

1 **NATIONAL ENERGY SECURITY ASSESSMENT**  
2 **IN A GEOPOLITICAL PERSPECTIVE**

3  
4 *E. Bompard<sup>(\*)</sup>, A. Carpignano<sup>(\*)</sup>, M. Erriquez<sup>(\*\*)</sup>, D. Grosso<sup>(\*)</sup>, M. Pession<sup>(\*)</sup>, F. Profumo<sup>(\*)</sup>*

5  
6 **Abstract**

7 The possibility of ensuring the energy needed by a country is a fundamental requirement for the economic growth and  
8 social welfare of that country. The fulfillment of this need is particularly challenging for those countries that are  
9 characterized by a low level of energy self-sufficiency. The evaluation of energy security needs to consider different  
10 dimensions and is of the utmost importance as a benchmark to conceive and implement different policies. The  
11 assessment of the level of security should rely on science-based models that are able to track the rapidly evolving  
12 geopolitical scenarios, and to provide detailed information and quantitative indexes to policy decision makers. In this  
13 paper, an overarching methodology is outlined to evaluate energy security, in which its external and internal dimensions  
14 are considered and integrated: the security of the energy supply from abroad (external) and the security of national  
15 energy infrastructures (internal). Attention is then focused on the external dimension, and two indexes are defined, by  
16 means of a probabilistic approach, in terms of the expected value of supply and economic impacts. The methodology is  
17 then applied to the Italian case, considering different geopolitical scenarios, and conclusions are provided about the  
18 energy security of the country.  
19

---

<sup>(\*)</sup> POLITECNICO DI TORINO, Dipartimento Energia, [ettore.bompard@polito.it](mailto:ettore.bompard@polito.it)

<sup>(\*\*)</sup>: Consultant and former officer of the Arma dei Carabinieri, [m.m.erriquez@gmail.com](mailto:m.m.erriquez@gmail.com)

## 20 1. INTRODUCTION

21 Energy security is a crucial issue for each and every country. It may be defined as the capability of ensuring the  
22 availability of different typologies of energy for the final uses, in the needed quantity, where requested, over short, mid  
23 and long time horizons. It is necessary to ensure access to the commodity sources, their transportation (using suitable  
24 corridors) to the country, the possible transformation into secondary commodities and its distribution inside the country  
25 itself, by means of appropriate infrastructures.

26 It should be underlined that – in general terms – the energy security of a country depends not only on the possibility of  
27 obtaining the needed amount of energy commodities by means of local production or by importing from abroad (supply  
28 side), but also on the flexibility in the end-use demand (demand side).

29 In countries characterised by a low self-sufficiency, such as Italy (24.1% in 2014), the security issues related to the  
30 acquisition of energy commodities, depending on geopolitical scenarios, is particularly critical. At the EU28 level, the  
31 energy self-sufficiency is about 46.5%. At the same time, the security of the internal transport/distribution of energy,  
32 related to the National infrastructures, is also relevant.

33 Thus, the evaluation of the level of energy risk, at a given point in time, and its evolution over a short time horizon, by  
34 means of science-based approaches, are crucial to define and improve defence and mitigation countermeasures. Instead,  
35 in the mid-long term, the analysis of the risk related to possible alternative scenarios allows strategical planning to be  
36 made in terms of new sources and new intra-national and infra-national infrastructures.

37 For these reasons, a methodological approach is proposed in this paper to assess, in a comprehensive way, the security  
38 of a country, through a quantification of the energy security, which is able to capture supply risks and provide the basis  
39 of a cost-benefit analysis.

40 The methodological contribution of this work is represented by the adaptation of the classical risk analysis approach,  
41 used in studies of industrial technologies and plants, to the analysis of the security of energy supply in a geopolitical  
42 perspective, and by the coupling of this new approach with a detailed characterisation of the energy corridors, which,  
43 in this way, makes it possible to take into account their spatial dimension and to embed it in the mathematical  
44 relationships defined to evaluate the risk parameter.

45 The risk indexes related to the single corridors and the overall national supply risk (both physical – in terms of energy  
46 losses – and economic) can thus be used to help support decision makers in assessing and ranking the criticalities of the  
47 energy system and in performing comparative scenario analyses of different strategical options that involve energy  
48 imports and infrastructures.

49 The relevance of the proposed approach, which links technical, geopolitical and economic considerations, lies in the  
50 fact that the energy supply of a country is affected by several aspects (economy, geopolitical relationships and security)  
51 that interact with each other and which need to be investigated in an integrated perspective. In particular, on one hand,  
52 the geopolitical situation can have a significant influence on the energy commodity costs, thus having an impact on the  
53 economy, and on the other can determine the country's level of energy supply security and have effects on the supply  
54 availability, which – in turn – again affects the economy.

55 The developed methodology is here illustrated with reference to the Italian situation.

56 The paper is structured as follows. The state of the art, related to the geopolitical risk indicators, is summarised in sec.2;  
57 the adopted methodological approach is described in sec.3; the results of an application to a case study, related to the  
58 energy supply to Italy, is presented in sec 4.

## 60 2. LITERATURE REVIEW OF ENERGY SECURITY INDICATORS

61 Over the last decade, the evaluation of the security and affordability of the energy supply has played an increasing role,  
62 and has been one of the main issues for policy makers, especially in high energy import dependent countries, like many  
63 of the European Union Member States, including Italy.

