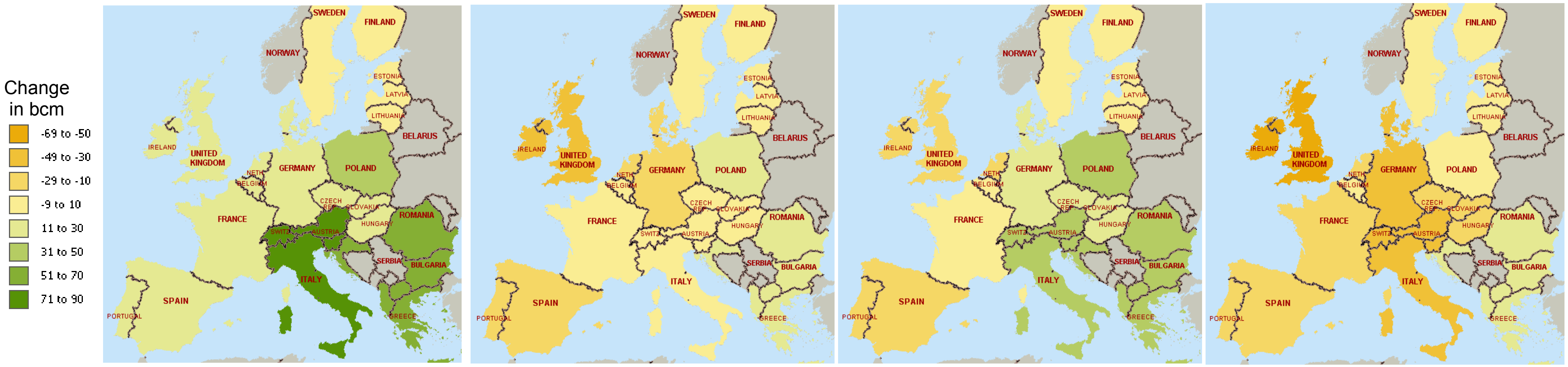
The main drivers for trans-national developments in gas infrastructure in the timeframe up until 2050 are the decline in indigenous gas production on the one hand, and the different demand dynamics across different countries in Europe on the other. Until recently, it was generally acknowledged that Europe would be facing an increasing gas import gap in the coming decades due to the increasing depletion of own gas reserves. While gas demand projections indicate increasing gas demand until at least 2020 – especially in the electricity sector (see Figure 4-1) – the production levels of traditional EU gas producers (i.e. the UK and the Netherlands) are expected to have peaked well before then. The recent strong surge in commercially viable shale gas production in the US has resulted in high expectations for shale gas developments throughout Europe, for example in Poland. The real future contribution of shale gas production in Europe remains speculative, amongst others due to environmental, public acceptance, and property rights issues. In the assessment of trans-national development on the gas market no role is assumed for large-scale future shale gas production. This leads to very low levels of indigenous gas production in the timeframe of 2030 to 2050, which do not vary across storylines. EU gas production (excluding Norway) peaks at about 120 billion m^3 in 2020 and is only about 30 billion m^3 per year in 2050.

4.2 Different gas demand dynamics across Europe

The gas demand dynamics throughout Europe and across storylines largely varies as can be observed in Figure 4-1. The different gas demand developments across Europe within any particular storyline can largely be explained by the developments in the electricity sector. Regions where the share of gas in the electricity generation mix was already high in 2010, such as for example in the Northwest European countries of the UK and the Netherlands, exhibit significantly lower gas demand growth rates, than countries in Southern and South-Eastern Europe where gas is projected to increase its share in the electricity generating mix in the coming decades at the expense of even dirtier carbon-based technologies such as coal and oil. This geographical divide is most obvious in the **Red** and **Green** storylines, whereas the **Yellow** and **Blue** storylines show somewhat more balanced demand developments across the whole of Europe. Comparing general demand for gas in Europe between storylines we find that this is strongly increasing in the storyline with the lowest push for RES (i.e. the **Red** storyline). The **Green** storyline is the only storyline where gas demand is steeply reduced by 2050. These results are shown in Figure 4-2.

4.3 Security of gas supply implications

The gas import dependency on external gas supplies in the 2030 to 2050 timeframe is especially high in a high gas demand future: total gas imports amount to about 815 billion m^3 in the **Red** storyline in 2050, which is more than the double of European gas imports in 2010. The level of diversification of gas imports is, however, also largest in high demand scenarios. This can be explained by the cost-optimization character of the modeling tools deployed: a higher gas demand gives rise to a higher price, encouraging the market entry of not only the relative low cost suppliers but also the higher-cost gas supplies further away from the European market. Russia, Algeria and Norway are the key (external) gas suppliers, irrespective of the storyline context.



(a) Red storyline (a) Yellow storyline (c) Blue storyline (d) Green storyline

Figure 4-1 Gas demand developments across Europe between 2010 and 2050 [De Joode *et al.*, 2011]

