Supply security in the European natural gas pipeline network

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Abstract

Energy security of natural gas supplies in Europe is becoming a key concern. As demand increases, infrastructure development focuses on extending the capacity of the pipeline system. While conventional approaches focus mainly on source dependence, we argue for a network perspective to also consider risks associated with transit countries, by borrowing methods from ecological food web analysis. We develop methods to estimate exposure and dominance of each country, by using network datasets of the present pipeline system, and future scenarios of 2020 and 2030. We found that future scenarios will not increase the robustness of the system. Pipeline development to 2030 will shift the relative weight of energy security concerns away from source to transit countries. The dominance of politically unstable countries will increase. The exposure will be slightly redistributed by improving the security of already secure countries, and increasing the exposure of those countries that are already in a vulnerable position.

Keywords: Energy security; European gas transport network; Political stability

Running headline: Gas pipeline security

Introduction

On the first days of 2009 a dispute between Russia and Ukraine led to a closure of major gaspipes, and the worst dropout of natural gas supply in Europe so far (Pirani et al., 2009). Supply to 18 countries was disrupted, and some areas with limited reserves and a lack of alternative supply channels were left without heating amidst a bone chilling cold snap. Initial cuts affected the supplies to Ukrainian consumption (January 1), while deliveries to Europe were reduced drastically on January 6 (e.g., Italy experienced losses for the 25% of its needs and decided to increase imports from Libya, Norway, and The Netherlands; Hungarian consumption was cut off by 40%). The impact was most sever in Central Europe. Thousands of residents in Bulgaria could only rely on an overloaded power grid to keep electric heaters running. Many households in Bosnia were also left without heating, giving a boost to a flu epidemic. Freezing residents in Serbia staged protests against Russia. Croatia and Slovakia declared a state of emergency, much of industrial production came to a halt. Poland and Hungary also imposed a limit to industrial uses of natural gas. Natural gas flows to all European customers did not return to normal levels until January 22.

In this chapter we bring methods and ideas from ecological network analysis – the analysis of food webs – to the problem of energy security in a complex distribution network. The events that unfolded in the crisis of 2009 suggested that supply risks are inherent to the network structure of the natural gas pipeline system.

The supply crisis of 2009 was not an isolated incident. The cascade of energy supply crisis in other similar incidents suggests that the same underlying mechanisms of system fragility are at play. In January 2006, a similar dispute between Ukraine and Russia has lasted four days, three of which has resulted in drops of European supplies Italy, for example, reported having lost around 25% of deliveries. Hungary was said to be down by 40% of its Russian supplies. (Stern, 2006). In June 2010 Russia cut natural gas supplies via Belarus amidst another dispute. While outside the heating season, this dispute nevertheless affected Lithuanian industrial production as gas imports dropped by 30%.

One ingredient in the repeated supply crises is a stress brought about by increasing load on the network system. Consumption of natural gas in Europe significantly increased over the last two decades. Beyond direct industrial and domestic use, natural gas became highly important in electricity generation also (Reymond, 2007; Weisser, 2007). The share of gas-fired power generation in all fossil fuels used towards electricity in the 27 current EU member states increased from 11% in 1990 to 34% in 2005, while the amount of electricity produced from coal decreased from 37% in 1974 to 27% in 2004 (IEA, 2007a). According to most major demand forecasts (see for example European Commission, 2002; IEA, 2007b, p. 492), there is a general agreement that this trend will continue in absolute and relative terms.

Another ingredient that makes crises waiting to happen is an ever increasing transportation distance. The quick decline of natural gas reserves near major downstream markets is a serious concern (Lochner and Bothe, 2009). According to a report published in 2007 (WEC, 2007), considering the static range of natural gas (i.e., the time to depletion of proven reserves given current production), conventional domestic reserves may only last for 12 years in North America, and 16 years in Europe. As a contrast, the global expected static range of natural gas is 56 years (WEC 2007, p. 147). If we look beyond the US, Europe, and Japan, we see emerging demand centers without significant domestic natural gas reserves (most importantly China and India). These processes make questions of supply security especially acute.

The European pipeline system is an intricate one in comparison to other energy distribution systems. On a global scale, Europe, USA, and Japan represent the main importers of natural gas. The supply networks to the USA and Japan are far less interesting cases of geopolitical uncertainty than the pipeline networks supplying natural gas to Europe[1]. Europe is located proximate to large reserves, and imports natural gas predominantly by pipelines. In 2008 more than 75% of the natural gas consumption to the 27 EU countries were imported. Pipeline imports are "*transported across several sovereign territories*" and "*Each border crossed adds an additional layer of security risk with the potential for conflict within these transit countries, and between the latter and the supplying country.*"

[1] In 2009 the volume of natural gas imported by USA via pipelines was more than 87.83% of total imports (3713 bcf supplied by Canada = 87.07% and Mexico = 0.76%), and only 12.17% (452 bcf) as LNG (traded from Egypt = 4.32%, Nigeria = 0.36%, Norway = 0.79%, Qatar = 0.34%, Trinidad & Tobago = 6.36%). These data were extracted from the EIA website: http://tonto.eia.doe.gov/dnav/ng/ng_move_impc_s1_a.htm. Japan is the top LNG importer (with around 3135 bcf, in 2006). Main sources of the Japanese LNG imports (in 2006) were: Indonesia (22%), Australia (20%), Malaysia (19%), Qatar (12%), Brunei (10%), United Arab Emirates (8%) and Oman (5%). These data were extracted from the eia website: www.eia.doe.gov/emeu/cabs/Japan/NaturalGas.html.

(Stern, 2002). European countries are strongly dependent on a few exporters for a major part of their gas imports. Eurostat (2008) reports that more than 80% of the EU-27 gas consumption, in 2006, was imported from only three countries: Russia (41.8%), Norway (23.3%) and Algeria (17.5%). In 2005 (IEA, 2005b), Russian natural gas covered the 100% of the imports to many countries (e.g., Finland, Romania, Bulgaria, Slovakia), with a high relative importance also for other EU-27 members (e.g., Hungary 91%, Poland 79%, Austria 78%, Germany 44%).

International trade by ships, for LNG, provides only 15% of natural gas imports to the EU-27 countries (BP, 2008). Pipelines are and, most likely, will remain the main vehicle for natural gas transfer. The peculiar rigidity in the topology of pipelines (i.e., structure of the distribution system) connecting suppliers (i.e., Russia, Algeria, Libya, Iran and Azerbaijan) to importing countries deserves attention, to investigate its mechanisms of functioning and consequences on supply security.

From food webs to energy supply systems

In this chapter we consider energy security from a network perspective. We consider the European pipeline network, a system of pipelines leading to countries in Europe via surrounding countries involved in natural gas distribution (such as Georgia, Syria) and originating from countries in Central Asia, North Africa, or the Middle East. We represent this system in terms of nodes (countries) and links between pairs of nodes (the total of pipeline capacity transferring natural gas across the border of those two countries). Our aim is to identify the role of network topology in security of supply, an approach that is not yet part of the energy policy toolkit (Kruyt et al., 2009)

Network analysis is widely adopted for studying complex systems such as the Internet, motorways, telephone connections, social communities, sexual contacts, or ecosystems (Girvan and Newman, 2002; Liljeros et al., 2001; Watts and Strogatz, 1998). In this article we borrow insights from ecological network analysis as there are many analogies between food webs and the gas pipeline network. Food webs are networks in which nodes correspond to species and links between them stand for energy flows exiting prey items and entering predators (Ulanowicz, 1986). They share many features with the gas transfer network. First, one can trace directed energy flows from sources (i.e., plants converting sunlight into chemical energy) to consumers (e.g., herbivores feeding on plants). Second, beyond just classifying node activity into the main roles of prey/source or predator/consumer, the trophic position of a species indicates its relative distance from the primary source of energy (i.e., sunlight), in a longer chain of predation. Third, all nodes (species) in ecological systems show biological respirations (energy dissipation that is not passed on to other species) that is analogous to the domestic natural gas consumption of countries. Fourth, biological primary producers (plants) rely exclusively on sunlight, without any incoming flows from other system compartments. These are equivalent to natural gas exporters (e.g., Norway, Algeria and Libya). Finally, the intensity of energy transfers is quantified, in weighted food webs, as energy or matter flows per unit of time and space (e.g., grams of carbon /[m^2·year]; kcal of energy/[cm^2·day]). This same approach can be applied on maximal technical capacities of pipelines (measured in normal cubic meters per hour, or Nm^3/h).

Our objective is to identify the consequences of source, transit and structural dependence on natural gas delivery, measuring how indirect effects of a crisis may spread along the pipeline network. We compare risks of countries interrupting gas transfer to the extinction mechanisms in ecosystems. In food web theory there are algorithms to identify bottlenecks (i.e., wasp-waist architecture with one species channeling large amount of energy; Jordán et al., 2005), and methods to forecast secondary extinctions (i.e., the possibility that species loss may lead to cascades of further extinctions; Allesina and Bodini, 2004; Dunne et al., 2002). In this article we assess the vulnerability of nodes (exposure) in terms of intensity and number of times by which their natural gas import may be affected. We also estimate secondary losses caused by country exclusion (i.e., a given country switching off natural gas exports), identifying which nodes are likely to cause the greatest impact if removed (dominators).

We aim to answer the following questions: 1) How robust or vulnerable is the configuration of the European gas pipeline network? 2) Will future developments currently planned decrease vulnerabilities in natural gas delivery? 3) How is political stability of countries related to their pipeline network position and vulnerability of the system?