64 Several approaches have been proposed to quantify the level of security of supply to a country, most of which are  
65 based on the definition of numerical risk parameters that are able to take into account geopolitical aspects and/or  
66 country-dependent energy indicators. Kruyt et al. [1] performed a classification of some of the main energy indexes by  
67 distinguishing between ten simple indicators (including import dependency, reserve-to-production ratio and energy  
68 prices) and five aggregated indexes (i.e. the Oil Vulnerability Index (OVI), the Willingness to Pay Index, the IEA  
69 Energy Security Index (ESI), the Supply-Demand Index and the Shannon Index).

70 Referring to these five indexes, Gupta [2] evaluated an overall oil vulnerability index (OVI) that depends on the  
71 combination of seven indicators, related to oil supply and consumption and to the economic level of the receiving  
72 country (GDP per capita, oil import dependency, oil consumption per GDP unit). Bollen [3] based his study on a cost-  
73 benefit analysis, and this led to the definition of a “Willingness to Pay” function that measures the percentage of GDP  
74 that the analysed country is willing to pay in order to decrease its risk. IEA ESI [4] evaluated the effects of the supply  
75 market concentration on energy commodity prices, taking into account the geopolitical risk rating of the supply  
76 countries. Scheepers et al. [5,6] analysed the Supply-Demand Index, defined on the basis of experts' judgement by  
77 means of scoring rules, and focused on the whole energy chain (including conversion, transport, supply and demand of  
78 energy in the mid-long term). The Shannon-Wiennier Index (SWI) [7], which quantifies diversification by taking into  
79 account the share of each commodity in the fuel mix composition, is also used to evaluate energy security.  
80 Martchamadol et al. [8] performed an analysis of the state of the art, in which several indicators were taken into

81 account. Among these indicators, the following can be mentioned: the WEC Assessment Index (AI) [9], which  
82 evaluates energy security by means of five indicators (including net energy imports and diversification of the energy  
83 supply); the WEC Energy Sustainability Country Index (ESCI) [10], which is based on 22 indicators, including oil  
84 reserves, stock and energy security; the APERC study [11], which considers five indicators (such as the net import  
85 dependency, the net oil import dependency and the oil import dependency from Middle Eastern countries); the  
86 UNDESA Energy Indicators for Sustainable Development [12]; the Global Network on Energy for Sustainable  
87 Development (GNESD) indicator [13]. They also developed a new composite index, the Aggregated Energy Security  
88 Performance Indicator (AESPI) [8], which ranges between 0 (low security) and 10 (high security), and which is built  
89 using 25 indicators. These indicators are evaluated on the basis of the historical data series of the population, the GDP,  
90 the energy production, the net import and consumption, the power generation capacity, the transformation and  
91 transmission losses, and the coal, crude oil and natural gas emission factor values.

92 Most of the energy risk indicators are assumed steady over time. Apart from the above mentioned AESPI index, only a  
93 few other indexes, such as the Supply-Demand Index defined by Scheepers et al. and the Composite Indicator  
94 developed by Badea et al. [14], have taken into consideration a forecasted time evolution. These indicators were both  
95 based on energy projections from the PRIMES model, and are used by the European Commission to evaluate the EU  
96 Trends up to 2030 [15]. The study by Checchi et al. [16] also focused on the long-term evaluation of the security of  
97 energy supply, referring to the results of the PRIMES model, but it did not set any index to quantify this evaluation.  
98 Among the indicators based on time series analyses, the International Index of Energy Security Risk (IIESR), set up by  
99 the U.S. Chamber of Commerce Institute for 21st Century Energy [17], allows the security level of 25 large consuming  
100 countries throughout the world to be compared on a yearly basis. This approach refers to the identification of eight  
101 index categories (including reserves and the production of oil, natural gas and coal, and energy imports). A set of 29  
102 metrics was defined for each of these categories. The 1980-2012 time horizon was taken into account for all of the  
103 metrics; moreover, each of these metrics was normalised with reference to the 1980 OECD value. The normalised  
104 metrics were then weighted, using the International Weightings Index, which gives the percentage contribution of each  
105 category to the total, in order to calculate the overall IIESR value. Sovacool [18] defined an indicator for the evaluation  
106 of the energy security of a country, referring to the European Union, the United States, China, India, Japan, South  
107 Korea, Australia, New Zealand and ten countries belonging to the Association of Southeast Asian Nations (ASEAN).  
108 For this purpose, five fundamental dimensions of energy security were identified (availability, reliability, technological  
109 development, sustainability and regulations). In turn, these dimensions were subdivided into 20 components, each of  
110 which was related to a metric. Frondel et al. [19,20,21] proposed and implemented a methodology aimed at classifying  
111 countries (in particular those belonging to the G7) on the basis of the risk level related to the primary energy commodity  
112 supply in the mid-long term; the authors defined, for each commodity, a risk indicator expressed as a function of the  
113 probability of commodity flow disruption for the various exporting countries, and of the square value of the percentage  
114 contribution given by each exporting country and by the local production to the energy demand fulfilment in the  
115 analysed country. In turn, the supply unavailability for a certain country was evaluated on the basis of considerations  
116 associated with the geopolitical situation and economic stability, while the share values for the exporting countries were  
117 correlated to the Herfindahl index [22], which measures the import concentration for a specific commodity.