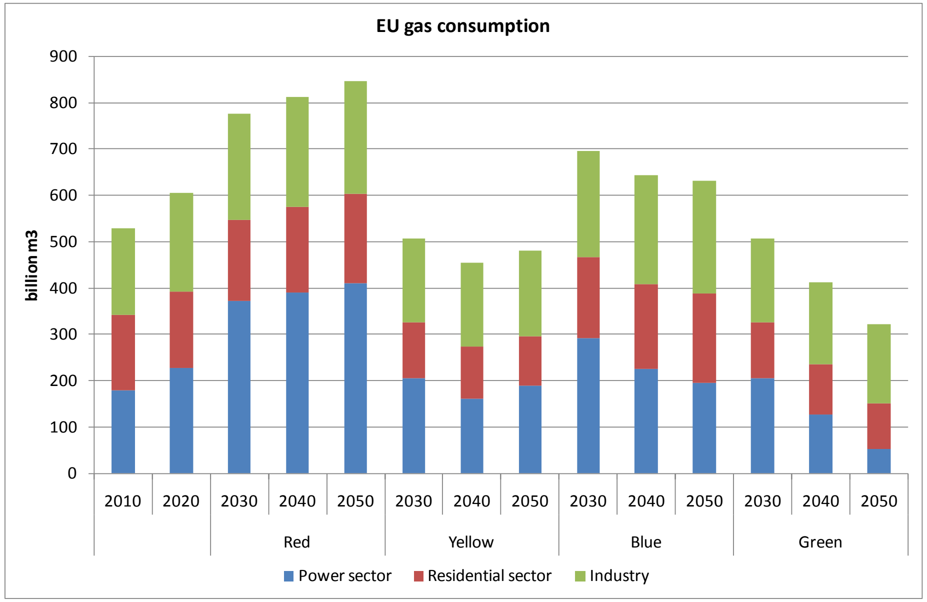


Figure 4-2 EU sectoral gas consumption across storylines [De Joode *et al.*, 2011]

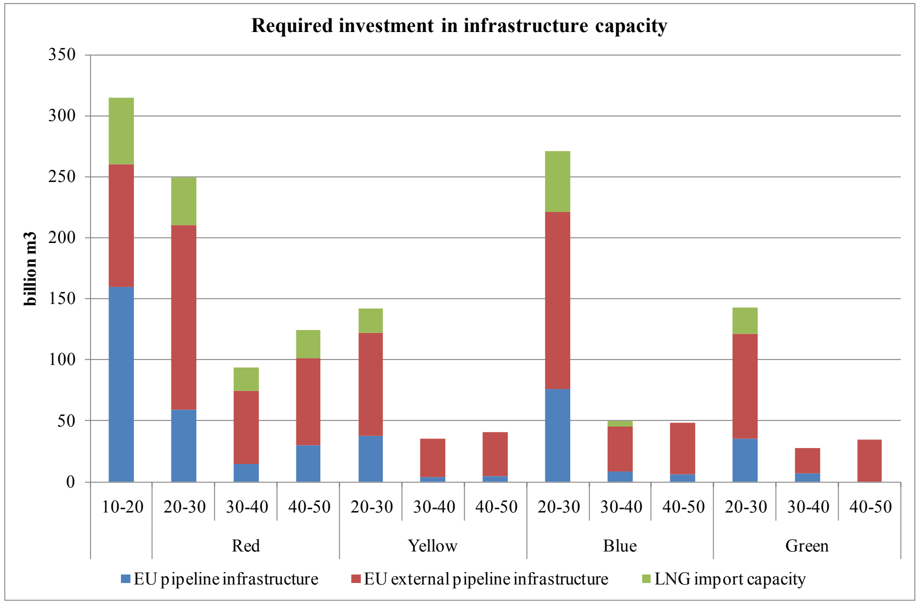


Figure 4-3 Required infrastructure investment across storylines[De Joode *et al.*, 2011]

4.4 Investment in trans-national gas infrastructure

Three particular gas infrastructure investments can be distinguished in the results from the trans-national analysis for the gas market: (1) investment in pipelines bringing gas to the EU border, (2) investment in LNG terminals facilitating EU gas imports, and (3) investment in gas pipelines within the EU facilitating a transit of gas received on the border.[5] The level of investment for each of these categories across storylines is presented in Figure 4-3. In all storylines the majority of investment takes place in the 2010 to 2030 timeframe because European gas demand is expected to peak in particular this timeframe in three out of the four storylines. Since EU gas production is simultaneously going into steep decline there is a particularly strong need for investment in gas infrastructure that enables the transport of gas to EU borders. New required import infrastructure predominantly consists of new pipelines with relatively modest investment in LNG terminals due to its generally less attractive economics versus pipeline supplies in a number of destination countries. In addition to EU import infrastructure, some additional investment in the internal EU pipeline system is needed to accommodate new internal gas flow patterns. Infrastructure investment in general is very high in the rather gas-intensive **Red** storyline, and relatively low in the **Green** storyline that is characterised by low gas demand levels. Investment in the 2030 to 2050 timeframe in the **Blue** and **Yellow** storylines is also low due to the stagnation or decrease in gas demand after the 2020-2030 gas demand peak. Figure 4-4 and Figure 4-5 show that the need for investment in new gas infrastructure largely varies across Europe. The main observations in this respect are:

- 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;
- A large increase in direct gas flows from Russia to Germany via the proposed North Stream corridor reduces the gas flows 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;
- The increasing depletion of gas reserves in the UK and the Netherlands significantly reduces the gas flows from North-western Europe to neighbouring countries (i.e. connections of the Netherlands to Germany and the UK to Belgium).

[5] The performed assessment provides insight into these different types of investment requirements from the perspective of economic cost optimization and thus does not include particular security of supply considerations.