In the subsequent parts of the chapter we explain the procedures adopted for constructing pipeline networks which represent the architecture of the present scenario (2008), plans that are likely to be realized by 2020 and hypothetical projects that could be operational by 2030. Then, we introduce whole-system indices used for understanding their global functioning. Next, inspired by the concept of trophic position (an ecological index measuring the average distance of a node from the sources of energy), we propose a method to calculate the average length of all the pathways that originate from natural gas sources and reach a given country. After that, we describe simulation techniques to infer exposure (average loss of domestic consumption suffered by closures in the pipelines upstream) and domination (average loss in domestic consumption induced at countries downstream by the closure of the pipelines) for each country in the dataset. Finally, we discuss our results about the robustness of future developments in the European pipeline network and its surroundings. We found that, beside the capability of delivering a greater amount of natural gas, the pipelines in the future will also result in few main pathways, increasing system rigidity and dependence on politically unstable countries. However, we also observed how more vulnerable countries display lower per-capita domestic consumption and will adopt strategies, as strengthening gas storage facilities, for preventing their exposure.

Data

We analyze the gas pipeline network as composed by 55 nodes representing European countries together with Asian and North-African ones on which they rely on for consumption (in subsequent sections we use the shorthand "European pipeline network" - see the Appendix A). We describe this system by directed data, depicting graphs of three scenarios. First, we illustrate the structure of pipeline connections in 2008. Then, we define the pipeline architecture as expected by plans up to 2020. Finally, we represent the network corresponding to long-term plans up to 2030. Countries (nodes) are connected by arrowhead links pointing from exporters towards importers. Link intensities (weights) are measured as cumulated maximal technical capacity (Nm^3/h) between two countries.

We record each of the 3 datasets as a matrix with 55 rows and columns. Element t_{ij} in this matrix corresponds to the cumulated maximal technical capacity if there is, at least, a pipeline from the row country i to the column country j, and 0 if there was none. We built this network data matrix using the grid map of technically available capacities at cross-border points on the primary market (GIE, 2008a), for EU countries, and other standardized data from specialized websites (Alexander's Gas & Oil Connections, Arab Fund for Economic and Social Development, British Petroleum, Eni, Gazprom, Gulf Oil & Gas, IHS - see the Appendix B for website addresses) and literature (EEGA, 2008; EIA, 2008; IEA, 1998; Olcott, 2004; Shirkani, 2008; Yenikeyeff, 2008), to include pipeline details on surrounding countries where main gas reserves are located.

Two 55-element vectors summarize production and current domestic consumption for each node, as reported by The World Factbook (CIA, 2008). Since productions consist of input to the system, in presence of LNG import they are summed together (GIE, 2008a). We consider available and future storage capacities of European countries, as listed in the GIE (2008b) database, and proven gas reserves (CIA, 2008). We also include the following governance indicators developed by the World Bank: rule of law, political stability, and government effectiveness (Kaufmann et al., 2009).

Beyond the network configuration of 2008 we also analyze future scenarios by including new pipelines that are likely to be constructed within 2020 and 2030 (Afgan et al., 2007; Mavrakis et al., 2006, pp. 1675-1676; Reymond, 2007; Shirkani, 2008; Yenikeyeff, 2008 - Alexander's Gas & Oil Connections, Arab Fund for Economic and Social Development, British Petroleum, Edison, Eni, Galsi, Gazprom, Hydrocarbons-technology, IHS, Medgaz, Nabucco Gas Pipeline Project, Nord Stream, Trans Adriatic Pipeline, White Stream - see the Appendix B for website addresses). Thus, our dataset describes the gas pipeline network at three points in time (basic assumptions on the pipelines are summarized in the Appendix D): the present (2008), the first step of construction (up to 2020), and a second step of construction (up to 2030). In these three networks we preserve the number of nodes (n = 55), including new links and adjusting the maximal technical capacity (weight of links) in case of planned new pipelines and expansion of existing connections. These networks are recorded and visualized by UCINET (Borgatti et al., 2002), a multi-purpose social network analysis software package.

Methods

The first step of our analysis is to compare general indicators about robustness, complexity, and redundancy of the 2008 configuration to the architecture of the plans to be realized by 2020 (step one) and hypothetical projects that could be operational by 2030 (step two). Will these two steps in the development of the European pipeline network bring about a more robust network structure? To answer this question we use indices describing the whole of the network structure, for the present, step one, and step two of future plans.

Then, for each country, we aim at investigating vulnerability and domination roles in gas delivery within the present pipeline network and its future configurations. Finally, we measure the distance of countries from gas reservoirs or LNG imports, and simulate the effects of their removal on natural gas transfer. Our goals are clarifying whether planned developments of the European pipeline network will affect energy security, and identifying possible bottlenecks.

Distance from the natural gas sources (DS)

Our baseline expectation is that exposure to supply disturbance is a function of the distance from the natural gas source. We will use this distance as a contrast to measures of exposure that take networks structures of supply also into account. We adopt the ecological concept of trophic position (TP): the average distance of a node to the sources of energy (Higashi et al., 1989). In food webs, primary producers (plants) receive sunlight energy that they convert into chemical energy. Thus the trophic position of plants is set to 1 (TP = 1). As a consequence, herbivores are at TP = 2, since energy to them travels a path of length 2 (sunshine → plants → herbivores). Primary predators feeding on herbivores are at the third trophic level, and so forth. In the presence of multiple pathways entering a node (representing a generalist trophic behavior), effective trophic position is calculated partitioning the energy flows into fractions belonging to different trophic levels. In the case of natural gas pipelines we apply the same algorithm to the pipeline network, defining the distance from natural gas sources (DS) as the weighted average length of all the routes that originate from gas reserves and reach a given country. Countries relying exclusively on gas reserves or LNG imports (considered as input to the system), without incoming flows from other nodes, have DS = 1 (e.g., Norway, Algeria, Turkmenistan). DS of countries with incoming pipelines is estimated as the sum of the fractions of integer steps performed by natural gas to reach them. Consider, for example, that the present potential maximal capacity of natural gas to Uzbekistan comes from reserves (7.440 Nm^3/h) and Turkmenistan (5.020 Nm^3/h). Uzbekistan has a total input of 12.460 Nm^3/h, receiving the 59.7% of its income from one-step pathway (underground → Uzbekistan):

$$\frac{7.440 Nm^3/h}{12.460 Nm^3/h} = 0.597 \tag{1}$$

and the remaining 40.3% comes from a route of two-steps (underground → Turkmenistan → Uzbekistan):

$$\frac{5.020 Nm^3/h}{12.460 Nm^3/h} = 0.403 \tag{2}$$

then, the DS of Uzbekistan comes out as follows:

$$1 \cdot 0.597 + 2 \cdot 0.403 = 1.403 \tag{3}$$

We adopt paired Student's t-test for testing differences between country distances from sources in the three scenarios.

Domination and exposure

We run simulations to quantify the direct and indirect effects caused by the removal of network components (i.e., the case of a country arresting natural gas delivery). The algorithm operates by interrupting, in turns, outgoing flows from each one of the 55 countries. Disruptions in the gas delivery may lead to direct consequences: absence of any natural gas input and energetic collapse for countries that exclusively rely on pipelines from the removed country; reduction of the potential import for countries with multiple inflows and including, at least, a pipeline from the country that switched off the natural gas supply. There are also countries without direct links to the node removed, but nevertheless they might be affected via their pathway upstream. Consider, for example, a linear pipeline connecting four countries; if the second node of this hypothetical chain interrupts the natural gas transfer, both the third and the fourth country would lose all of its natural gas supply, being exposed to direct and indirect effects, respectively[2]. However, when the structure of the network is characterized by some pipeline redundancy, the impacts of a node removal may imply only a slight decrease, or no losses, in the natural gas input of the target countries, rather then their collapse.

If nodes are affected by lower potential import, we set two basic rules for the simulations. First, countries aim to preserve their own domestic consumptions. Second, they distribute further natural gas, when available, in proportion to the magnitude of their outgoing pipeline capacities. This procedure is illustrated in Fig. 1.

[2] For the purposes methodological simplification, we do not consider the length of disruption. The timing of response measures by various European countries during the gas crisis between Russia and Ukraine in January 2009 provides relevant examples in this respect. As observed by Pirani et al. (2009), various strategies were adopted (i.e., increased imports via alternative pipelines, intensification of LNG trades, gas storage withdrawal, switching to alternative fuels). All of these strategies had a common objective: minimizing dropouts in domestic consumption. However, all these strategies represent short-term solutions (i.e., lasting for 15-120 days), while the presence of multiple pipelines linking a consumer country to different sources provide stability on longer term.