118 Guivarch et al. [23] analysed the possible evolution of energy security in Europe from a decarbonisation perspective, by  
119 taking into account the time evolution of a set of indicators (based on the concepts of resilience, robustness and  
120 sovereignty) in the case of different scenarios. A study focusing on the impacts of alternative climate mitigation policy  
121 scenarios on South Korea, Japan and China was instead performed by Matsumoto et al. [24] by means of a computable  
122 general equilibrium model.

123 Valdés Lucas et al. [25] explored, over a long-term time horizon, the correlation between the deployment of renewables  
124 and energy security, considering several indicators related to three energy policy dimensions: competitiveness, security  
125 of supply and environment.

126 Biresselioglu et al. [26] considered natural gas supply security and the evolution of different indicators (including the  
127 number of supply countries, the total volume of gas imported and the fragility of supply countries over the 2001-2013  
128 period in order to build a Supply Security Index (SSI) through an application of the Principal Component Analysis  
129 (PCA) technique. Another study – carried out by Flouri et al. [27] – focused on natural gas, and was devoted to  
130 exploring, using a Monte Carlo simulation approach, how a disruption in the natural gas supply from Algeria, for  
131 geopolitical reasons, could affect the natural gas supply security of the EU: this analysis in particular highlighted the  
132 relevant role played by the diversification of suppliers in increasing energy security.

133 Kisel et al. [28] described the different methods and indicators that are adopted to assess energy security and to  
134 delineate energy policies, and they proposed an Energy Security Matrix that is able to organise the most significant  
135 indicators in a structured way from the point of view of operational and technical resilience, technical vulnerability,  
136 economic dependence and political affectability in different sectors.

137 Among the other studies that have focused on the relevance of the geopolitical element in the evaluation of the risk  
138 related to the energy supply, those carried out by Correlje and van der Linde [29], Costantini et al. [30], Hedenus [31]  
139 and Umbach [32] can be mentioned. The FP-7 European project “Risk of Energy Availability: Common Corridors for  
140 Europe Supply Security” (REACCESS) [33] developed tools that can be used to conduct a quantitative assessment of  
141 the geopolitical risk for scenario analyses. In this project – characterized by the link between three forecasting TIMES-  
142 based [34] optimisation energy models – a risk index (steady over time and ranging between 0 and 100) was defined for

143 all the commodity source countries and for all the countries crossed by the above mentioned corridors. This index is a  
 144 function of the socio-political, energetic, political-institutional and economic security level of the country, and it was  
 145 calculated by means of factor analysis techniques (Marín-Quemada et al. [35,36,37]). During the follow-up phase of the  
 146 project, these indexes were combined, through an application of the reliability theory, in order to define a single risk  
 147 index for each corridor; for this purpose, the risk index related to each crossed country was assumed as the probability  
 148 that a corridor crossing that country would fail (Gerboni et al. [38]). Furthermore, starting from the same risk indexes  
 149 per country, Doukas et al. [39] developed a web-based tool for the analysis of the natural gas and oil corridors, and they  
 150 tested it by means of a case study focused on the Greek energy supply. Using the same approach (based on the factor  
 151 analysis), Muñoz et al. [40] defined the country composite indicator GESRI (Geopolitical Energy Supply Risk Index),  
 152 which – unlike the one proposed by Marín-Quemada et al. – combines the social and political dimensions in a single  
 153 risk vector and introduces a new vector that describes the relations between the exporting and transit countries with the  
 154 EU-27. Finally, in the framework of the REACCESS project, Carpignano et al. [41] proposed a methodological  
 155 approach to evaluate the technological risk and the loss of production caused by corridor failures, and included these  
 156 parameters among those used to analyse optimal scenarios for the EU energy supply.

### 158 3. INDICATORS FOR NATIONAL ENERGY SECURITY ASSESSMENT

159 The overall energy security of a country depends on two different “fronts”. The first is “internal” and is related to: a) the  
 160 quantification of the highest or lowest availability of national resources for each considered primary energy commodity  
 161 (natural gas, oil, coal); b) resilience to possible internal attacks against the infrastructures (distribution networks) or  
 162 transformation plants (refineries, regasification terminals, etc.).

163 The second is “external” and includes: a) the geopolitical security of the commodity source country; b) the security of  
 164 the infrastructures up to the national entry point, taking into consideration the route of the energy corridors (open sea or  
 165 captive) and the risk indexes associated with each crossed country; c) the possible effects on imports due to the  
 166 unavailability (at different temporal scales) of the above mentioned infrastructures.

167 A security index can be conceived for each of these “fronts”, and the combination of the two provides the overall  
 168 assessment of the national security of the Country.

169 The nomenclature of the main indexes and parameters is given in Table 2. Generally speaking, the internal risk can be  
 170 expressed as a function of the resilience of the transmission/distribution infrastructure:

$$171 R_{int} = f(\vartheta_{c,d})$$

172 Assuming  $\vartheta_{c,d}$  as the Resilience index, which is used to quantify the resilience of the internal distribution/transmission  
 173 network  $d_d$  for commodity  $c_c$ . This index has been disregarded in this paper and attention has been focused on the  
 174 external one.