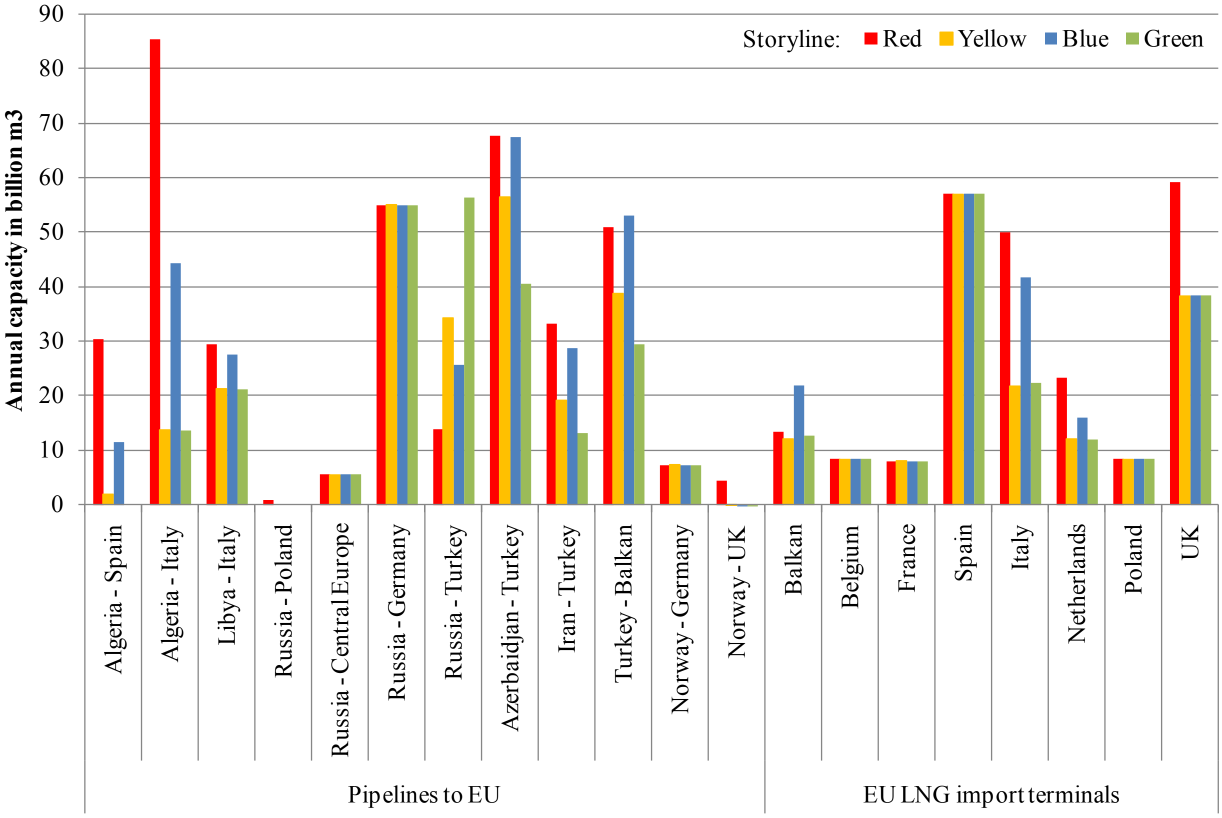


Figure 4-4 Investment in EU gas import capacity [De Joode *et al.*, 2011]

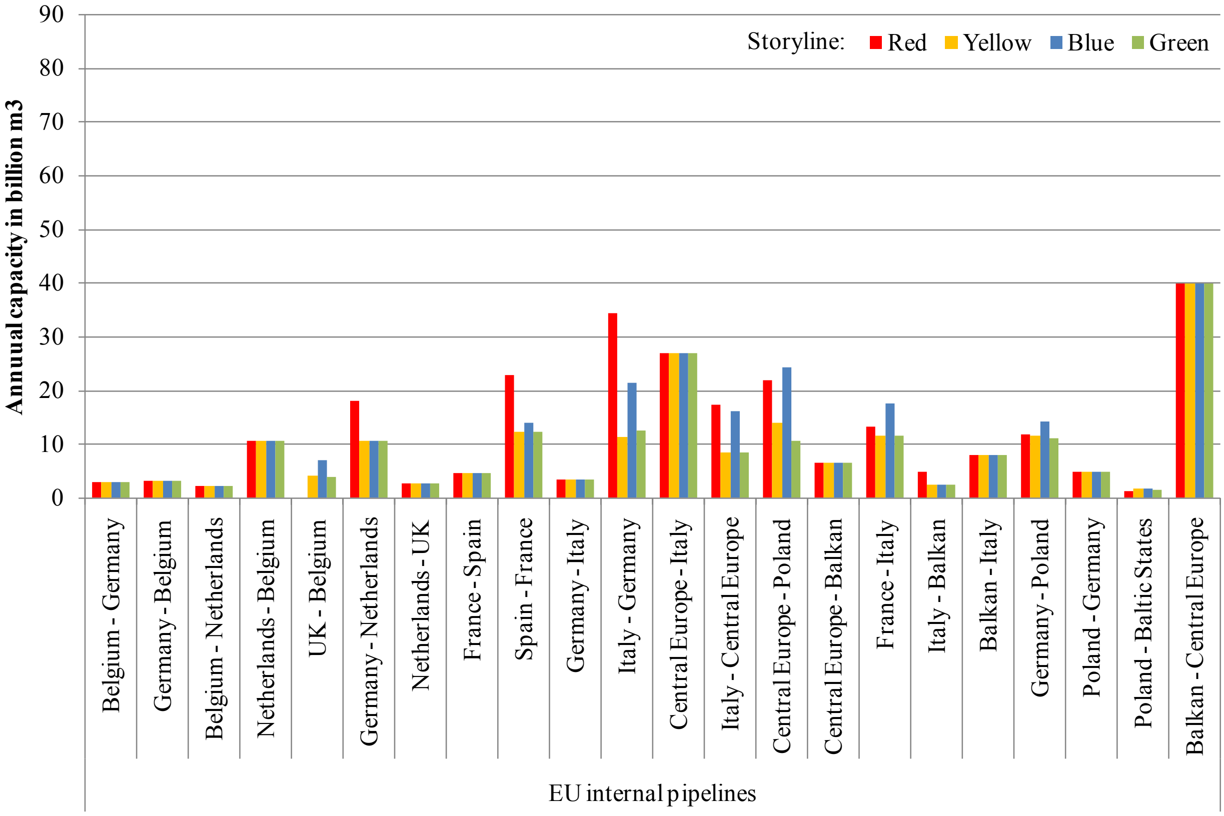


Figure 4-5 Investment in EU internal gas pipeline capacity [De Joode *et al.*, 2011]

