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An Optimization Model of the European Natural Gas System

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ABSTRACT

The European Commission has identified the Energy Union, as one of its major priorities. This aims to deliver secure, climate-friendly and affordable energy to the European citizens. Towards implementing those goals, the European Commission is working towards diversifying routes and resources, and implementing the target model for the gas and electricity markets. This paper presents an optimization model of the European natural gas system. The model identifies the natural gas suppliers' mix for Europe and for each Member State. The model, being an optimization model, provides the economically optimum energy mix, subject to the technical and policy constraints of the gas transmission system. The model can also provide useful insights to the decision makers and market participants on the needed critical infrastructure. Model results show that the Russian natural gas is expected to have a prominent role in the EU, even by imposing energy security constraints. The incorporation in the model of the strategy of the companies, as well as the reserved capacity in the interconnections in each member state, would provide a more robust identification of the energy mix, the wholesale prices and the needed infrastructure.

Keywords: Natural Gas, Optimization, Pipelines, Europe
JEL Classifications: Q4, C61, L95

1. INTRODUCTION

The Ukrainian crisis has revealed the importance of energy security for the European Union -EU, as well as the need for an internal energy market. Although there is a debate on the issue (Goldthau, 2008), this has led the European Commission to identify the Energy Union and Climate, as one of its ten major priorities,[1] aiming at providing secure, affordable and sustainable energy to the European citizens. Towards implementing those goals, the European Commission is working towards diversifying routes and resources, and implementing the target model for the gas and electricity markets. A recent report examined how the EU could diversify its energy supply to improve its energy security (Leal-Arcas and Alemany, 2015). Many E.U. Member-States have experienced negative effects from the Russia-Ukraine gas price disputes (Dagoumas and Charokopos, 2016; Charokopos and Dagoumas, 2017). Therefore, this diversification of sources can be seen as an "insurance policy" to future possible supply disruptions (Ratner et al., 2013). Furthermore, the European Commission conducted an in-depth study on European Energy Security (EC, 2014a), accompanied by its communication on European Energy Security Strategy (EC, 2014b) as well as a study on the progress towards implementing the Internal Energy Market (EC, 2014c). The electricity and gas markets, although being commodity markets within a free zone, namely the EU, are grid-bound and therefore the evolution of a liquid and efficient internal market strongly depends on the construction of critical infrastructure. The European Commission has drawn up a list of key energy infrastructure projects, known as Projects of Common Interest (PCIs), aiming at diversification of routes and resources.

The latter is strongly enhanced by the potential of liquefied natural gas (LNG), which has been increased over the last years. According to a recent paper (Stern and Rogers, 2014), the period with the highest risk of LNG oversupply will be between 2018 and 2023, but there is difficulty in predicting the future equilibrium between supply and demand because of six "key" uncertainties: The Asian, especially Chinese, gas and LNG demand; the

1 https://ec.europa.eu/priorities/index_en, viewed on October 20, 2016

transition away from J.C.C. (Japan Customs Cleared Crude Oil Price) pricing in Asian markets; the U.S. shale gas performance that defines the scale and pace of U.S. LNG export volumes; the impact of shale gas development outside the U.S.; the volume and timing of LNG supply from new projects outside the U.S.; Russia's response to increased competition, which could lead to "overspill" of excess LNG into the European market. Besides, it is also stated that "The only major supplier with significant upstream spare capacity is Russia, which will increasingly emerge as a "buffer" or shock absorber in the new global order." US shale oil is not only challenging Russian exports, but also alternative suppliers (Fattouh et al., 2015).

Towards identifying the natural gas suppliers' mix in Europe and examining thoroughly crucial problems, such as energy security and market coupling, robust quantitative approaches are needed. The literature includes a number of methodologies towards identifying the penetration of natural gas in the European energy system. The vast majority concerns energy system models (Bhattacharyya, 2010), such as the MARKAL/TIMES family of models which provide pathways of natural gas system penetration implementing on a partial or energy equilibrium methodology. Zheng et al. (2010) provide a detailed discussion of optimization models in the natural gas industry with the focus on the natural gas production, transportation, and market. Moreover, there exist few models concerning natural gas demand forecasting (Soldo, 2012; Panapakidis and Dagoumas, 2017). However, very few models have been developed towards identifying the suppliers' potential and capacity to meet European natural gas demand.

The gas trade model - GTM (Beltramo et al., 1986) is a model that provides insights into North American natural gas trade issues. It is a partial equilibrium model, designed to allow interdependence between prices and quantities traded at a particular point in time between interrelated natural gas markets and also assumes that both GNP growth and the international price of oil to be exogenously determined. Furthermore, the model computes a possible trade pattern of flows between eleven supply regions (one in Mexico, three in Canada, and seven in the U.S.) and fourteen demand regions (one in Mexico, three in Canada and ten in the U.S.). The model aims to maximize the sum of consumers' benefits less the costs of production and transportation, subject to policy or technical constraints, such as: Pipeline capacity limits, take-or-pay contracts, reproducibility constraints, controlled prices and/or fuel-use allocation rules, export controls. However, the GTM computes a static market equilibrium in which denoted natural gas prices are the only variables that affect demand, and because of that it cannot be used directly to assess the optimal timing of resource extraction. According to the authors, the GTM focuses on long-term market equilibrium, rather than on short-term institutional and regulatory issues.

The International Natural Gas Model –INGM (Justine et al., 2009) is used to address the impact of different oil prices on natural gas markets. By using natural gas and NGL resources in each node, processing and transport capacities, and demand of natural gas and other fuels, the model simulates the natural gas and LNG markets from production to end-user markets for sixty nodes and accounts all the activities in midstream such as processing and transportation of gas. INGM uses a linear program (Hogan, 2002) to simulate gas markets, and the objective function maximizes the cumulative discounted sum of producer and consumer surplus, thus, finding market-clearing prices and flows, while developing the market equilibrium, capacity investment decisions and capacity utilization in three seasons (i.e., winter, summer, and spring or fall). Additionally, the model allows for inter-fuel competition. However, the model does not include contractual flows or prices. It assumes that LNG contracts will have short-term impact on the market and in the long-term LNG will flow based on marginal prices. Finally, it is worth mentioning that the model is destined to be used for world natural gas supply projections for the International Energy Outlook and to support LNG supply projections for the Annual Energy Outlook, both published annually by the E.I.A.

The RWGTM (Hartley and Medlock, 2009) is a dynamic spatial equilibrium model and was developed at Rice University's Baker Institute. It encompasses the world natural gas market based in geologic data and economic theory. Dynamic spatial general equilibrium is linked through time by optimal scheduling of resource extraction. The model has been developed to examine the effects of critical economic and political influences on the global natural gas market and provides an equilibrium in which the sources of supply, the demand sinks, and the transportation links connecting them, are developed over time to maximize the net present value of producer rents within a competitive framework. RWGTM is an agent-based model and each agent participating in it seeks to maximize its profit by minimizing its costs. However, the solution is not required to be economically efficient and it also requires that all opportunities for either spatial or temporal arbitrage have been eliminated. The supply data is combined with economic models of the demand for natural gas, and the demand functions were estimated using longitudinal state level data. For the U.S. is estimated directly and for the rest of the world indirectly considering both the energy intensity of the country and the natural gas share in its energy mix. Energy intensity is estimated as a function of per capita income and price. Additionally, the natural gas share is estimated as a function of GDP per capita, own price, oil price, installed thermal capacity, and the extent to which the country imports energy. Finally, the model has made a considerable contribution in showing that in a continuously globalizing natural gas market; events in one region of the world will influence all other regions: wholesale prices convergence, Russia is going to play a pivotal role in price arbitrage and natural gas is a "transition" fuel.