175 The proposed index for the external risk is a weighted function of the contribution given by the risk indexes associated  
 176 with the source and crossed countries, and of the energy content of the commodity imported through each corridor.

177 An index  $\varphi_k \in [0,100]$ , which is mainly related to the geopolitical situation, has been associated to each country to  
 178 quantify the criticality of that country; this index is estimated as described in sec. 2 and can continuously be tracked and  
 179 updated over time.

180 A corridor  $i$  is defined as:

$$181 \forall i_i \in \mathcal{J} : i_i = \{c_c, l_i, \mathcal{K}_i\} \mid c \neq l = i,$$

182 corridor  $i_i \in \mathcal{J}$  is defined by a length  $l_i \in \mathcal{L}$ , a commodity  $c_i \in \mathcal{C}_i$ , a set of crossed countries  $\mathcal{K}^i$  with  $k_i \in \mathcal{K}^i$ , the  
 183 country of origin,  $\dim(\mathcal{K}^i) = K_i$  the number of countries crossed.

184 A risk index  $\xi'_i$  is defined for each corridor  $i_i$  and its probability of failure is identified [38]:

$$185 \xi'_i = 100 \cdot \left[ 1 - \prod_{k_i \in \mathcal{K}_i} \left( 1 - \frac{\varphi_k}{100} \right) \right] \quad (1)$$

186 In (1):

187  $\left( 1 - \frac{\varphi_k}{100} \right)$  is the probability of success of crossing country  $k$ ,

188  $\prod_{k_i \in \mathcal{K}_i} \left( 1 - \frac{\varphi_k}{100} \right)$  is the probability (of independent events) of success of crossing all the countries involved along  
 189 the corridor route,

190  $1 - \prod_{k_i \in \mathcal{K}_i} \left( 1 - \frac{\varphi_k}{100} \right)$  is the probability of failure for the entire corridor, and it is expressed as the complement of  
 191 the probability of success.

197 Corridors are composed of different branches in different countries; each segment has a different length; a “spatial  
 198 dimension” in the exposure to risk is assumed, in the sense that, given a  $\varphi_k$  index for a country, its contribution to the  
 199 overall risk of the corridor would be proportional to the length of the segment of the corridor in that country.  
 200 The total length  $l_i$  of corridor  $i$ , is given by the sum of the length of the branches of the corridor in the crossed countries:

$$201 l_i = \|B^i\|_1$$

202  
 203 An empirical weighting function  $\gamma_k$  is introduced into (1) in order to incorporate this aspect:

$$204 \xi_i = 100 \cdot \left[ 1 - \prod_{k_i \in \mathcal{K}_i} \left( 1 - \frac{\gamma_k \cdot \varphi_k}{100} \right) \right] \quad (2)$$

205  
 206 The assumed values of  $\gamma_k$  are reported in Tab. 1 as a function of the ratio between the real length of the corridor branch,  
 207  $b_b$ , and the average length of the corridor branches  $\bar{b}_i$  (3).

$$208 \bar{b}_i = \frac{l_i}{K_i} \quad (3)$$

209  
 210 Open sea routes and submarine pipelines, territorial waters and international waters are all involved in the risk  
 211 assessment of the corridor. In order to avoid an underestimation of the risk related to maritime routes, in comparison to  
 212 the one related to terrestrial corridors, a zone of influence is defined for each country, and a portion of the international  
 213 waters is also covered, to which the same index  $\varphi_k$  as the country is provided.

214 The risk,  $R_i$ , associated to corridor  $i$ , is defined as the product between the probability of failure  $\xi_i$  and the damage, in  
 215 terms of loss of energy  $E_{c,i}$ , associated to a commodity  $c_c$ :

$$216 R_i = \sum_{c_i \in \mathcal{C}_i} \frac{\xi_i}{100} \cdot E_{c,i} \quad (4)$$

217  
 218 The overall external risk, for all the corridors supplying the given country, is:

$$219 R_{ext} = \sum_{i_i \in \mathcal{J}} R_i \quad (5)$$

220  
 221 As far as time granularity is concerned, the analyses can be carried out considering different time scales (year, quarter,  
 222 months,...). A higher time discretization, such as a monthly analysis, would allow specific criticalities, such as those  
 223 related to the natural gas supply during winter months, to be highlighted.

224 The risk in (5) can be converted into equivalent monetary units through the national *energy intensity of the economy*  $Q$   
 225 ( $TJ/G\text{€}$ ), which is defined as the ratio between the gross internal energy consumption (TJ) and the Gross Domestic  
 226 Product (GDP, G€):

$$227 R_{int,m} = \frac{R_{int}}{Q} \quad (6)$$

$$228 R_{ext,m} = \frac{R_{ext}}{Q} \quad (7)$$

229 This conversion is useful to evaluate the economic impact of the geopolitical energy risk, because a possible loss of  
 230 energy, due to the unavailability of an energy supply, causes a loss of GDP [42].