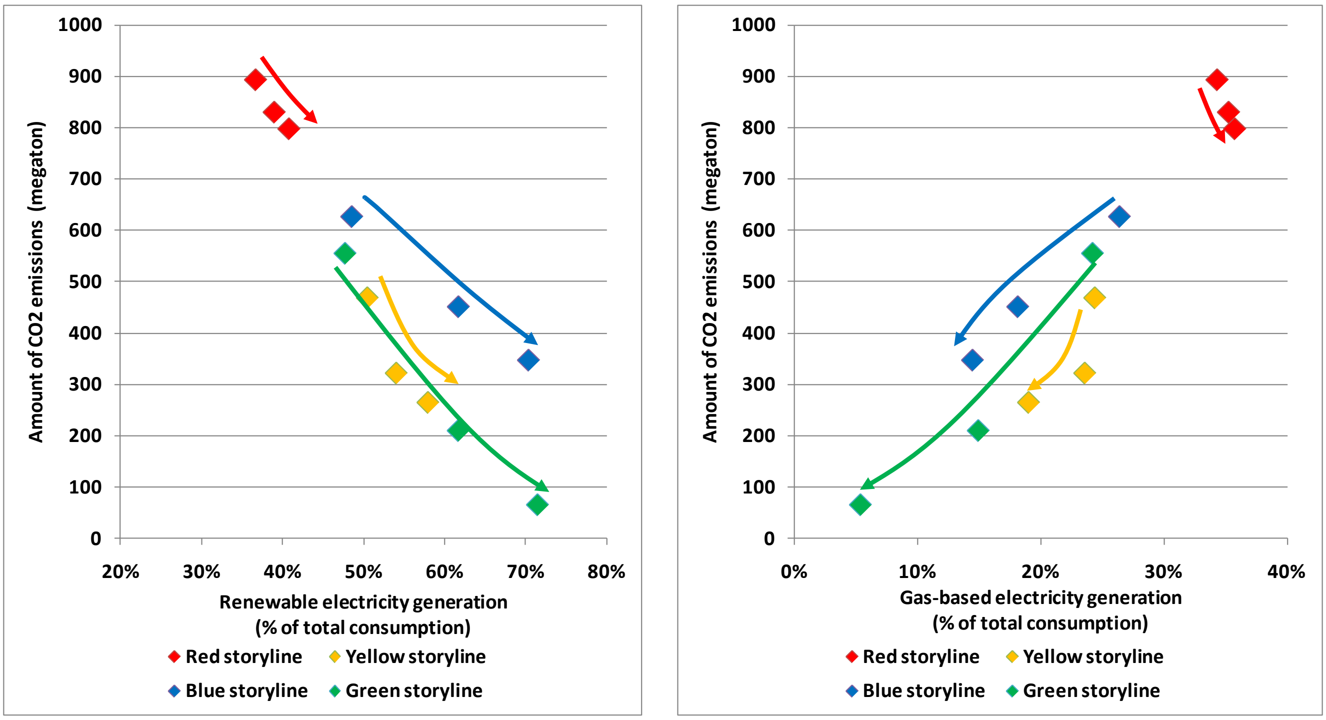
5 IMPACT ASSESSMENT ON KEY ASPECTS

Below we highlight the results for three aspects that are key when assessing the impact of RES penetration on the energy system. These concern the impact of RES penetration on:

1. The level of CO_2 emissions;
2. The cost of electricity generation;
3. The combined trans-national electricity and gas infrastructure requirements.

5.1 Impact of RES on the level of CO_2 emissions

Both changes in overall electricity demand and a shift in the deployment of non-renewable to renewable electricity generation technologies affect the total level of CO_2-emissions of the electricity system. Figure 5-1 shows the relationship between the amount of CO_2 emitted in the electricity generation sector and the share of renewable electricity generation and gas-based electricity generation in the electricity generating mix across the four storylines. The results show the combined impact of larger shares of RES and lower or higher electricity demand. Although different factors may influence the relationship, obtained results suggest a negative relationship between the amount of CO_2 emissions and the share of RES: a 1% increase in the share of RES links to a 20 megaton decrease in CO_2 emissions.[6] The impact of the share of gas on the level of emissions is less straightforward. The decreasing share of gas in three out of four storylines occurs simultaneously with a decrease in CO2 emissions, whereas the **Red** storyline sees a combination of an increasing share of gas with a small decrease in CO_2 emissions.



(a) Relation RES and CO_2 emissions (b) Relation gas and CO_2 emissions

Figure 5-1 Relationship between CO_2 emissions and the share of respectively renewable electricity generation and gas-based electricity generation (arrows indicate the transition from 2030 to 2050) [De Joode *et al.*, 2011]

[6] This is an average obtained from assessing the trend across four storylines. This figure may vary in reality with, among other factors, the type of RES technology underlying the RES share in the electricity generating mix.