The world gas model (WGM) (Egging et al., 2008) is developed at the University of Maryland along with the cooperation of the Deutschen Instituts für Wirtschaftsforschung in Berlin. It is a large-scale agent-based model of the global gas markets where agents include producers, traders, storage operators, an integrated pipeline and system operator, and marketers. It also allows to model capacity investments endogenously. Collecting all the Karush-Kuhn-Taker conditions for all market agent optimization problems along with market-clearing conditions connecting among the players, leads to a mixed complementarity problem. Overall, the dynamic version of the WGM has contributed in assessing the potential impact of a closer cooperation by the countries belonging in the gas exporting countries forum (GECF). The main conclusion by the authors was that "an intensified collusion between groups of gas exporting countries would reduce production, thus raising prices." The GECF has recently developed its CECF global gas model (GGM), providing detailed disaggregation of 113 regions and countries in terms of gas supply and demand. The GECF GGM is a specialized, energy/gas forecasting tool that reflects the dynamic changes taking place in the gas markets at a specific time horizon. It can stimulate the impact of expected/potential/virtual changes on the global gas chain, tackling key uncertainties on the medium and long-term supply and demand of gas.

Mitrova et al. (2016) present several scenarios to assess the share of Russian natural gas in the European natural gas mix. Scenarios were calculated using the NEXANT WGM[2], concluding that absent of very drastic policy interventions Russian natural gas will continue to play a prominent role in the EU. Deane et al. (2017) developed a detailed integrated electricity and gas model for the EU-28, towards identifying the impact of gas supply disruption on the power system operation and the gas flow in Europe. The model was developed using the PLEXOS software package, which allows for both gas and power objects within its framework. Model results show that interruption of Russian gas supply to the EU could lead to a rise in average gas prices of 28% and 12% in electricity prices. The model is also used to examine the importance of gas storage infrastructure. Baltensperger et al. (2017) developed a spatial partial equilibrium model to analyze the changes in consumption, prices, and social welfare induced by the infrastructure expansions. The paper, based on model results, distinguish three categories of projects: Projects increasing social welfare in all scenarios in most countries, projects increasing social welfare in the newly connected countries, while social welfare drops slightly everywhere else and projects with a marginal effect on the market. Model results indicate that if all proposed infrastructure projects are realized, the EU's single market will become a reality in 2019. Moreover, there exist more technical models, focusing on the natural gas transportation systems, such as the model developed by Pambour et al. (2016) which concern an integrated transient hydraulic model for simulating the dynamic operation of natural gas transport systems. The model includes sub models of the most important facilities, such as pipelines, compressor stations, pressure reduction stations, underground gas storage facilities and LNG terminals. The model has been applied performing a dynamic simulation on the Bulgarian and Greek bi-national gas transmission system.

The above literature review shows that although there are some models developed at a global or regional level, the literature concerning modelling of the European natural gas system is limited. This paper aims at developing an optimization model for the European natural gas system. It aims at identifying the natural gas suppliers' mix for Europe and for each member state. The model, being an optimization model provides the economically optimum energy mix, under the technical and policy constraints of the gas transmissions system. Moreover, it enables the identification of bottlenecks among the different regions in the EU and providing useful insights to the decision makers, involved companies and market participants on the market dynamics of the alternative natural gas supplies and crucial infrastructure projects. The rest of the paper is organized as following: Section 2 describes the European natural gas system, while Section 3 presents the optimization model for the modelling the European natural gas system. Section 4 provides the results of indicative scenarios. Section 5 comes with conclusions and policy recommendations.

2. EUROPEAN NATURAL GAS SYSTEM

Figure 1, shows the evolution of natural gas dependence of EU countries over the period 1990–2014, based on data from Eurostat. Energy dependency shows the extent to which an economy relies upon imports in order to meet its energy needs. This indicator is calculated as net imports divided by the sum of gross inland energy consumption plus bunkers.

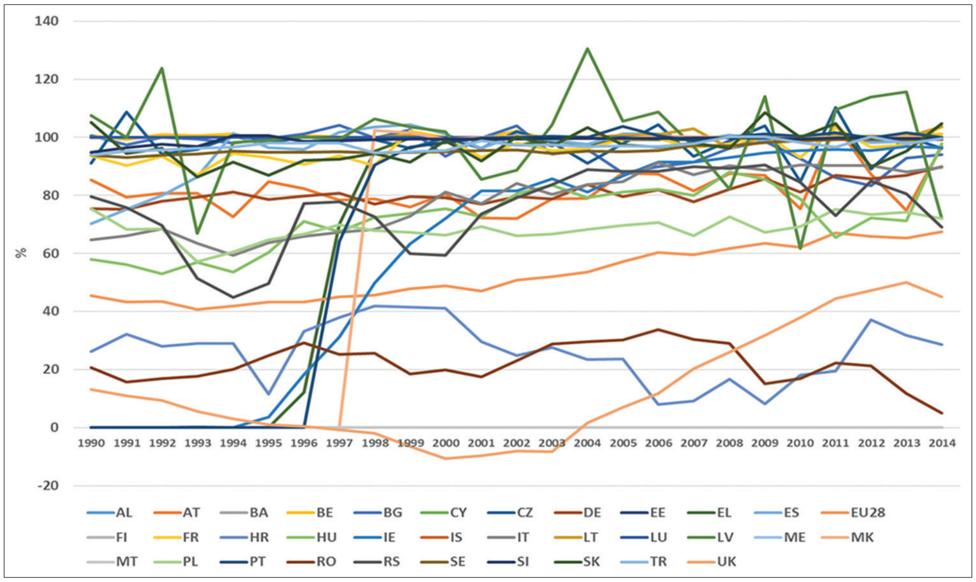
In Figure 1, Norway and Netherlands are excluded as they export gas. Therefore, their dependence is negative, taking very high prices at the level of −2000%, which would undermine all other values of the other countries. Figure 1 shows that, besides UK, Romania, Hungary and Portugal, which have some considerable domestic gas production, the dependence of other European countries are above 50% and in several countries exactly or almost 100%. Some countries have even higher to 100% dependence, which practically means that they are transit country, as gas flows through its territory to neighboring countries. This strong dependence was analyzed in a recent report (EC, 2016) which showed that in 2015, EU gas imports are above 50% of its demand, having increasing rates. In 2015, gas imports were 11% higher than in 2014, where Russian supplies represented 40% of total extra-EU imports, followed by Norway (37%), Algeria (7%) and Libya (2%); LNG imports covered the remaining 13% (EC, 2016). Figure 2 provides the dependence of EU countries from Russian gas, but as well from Ukraine as transit country.

To assess the effects of a possible disruption of supply on the EU, the Commission published a statement on the short-term resilience of the European gas system and the level of preparedness for a possible disruption of supplies from the East during the fall and winter of 2014/2015 (EC, 2014d). Table 1 illustrates the effect of a 6-month gas disruption from Russia in the European countries. These figures clearly highlight the fact that specific regions in the EU, such as the Baltics, Eastern Europe and the Balkan Peninsula are vulnerable to an energy supply disruption.