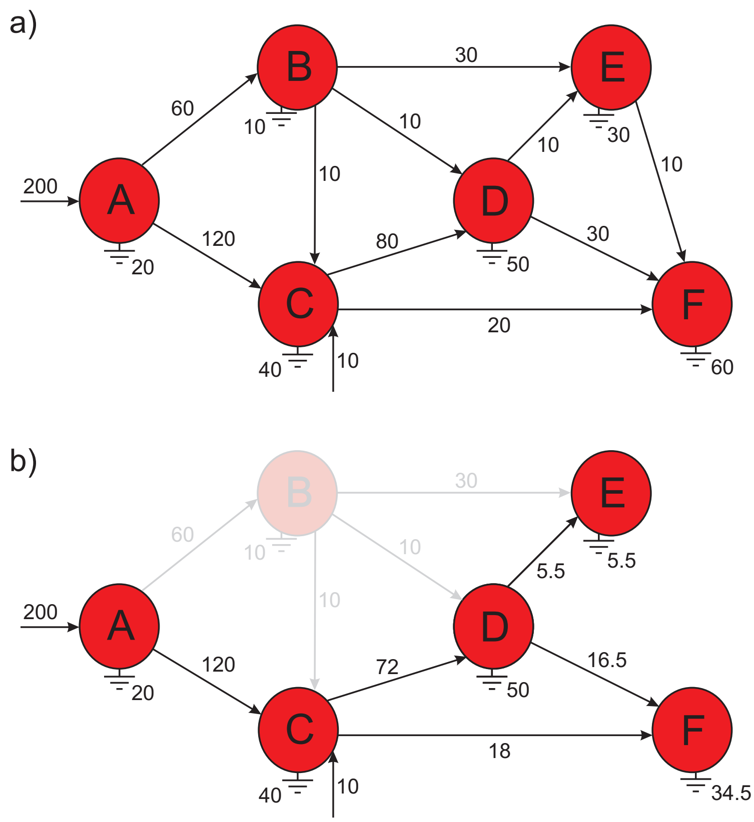

Fig. 1 - Hypothetical network of six nodes: a) unaffected flow structure; b) gas transfers and domestic consumptions when the unilateral closure of pipeline valves in B occurs.

In the hypothetical six-countries network, natural gas is conveyed following the arrow direction, with maximal technical capacity labeled next to each link and ground symbols standing for domestic consumption patterns. We represent the resulting scenario of natural gas distribution if country B becomes isolated from the system: nodes C, D and E experience a direct loss, but only the latter shows a drop in its consumptions (from 30 Nm^3/h to 5.5 Nm^3/h). These patterns can be explained by taking into account indirect effects. In this scenario (Fig. 1b), imports to C decrease by 10 Nm^3/h (in comparison to the 140 Nm^3/h of Fig. 1a), without affecting its domestic consumptions (40 Nm^3/h); however, this deficit is distributed to pipelines exiting C, in proportion to their strength:

$$C \rightarrow D = 80Nm^3/h - 10Nm^3/h \cdot \frac{80Nm^3/h}{100Nm^3/h} = 72Nm^3/h \qquad (4)$$

$$C \rightarrow F = 20Nm^3/h - 10Nm^3/h \cdot \frac{20Nm^3/h}{100Nm^3/h} = 18Nm^3/h \qquad (5)$$

The same principle is applied in computing the new flows from D to E (5.5 Nm^3/h) and F (16.5 Nm^3/h), and in deleting the natural gas transfer from E to F.

Simulating disruptions in the hypothetical pipeline network (Fig. 1b) we estimate, for all the nodes, exposure and domination. They are described as impacts on domestic consumptions, in accordance with the principles adopted for simulations. We assume that, in the presence of decreased import, country internal consumptions tend to be preserved before satisfying gas supply to the other countries. Then, a decline in the total input to a country could exclusively result in decreased provisions to neighbors, without affecting its consumptions.

Country exposure is measured as the average percentage of domestic consumption losses caused by the removal of upstream countries. Country domination is computed as the ratio between total impacts to all the nodes and the sum of their unaffected domestic consumptions.

For estimating exposure and domination we need data on domestic consumption, impacts of country removals and reachability patterns (the set of countries that lie downstream from a given country in the pipeline). We describe these features using the hypothetical network of Fig. 1a as a reference. In Fig. 2a, domestic consumptions are summarized by a column vector (D). The impact matrix [L] (Fig. 2b) illustrates how row-node removals impact the domestic consumptions of column-nodes. A crisis involving the supply of natural gas passing through node B has consequences on nodes E and F; then non-zero entries in the row B correspond to column identifiers of these latter. Finally, the reachability matrix [R] is represented in Fig. 2c. Reachability is the number of countries (non-zero row values) in all the upstream pathways pointing to the target (column) node (e.g., pipelines to B come only from A and its reachability value is 1, while that of source countries like A is 0). The reachability matrix may also be used to extract nodes in each row-compartment downstream (e.g., node B has a row sum equal to 4, being connected with direct or indirect pathways to all the other system-compartments, except nodes A and B).

a)

A	20
B	10
C	40
D	50
E	30
F	60

(D)

b)

	A	B	C	D	E	F	Σ
A	0	10	30	50	30	60	180
B	0	0	0	0	24.5	25.5	50
C	0	0	0	40	0	60	100
D	0	0	0	0	0	40	40
E	0	0	0	0	0	10	10
F	0	0	0	0	0	0	0
Σ	0	10	30	90	54.5	196	

[L]

c)

	A	B	C	D	E	F	Σ
A	0	1	1	1	1	1	5
B	0	0	1	1	1	1	4
C	0	0	0	1	1	1	3
D	0	0	0	0	1	1	2
E	0	0	0	0	0	1	1
F	0	0	0	0	0	0	0
Σ	0	1	2	3	4	5	

[R]

Fig. 2 - Using the network of Fig. 1a as a reference we illustrate: a) vector of domestic consumptions (D); b) impact matrix [L], where the cuts to internal consumptions of column nodes are caused by gas disruptions in row nodes (j^{th} column sum indicates the total impact on column node j when, by turn, all the countries arrest gas delivery; i^{th} row sum stands for whole reduction of internal consumptions when a gas crisis occur in the row node i); c) reachability matrix [R], where upstream (downstream) countries of column (row) nodes corresponds to non-zero row (column) entries. Total upstream and downstream countries are, respectively, column and row sums.

Exposure of the column-node j (Exp_j) is computed as the sum of the l_{ij} elements that are listed in the j^{th} column of the impact matrix [L], divided by the product of its unaffected domestic consumptions (d_j) and total upstream countries (j^{th} column-sum of r_{ij} elements extracted from the reachability matrix):

$$Exp_j = \frac{\sum_{i:i \neq j}^{n} l_{ij}}{d_j \cdot \sum_{i:i \neq j}^{n} r_{ij}} \qquad (6)$$

This indicator measures the losses experienced by domestic consumptions of each country when removing, in turn, all the other countries from the network. Effects of the gas crisis occurring in a country may spread beyond neighbor nodes (e.g., indirect consequences on domestic consumptions of node E when the country B arrests natural gas supply - see Fig. 1). These processes correspond to what is called "trophic cascade" in the food web theory (Carpenter et al., 1985; Schmitz et al., 2000).

The extent to which node i behaves as a dominator (Dom_i) is estimated by its downstream effects (i.e., impacts on internal consumptions of the other nodes when i is removed). It is computed by the ratio between row-sum of the l_{ij} elements extracted from the [L] matrix and the sum of all the unaffected domestic consumptions (d_j), as listed in (D):

$$Dom_i = \frac{\sum_{j:j\neq i}^{n} l_{ij}}{\sum_{j:j\neq i}^{n} d_j} \quad (7)$$

We apply the concept of domination to infer impacts due to gas transfer collapse. Domination represents the distribution of losses at all the other nodes in the network caused by the removal of a country.

We use cluster analysis based on increase in sum of squares (Ward Jr., 1963) to classify countries by studying present (in 2008) and future (in 2020 and 2030) trends of exposure and domination. To evaluate which components of the supply security are involved in country exposure and domination, we analyze values extracted from simulations (which take into account constraints of network topology) in comparison to distance from sources, domestic production and proven gas reserves. Next, we correlate exposure, domination and distance from sources with political indicators[3] (rule of law, political stability and government effectiveness), and technological indicators (present - 2008 - and future storage facilities). Then, we investigate which are the relationships connecting the size of gas reserves to indices of political stability. Finally, we test whether there are patterns linking exposure and distance from sources to normalized data (by population, GDP and country area) of domestic consumptions. To perform correlation analysis we apply the Pearson's product moment correlation coefficient (ρ) for association between paired samples.

Results

European demand for natural gas is expected to increase from 478 billion cubic meters per year (bcm/year) in 2002 to 786 bcm/year in 2030 (IEA, 2005b). Determining whether and how the pipeline network is changing to meet these needs is of critical importance for the security of gas supply. The immediate aim of pipeline infrastructure extension projects is to secure the increase in capacities needed to serve this growth in demand. Analyzing the changes projected for 2020 and estimated for 2030 we see that total system throughput (TST, the sum of all maximal technical capacities occurring in the network) will increase markedly. These future projects will boost the total capacity of the system between 2008 and 2020 by 29.6% (58.82 million Nm^3/h). Further development from 2020 to 2030 will result in 25.1% increase (64.53 million Nm^3/h). Taken these infrastructure investment steps together, we see a 62.1% increase (123.35 million Nm^3/h) between

[3] Using the definition provided by Kaufmann et al. (2009, p. 6), rule of law is defined as : "the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence." Political stability is defined as: "capturing perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including politically-motivated violence and terrorism." Government effectiveness is defined as "the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies."

2008 and 2030. So the pipeline will most likely serve the increasing demand - but will it become more secure also?