5.2 Impact of RES on electricity generation costs

The level and structure of the average cost of generating electricity is affected by the generation mix deployed. An increasing share of RES technologies –at the expense of traditional carbon-based technologies such as coal and oil– has implications for the capital cost, fuel cost and cost of CO_2 emissions for the average unit of electricity produced. Figure 5-2 presents the dynamics of these different cost components across storylines. These results lead to the following observations:

- The capital cost[7] per unit of electricity generated strongly increases when more and more RES-based generation enters the system. This is especially clear when comparing the **Green** storyline with the other storylines.
- The fuel cost and CO_2 emission costs per unit of electricity generated strongly decrease with the amount of renewable electricity entering the system.
- The negative impact of an increasing amount of renewable electricity generation on the capital cost per unit of electricity generated is more than compensated by the positive impact on the fuel and CO_2 emission cost per unit of electricity generated.

For the correct interpretation of these observations it is important to note that the different storylines each have very distinct levels of electricity demand: electricity demand in the **Red** storyline is much higher than in the **Green** storyline which also affects the average level of generation cost.

5.3 Impact on trans-national electricity and gas infrastructure

As was illustrated earlier on, the geographical spread of changes in the supply and demand of electricity do not always match, which gives rise to a need for increasing trans-national electricity network capacity. Not surprisingly given the larger gas import dependency of Europe the same is true for trans-national gas pipeline requirements. Figure 5-3 presents a comparison of the physical need for additional network capacity on the electricity and gas market. [De Joode *et al.*, 2011] also translates these physical requirements in investment costs. Total gas infrastructure investment costs are at levels that are comparable to investment cost estimates in the Energy Infrastructure Package [EC, 2010]. Total investment costs for electricity are less comparable for reasons related to the way the electricity system is represented in the adopted electricity market model [De Joode *et al.*, 2011].

[7] Capital costs refer to the up-front investment of electricity generation capacity. The model used in analyzing trans-national developments in the electricity market does not endogenously model new investment in generation capacity and does not provide for investment cost. An approximation of capital cost across storylines is acquired by combining exogenously estimated levelised investment costs for different electricity generation technologies with the amount of electricity generated across different electricity generation technologies as provided by the model.

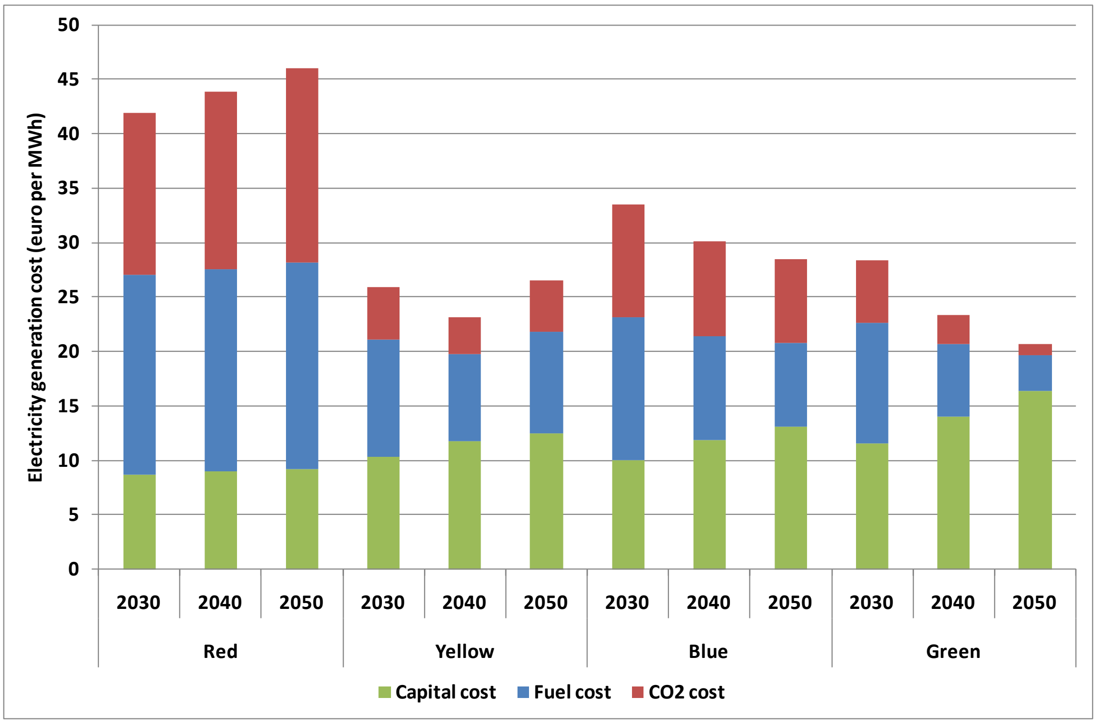


Figure 5-2 Level and structure of average electricity generation costs across storylines [De Joode *et al.*, 2011]