The European Commission strongly supports the completion of the internal energy market and the further development of energy infrastructure. It considers that because of EU market liberalization, industrial, household consumers, small and medium enterprises, can already reduce their prices by changing to better tariff regimes with existing suppliers. However, a fully functional internal energy market requires critical infrastructure towards enabling energy flow from cheap to expensive systems. Figure 3 provides a comparison of wholesale gas markets in EU Member States for the first quarter of 2016. It is obvious that European

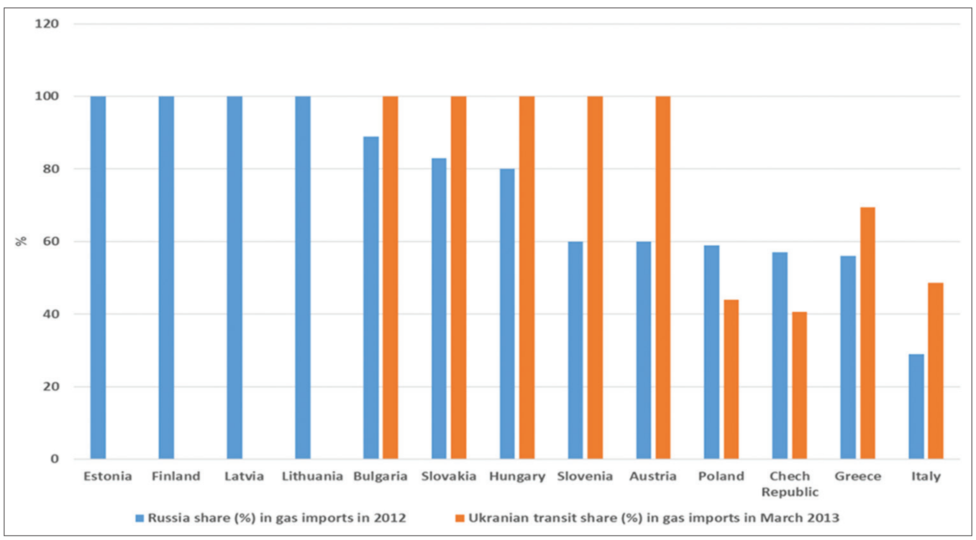
2 http://thinking.nexant.com/program/world-gas-model

Figure 1: Natural gas dependence of European countries over the period 1990–2014



Source: Eurostat

Figure 2: Gas dependency of selected European countries from Russia and from Ukraine as a transit country



Source: Eurogas (2015)

companies and citizens are facing different gas prices, as the price signals from the wholesale gas markets show differences even above 30% between countries. This is exactly the role of the PCI to identify the bottlenecks among gas systems and enhance market coupling but also energy security.

On one hand, there is existence of a detailed natural gas infrastructure in Western and Central Europe, and on the other hand there is lack of infrastructure in Eastern and South-Eastern Europe. This explains the high dependency of those countries from Russian gas and Ukrainian transmission system, as well as the considerable differences on wholesale natural gas prices among European countries. The needed infrastructure concerns pipeline projects for diversifying routes and resources, as well as liquefied natural gas (LNG) terminal projects for diversifying resources, storage facilities for increasing robustness in case of disruption in supplies, reverse flow systems and compressor stations for optimizing the use of existing infrastructure. The implementation of such projects will lead to a fully functioning market for all European countries, enhancing the reduction of energy prices and increasing competition.

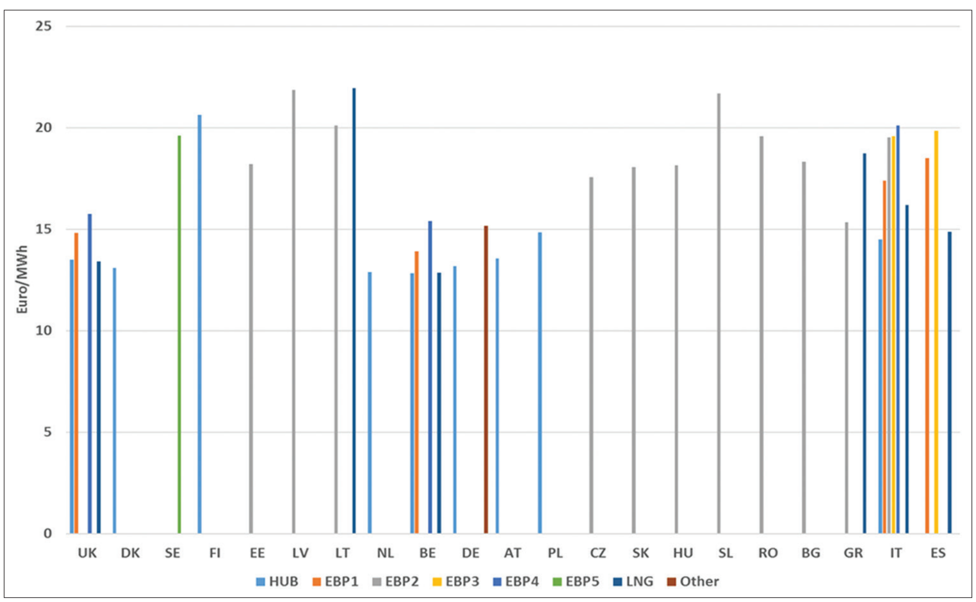
The model development has elaborated several data sources (ENTSOG, 2014; I.E.A., 2016; I.G.U., 2016) to incorporate detail of the European natural gas system, as well as of its suppliers. Critical infrastructure is considered the LNG facilities. Investment in LNG and LNG storage infrastructure development is the best way for E.U. to mitigate its import dependency on "traditional" pipeline suppliers. Although the plans for LNG facilities are quite promising, their development is of an earlier stage, and of fewer number than that of the pipeline PCIs, considering the higher initial cost to build LNG terminals than pipeline interconnections. However, the most developed LNG markets in the E.U. are placed in the Western and North part of the continent (U.K. and Spain), whereas the South-Eastern part is quite left behind. That difference between the North-Western and South-Eastern sub-regions can be seen in Figures 4 and 5, where the maximum regasification capacities and LNG storage capacities of each Member-State are presented respectively, divided into three clusters according to projects that are already operational, under construction, and planned. EU expands its demand capacity in order to achieve the target "energy security."

Table 1: Possibility (%) of supply interruptions at the end of the 6-month Russian gas supply disruption case during a cold spell, in cooperative and non-cooperative scenarios, in European countries, source: EC (2014d)

Country	Cooperative scenario (%)	Non-cooperative scenario (%)
Finland	80–100	80–100
Latvia	20–60	10–20
Lithuania	20–60	20–60
Estonia	20–60	60–80
Poland	10–20	10–20
Romania	20–60	20–60
Hungary	20–60	20–60
Bulgaria	20–60	60–80
Serbia	20–60	60–80
Bosnia	20–60	80–100
FYROM	20–60	80–100
Greece	20–60	10–20
Croatia	<10	10–20
Slovenia	<10	10–20
Sweden	<10	0
Denmark	<10	0
Germany	<10	0
Czech Republic	<10	0
Slovakia	<10	0
Austria	<10	0
Italy	<10	0