To answer this question we turn to measures developed in ecosystem perspectives: principles adopted in food web theory can be applied for studying the European gas pipeline network. By analyzing energy exchanges through network architectures, ecologists have been able to unveil how efficiently an ecosystem uses energy and to identify which nodes are likely to cause the greatest impact if removed (Allesina and Bodini, 2004; Dunne et al., 2002). Achieving energy security in the pipeline network depends on pathway redundancy, to decrease the vulnerability of domestic consumptions to perturbations in gas supply. Average mutual information (AMI) is an index that captures this structural property (with higher values indicating higher vulnerability).

Considering the changes from 2008 to 2020, and from that intermediate step to 2030, we definitely do not see a decrease in vulnerabilities at the whole-system level. From 2008 to 2020 AMI increases by 9.3%, and from 2020 to 2030 AMI increases by 2.1%. No significant differences exist between present and future scenarios of gas supply, when the contribution of each country to the whole AMI is considered (all Student's t-tests: $p > 0.05$). So the marked increase in pipeline capacities will not go together with increased topological redundancy.

Further evidence of the pipeline network rigidity is provided by the constant ratio between ascendency and development capacity. Ascendency quantifies the level of constraints to the total system capacity, and its upper limit is measured by the development capacity. Higher ratios characterize rigid systems that transfer natural gas via hierarchical pathways. Extremely organized configurations have no redundant connections, a feature that poses serious concerns on energy security. Indeed, redundant trunk lines could serve as degrees of freedom which the system can call upon in case of disruptions (Ulanowicz, 1997), buffering the negative consequences of possible cuts to gas delivery of upstream countries.

Ascendency of the European pipeline network ranges from 57.5% (2008) to 58.8% (2030) of the development capacity. Despite the strong increase in the total system capacity (ΔTST between 2008 and 2030 = 62.1%), no significant variations occur in the multiplicity of pathways for gas transfer. The comparison of the ratio between ascendency and development capacity, as measured in the pipeline network, and values displayed by ecological systems can shed light on its meaning. In ecological networks, ascendency of flows ranges between 25% and 50% of the development capacity (Scotti, 2008), while in our study it exceeds 57%. These results corroborate previous outcomes that found human systems to be highly organized (Bodini and Bondavalli, 2002).

Comparing the distance of each country from the natural gas sources (DS), in the present and two future steps, we see that longer routes will separate gas reserves from consumers in the future. While at present, on average a country is 2.39 steps from gas reserves, by 2020 this average distance increases to 2.75, and by 2030 it increases to 2.79. These changes are statistically significant according to paired-sample Student's t-tests: for both tests $p < 0.01$. This means that in the near future a few main pathways (characterized by higher maximal technical capacities) will be responsible for the majority of gas transfers. These main pathways will contribute to vulnerability, as on average there will be more intermediary countries between a consumer and a source country.

In 2008, EU consumers depend on a few sources (i.e., Russia, Norway and Algeria), that some see as "dangerously too few" (Weisser, 2007, p. 1). Our goal in this part of the analysis is to see whether infrastructure development mitigates this dependence. To estimate vulnerabilities to supply interruptions we performed simulations in case of pipeline disruptions by removing each country one by one, and re-calculating the flow. Our goal is to calculate the changes in exposure for each country, and also the changes in domination.

Changes in domination

First, we examine changes in domination - the influence a country can exert on the natural gas consumption of other European countries. With cluster analysis we classify countries on the basis of their domination at the three points in time that we examine. We consider both 2008 values and expected variations (in 2020 and 2030). Results are summarized by box-plots in Fig. 3 and Table 1. In the four domination clusters, Russia occupies the leading position (D4). The second class of dominators includes both countries increasing (e.g., Turkmenistan, Uzbekistan and Kazakhstan) and reducing (e.g., Slovakia and Ukraine) their importance, with average impacts on the total European consumptions ranging between 2.5% and 7% (D3). The remaining countries with lower or no effects are grouped in D2 and D1, respectively.

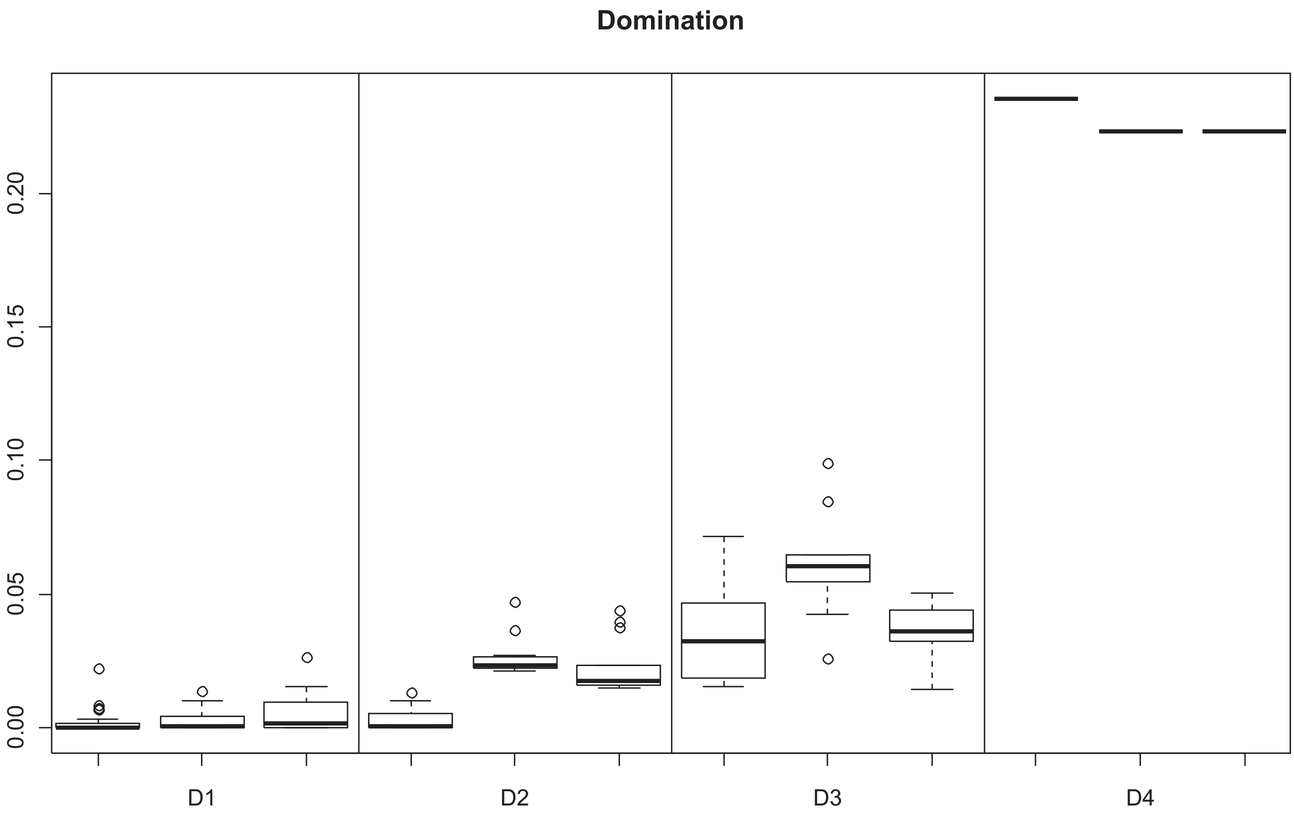

Fig. 3 - Box-plots of countries classified on the basis of current and expected domination. For each group, three box-plots are depicted to describe domination in 2008, 2020 and 2030 (D1 = very low; D2 = low; D3 = intermediate; D4 = high). Values on the y-axis are included between 0 and 1, as they represent relative intensities of domination. Country list in Table 1.

As expected, Russia is the main actor dominating natural gas supply in the European pipeline network, and it will keep its dominant role in the near future of the pipeline system. At present (2008), unilateral closure of pipeline valves by Russia would result in 23.5% loss of European consumption. Although a slight decrease of this domination is expected with future developments (see Appendix D), Russia will maintain its potential to dominate 22.3% of European consumption, both in 2020 and 2030. In the future pipeline configurations, Russia will increase natural gas imports from the Caucasian and Central Asian regions (e.g., Turkmenistan, Uzbekistan and Kazakhstan), both extending the capacities of existing trunk lines and constructing new pipelines. These countries will extend their domination both as relative and absolute values, with the potential for impacting more than the 6% of European consumptions. The new projects that often state the aim to decrease European dependency on Russia (such as the Nabucco, Trans-Adriatic, Greece-Italy, Medgaz, Galsi pipelines) will only achieve this goal marginally.

Table 1 - Dominator countries as classified by clustering analysis (see Fig. 4).

D1	D2	D3	D4
Albania	Azerbaijan	Algeria	Russia
Armenia	Belgium	Germany	
Austria	Bosnia and H.	Kazakhstan	
Belarus	Bulgaria	Turkmenistan Tunisia	
Croatia	Czech Republic,	Norway	
Denmark	Georgia	Slovakia	
Egypt	Greece	Ukraine	
Estonia	Hungary	Uzbekistan	
Finland	Iran	The Netherlands	
France	Macedonia		
Ireland	Poland		
Israel	Romania		
Italy	Serbia		
Jordan	Turkey		
Latvia			
Lebanon			
Libya			
Lithuania Luxembourg			
Moldova			
Morocco			
Northern Ireland			
Portugal			
Rep. of Kaliningrad			
Sweden			
Slovenia			
Spain			
Switzerland			
Syria			
United Kingdom			

In Fig. 4 we illustrate the effects of developments planned for 2020 on the present domination patterns. We depict the expected topology for 2020, with size of nodes proportional to country domination at that step. The shape of nodes describes whether there are changes in domination strength (up triangular indicates an increase of, at least, 15%; down triangular indicates a decrease of, at least 15%; the square indicates no change), with respect to present values, and colors show country political stability (grey nodes have a sum of three scores - political stability, government effectiveness and rule of law - less than 50% of the maximum). Thickness of links between nodes is proportional to pipeline maximal technical capacity (Nm^3/h), with arrows indicating the natural gas direction. Present pipes are solid lines; pipelines to be completed by 2020 are dotted lines.