231 The sum of the two indicators, weighted using two coefficients,  $w_1$  and  $w_2$ , allows the *National Energy Security Index*  
 232  $R_n$  to be defined (Fig.1):

$$233 R_n = w_1 \cdot R_{int} + w_2 \cdot R_{ext} \quad (8)$$

234  
 235 where  $w_1$  and  $w_2$  are defined on the basis of the percentage import dependency  $\chi$ :

$$236 w_1 = 1 - \chi \quad (9)$$

$$237 w_2 = \chi \quad (10)$$

238

239 The above described methodology is able to highlight any possible criticalities related to the fulfilment of the national  
 240 requirement in the case of geopolitical issues that affect the supply and/or the transport/distribution of energy to end-  
 241 users.  
 242 Focusing on the external dimension of security, it is possible to define the “expected supply”. The probability of success  
 243 (availability) of each corridor is:

$$\omega_i = 100 \cdot \left[ \prod_{k \in \mathcal{K}_i} \left( 1 - \frac{\gamma_k \cdot \varphi_k}{100} \right) \right] \quad (11)$$

245  
 246 The expected supply value  $S_i$  for corridor  $i_i$  is the product of  $\omega_i$  and the energy flow  $E_{c,i}$  of the commodity  $c_c$  carried by  
 247 the corridor:

$$S_i = \sum_{c_i \in \mathcal{C}_i} \frac{\omega_i}{100} \cdot E_{c,i} \quad (12)$$

249  
 250 The total expected supply  $S_{ext}$  (TJ) can be evaluated as:

$$S_{ext} = \sum_{i_i \in \mathcal{J}} S_i \quad (13)$$

252  
 253 The expected supply corresponds to the difference between the total supply, in energy terms  $E$ , and the overall external  
 254 risk  $R_{ext}$ :

$$S_{ext} = E - R_{ext} \quad (14)$$

256  
 257 The adopted approach assumes that the events are independent, and offers a conservative overestimation of the risk.

258  
 259 Finally, it should be highlighted that the error analysis in the proposed modelling approach on the main parameters  
 260 (such as energy flows, or corridor branch lengths) is not particularly relevant in comparison with the need to  
 261 understand whether a certain event could happen or not. The aim of the adopted procedure is to associate a certain  
 262 probability value to the single countries, which is able to describe the likelihood that a certain supply corridor crossing  
 263 them fails due to geopolitical reasons, and is not to perform forecasting analyses on unpredictable events. Naturally,  
 264 disruptive geopolitical events can suddenly occur, and these could significantly modify the probability value of the  
 265 countries. For this reason, sensitivity analyses on the country risk index parameter are useful to evaluate the effects of  
 266 such events on the global energy risk. Furthermore, when defining sensitivity scenarios, it could be appropriate to  
 267 consider that a geopolitical event in a certain country can also affect other countries in the same geographical area, and  
 268 as a result in some cases the geopolitical risk level should be considered jointly, and in the same way modified for the  
 269 whole set of countries belonging to the same area. This could be particularly relevant for zones like the Middle-East and  
 270 North-Africa (some examples are those of the so-called “Arab Spring” and the penetration of terroristic groups in these  
 271 areas).

## 273 4. CASE STUDY: THE EXTERNAL SUPPLY TO ITALY

### 274 4.1 Definition of the scenarios

275 The proposed methodology has been applied to the security analysis of the Italian national energy supply. The  
 276 contribution to the risk given by the internal component  $R_{int}$  has been neglected, and the analysis has only focused on  
 277 the evaluation of the  $R_{ext}$  parameter.

278 A total of 263 corridors (pipelines, ships, railways, roads, power lines), carrying 6 commodities (coal, crude oil, refined  
 279 petroleum products, natural gas, LNG, electricity) and accounting for 97.5% of the Italian energy inflows in 2014 have  
 280 been considered [43,44]. Country risk indexes have been assumed on the basis of the FP-7 REACCESS ([35], [36],  
 281 [37], [38]) project (Fig. 2, Tab. 3).

282  
 283 Italian energy security has been assessed against five possible adverse scenarios. The scenarios are characterized by two  
 284 different types of situation; in the first, the criticality of the country is increased due to a deterioration of the geopolitical  
 285 situation in the area (modelled by an increase in the geopolitical country index), while in the second the situation, the  
 286 country causes actions that provide the actual failure of a corridor.

287 Five scenarios (S1-S5) have been taken into account (Tab. 4):

- 288 S1) Increased activity of terroristic groups in North Africa (Algeria, Egypt, Libya and Tunisia);
- 289 S2) Deterioration of the Italian/Qatari diplomatic relations, with cuts in gas/oil exports to Italy;
- 290 S3) Antagonistic actions in Libya with disruption of the Greenstream gas pipeline;

291 S4) Increase in the contrast between Russia and the Ukraine, with a country risk increase and disruption of the NG and  
292 oil corridors from Russia across the Ukraine;  
293 S5) The simultaneous occurrence of S1 and S4.

294  
295

#### 4.2 Energy security analysis for different scenarios

296 The impact of the considered scenarios has been assessed, considering the energy risk  $R_{ee}$  and economic risk  $R_{em}$  values  
297 (Tab. 5) and they have been compared with the values related to the year 2014 (Reference situation, REF:  
298 corresponding to the actual configuration of flows, corridors and suppliers) with the Country indexes reported in Tab. 3.  
299 In Tab. 6, the indexes have been computed considering only the natural gas supply, which accounts for 33% of the  
300 Italian energy inflows in 2014.