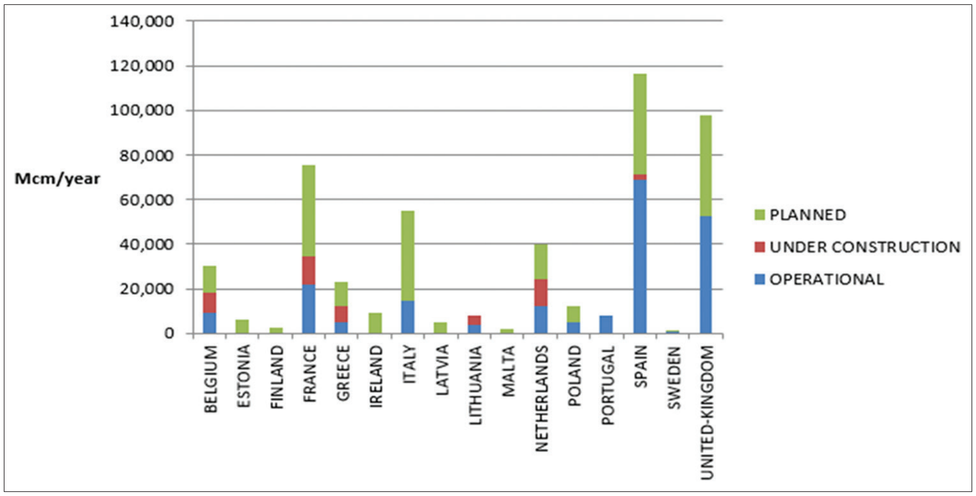
Gas storage is another measure to ensure security of energy supply during sudden demand or supply shocks, and in times when winter temperatures are colder-than-normal. EU confirms that investments in the expansion of gas storage capacities, along with a sufficient gas transmission system can mitigate the ensure internal market integration. Romania is a Member-State of the EU that has its own production of natural gas, and it is also placed in a geostrategic position in the Eastern parts, because it is surrounded by many states that satisfy their own needs by importing gas from third countries (mainly Russia). By developing gas storage facilities in the country, EU can safeguard the continuous provision of energy, and the continuous flow of natural gas to the surrounding Member-States that are heavily dependent on gas imports from Russia. Thus, the storage facility developments in that Member-State are of major importance to the energy integration of the Union. However, the lack of interconnection points between Romania, Bulgaria, and Hungary makes it difficult for Romania to export its domestic production to the neighboring Member-States. In Figure 6 we see the capacities of storage facilities across

Figure 3: Wholesale gas prices in EU Member States in first quarter 2016



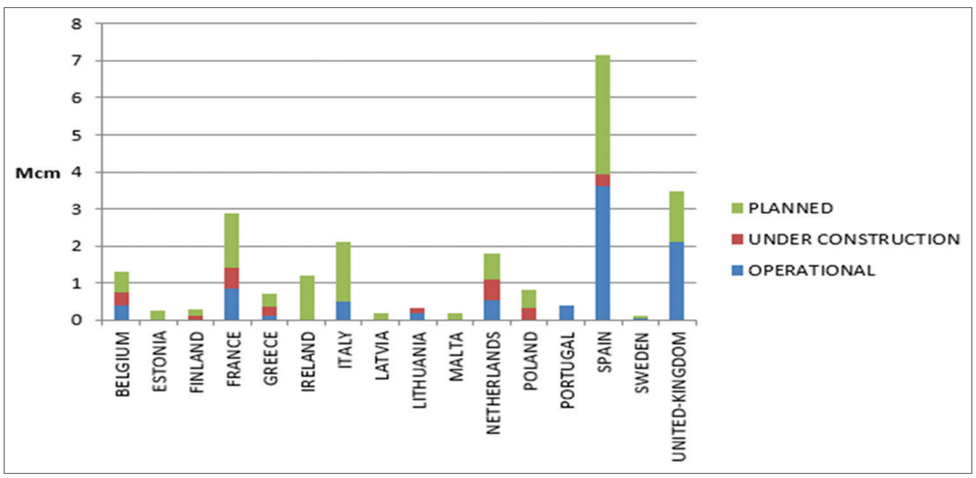
Source: EC (2016). EC, 2016: Elaborated data from sources: EBP estimates and LNG: Eurostat COMEXT, ThomsonReuters; HUB: Platts, Finnish Gas Exchange, Gaspoint Nordic for Denmark; POLPX for Poland; BAFA for border prices for Germany.). EBP1 prices are estimations of border prices for gas from Norway; June-August 2014, EBP2 prices are estimations of border prices for gas from Russia; June-August 2014, EBP3 prices are estimations of border prices for gas from Algeria; June-August 2014, EBP4 prices are estimations of border prices for gas from the Netherlands; May-July 2014, EBP5 prices are estimations of border prices for gas from Denmark; May-July 2014. LNG prices for Belgium, France, Spain and the UK are landed prices as reported by Thomson-Reuters for July-September 2014 (simple averages of monthly data). LNG prices for Greece and Italy are estimations based on customs data reported to ESTAT COMEXT for first 4 months of 2014. Portugal not reported due to missing data in ESTAT COMEXT since October 2013

Figure 4: Liquefied natural gas maximum regasification capacities of each Member-State as of May 2015



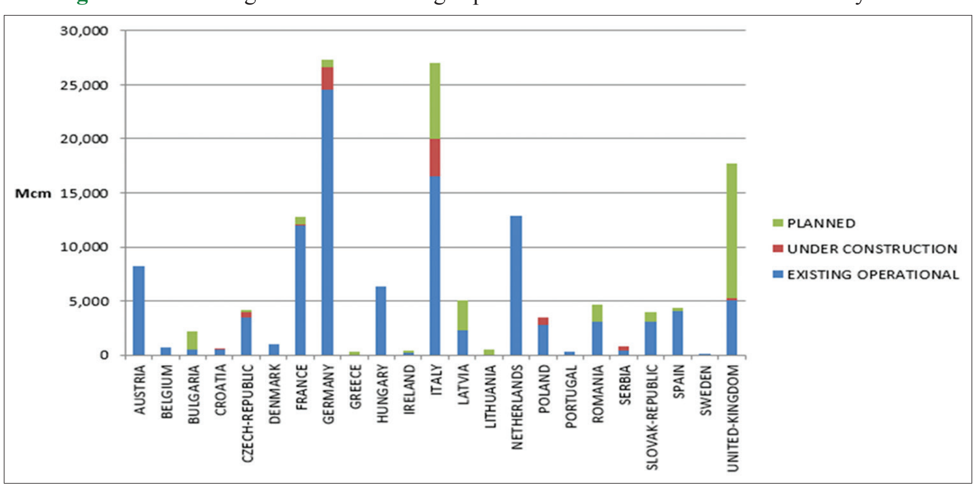
Source: Gas infrastructure Europe (G.I.E.), http://www.gie.eu/index.php/mapsdata/lng-map

Figure 5: Liquefied natural gas storage capacities of each Member-State as of May 2015



Source: Gas infrastructure Europe (G.I.E.), http://www.gie.eu/index.php/mapsdata/lng-map

Figure 6: Gas storage technical working capacities of each Member-State as of May 2015



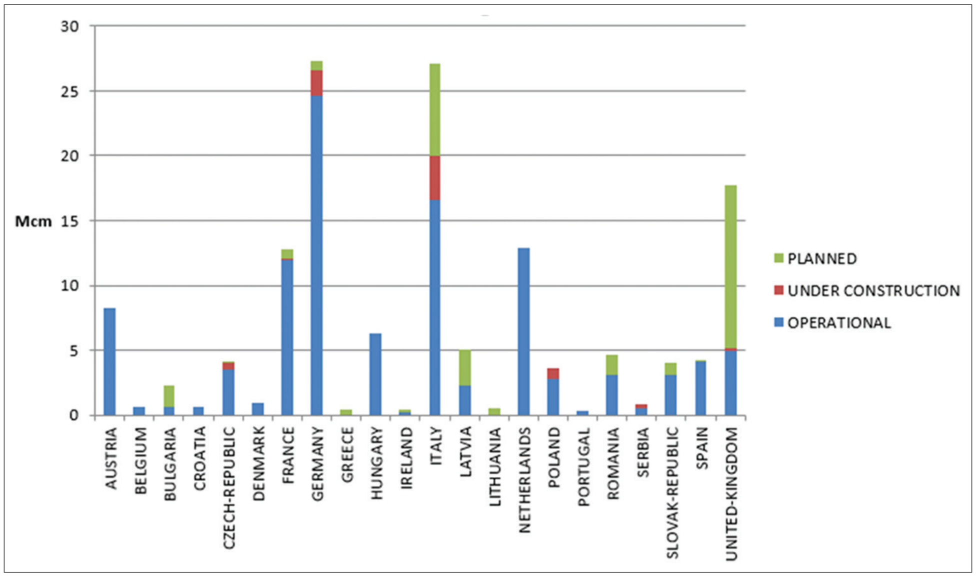
Source: Gas infrastructure Europe (G.I.E.), http://www.gie.eu/index.php/mapsdata/gse-storage-map

each Member-State, whereas in Figure 7 the working technical capacities of underground storage facilities in each Member-State. Again, divided into three different clusters regarding their completion status.