As supposed by previous studies (Çetin and Oguz, 2007; Mavrakis et al., 2006), Turkey will challenge the current leading role of Ukraine in natural gas transit to Europe. While Turkey currently does not dominate any of Europe's gas consumption, by 2020 it will dominate 4% of it. Its relative position made Turkey an ideal candidate to become the main natural gas corridor from Central Asia and the Caspian region to the EU markets, although Çetin and Oguz (2007) observed that is currently prevented to be the main gate because of the strong dependence on Russia (i.e., natural gas supply is poorly diversified and no significant alternative routes exist for importing gas). Future developments will increase the pipeline redundancy in Turkish import structures (i.e., from Russia, Iran, Azerbaijan via Georgia, and Egypt through an extension of the Arab Gas Pipeline), contributing to decrease its vulnerability (Fig. 4). The future gas pipeline corridor passing through Turkey will benefit of a flexible supply structure, together with higher maximal potential capacity of new infrastructures (e.g., Nabucco Gas Pipeline Project).

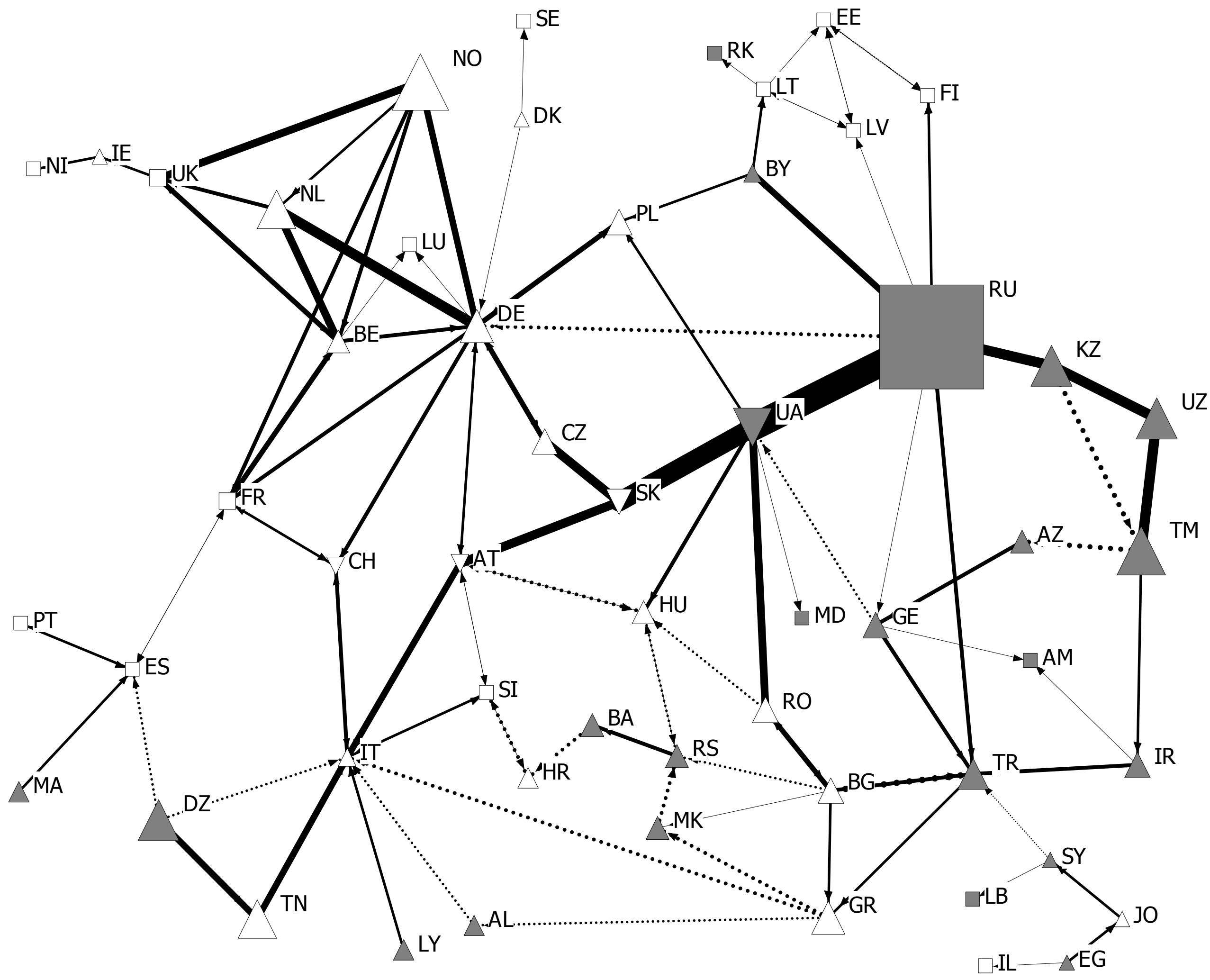

Fig. 4 - Expected pipeline architecture and domination in 2020. The presence of pipeline connections between couples of nodes, as forecasted for the 2020 scenario, is illustrated (2008 pipes are solid links; new pipes that will be operational in the 2020 network are dotted lines). Natural gas direction is indicated by arrows. Link thickness is proportional to the cumulated amount of natural gas that is expected to be transported by pipelines in 2020 (measured in Nm^3/h). The size of the nodes (countries) reflects their domination (bigger is the node, higher are the losses in the domestic consumption of the other countries, in case the target node interrupts gas delivery). The shape of nodes stands for the changes in 2020 domination, in comparison to 2008: increasing and decreasing patterns with percentages higher than 15% are represented by upper and down triangles, respectively; squared nodes indicates weaker fluctuations. Colors of nodes describe country political stability (grey nodes have a sum of three scores - political stability, government effectiveness and rule of law - less than 50% of the maximum).

Domination patterns under future scenarios suggest also Greece as an emerging bottleneck to the natural gas delivery. Its strategic position will be the consequence of new constructions bridging Asian gas producers to the Southern Europe demand. Greece will play two different roles: first, representing an alternative by-pass to the Turkish corridor, and conveying the Russian natural gas (received through Bulgaria by means of the South Stream pipeline); second, distributing to Italy the natural gas received from Turkey (Interconnector Turkey-Greece-Italy). Similarly to Turkey, the dominance of Greece is strengthened by very low levels of exposure.

Another interesting pattern characterizes the domination of transit countries between the Russian and the Caspian see region sources (i.e., Turkmensitan, Kazakhstan, and Uzbekistan), and Western European consumers. The majority of Eastern European (e.g., Bulgaria, Romania), Central European (e.g., Hungary, Czech Republic, Poland) and Balkan countries (e.g., Serbia, Croatia, Bosnia and Herzegovina) will increase their domination, while the current main corridor conveying natural gas from Russia through Ukraine and Slovakia will become less important. Significant changes will also take place in the pathway for transporting natural gas towards Turkey and Greece, reflecting the aspiration of the former to become the main Eurasian natural gas pipeline corridor. Also North African countries (e.g., Libya and Algeria) will display higher domination levels.

Is domination a simple function of countries being closer to natural gas reserves? If yes, then there is no complexity in answering the question of what makes counties dominant, and how to mitigate dependency on them. Considering the correlation between our measure of domination and distance from the source, we can reject the hypothesis that domination is a simple matter of being upstream (see Table 2). There is no significant correlation between domination and distance from the source, which suggest that domination is more a function of the topology of the network.

Is domination only a function of countries having gas reserves themselves? Again, if the answer is yes, there is no need to consider the network topology of pipelines. We see in Table 2 that the correlation between domination and gas reserves is significant and positive in the present, although the correlation is considerable smaller than one. However, as we consider plans into the future, the correlation is decreasing, and by 2020 it is not significant at the $p < 0.05$ level. The same trend is found when we analyze domination in comparison to domestic production: the significant correlation observed for 2008 ($\rho = 0.568$, $p = 0.003$) vanishes in future scenarios (see Table 2). We also consider this latter hypothesis because, in some cases, the existence of reserves and pipelines does not mean that the gas is delivered (e.g., Iran has the second largest reserves in the world but is still a net importer). Our findings indicate that the development of the pipeline system will shift security concerns from source countries to transit countries. In the future, domination will be more based on network position, rather than gas reserves.

Table 2 - Correlation coefficients of log domination vs. distance from natural gas sources (DS), log size of gas reserves (million m^3), and log domestic production (bcm/year).

		DS		**Gas reserves**		**Domestic production**	
		ρ	**p**	**ρ**	**p**	**ρ**	**p**
	2008	-0.293	0.116	0.529	0.005	0.568	0.003
Domination	2020	-0.072	0.656	0.380	0.022	0.288	0.093
	2030	-0.144	0.357	0.311	0.065	0.233	0.177

Thus far we considered domination equally for all countries. For example, closure of all pipelines by Ukraine would mean a 7.2% loss in European consumption, and pipeline closure by Norway would mean a similar 6.3% loss in European consumption. European consumption is less at risk by Norway, than by Ukraine: not all countries are equally likely to translate their dominance into energy security concerns. To incorporate this idea in our analysis we considered the correlation between rule of law, political stability, and government effectiveness (Table 3).