301

302 S1 shows an increase, of about 3%, in both  $R_{ee}$  and  $R_{em}$ , mostly due to the large number of corridors (79, 30% of the  
303 total) that are affected by the increase in geopolitical risk in the four countries; their average risk index for corridor  $\xi$   
304 increases by 17.6%, in comparison with the Reference, while the overall value of  $\xi$  increases by 5.4%.

305 In Tab. 7, the analysis is undertaken on a monthly time basis; both risk indexes, in this case, have a peak increase in  
306 September, due to an increase in the flow exported by the countries involved in S1, in comparison with the one exported  
307 by countries that do not undergo changes. An increase in the risk can be observed for S1 but, due to the absence of  
308 actual disruptions, the inflows are still there.

309

310 S2 shows a criticality related to the LNG supply (the LNG supply from Qatar in 2014 was equal to 172.8 PJ/y). By  
311 setting the corridor risk to 100% (i.e. full unavailability and expected supply = 0) for all the Qatari corridors, the overall  
312 risk increases by 2.46%: this variation is due to the natural gas corridors (whose contribution to the total risk increases  
313 by 5.79%, in comparison with the reference case).

314

315 S3 shows an increase of 3.52% in the overall risk caused by the disruption of the Greenstream NG corridor ( $\xi = 100\%$ ).  
316 This unavailability has a relevant effect on the NG risk, which increases by 8.27%. Furthermore, the amount of energy  
317 lost in the case of a disruption of the Greenstream pipeline cannot be replaced by the same amount imported as LNG  
318 from the same supplier, because the only Libyan LNG terminal (i.e. the one located in Marsa al-Brega) is presently out  
319 of service and has been since 2011, as it was damaged during the civil war.

320

321 S4 involves the whole Italian natural gas import from Russia (corresponding to 48.82% of the total natural gas import)  
322 and 3% of the crude oil import (one corridor). This situation has a particular impact on the overall risk, as it causes an  
323 increase of 8.68% (which reaches 16.33% for the risk contribution only related to the natural gas supply). This effect is  
324 prevalently due to the high level of import dependency on Russia: as a consequence, this can be a significant example of  
325 the importance of supply diversification (in terms of energy sources, supply countries and corridors), in order to avoid  
326 such criticalities and enhance the security level of a Country.

327

328 S5 combines the effects of S1 and S4. This situation is extremely risky because it affects 46.1% of the total Italian  
329 energy supply, and it leads to a critical situation, especially for natural gas supply, as more than 70% of the imported  
330 flux is involved; the percentage of oil, RPP and coal imports involved is lower, but is significant, as it ranges between  
331 20% and 50%. The overall energy risk increases by 11.7%, above all due to the specific risk contribution of natural gas  
332 (+20.4%). This relevant growth is justified by the fact that seven suppliers (Russia, the Ukraine, Algeria, Libya, Egypt,  
333 Tunisia and Nigeria) and 98 corridors undergo changes. In particular, the average  $\xi$  increases by 17.5%, in comparison  
334 with the Reference case.

335

#### 4.3 Mitigation actions

337 If a scenario leads to a loss of energy flow (S2-S5), specific countermeasures have to be planned and implemented to  
338 ensure the needed supply. Some of the possible mitigation options have been tested using the here presented model,  
339 their feasibility has been analysed and their effects have been compared in terms of risk reduction, in comparison with  
340 the related scenario. For S2, the following options were considered:

341

342 MA1-S2) Replacement of the Qatari LNG flow with a flow from Algeria (50%, Transmed pipeline;) and Russia (50%,  
343 TAG pipeline).

344 This configuration – which is coherent with the maximum capacities at the national entry points – allows the needed  
345 annual quantity of natural gas to be ensured with a risk reduction of 1.21%, in comparison with S2.

346 MA2-S2) Replacement of the Qatari LNG flow with a flow from Norway (25%, Transitgas pipeline), the Netherlands  
347 (25%, Transitgas pipeline) and Russia (50%, TAG pipeline).

348 In this case, the reduction in the overall risk is lower than the one obtained from MA1-S2 (and equal to 2.10%), due to  
349 the low risk level of the two European countries.

350 *MA3-S2) Replacement of the Qatari LNG flow with a flow from the UAE (100%, LNG to regasification terminals*  
351 *located near Panigaglia and Porto Levante).*

352 The resulting overall risk reduction is close to the one obtained for MA2-S2 (-2.39% vs. - 2.10%). The obtained  
353 configuration is similar to the reference one, due to the fact that the country indexes for Qatar (38.5) and the UAE  
354 (39.4), and the ship route to deliver LNG to Italy, are comparable.

355 The effects of the mitigation actions are reported in Tab. 8.

356

357 For S3, two mitigation actions were identified:

358

359 *MA1-S3) Replacement of the Libyan NG flow with a flow from Algeria (50%, Transmed pipeline) and Nigeria (50%:*  
360 *25% Transmed pipeline; 25% LNG).*

361 The risk reduces by 1.56%, in comparison with the S3 scenario. It should be noticed that the  $\xi$  associated to these  
362 corridors is higher than the Greenstream one: this is not due to the source country indexes (as they are similar to the  
363 Libyan one for both Algeria and Nigeria), but – and particularly for Nigeria – to the high number of countries that are  
364 crossed.

365 *MA2-S3) Replacement of the Libyan NG flow with a flow from the UAE (50%, LNG) and Qatar (50%, LNG).*

366 The resulting risk reduces by 3.49%. This option allows only maritime routes, which are more flexible and therefore  
367 more effective from the security point of view, to be used.