3. METHODOLOGY

A new mixed integer programming optimization model is developed in generic modelling algebraic system (Gilbert and

Figure 7: Underground gas storage technical working capacities of each Member-State as of May 2015



Source: Gas infrastructure Europe (G.I.E.), http://www.gie.eu/index.php/mapsdata/gse-storage-map

Tower, 2009). It determines the optimal energy sources' mix for meeting natural gas demand, under technical and policy constraints.

3.1. Objective Function

The proposed objective function is based on the minimization of the total energy system cost of a gas system at an examined period. Therefore, the model's objective function includes: (i) Domestic natural gas resources cost, (ii) natural gas imports cost, (iii) natural gas exports revenues, (iv) LNG terminal costs, (v) pipeline transmission costs among different systems and within the same system, (vi) LNG transportation cost, (viii) the investment cost of PCIs and (ix) the investment cost of exploitation of new gas resources, as represented by Equation (1). The nomenclature is provided in Annex 1.

$$
\begin{aligned}
\text{Min cost}^{\text{period}} = & \overbrace{\sum_{t}\sum_{s}\sum_{r}\text{Dom\_NGPC}_{r,s,t}}^{\text{Domestic natural gas production cost}} + \\
& \overbrace{\sum_{t}\sum_{s}\sum_{s'}\sum_{r}\text{IMP\_NGPC}_{r,s,s',t}}^{\text{Imported natural gas cost}} - \overbrace{\sum_{t}\sum_{s}\sum_{s'}\sum_{r}\text{EXP\_NGPC}_{r,s,s',t}}^{\text{Exported natural gas revenue}} + \\
& \overbrace{\sum_{t}\sum_{s}\sum_{s'}\sum_{r}\text{TRC\_PIP}_{r,s,s',t}}^{\text{Pipelines transmission cost}} + \overbrace{\sum_{t}\sum_{s}\sum_{s'}\sum_{r}\text{TRC\_LNG}_{r,s,s',t}}^{\text{LNG ships transportation cost}} + \\
& \overbrace{\sum_{t}\sum_{s}\sum_{lt}\text{LNGC\_Term}_{lt,s,t}}^{\text{LNG terminal operational cost}} + \overbrace{\sum_{t}\sum_{s}\sum_{st}\text{Dom\_STCC}_{st,s,t}}^{\text{Storage facilities operational cost}} + \\
& \overbrace{\sum_{t}\sum_{s}\sum_{s'}\sum_{i}\text{PCIC}_{i,s,s',t}}^{\text{Projects of commin interest discounted investment cost}} + \\
& \overbrace{\sum_{t}\sum_{s}\sum_{s'}\sum_{r}\text{New\_NGIC}_{r,s,s',t}}^{\text{New natural gas resources discounted investment cost}} + \overbrace{\sum_{t}\sum_{s}\sum_{s'}\sum_{r}\text{New\_NGPC}_{r,s,s',t}}^{\text{New natural gas resources production cost}}
\end{aligned}
\quad (1)
$$

The overall problem is formulated as an MILP (mixed-integer linear programming) problem, involving the cost minimization objective function (1) subject to following constraints.

3.2. Model Constraints

3.2.1. Energy balance

Equation (2) describes the energy demand balance in each natural gas system s. The imported natural gas from all other subsystems s' to system s, minus the exports of this system to all other subsystems s', plus the domestic production quantity of system s, must be at least equal to the natural gas demand in system s plus the energy stored in the storage facility in system s.

$$
\begin{aligned}
& \sum_{r}\text{Dom}_{\text{NGPQ}r,s,t} + \\
& \sum_{r}\sum_{s'}\text{IMP}_{\text{NGPQ}r,s,s',t} - \\
& \sum_{r}\sum_{s'}\text{EXP}_{\text{NGPQ}r,s,s',t} \geq \\
& \text{D}_{\text{NGR}s,t} + \text{Dom}_{\text{STCQ}st,s,t}
\end{aligned}
\qquad \forall r \in R^{s}, st \in ST, s, s' \in S, t \in T \quad (2)
$$

Where, the energy stored in the storage facility cannot exceed the storage facility capacity minus the stored energy of the previous year.

$$\text{Dom\_STCQ}_{st,s,t} \leq \text{Dom\_STC}_{st,s,t} - \text{Dom\_STCQ}_{st,s,t} \quad \forall st \in ST, s, s' \in S, t \in T \quad (3)$$

3.3. Domestic Resources

The domestic resource quantity can't exceed the domestic reserves in each system s, denoted for period t. The latter derives by dividing the total reserves by a period until their depletion.

$$\text{Dom\_NGPQ}_{r,s,t} \leq \text{Dom\_NGR}_{r,s,t} \quad \forall r \in R^{s}, s \in S, t \in T \quad (4)$$

$$\text{Dom\_NGR}_{r,s,t} = \text{Dom\_NGR}_{r,s} / \text{DP}_{r,s,t} \quad \forall r \in R^{s}, s \in S, t \in T \quad (5)$$

3.4. Production Costs

Equation (6) presents the production cost of a domestic natural resources $Dom\_NGPMC_{r,s,b,t}$, which is the product of marginal production cost with the produced quantity, for each block of the production cost curve.

As equation (7) states the production cost, is the sum of the fuel (extraction) cost and the rest operational and maintenance costs.

$$Dom\_NGPC_{r,s,b,t} = Dom\_NGPMC_{r,s,b,t} * Dom\_NGPQ_{r,s,b,t} \quad \forall r \in R^s, s \in S, b \in B, t \in T \quad (6)$$

$$Dom\_NGPMC_{r,s,b,t} = Dom\_NGPMFC_{r,s,b,t} + Dom\_NGPOMC_{r,s,b,t} \quad \forall r \in R^s, s \in S, b \in B, t \in T \quad (7)$$

Similar equations exist for imported natural gas.

$$IMP\_NGPC_{r,s,s',b,t} = IMP\_NGPMC_{r,s,s'b,t} * IMP\_NGPQ_{r,s,s',b,t} \quad \forall r \in R^{s'}, s,s' \in S, b \in B, t \in T \quad (8)$$

$$IMP\_NGPMC_{r,s,s',b,t} = Dom\_NGPMFC_{r,s,s',b,t} + Dom\_NGPOMC_{r,s,s',b,t} \quad \forall r \in R^{s'}, s,s' \in S, b \in B, t \in T \quad (9)$$

3.5. Interconnection Constraints

The natural gas net flow between systems s and s' can't exceed the pipelines' interconnection capacity.

$$PFL_{s,s',t} = IMP\_NGPQ_{s,s',t} - EXP\_NGPC_{s,s',t} \quad \forall s,s' \in S, t \in T \quad (10)$$

$$ABS(PFL_{s,s',t}) \leq PIPC_{s,s',t} \quad \forall s,s' \in S, t \in T \quad (11)$$

The above equation exists in case there is allowed a reverse gas flow. In such case, binary variables $FLA_{s,s',t}$ and $FLA_{s',s,t}$ take the value of one. If reverse power flow is not allowed, one of those variables is set to zero.