In the present (2008) natural gas pipeline system there is no correlation between rule of law and domination. That is, the rule of law in countries with potentially high impact on the domestic natural gas consumption of other countries downstream is not different from the average rule of law of all countries. However in 2020 and 2030 this correlation will become negative and statistically significant: countries with higher domination in the future will also have a weaker rule of law. Similarly with political stability, there is no correlation with domination in the present system, but by 2020 it is becoming a significant negative correlation. Government effectiveness works in a similar way, though the correlation is slightly below the threshold of 0.05. This suggests that, in the future development of the system, domination will shift to politically unstable countries with weak rule of law. We also note that there is a correlation between natural gas reserves in a country and poorer scores on these three dimensions of institutional stability (Table 3). This finding is in line with the expectation that abundance of natural resources would go together with poorer developmental outcomes and poorly performing state institutions (Karl, 1997). As argued by Corden and Neary (1982), discovery and exploitation of large gas reserves may have negative impact on the traded sector, making the other products of the country less price competitive on the export market. This mechanism, also known as "Dutch disease problem", may lead to negative growth effects, with the reallocation of production factors apart from resource exploitation.

Table 3 - Comparison between indicators of political stability, log domination, and log size (in bcm) of gas reserves.

		Rule of law		**Political stability**		**Government effectiveness**	
		ρ	p	ρ	p	ρ	p
	2008	-0.022	0.910	0.115	0.546	0.000	0.999
Domination	2020	-0.346	0.027	-0.228	0.152	-0.215	0.177
	2030	-0.324	0.034	-0.298	0.052	-0.277	0.072
Gas reserves		-0.348	0.032	-0.219	0.186	-0.361	0.026

Changes in exposure

We now turn to analyzing the exposure of domestic consumption in each country to interruptions in the pipeline system by other countries. Considering change in exposure between 2008 and 2020, we see that there are fifteen countries where exposure will decrease, but there are sixteen countries where exposure will increase, as a result of new developments. As we consider infrastructure work to be completed by 2030, we see bit more positive distribution, with twenty countries improving on their present exposure, and only eleven countries becoming more vulnerable. However, the improvements of exposure tend to be very small, and the increases in exposure tend to be much more pronounced.

To describe typical trends across exposure at three points in time, we identify four clusters (Fig. 5 and Table 4). Most of the countries, more than two thirds, fall into our first cluster, E1. These countries start with a low level of exposure in the present: on average only about 4% of their domestic consumption is at risk by pipeline closure upstream. Infrastructure development will improve their low exposure, on average by two percentage points. The second cluster, E2, with nine countries start from an exposure of 18% on average, which increases considerably, by about 12 percentage points by 2030. The third cluster, E3, repeats this pattern: five countries in this cluster start from an average exposure of 37% which increases dramatically, to 81% on average. We only found two cases, Estonia, and Bosnia and Herzegovina, our forth cluster, E4, where pipeline development will result in a major decrease in vulnerability, from 75% to about 20%.

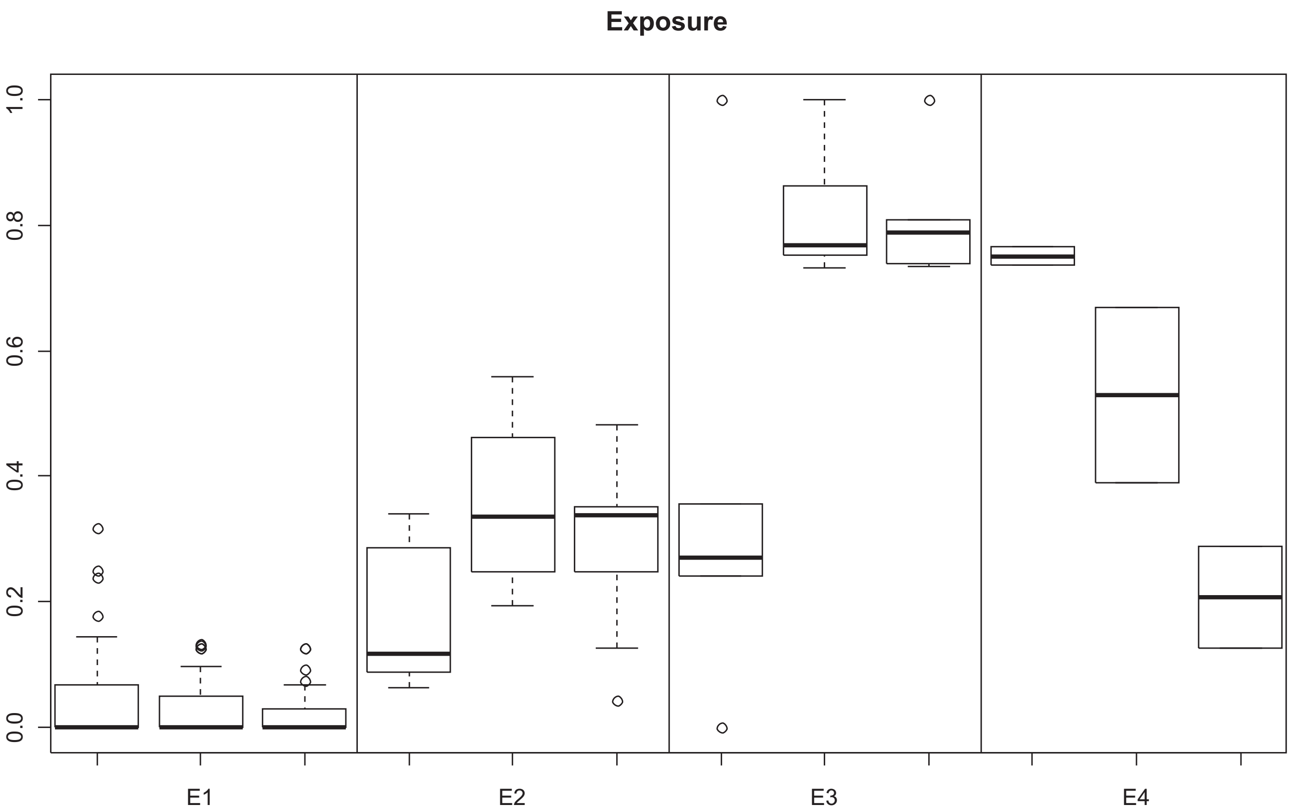

Fig. 5 - Present and future exposures are used to classify countries in four categories. For each group, we depict box-plots of 2008, 2020 and 2030 exposure values (included between 0 and 1). We identify countries preserving low vulnerability (E1), increasing exposure (E2 and E3) and strengthening stability (E4). The full list of countries is provided in Table 4.

Pipeline development will not eliminate country exposures - it will mostly redistribute it. Improvements are expected for those countries that have low exposures, while countries with higher exposures tend to become more exposed. Only the development projects in the more distant future seem to bring a significant decrease in the number of exposed countries.

Exposure is not a simple function of distance from natural gas sources: this correlation is not significant in the 2008 and 2030 scenarios (Table 5). However, in the 2020 topology, a significant correlation linked exposure to distance from natural gas sources ($\rho = 0.387$, $p = 0.026$). Countries with higher exposure ($Exp \geq 0.50$) tend to have lower than 0.6 million Nm^3/h natural gas consumption per capita, which probably reflects longer term (at least five years) adjustment of the energy mix to energy security concerns (Table 5). This adjustment is also reflected in the capacity of natural gas storage facilities. If we consider the projects under construction or planned by 2008 (GIE, 2008b), it seems that decisions to build storage facilities are more based on distance from natural gas sources than on exposure (Table 6). In other words, it seems that the topological risks are not included in calculations of risks. In the future however, we see that storage capacities will much more closely match the exposure of countries. Whether this means a change in storage planning calculations, or just a fortunate coincidence, we cannot tell based on our data.

Table 4 - Country exposure as classified by cluster analysis (see Fig. 6).

E1	E2	E3	E4
Albania	Austria	Ireland	Bosnia and H.
Algeria	Belarus	Northern Ireland	Estonia
Armenia	Croatia	Slovenia	
Azerbaijan	Czech Republic	Sweden	
Belgium	Hungary	Switzerland	
Bulgaria	Lithuania		
Denmark	Moldova		
Egypt	Slovakia		
Finland	Tunisia		
France			
Georgia			
Germany			
Greece			
Iran			
Israel			
Italy			
Jordan			
Kazakhstan			
Lebanon			
Libya			
Luxembourg			
Morocco			
The Netherlands			
Norway			
Portugal			
Rep. of Kaliningrad			
Russia			
Spain			
Syria			
Turkey			
Turkmenistan			
Ukraine			
United Kingdom			
Uzbekistan			
Latvia			
Macedonia			
Poland			
Romania			
Serbia			

Table 5 - Correlation coefficients of log exposure vs. distance from natural gas sources (DS) and log normalized consumptions. Domestic consumptions are normalized by the ratio with number of inhabitants (Population - # of inhabitants), gross domestic product (GDP - $) and land area (Area - km^2).