368 The missing flow cannot be replaced entirely by European Countries (Norway and the Netherlands) as the required  
369 capacity is higher than the maximum one for the Transigas corridor, which should be involved in this case.

370 The effects of the mitigation actions are reported in Tab. 9.

371

372 For S4, two mitigation options are defined:

373

374 *MA1-S4) Replacement of the Russian crude oil flow with a flow from Kazakhstan (50%) and Azerbaijan (50%;*  
375 *replacement of the Russian NG flow with a flow from Algeria (30%), Nigeria (30%), the Netherlands (10%), Norway*  
376 *(10%), Libya (7%), Qatar (7%) and the UAE (6%), i.e. from all the other countries that supply Italy, according to the*  
377 *maximum capacity of the pipelines.*

378 In this way, the overall risk decreases by 9.88%: this is mostly due to the decrease in the risk related to natural gas (-  
379 21%).

380 *MA2-S4) Replacement of the Russian crude oil flow with a flow from the Russian corridors that do not cross the*  
381 *Ukraine; replacement of the Russian NG flows as in MA1-S4.*

382 The results show a reduction in the overall risk index of -10.08%, which is comparable with the one obtained in MA2-  
383 S3. As in MA2-S3, this reduction is mostly related to the diversification of the NG supply.

384 The possible evolution of the corridors can provide additional possibilities, in terms of mitigation effects. The supply  
385 from Russia through different corridors (whose routes do not cross the Ukraine), mainly depends on future strategies  
386 related to the possible new pipelines that could be built. One of these alternatives could be represented by the South  
387 Stream project, even though this solution does not currently seem feasible. In fact, the South Stream project (a pipeline  
388 of a total length of about 2380 km, of which 931 will be offshore through the Black Sea, from Russia to Bulgaria, with a  
389 capacity of 63 bcm/y) was declared, at the end of 2013, not to be compliant with the EU Third Energy Package  
390 regulations [45], which introduced incompatibility between producers and TSOs (thus affecting the role played by the  
391 Russian natural gas production and distribution company Gazprom); furthermore, this decision has to be contextualized  
392 in a more general framework of geopolitical tensions between the EU and Russia, caused by the economic sanctions  
393 imposed after the Crimea crisis. After the declared abandon of the South Stream project by Russia, the alternative  
394 Turkish Stream (or TurkStream) project was proposed. This pipeline – originally expected to have the same capacity as  
395 the South Stream one – should run from Russia to Turkey and cross the Black Sea (with a subsea branch of about 900  
396 km) and to deliver 31.5 bcm/y; the construction is planned to start in 2017 and to be completed by 2019. According to  
397 the most recent information available, Russia could build an additional line to connect Turkey to Greece, thus allowing  
398 Europe to be supplied (15.75 bcm/y to Turkey, 15.75 bcm/y to Europe). Among all the possible options, an  
399 interconnection between the Turkish Stream and the Trans Adriatic Pipeline (TAP) can be mentioned. The TAP  
400 pipeline infrastructure is presently under construction (with a length of 878 km, an initial capacity equal to 10 bcm/y  
401 and a planned maximum capacity of 20 bcm/y). It runs from Greece to Italy and will be connected to the Trans  
402 Anatolian Pipeline (TANAP) – as part of the Southern Gas Corridor (SGC) – in order to carry natural gas from the  
403 Azeri field of Shah Deniz to Europe. The construction of the TAP pipeline, and in particular the possibility of linking it  
404 to the Turkish Stream, could be relevant for Italy, as this situation could allow it to become a European hub for natural  
405 gas imported from Azerbaijan and Russia. As far as the security point of view is concerned, in 2014 (the reference year  
406 of the case study), Italy's overall natural gas import was equal to 55.78 bcm, of which 26.15 bcm came from Russia  
407 (46.9%). In the long term, hypothesising that the TAP pipeline could reach its maximum capacity, if the gas import  
408 remains constant, this corridor could impact on the supply for about 36%. By considering the latest data made available  
409 by the Italian Ministry of Economic Development and referring to 2015 [46], an increase in the overall imports can be



410 observed of up to 61.20 bcm; furthermore, if the historical trends are analysed, it can be noticed that the 2014 gas  
411 import value is significantly lower than the average import related to the last 12 years (69.27 bcm, with a peak of 77.40  
412 bcm in 2006). These observations, coupled with the constantly decreasing trend of local gas production (which  
413 accounted for 11.5% of the Gross Inland Consumption in 2014), have lead us to suppose that the import of natural gas  
414 in 2020 (the planned year for starting the TAP pipeline) could be higher than the present one. However, it can  
415 reasonably be expected that it will be lower than 80 bcm/y: in this case, the contribution of the TAP will range from  
416 12.5% (starting capacity = 10 bcm/y) to 25% (expansion up to the maximum capacity = 20 bcm/y). Focusing on the risk  
417 indexes (Tab. 3), it is possible to notice that the country risk index related to Azerbaijan is higher than that of Russia  
418 (43.9 vs. 34.0), and that the corridor route of the TAP pipeline (which crosses Azerbaijan, Armenia, Turkey, Greece and  
419 Albania) cannot be considered “safer” than the TAG pipeline one (which crosses Russia, the Ukraine, Slovak and  
420 Austria). For these reasons, it is possible to conclude that the TAP corridor would probably not reduce the absolute  
421 value of the supply risk, but it could be useful to increase diversification of the supply, and it could also offer a relevant  
422 alternative that could help in the case of geopolitical tensions between Russia and the Ukraine.