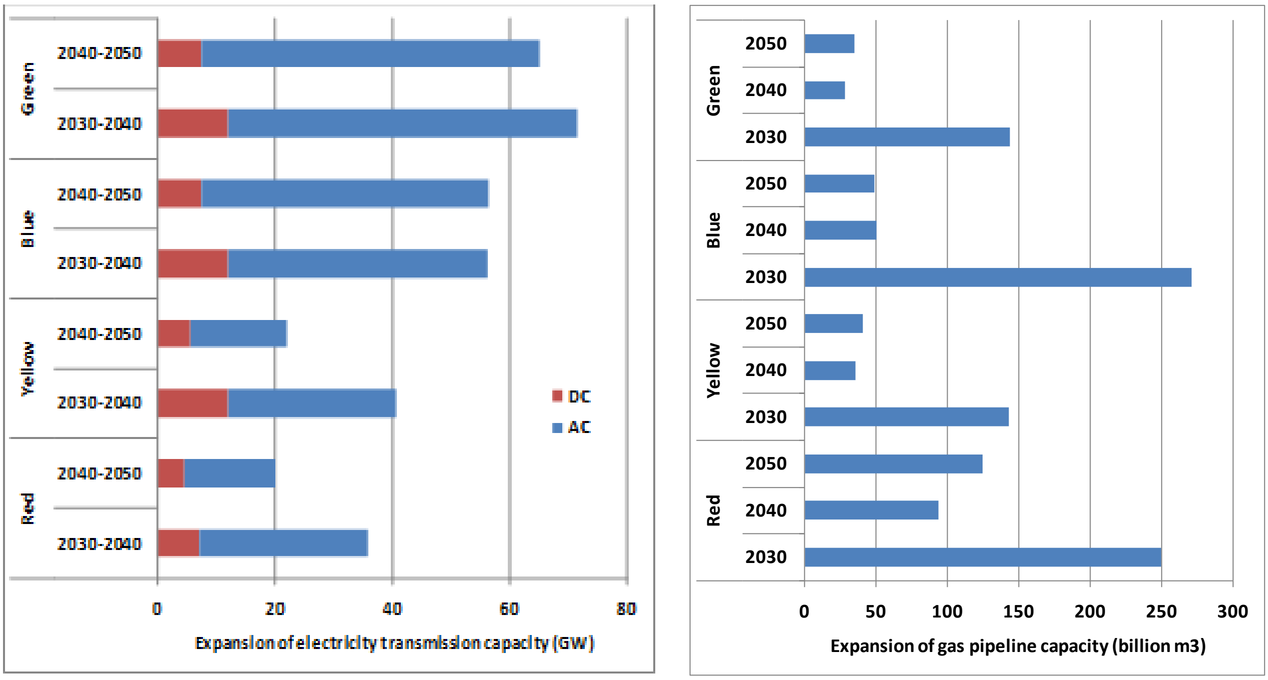


Figure 5-3 Expansion of electricity and gas infrastructure across storylines [De Joode *et al.*, 2011]

Based on the physical needs presented in Figure 5-3 the following observations are made:

- Relatively high investment costs for trans-national electricity infrastructure are needed in the storyline with low electricity demand and high RES penetration. This is explained by the fact that this combination leads to a larger imbalance in electricity supply and demand across regions in Europe, giving rise to relatively higher electricity import and exports throughout Europe. Moreover, large-scale infrastructure investments are particularly needed in the **Blue** storyline, which is characterised by a large increase in the deployment of offshore wind-based electricity generation.

- Relatively little investment in trans-national electricity infrastructure is required in the **Red** storyline, which has an explanation that is opposite to the one raised in the previous bullet. The combination of relatively high level of electricity demand and a low share of RES-based generation increases the chance of local and regional electricity supply and demand being in balance, implying that there is less need for electricity imports or exports.
- Large investment requirements for trans-national electricity networks do not necessarily correspond to large investment requirements for trans-national gas infrastructure; it is rather the other way around. A thermal-based storyline (**Red**) implies a generation mix development with a larger role for gas, leading to higher gas infrastructure demand.

5.4 Summary of results

Figure 5-4 summarizes the results of the electricity and gas market assessments for the considered storyline, and provides a comparison between storylines on a number of key indicators by using a colouring scale. The colouring scale indicates whether a storyline performs generally better or worse on a particular indicator than other storylines. For example, a relatively lower (higher) level of electricity / gas consumption, CO_2 emissions, need for electricity /gas infrastructure expansion and share of fossil fuels in electricity generation is indicated by the colour green (red).

Yellow

		2030	2040	2050
Electricity consumption	PWh	4.2	4.2	4.2
Renewable electricity generation	PWh	2.1	2.4	2.3
	%	50%	58%	54%
Gas consumption	Billion m3	507	455	480
Gas imports	Billion m3	422	403	449
Electricity infrastructure expansion	GW		41	22
Gas pipeline expansion	Billion m3	142	35	41
CO2 emissions electricity sector	Megaton	468	264	321

Green

		2030	2040	2050
Electricity consumption	PWh	4.2	4.2	4.2
Renewable electricity generation	PWh	2.0	2.6	3.0
	%	48%	62%	71%
Gas consumption	Billion m3	507	412	321
Gas imports	Billion m3	422	361	291
Electricity infrastructure expansion	GW		72	65
Gas pipeline expansion	Billion m3	143	28	34
CO2 emissions electricity sector	Megaton	556	210	66

Red

		2030	2040	2050
Electricity consumption	PWh	4.8	5.1	5.3
Renewable electricity generation	PWh	1.8	2.0	2.2
	%	37%	39%	41%
Gas consumption	Billion m3	777	812	846
Gas imports	Billion m3	692	761	815
Electricity infrastructure expansion	GW		36	20
Gas pipeline expansion	Billion m3	250	93	125
CO2 emissions electricity sector	Megaton	893	830	798

Blue

		2030	2040	2050
Electricity consumption	PWh	4.9	5.1	5.4
Renewable electricity generation	PWh	2.4	3.2	3.8
	%	49%	62%	70%
Gas consumption	Billion m3	696	644	631
Gas imports	Billion m3	611	593	601
Electricity infrastructure expansion	GW		56	56
Gas pipeline expansion	Billion m3	271	50	48
CO2 emissions electricity sector	Megaton	627	451	347

Figure 5-4 Summary of results across storylines, evaluation per storyline as indicated by colouring scale is relative compared with other storylines [De Joode *et al.*, 2011]

When comparing the relative performance of each storyline with its peers the main observation is that the **Red** storyline is the worst performing storyline on almost all aspects (except for the need for trans-national electricity infrastructure expansion. On the other side of the spectrum the **Green** storyline is the best performer on all aspects, excluding the need for trans-national electricity infrastructure expansion. The **Blue** and **Yellow** storylines perform comparable on most indicators, but the higher level of both electricity and gas consumption in the **Blue** storyline gives rise to a slightly more positive picture for the **Yellow** storyline.