		DS		Consumption					
				Population		GDP		Area	
		ρ	p	ρ	p	ρ	p	ρ	p
Exposure	2008	0.193	0.289	-0.395	0.031	-0.202	0.284	-0.253	0.178
	2020	0.387	0.026	-0.431	0.017	-0.127	0.505	-0.006	0.973
	2030	0.303	0.092	-0.472	0.010	-0.073	0.705	-0.024	0.902

Table 6 - Correlation coefficients of (present and future) log normalized storage size vs. log exposure and distance from gas resources (DS). Storage facilities are normalized by the ratio between storage size (million Nm^3) and domestic consumption (million Nm^3/year).

		Storage facilities (present)		Storage facilities (future)	
		ρ	p	ρ	p
Exposure	2008	0.373	0.232	0.291	0.335
	2020			0.717	0.004
	2030			0.668	0.009
DS	2008	0.474	0.054	0.358	0.144
	2020			0.465	0.052
	2030			0.514	0.029

Conclusions

Adopting a network perspective, we develop an integrated approach to energy security concerns of availability (i.e., elements related to geological existence and location of gas reserve - source dependence) and accessibility (i.e., natural gas transportation that often involves geopolitical implications, leading to transit dependence). Network analysis considers features as import dependence, source and transit diversity both at the whole-system level (e.g., TST, AMI, A/DC) and at the country level (e.g., DS, exposure, domination). For a broader understanding of the European gas security, we also extended our study by including political stability and storage facilities. With this approach we aim to address energy security as a multifaceted concept (Kruyt et al., 2009): to develop metrics useful in policy making contexts (allowing the setting of targets in a similar way to setting greenhouse gas reduction goals), multiple dimensions of energy security needs to be captured.

Our findings are paradoxical in several respects. Contrary to widespread expectations that pipeline development projects (listed in Appendix D) will increase gas security, we found that the European pipeline network is evolving towards a more fragile configuration. Moreover, there is evidence for an increasing dependence on politically unstable countries, such as Russia, Ukraine, Turkey, Algeria, and Libya. Considering expected pipeline development from 2008 to 2020 and 2030, we will see a restricted number of routes transporting higher amounts of natural gas, and crossing several national borders, with the emergence of new bottlenecks threatening the security of supply (Stern, 2002)[4]. Beside Ukraine and Belarus, two main transit constraints in the 2008 pipeline configuration, other countries (e.g., Greece, Turkey, Bulgaria, Romania and Poland) will emerge as key players for gas delivery in 2020 and 2030. They will occupy strategic positions in future routes for gas transportation (i.e., Nabucco, South Stream, Poland-Czech Republic interconnector, Trans-Adriatic pipeline). Infrastructure development seems mainly focused on increasing the range of choice with respect to the gas reserves reached. Despite projects explicitly aimed at avoiding transit

[4] Future projects of interest here are especially those that will entail the construction and expansion of pipelines transporting amounts of natural gas ranging between 1 million normal cubic meters per hour (Nm^3/h) and 3 million Nm^3/h. Some of these routes will aim at increasing imports from the North African area to European countries (e.g., the GALSI pipeline that is expected to be operational by 2014, for transporting natural gas from Algeria to Sardinia, and further Northern Italy). Other projects are planned for connecting Caucasian and Central Asian regions to the European market: South Stream (Russia ☐ Bulgaria ☐ Republic of Serbia ☐ Hungary (☐ Slovenia) ☐ Austria; Russia ☐ Bulgaria ☐ Greece ☐ Italy; due by 2015) and Nabucco (Turkey ☐ Bulgaria ☐ Romania ☐ Hungary ☐ Austria; operational by 2015) pipelines.

problems (consider the pipelines North Stream and South Stream, for example), our findings indicate that transit risks will not be less acute. Although Russia will remain the main actor, higher amounts of natural gas will be supplied by other source countries (e.g., Central Asian and North African). The current strong correlation between domination and both gas reserves and domestic production will mitigate, and domination will shift towards transit countries. For example, the Turkey-Greece corridor will challenge the current leading role of the Ukrainian gate for natural gas transfers from Asian resources to the EU market.

Investments for constructing new pipelines or extending the capacities of existing trunk lines will not improve radically the current patterns of exposure for many countries. In particular, with the pipelines that are likely to be operational by 2020 and 2030, just Estonia (Exp-2008 = 0.76; Exp-2030 = 0.13) and Bosnia and Herzegovina (Exp-2008 = 0.74; Exp-2030 = 0.29) are expected to strongly reduce their exposure. Countries falling into the category E1 (Fig. 6) are not affected by high exposure, neither in the present nor in future scenario (avg Exp-2008 = 0.05; avg Exp-2030 = 0.02). However, 14 countries out of 55 (categories E2 and E3, Fig. 6) will be exposed to higher transit risks as a consequence of future pipeline configurations (2020 and 2030). In the current network (2008), they already display concerns on energy security (avg Exp group E2 = 0.18; avg Exp group E3 = 0.37), but they will be further endangered by the developments due by 2030 (avg Exp group E2 = 0.30; avg Exp group E3 = 0.81).

Storage facilities do not represent a comprehensive solution to the issues of transit and source dependence. However, they can be effective in withstanding the consequences of short-term cut-off (Weisser, 2007). Consider, as an example, the role played by natural gas storage facilities during the Russian-Ukrainian crisis of January 2009. Some European countries used alternative fuels for satisfying natural gas requirements of industrial activities (e.g., Bulgaria, Croatia, Bosnia and Herzegovina), but in other cases storage facilities were able to cover demand for several weeks (e.g., Austria, Hungary, Poland, Germany).

Our analysis is open to improvement by further investigations. First, to shed light on facility dependence (Luciani, 2004), the European gas transit network could be detailed at the level of particular pipelines (as opposed to summing pipeline capacities for country pairs). One could also increase network resolution by describing the structure within countries, including routes connecting facilities to consumer nodes. Second, differences in tariffs could be used to simulate the most likely gas routing within the network (Pelletier and Wortmann, 2009). Finally, one could learn a lot by comparing the carbon budgets (for all energetic consumptions) with country exposure. This approach could also address the issue of climate change jointly with energy security in the same framework (Kruyt et al., 2009).

References

Afgan, N.H., Carvalho, M.G., Pilavachi, P.A., Martins, N., 2007. Evaluation of natural gas supply options for south east and central Europe. Part 1: Indicator definitions and single indicator analysis. Energy Conversion and Management, 48, 2517-2524.

Alhajji, A.F., 2007. What Is Energy Security? Definitions And Concepts. Middle East Economic Survey VOL. L No 45 5-November-2007. Available at: <www.mees.com/postedarticles/oped/v50n45-5OD01.htm>.

Allesina, S., Bodini, A., 2004. Who dominates whom in the ecosystem? Energy flow bottlenecks and cascading extinctions. Journal of Theoretical Biology, 230, 351–358.

Barabási, A.-L., 2002. Linked: The New Science of Networks. Perseus Publishing: Cambridge, MA.

Bodini, A., Bondavalli, C., 2002. Towards a sustainable use of water resources: a whole-ecosystem approach using network analysis. International Journal of Environment and Pollution, 18, 463-485.

Borgatti, S.P., Everett, M.G., Freeman, L.C., 2002. Ucinet for Windows: Software for Social Network Analysis. Analytic Technologies, Harvard.

BP, 2008. BP Statistical Review of World Energy 2008.

Bruce, C., 2005. Fraternal Friction or Fraternal Fiction? The Gas Factor in Russian-Belarusian Relations. Oxford Institute for Energy Studies, Oxford OIES NG 8.

Carpenter, S.R., Kitchell, J.F., Hodgson, J.R., 1985. Cascading trophic interactions and lake productivity. BioScience, 35, 634-639.

Çetin, T., Oguz, F., 2007. The reform in the Turkish natural gas market: A critical evaluation. Energy Policy, 35, 3856-3867.

Chevalier, J.M., 2005. Security of energy supply for the European Union; to be published in the forthcoming international journal of European Sustainable energy market.

CIA - Central Intelligence Agency, 2008. The World Factbook. Available at: <www.cia.gov/library/publications/the-world-factbook/index.html>.

Corden, W.M., Neary, J.P., 1982. Booming sector and de-industrialisation in a small open economy. Economic Journal, 92, 825-848.

Dunne, J.A., Williams, R.J., Martinez, N.D., 2002. Network structure and biodiversity loss in food webs: Robustness increases with connectance. Ecology Letters, 5, 558-567.

EEGA - East European Gas Analysis, 2008. Major Gas Pipelines of the Former Soviet Union and Capacity of Export Pipelines. Available at: <www.eegas.com/fsu.htm>.

EIA – Energy Information Administration, 2008. Country Analysis Briefs. Available at: <www.eia.doe.gov/emeu/cabs>.

EU, 2009. Future Development of the Energy Gas Market in the Baltic Sea Region. Final Report prepared for the EU Commission DG TREN C1 by Ramboll Oil & Gas, Denmark. Available at: <http://ec.europa.eu/energy/infrastructure/doc/2009_bemip_ramboll_bemip_final_report.pdf>

European Commission, 2002. EU Green Paper: Towards a European Strategy for the Security of Energy Supply.

GIE - Gas Infrastructure Europe, 2008a. The European Natural Gas Network (Capacities at cross-border points on the primary market). Available at: <www.gie.eu/maps_data/capacity.html>.

GIE - Gas Infrastructure Europe, 2008b. Storage Map - Information by point. Available at: <www.gie.eu.com/maps_data/storage.html>.