Moreover, for each block b∈B of the flow among the interconnected systems s,s'∈S, there are limits for imports and exports respectively.

$$IMP\_NGPQ_{s,s',b,t} = \sum_r IMP\_NGPQ_{r,s,s',b,t} \quad \forall r \in R, s,s' \in S, b \in B, t \in T \quad (12)$$

$$EXP\_NGPQ_{s,s',b,t} = \sum_r EXP\_NGPQ_{r,s,s',b,t} \quad \forall r \in R, s,s' \in S, b \in B, t \in T \quad (13)$$

$$IMP\_NGPQ_{s,s^{\wedge\prime},b,t} \leq IMP\_NGPQ_{s,s',t} \quad \forall s, s' \in S, b \in B, t \in T \quad (14)$$

$$EXP\_NGPQ_{s,s',b,t} \leq EXP\_NGPQ_{s,s',t} \quad \forall s, s' \in S, b \in B, t \in T \quad (15)$$

3.6. LNG Terminal Constraints

The natural gas transported between systems s and s' using LNG terminals can't exceed the terminals nominal capacity.

$$LNGFL_{lt,s,s',t} = \sum_r IMP\_LNGQ_{lt,r,s,s',t} - \sum_r EXP\_LNGC_{lt,s,s',t} \quad \forall s,s' \in S, t \in T \quad (16)$$

$$ABS(LNGFL_{lt,s,s',t}) \leq LNGC_{lt,s,t} \quad \forall lt \in LT, s,s' \in S, t \in T \quad (17)$$

$$ABS(LNGFL_{lt,s,s',t}) \leq LNGC_{lt,s',t} \quad \forall lt \in LT, s,s' \in S, t \in T \quad (18)$$

3.7. Demand

Consumers' surpluses are described as the integral of the inverse demand function $g_{s,t}$ ($D\_NGR_{s,t}$), which is the area below the demand function. The function describing consumers' benefits is a demand function of the following form, always subject to demand constraints:

$$g_{s,t}(D\_NGR_{s,t} = a\, D\_NGR_{s,t}^{-b} \quad \forall lt \in LT, s,s' \in S, t \in T \quad (19)$$

Where the negative exponent −b is the reciprocal of the price elasticity of demand, which is constant along the function, and the constant a can be determined from a single point across the demand function of each region. That function represents the "willingness-to-pay" of the consumers and the demand is affected only by the price of natural gas in each region.

3.8. Assumptions

Crucial for the formation of the model are the assumption on the supply and demand curves, which are presented in a recent work (Skarakis, 2017). The supply and demand prices for every producer and consumer country are presented in the following Figures 8 and 9 respectively. The competitiveness of the Russian gas is based on official data from Gazprom, elaborated by Mikhail Korchemkin, as shown in Figure 10.

4. RESULTS

The model is operational, being able to identify the supplier's natural gas mix for Europe. The model is operational, however it has not incorporated yet all the technical details of the European gas system, such as compressor and storage stations, which does not allow for assessment of all natural gas flows. The model is able to identify the energy mix, concerning the imports from different countries. However, being an optimization model provides the

Figure 8: Indicative supply prices per suppling region in reference case scenario ($/MMBtu)

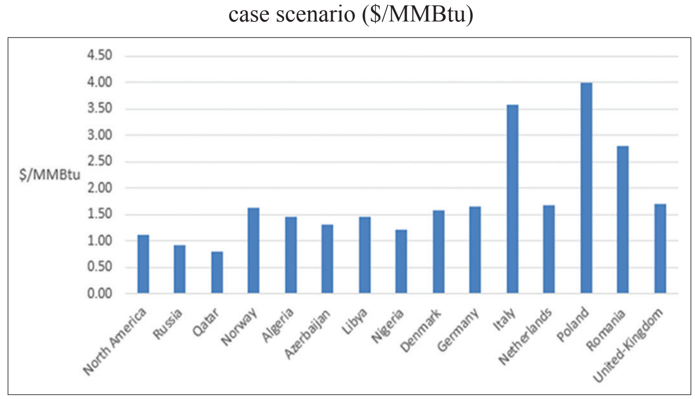


Figure 9: Indicative price elasticities per consuming region in reference case scenario ($/MMBtu)

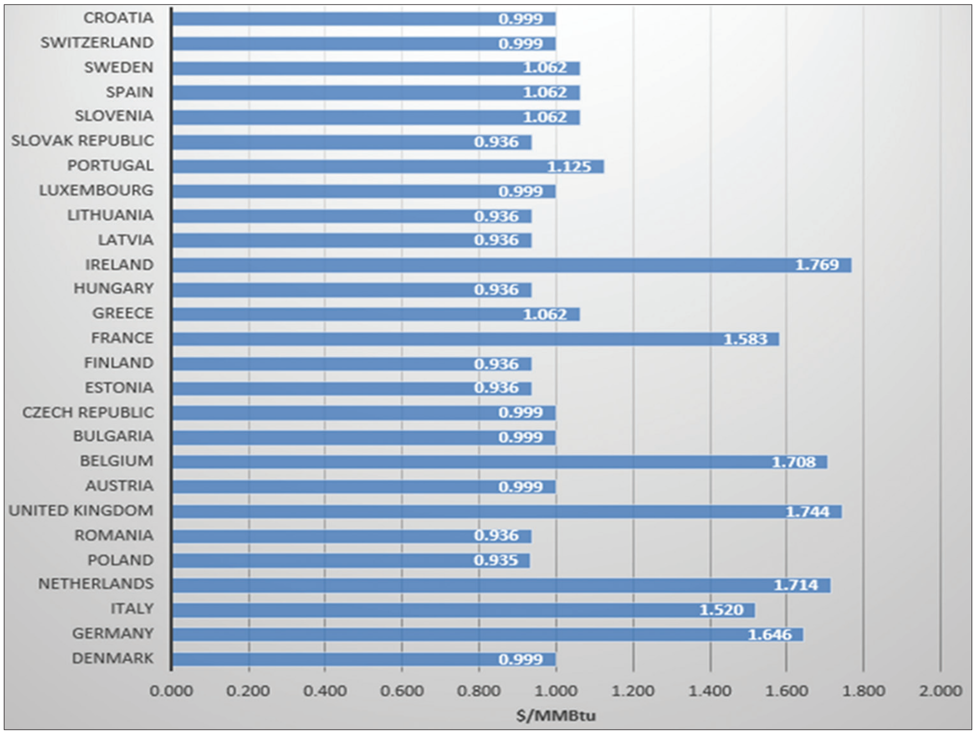
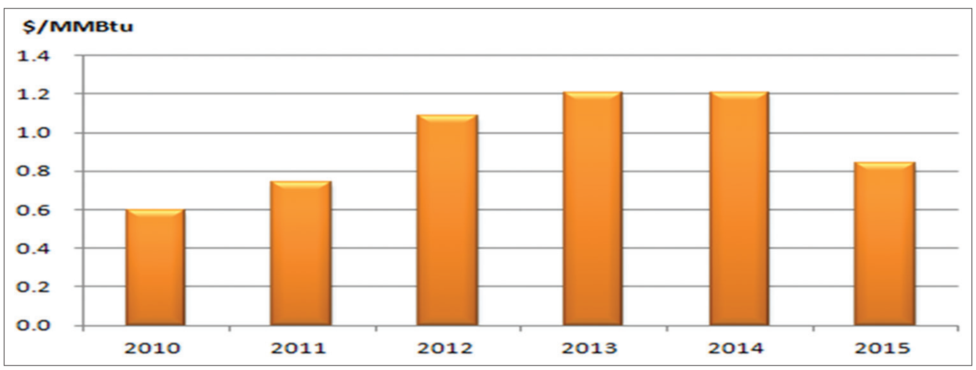


Figure 10: Gazprom production costs



Source: Mikhail Korchemkin, EEGA, 2016 http://www.eegas.com/rep2015q4-cost_e.htm

economically optimum energy mix, under the technical constraints of the gas transmissions system. However, the actual energy mix deviates for the economically optimum, estimated from the model, as the member states have different type of contracts, (long-term vs. short-term, oil-linked vs hub based), while they have different policy and actual indicators of energy security and energy dependence.