6 CONCLUSIONS & POLICY RECOMMENDATIONS

Main findings and conclusions from the transnational scenario analysis (WP3) of the SUSPLAN project, based on the four different SUSPLAN futures, are presented in this section, along with key recommendations to ensure sufficient and timely investment in necessary infrastructure investments.

6.1 Conclusions from the study

The assessment of the need for trans-national infrastructure developments in the 2030-2050 timeframe allows conclusions to be drawn on three different levels: electricity market developments, gas market developments, and overall developments of the energy system (i.e. electricity and gas developments combined).

6.1.1 Electricity market developments

Future developments in trans-national electricity infrastructure in the 2030 to 2050 timeframe are driven by the differences across countries and European regions regarding three key drivers:

1. The potential to (further) deploy available RES-based electricity generation technologies;
2. The economics of available thermal-based technologies, and;
3. The growth in electricity consumption.

The storylines adopted in the analysis allows for an assessment of the national and regional electricity imbalances and the consequential need for trans-national infrastructure investment. The larger the geographical 'mismatch' in developments of the key drivers, the larger the need for expansion of the trans-national infrastructure. Different penetration rates of renewable-based electricity generation across storylines cause different expansion needs across Europe. Some trans-national infrastructure expansion requirements depend on the storyline context, but some are robust for the storyline context. An example of robust infrastructure requirements concerns the connections between South-Western Europe and Central Europe. This involves the transfer of solar and wind-based electricity generated in Spain and France to Italy and Germany. An example of storyline dependent infrastructure requirement is the connection of large-scale offshore wind parks in North-western Europe with electricity consumption centres in North-western and Central Europe. This involves the transport of electricity from the UK, the Netherlands, and Norway to Germany (and possibly further). Required expansion of trans-national electricity infrastructure capacity in the 2030 to 2050 timeframe may be 2 ½ times larger in a future energy system with low energy demand with a large share of renewable-based electricity generation future than in a future energy system with high energy demand and a low share of renewable-based electricity generation.

6.1.2 Gas market developments

Required investment in future trans-national gas infrastructure is dependent on the location of demand and supply of gas over time. It is important to make a distinction between the timeframe before and after 2030 when assessing trans-national gas infrastructure developments.

Total gas demand in Europe is expected to peak somewhere before 2030, with the exact year being dependent on various factors, among which the rate of penetration of renewable-based electricity generation technologies in the electricity sector. An exception to the pre-2030 gas demand peak concerns gas-intensive scenarios which show an increasing gas demand after 2030 at the expense of not achieving targeted sustainability goals for 2050. The likely peak in gas demand coincides with a steep decline in gas reserve availability in Europe, in particular due to the depletion of UK and Dutch gas reserves. This causes large investments in new European import infrastructure. This predominantly involves the development of new supply pipelines and to lesser extent the development of new LNG terminals.

Trans-national gas infrastructure developments post-2030 are closer related to the role of gas in the electricity sector but in general are less substantial than infrastructure expansion requirements in the pre-2030 timeframe. Some future investment requirements for trans-national gas infrastructure are robust across storylines, whereas others are dependent on storyline context. An example of a robust trans-national infrastructure expansion requirement is the gas transit corridor connecting Turkey with Southeastern Europe and Central Europe. Another robust trans-national gas infrastructure development is the emergence of Italy as a hub for gas imports from Northern Africa (via pipelines) and LNG producers throughout the world (via LNG import terminals) destined for gas demand centers in Italy and further downstream in Central Europe. An example of trans-national investment in gas infrastructure that is dependent on storyline context is the expansion of a gas corridor from Northern Africa, via Spain to Northwestern and Central Europe: this corridor is important in relatively gas-intensive energy system scenarios.

Required expansion of trans-national gas infrastructure across Europe in the 2030 to 2050 timeframe involves an investment of about €26 to €83 billion, on top of about €58 billion up until 2030. For the 2030 to 2050 timeframe, a high gas demand future energy system requires 2.2 times higher capacity expansion than a low gas demand future energy system. Relative gas import dependency in Europe remains high irrespective of the storyline context. Higher gas demand raises the amount of European gas imports, but also increases the level of diversification.

Observations on future trans-national gas infrastructure development are in line with industry views on future gas pipeline investment requirements for particularly the respective regions. Conclusions may, however, be affected by alternative storylines that include a large increase in shale gas operations in Europe. Given the distribution of known shale deposits this would affect gas flow pattern and trans-national infrastructure investment requirements across Europe.

6.1.3 Overall energy system aspects

A number of important aspects of the integration of renewable-based electricity generation can be commented in addition to sector specific trans-national infrastructure developments.

Different rates of CO_2 emission reduction in the 2030 to 2050 timeframe emerge across storyline context as a result of total energy demand and the share of renewable-based electricity generation in total electricity generation. A 1%-point increase in the share of renewable-based electricity generation leads to about 20 megaton reduction in CO_2 emission levels; dependent on the adopted model-based methodology and given the defined storyline background. This figure is among other factors dependent on assumptions regarding the cost-effectiveness of renewable-based technologies, fuel prices, and the price of CO_2 emission prices.