Girvan, M., Newman, M.E.J., 2002. Community structure in social and biological networks. Proceedings of the National Academy of Sciences of the United States of America, 99, 7821-7826.

Graus, W., Roglieri, M., Jaworski, P., Alberio, L., 2008. Efficiency and capture-readiness of new fossil power plants in the EU. Ecofys. Utrecht, The Netherlands.

Graus, W., Worrell, E., 2009. Trend in efficiency and capacity of fossil power generation in the EU. Energy Policy, 37, 2147-2160.

GTE+, 2009. Reverse Flow Study TF - Report on Technical Solutions, GTE+, Ref 09 GTE+209.

Hayes, M.H., 2004. Algerian Gas to Europe: The Transmed Pipeline and Early Spanish Gas Import Projects. Working Paper #27. Stanford University, Program on Energy and Sustainable

Development. pp. 9-11. Available at: <www.rice.edu/energy/publications/docs/GAS_TransmedPipeline.pdf>.
Higashi, M., Burns, T.P., Patten, B.C., 1989. Food network unfolding: an extension of trophic dynamics for application to natural ecosystems. Journal of Theoretical Biology, 140, 243-261.
IEA, 1998. Caspian Oil and Gas. International Energy Agency (IEA), Paris, France. Available at: <www.iea.org/textbase/nppdf/free/1990/caspian_oil_gas98.pdf>.
IEA, 2005a. CO_2 Emissions from Fuel Combustion - 2005. International Energy Agency (IEA), Paris, France.
IEA, 2005b. Natural Gas Information 2005, IEA/OECD Paris, 2005.
IEA, 2007a. Energy balances of OECD countries 1960-2005. International Energy Agency (IEA). Paris, France.
IEA, 2007b. World Energy Outlook 2007. Organization for Economic Cooperation and Development/ International Energy Agency, Paris.
INDES Study, 2004. Executive Summary, update May 2004. Insurance against Disruptions of Energy Supply.
IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories Workbook Vol. 2. Intergovernmental Panel on Climate Change.
Jansen, J.C., van Arkel, W.G., Boots, M.G., 2004. Designing indicators of long-term energy supply security ECN-C-04-007; 35 pp.
Jenny, F., 2007. Energy Security; a market oriented approach, presentation at the OECD Forum on innovation, growth and equity. Available at: <www.oecd.org/dataoecd/42/49/38587081.pdf>.
Jordán, F., Liu, W., Wyatt, T., 2005. Topological constraints on the dynamics of wasp-waist ecosystems. Journal of Marine Systems, 57, 250-263.
Karl, T.L., 1997. The Paradox of Plenty: Oil Booms and Petro-States. University of California Press.
Kaufmann, D., Kraay, A., Mastruzzi, M., 2009. Governance Matters VIII: Aggregate and Individual Governance Indicators, 1996-2008. World Bank Policy Research Working Paper No. 4978.
Kruyt, B., van Vuuren, D.P., de Vries H.J.M., Groenenberg, H., 2009. Indicators for energy security. Energy Policy, 37, 2166-2181.
Liljeros, F., Edling, C. R., Nunes Amaral, L. A. N., Stanley, H. E., □berg, Y., 2001. The web of human sexual contacts. Nature, 411, 907-908.
Luciani, G., 2004. Security of Supply for Natural Gas Markets: What is it and what is it not? FEEM Working Paper No. 119.04.
Mavrakis, D., Thomaidis, F., Ntroukas, I.,2006. An assessment of the natural gas supply potential of the south energy corridor from the Caspian Region to the EU. Energy Policy, 34, 1671-1680.
Milev, N., 2005. Bulgargas in the SEE gas scene, gas seminar on SE Europe investment, Transit, Trend, Istanbul, Turkey.
Nord Stream, 2009. Overview of all existing/planned pipelines in the Baltic Sea, St. Petersburg.
Olcott, M.B., 2004. International Gas Trade in Central Asia: Turkmenistan, Iran, Russia and Afghanistan. Working Paper #28. Stanford Institute for International Studies. Available at: <www.rice.edu/energy/publications/docs/GAS_InternationalGasTradeinCentralAsia.pdf>.
Olcott, M.B., 2004. International Gas Trade in Central Asia: Turkmenistan, Iran, Russia and Afghanistan. Working Paper #28. Stanford Institute for International Studies. Available at: <http://www.rice.edu/energy/publications/docs/GAS_InternationalGasTradeinCentralAsia.pdf >
Pelletier, C., Wortmann, J.C., 2009. A risk analysis for gas transport network planning expansion under regulatory uncertainty in Western Europe. Energy Policy, 37, 721-732.
Pirani, S., Stern, J., Yafimava, K., 2009. The Russo-Ukrainian gas dispute of January 2009: a comprehensive assessment. Oxford Institute for Energy Studies, Oxford OIES NG 27.
Reymond, M., 2007. European key issues concerning natural gas: Dependence and vulnerability. Energy Policy, 35, 4169-4176.
Rutledge, R.W., Basorre, B., Mulholland, R., 1976. Ecological stability: an information theory viewpoint. Journal of Theoretical Biology, 57, 355-371.

Scheepers, M.J.J., Seebregts, A.J., de Jong, J.J., Maters, J.M., 2007. EU Standards for Energy Security of Supply-Updates on the Crisis Capability Index and the Supply/Demand Index Quantification for EU-27. ECN-E–07-004, 101 pp.
Schmitz, O.J., Hambäck, P.A., Beckerman, A.P., 2000. Trophic Cascades in Terrestrial Systems: A Review of the Effects of Carnivore Removals on Plants. American Naturalist, 155, 141-153.
Scotti, M., 2008. Development Capacity, in: Jørgensen, S.E., Fath, B.D. (Eds.), Ecological Indicators. Vol. [2] of Encyclopedia of Ecology. Elsevier, Oxford, 911-920.
Scotti, M., Bondavalli, C., Bodini, A., 2009. Linking trophic positions and flow structure constraints in ecological networks: Energy transfer efficiency or topology effect. Ecological Modelling, 220, 3070-3080.
Shirkani, N., 2008. Egyptian gas flows to Israel. Upstream Online. Available at: <www.upstreamonline.com/live/article150348.ece>.
Stern, J., 2002. Security of European natural gas supplies: the impact of import dependence and liberalization. Royal Institute of International Affairs, London, 36 pp. Available at: <www.isn.ethz.ch/isn/Digital-Library/Publications/Detail/?id=99313&lng=en>.
Stern, J., 2006. Natural Gas Security Problems in Europe: the Russian-Ukrainian Crisis of 2006. Asia-Pacific Review, 13, 32-59.
Ulanowicz, R.E., 1986. Growth & Development: Ecosystems Phenomenology, Springer Verlag, New York.
Ulanowicz, R.E., 1997. Ecology: the Ascendent Perspective, Columbia University Press, New York, 201 pp.
Ulanowicz, R.E., 2004. Quantitative methods for ecological network analysis. Computational Biology and Chemistry, 28, 321-339.
Vashakmadze, G., 2009. The White Stream gas transportation project–a project to deliver Caspian gas to the EU. The Future of the Energy Sector in the Balkans. Belgrad, Serbia: Ekonomist Media Group. Available at: <www.emportal.rs/data/File/Ekonference/2009/Energetika/Giorgi%20Vashakmadze%20GUEU%20White%20Stream.PDF>.
Ward Jr., J.H., 1963. Hierarchical Grouping to Optimize an Objective Function. Journal of the American Statistical Association, 58, 236-244.
Watts, D., Strogatz, S.H., 1998. Collective dynamics of 'small-world' networks. Nature, 393, 440-442.
WEC, 2007. 2007 Survey of Energy Resources. World Energy Council, London.
Weisser, H., 2004. Strategic stockpiling: best practices, pitfalls and lessons learned. In: Symposium on Strategic Stockpiling in the 21st Century, November/December 2004.
Weisser, H., 2007. The security of gas supply - a critical issue for Europe? Energy Policy, 35, 1-5.
Yenikeyeff, S.M., 2008. Kazakhstan's Gas: Export Markets and Export Routes. Oxford Institute for Energy Studies. Available at: <www.oxfordenergy.org/pdfs/NG25.pdf>.

Appendix - List of the 55 countries included in the pipeline network and their abbreviations.

Country	Code
Albania	AL
Algeria	DZ
Armenia	AM
Austria	AT
Azerbaijan	AZ
Belarus	BY
Belgium	BE
Bosnia and Herzegovina	BA
Bulgaria	BG
Croatia	HR
Czech Republic	CZ
Denmark	DK
Egypt	EG
Estonia	EE
Finland	FI
France	FR
Georgia	GE
Germany	DE
Greece	GR
Hungary	HU
Iran	IR
Ireland	IE
Israel	IL
Italy	IT
Jordan	JO
Kazakhstan	KZ
Latvia	LV
Lebanon	LB
Libya	LY
Lithuania	LT
Luxembourg	LU
Macedonia	MK
Moldova	MD
Morocco	MA
The Netherlands	NL
Norway	NO
Poland	PL
Portugal	PT
Romania	RO
Russia-Kaliningrad	RK
Russian Federation	RU
Serbia	RS
Slovakia (Slovak Republic)	SK
Slovenia	SI
Spain	ES
Sweden	SE
Switzerland	CH
Syria	SY
Tunisia	TN
Turkey	TR
Turkmenistan	TM
UK-Northern Ireland	NI
Ukraine	UA
United Kingdom	UK
Uzbekistan	UZ