Two indicative scenarios have been examined, "reference" scenario with the current market conditions and alternative scenario aiming a more diversified mix, by imposed a cap of exports for a supplier to each Member-State at 35%. Of course, there are Member-States, where the existing infrastructure does not allow of meeting these criteria (i.e., for member-states with one or two suppliers). The results for the scenarios examined show that Russia in the reference scenario could have more than 60% of EU gas imports share (Figure 11), as it stands for the most competitive option. Moreover, Figure 12 shows the natural gas flows between supplying and consuming in the "reference" scenario. However, this share as well those gas flows have never been reported historically. This is mainly attributed to the fact that the EU Member-States, practically the companies operating in them, usually prefer to deviate from a single source, Gazprom, which is currently the cheaper option, by importing gas from other sources. The case of Greece is a good example, as the LNG is about 2–3 €/MWh more expensive from the pipeline gas. In Italy, the low transportation costs for LNG from Algeria as well the significant volumes, lead to exactly the opposite outcome, where LNG is more attractive than pipeline gas. However, the need of significant volumes for a long-period, but as well the need to diversify and hedge risks when importing from one source, lead companies to sign long-term contracts, which might not prove to be attractive for some years, compared to alternative options.

The tendency for a diversified suppliers' mix is modelled with a rather simplified approach in the "energy security" scenario,

Figure 11: (a and b) Suppliers' energy mix (%) for the "reference" and "energy security" scenarios in 2020

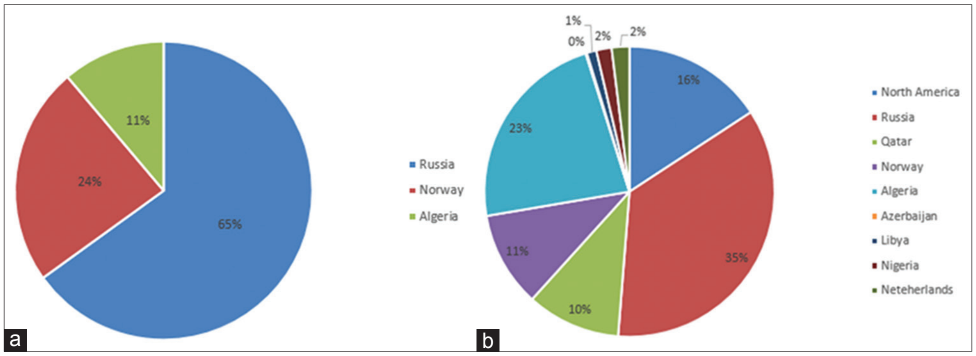
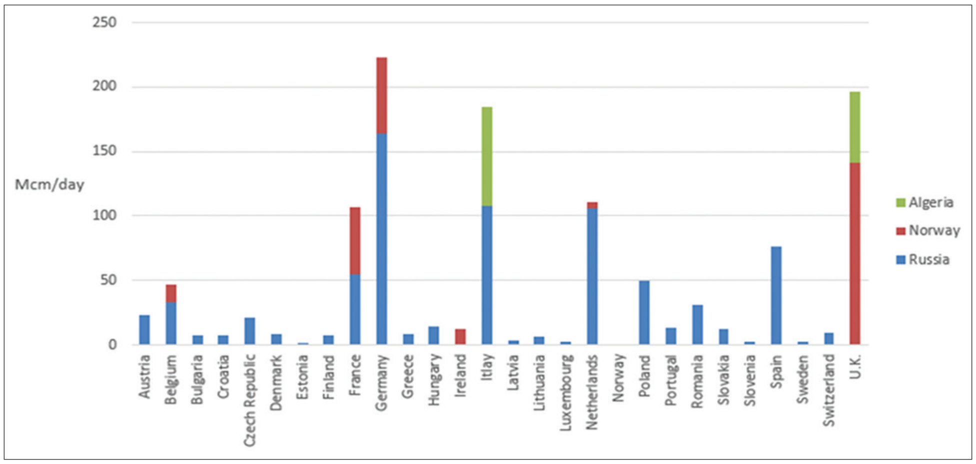


Figure 12: Natural gas flows between supplying and consuming in the "reference" scenario in 2020 (Mcm/day)



which provides results closer to the real figures at aggregate level, as depicted in Figure 11. The application of the "energy security" scenario, leads the number of suppliers increase to nine in comparison to the "reference" scenario, where there were only three. Figure 13 represents the natural gas flows between supplying and consuming in the "energy security" scenario. In that case, we see that Norway competes hard with North America, Qatar, and Algeria and becomes the second preferable supplier after Russia. Finally, Russia still holds the first position amongst suppliers and supplies 35.47% of total demand, which is higher than the 35% cap as some member-states depend totally on the Russian natural gas.

A more robust approach would be to incorporate in the model the strategy of the companies of each member state, which would provide a more robust identification of the suppliers' mix and of the wholesale prices. The model can also identify the Member-States or regions that should become priority for the development of PCIs. Such a case is the Baltic counties, or the South-East Europe, where the wholesale gas prices diverge significantly from neighboring countries. The price signal is the first and crucial information of the viability and bankability of a project, and justifies the European Commission to allocate resources from its Connecting Europe Facility fund. However, the implementation of those projects is a more difficult case, as they require binding offers – and not just expression of interest- from suppliers and final consumers, that operate in those countries. But, those suppliers and final consumers have usually existing long-term contracts with considerable volumes, under the clause of take-or-pay. This means that the implementation of PCIs, is a complex issue, based on the price signals from the wholesale markets, but considering also the existence of long-term or short-term contracts, but as well their pricing formula, oil linked, hub-based or hybrid schemes.

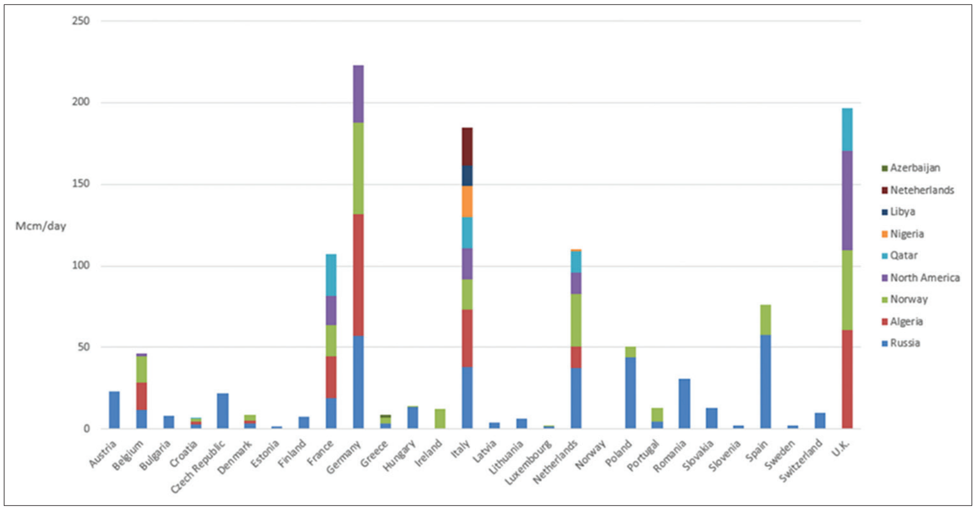
A more detailed representation of the natural gas contracts, as well as the reserved capacity in the interconnections is again needed, for providing a more robust model, useful in daily operations of market participants. However, the model in its current form is useful to decision makers at aggregate levels, providing clear indications on the penetration capability of its supplier.