The average cost of electricity generation over time is affected by the economics of the different electricity generating technologies. An increase in the penetration rate of renewable-based electricity generation raises the average capital cost, but lowers the average fuel and CO_2 cost of a unit of electricity produced: thermal generation is characterized by relatively lower capital, but higher fuel and CO_2 emission cost than renewable-based generation. The level of average electricity generation cost is lower in a storyline with a relatively larger share of renewable-based electricity generation than in a storyline with a relatively high share of thermal-based electricity generation, assuming CO_2 prices rise to levels above €80 per ton from 2030 onwards.

Above we mentioned a number of key trans-national electricity and gas interconnections that need to be developed in the future. The need for trans-national electricity and gas infrastructure capacity sometimes coincide in particular regions or country borders. A first example is the parallel development of electricity transmission lines connecting wind-parks in the North Sea with Continental Europe on the one hand, and expanded gas pipelines from Norway to the UK and Netherlands and Germany on the other. A second example is the development of trans-national capacity for electricity and gas between Italy and Algeria and Libya, and Spain and Algeria. Parallel development of electricity and gas may bring benefits in terms of planning, coordination cost, building cost, and permitting procedures.

The transition towards a future energy system with lower CO_2 emissions may be characterized by interdependency between the amount of renewable energy, the need for trans-national electricity infrastructure investment, and the level of electricity demand. The lower total energy demand and the larger the penetration or renewable in the energy mix, the lower the level of CO_2 emissions. The impact of an increasing amount of renewable-based electricity generation on investment in trans-national electricity infrastructure depends on the level of electricity demand: higher electricity demand throughout Europe lowers the network integration costs of renewable electricity, since it leads to smaller regional and country imbalances in electricity generation and thereby reduces the need to transfer electricity to other regions or countries.

6.2 Policy recommendations

A list of key recommendations for policy makers is provided below. It should be noted that in particular recommendations 2, 3 and 5 are further elaborated in WP5 of the SUSPLAN project.

1. Ensure that long-term sustainability targets are combined with sufficiently strong incentives to reduce CO_2 emissions

The transition to a future sustainable energy system has fundamental implications for both electricity and gas markets and involves large investment in generation and infrastructure capacity. Generation and infrastructure assets are generally built to operate between 30 and 50 years. The SUSPLAN storylines reflect different future energy systems for the 2030 to 2050 timeframe, including different levels of CO_2 emission prices, giving rise to different investment requirements over time. Uncertainty regarding the long-term transition perspective would become a barrier for the financing of future energy infrastructure. The CO_2 emission is a major uncertain factor as it is one of the key drivers for the large-scale deployment of renewable energy technologies. A clear long-term commitment from the EU to implement a climate policy that is successful in providing sufficiently high CO_2 prices that truly encourage adoption of renewable energy and discourages the use of fossil fuels would ease the challenge of acquiring the required investment funds.

2. Ensure appropriate framework and support for critical energy corridors and infrastructure requirements

The SUSPLAN analysis has shown that a number of critical energy corridors and infrastructure expansion requirements (electricity and gas) are needed across a wider range of possible future energy market and energy consumption developments. Measures must be implemented to ensure sufficient support towards the development of these infrastructure expansion requirements. The recent Energy Infrastructure Blueprint Communication of the European Commission [EC, 2010] proposes measures to this purpose, i.e. the process of identifying projects of European interest, including selection criteria for EC funding of such projects. These measures should be further developed to incorporate longer term (2050) infrastructure investment needs, such as those identified as robust in all of the SUSPLAN storylines.

In doing so, a distinction should be made between those connections that will be needed before 2030 and those that are required in the time frame 2030 to 2050. A support framework should also include trans-national projects that are not robust across all storylines but are of high importance in particular transition scenarios. The need for these specific projects can for example be monitored as part of the long-term planning procedures that fall under the responsibility of European TSOs (ENTSO-E and ENTSO-G). A long-term network development strategy should be developed that complements the existing ten year network development plan: ten years is a too short timeframe in this context.

3. *Ensure coordinated development of electricity and gas infrastructures*

Electricity and gas markets are strongly intertwined, both in the short term (on operational issues), as well as the long-term, in particular for infrastructure development. Focussing on single strategies for either market, whether from a market integration, security of supply or sustainability perspective is bound to give rise to inadequate policies and regulations and undesirable energy market developments. To ensure efficiency in development of necessary infrastructure in the long term, coordinated strategies for electricity and grid infrastructure development should be encouraged. This should be incorporated into the new method of strategic planning to map out necessary infrastructures, presented in the recent Energy Infrastructure Blueprint Communication of the European Commission [EC, 2010].

4. *Ensure coordinated policies for energy infrastructure development and energy efficiency policy*

The future need for trans-national electricity and gas interconnections due to an increasing share of renewable energy depends on the level of energy demand. Strong energy efficiency improvements are an important instrument in reaching medium and long-term sustainability targets but at the same time may cause additional infrastructure requirements. The potential for deploying renewable energy vary across Europe and a lower energy demand may increase the need to transfer (renewable-based) electricity between countries. Targets for energy efficiency and the monitoring of the progress made on energy efficiency should therefore have a prominent role in infrastructure policy and long-term infrastructure planning.

5. *Ensure that energy policy and energy infrastructure policy meet a high level of public acceptance*

Public acceptance is a key issue in realising a future sustainable energy system. A lack of public acceptance can be a barrier in the transition process in numerous ways. The investment cost burden corresponding with the transition towards a sustainable energy system will not be shouldered by energy consumers unless there is a sufficient level of acceptance for the general goal and its welfare implications. In addition, public acceptance is a big issue in realising required trans-national infrastructure capacity. Local public acceptance for the building of infrastructure capacity may lack because the project pre-dominantly brings benefits for people elsewhere, or because of widely known NIMBY-effects.

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