5. CONCLUSIONS

The European Commission has identified the Energy Union, as one of its ten major priorities, aiming at providing secure, affordable and sustainable energy to the European citizens. Towards implementing those goals, the European Commission is working towards diversifying routes and resources, and implementing the target model for the gas and electricity markets, which requires the construction of critical infrastructure.

This paper presents an optimization model that is developed for modelling the European natural gas system. The model identifies the natural gas suppliers' mix for Europe and for each member-state. The model, being an optimization model, provides the economically optimum energy mix, under the technical constraints of the gas transmissions system. Therefore, under the current

Figure 13: Natural gas flows between supplying and consuming systems in the "energy security" scenario in 2020 (Mcm/day)



conditions, in its "reference" scenario it identifies that the Russian share in EU natural gas import mix could be more than 60%. However, the actual energy mix deviates for the economically optimum, as the member-states have different type of contracts, (long-term vs short-term, oil-linked vs hub based), while they have different policy and actual indicators of energy security and energy dependence. This diversification tendency is modelled by the "energy security" scenario, imposing a simplified cap on supplier's share in the natural gas mix in each Member State. The latter scenario, provides more realistic results at aggregate level. However, what is evident from the model results is that the Russian natural gas is expected to have a prominent role in the EU, even by imposing energy security constraints.

The model could also provide useful insights to the decision makers and market participants on the needed critical infrastructure, such as the PCI. The incorporation in the model of the strategy of the companies as well as the reserved capacity in the interconnections in each member state, would provide a more robust identification of the energy mix and wholesale prices. It would also strengthen the above-mentioned outcomes, concerning the energy mix, as well as which of them could be selected towards an internal energy market and meeting domestic or regional energy security targets.

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ANNEX 1

Annex 1

Nomenclature	
Sets	
$(s,s')\in S$	Set of natural gas subsystems
$(t,t')\in T$	Set of time periods
$r\in R$	Set of all natural gas resources
$r\in R^s$	Set of natural gas resources $r\in R$ that exist (or are found) in system $s\in S$
$b\in B$	Set of blocks of natural gas production function
$i\in I$	Set of PCIs
$i\in I^{s,s'}$	Set of PCIs $i\in I$ that concern subsystem $s\in S$ and or subsystem $s'\in S$
$lt\in LT$	Set of LNG terminal
$lt\in LT^s$	Set of LNG terminal $lt\in LT$ in subsystem $s\in S$
$st\in ST$	Set of natural gas storage facilities
$st\in ST^s$	Set of natural gas storage facilities $st\in ST$ in subsystem $s\in S$
Parameters	
$Dom\_NGPQ_{r,s,t}$	Domestic natural gas production quantity of resource r, in subsystem $s\in S$ in period $t\in T$
$Dom\_NGPQ_{r,s,b,t}$	Domestic natural gas production quantity of resource r, for block $b\in B$ in subsystem $s\in S$ in period $t\in T$
$Dom\_NGPC_{r,s,b,t}$	Domestic natural gas production cost of resource r, for block $b\in B$ in subsystem $s\in S$ in period $t\in T$
$Dom\_NGPMC_{r,s,b,t}$	Domestic natural gas marginal production cost of resource r, for block $b\in B$ in subsystem $s\in S$ in period $t\in T$
$Dom\_NGPMFC_{r,s,b,t}$	Domestic natural gas marginal fuel cost of resource r, for block $b\in B$ in subsystem $s\in S$ in period $t\in T$
$Dom\_NGPOMC_{r,s,b,t}$	Domestic natural gas marginal rest operational and maintenance cost of resource r, for block $b\in B$ in subsystem $s\in S$ in period $t\in T$
$IMP\_NGPQ_{r,s,s',t}$	Imported quantity of natural gas of resource $r\in R$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$IMP\_NGPQ_{s,s',t}$	Imported quantity of natural gas from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$IMP\_NGPQ_{r,s,b,t}$	Imported natural gas production quantity of resource r, for block $b\in B$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$IMP\_NGPC_{r,s,b,t}$	Imported natural gas production cost of resource r, for block $b\in B$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$IMP\_NGPMC_{r,s,b,t}$	Imported natural gas marginal production cost of resource r, for block $b\in B$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$IMP\_NGPMFC_{r,s,b,t}$	Imported natural gas marginal fuel cost of resource r, for block $b\in B$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$IMP\_NGPOMC_{r,s,b,t}$	Imported natural gas marginal rest operational and maintenance cost of resource r, for block $b\in B$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$EXP\_NGPQ_{r,s,s't}$	Exported quantity of natural gas of resource $r\in R$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$EXP\_NGPQ_{s,s',t}$	Exported quantity of natural gas from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$EXP\_NGPQr_{,s,s',b,t}$	Exported quantity of natural gas of resource $r\in R$ for block $b\in B$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$D\_NGR_{s,t}$	Demand for natural gas in subsystem $s\in S$ in period $t\in T$
$Dom\_STCQ_{st,s,t}$	Quantity of natural gas stored in domestic storage facility $st\in ST$ in subsystem $s\in S$ in period $t\in T$
$Dom\_STC_{st,s,t}$	Nominal capacity of natural gas that can be stored in domestic storage facility $st\in ST$ in subsystem $s\in S$ in period $t\in T$
$Dom\_NGR_{r,s,t}$	Domestic natural gas reserve of resource r, in subsystem $s\in S$ in period $t\in T$ that can be used for production
$Dom\_NGR_{r,s}$	Domestic natural gas reserve of resource r, in subsystem $s\in S$ that can be used for production
$DP_{r,s,t}$	Period until the depletion of natural gas resource r, in subsystem $s\in S$ in period $t\in T$
$PFL_{s,s',t}$	Pipeline natural gas flow from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$PIPC_{s,s',t}$	Pipeline natural gas capacity from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$LNGFL_{s,s',t}$	LNG flow from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$IMP\_LNGQ_{lt,r,s,s',t}$	Imported quantity of LNG of resource $r\in R$ in terminal $lt\in LT$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$EXP\_LNGQ_{lt,r,s,s',t}$	Exported quantity of LNG of resource $r\in R$ in terminal $lt\in LT$ from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$LNGC_{lt,s,t}$	LNG capacity of terminal $lt\in LT$ in subsystem $s\in S$ in period $t\in T$
Binary variables	
$FLA_{s',s,t}$	Flag shown if natural gas flow is allowed from subsystem $s\in S$ to subsystem $s'\in S$ in period $t\in T$
$FLA_{s,s',t}$	Flag shown if natural gas flow is allowed from subsystem $s'\in S$ to subsystem $s\in S$ in period $t\in T$

PCIs: Projects of common interest