423 Other options, such as the use of the Yamal pipeline, cannot be considered, because of the constraint on the maximum  
424 capacity at the entry point, which is located in Passo Gries.

425 The effects of the mitigation actions are reported in Tab. 10.

426

427 For S5, flows from Russia and crossing the Ukraine (3 gas corridors and 1 oil corridor) have to be supplied in another  
428 way (as in S4), while this is not compulsory for those from North Africa (but could be recommended because of the  
429 high risk in comparison with the Reference scenario, due to hypothesised increase in the activity of terroristic groups).  
430 If the Russian flows are replaced in such a way as to avoid the North African corridors, it can be seen that several  
431 alternative options are available for oil import: ship transportation could be used (with the oil still coming from Russia)  
432 or the supplier could be changed (Caucasian countries, North and South America). As far as natural gas is concerned, if  
433 the supply from North African countries is avoided, only 60% of the flow that has to be replaced can be provided  
434 without overcoming the maximum capacity of the national entry points. As a consequence, with the current  
435 configuration of infrastructures, suppliers and corridors, the problem cannot be solved. In order to overcome this issue,  
436 some important changes have to be considered, including improvements of the infrastructures (new regasification plants  
437 or new pipelines) and the increase in the diversification of suppliers.

438

439 The approach described in sec. 3 and the case study analysed in sec. 4 are proposed from a single country perspective.  
440 However, the methodology could be applied at different scales (country, region, macro-areas). In fact, it could be useful  
441 to explore the energy security issues, especially for developing countries like China or India (for example, mention can  
442 be made to the studies performed by Jiang-Bo et al. [47] – which focus on the historical evolution of Chinese energy  
443 supply security, considering four dimensions and seven indexes – and the one carried out by Bambawale et al. [48],  
444 which was based on the analysis of Indian energy security from different perspectives), which are characterised by a  
445 relevant energy consumption growth rate, and for countries that show a relevant import dependency.

446 As far as the latter ones are concerned, Asian countries, like Japan and South Korea, can be mentioned. The overall  
447 Japanese energy import dependency in 2014 was equal to 93.5%, with relevant values for natural gas (97.6%) and  
448 crude oil (99.7%), while for South Korea, the import dependency in 2014 was equal to 82.8% (99.3% for natural gas  
449 and 99.5% for crude oil) [49]. Some European Countries are also affected to a great extent by this issue [50]: among  
450 the most populated ones, the dependency level of Italy is significantly high, but the situation of smaller countries, such  
451 as the Baltic ones, should also be highlighted, due to the fact that, since their independence and up to recent years, they  
452 have depended completely on a single supplier (Russia) [51].

453

## 454 5. CONCLUSIONS

455 The proposed methodology (and the implemented tool) can provide a quantitative assessment of the energy security of a  
456 country in a geopolitical perspective. The methodology, implemented and tested with reference to the Italian case, has  
457 proved to be effective in supporting policy decision making in the short, mid and long term.

458 This methodology allows a comprehensive representation of the inflow of a country, the assessment of its geopolitical  
459 risk and a cost benefit analysis, which is useful to compare different strategic options, to be obtained; a) in the short-  
460 mid-term, to allocate efforts with the aim of protecting a given corridor b) in the mid/long term, to plan and activate  
461 new supply options and corridors.

462 In addition, this methodology provides an effective way of designing mitigation countermeasures in the presence of an  
463 increase in the geopolitical risk or of adverse events, which could causing a certain percentage of the needed supply to  
464 become unavailable; it allows their effectiveness to be compared, and the related economic impacts to be assessed in  
465 terms of reduction in GDP loss.

466 With reference to the case of the Italian external supply, the analysis of the considered scenarios has highlighted the  
467 relevant role played by diversification in reducing the overall external risk. In a low self-sufficient country, the spatial  
468 dimension of energy corridors (the routes, lengths and the geopolitical security of the crossed countries) significantly  
469 affects the risk value. Moreover, in a strategic perspective, as natural gas is the most “risky” commodity, investments in

470 new LNG connections and terminals, or to increase the capacity of existing ones, could be beneficial from the security  
471 point of view.  
472 Investments in preventive actions against terroristic attacks against sensitive targets, such as pipelines, for example, the  
473 Greenstream corridor, could also lead to significant benefits from an economic point of view, as they could prevent the  
474 loss of a relevant amount of the GDP as the consequence of the sudden unavailability of an energy supply.  
475 The examined scenarios are related to the current energy system. From a more general perspective, the need to take into  
476 account climate changes, and to introduce adequate policies and countermeasures could have an effect on energy  
477 security [52] and lead to a new paradigm, based on a strong decarbonisation of the energy system and on the relevant  
478 role that renewables could play. According to this approach, among the future energy scenarios, the one that considers  
479 electrical UHV super-grids at a global scale, which would be able to transport electricity generated from renewable  
480 sources, such as wind and solar, from large production areas (the North Pole and African desert zones, respectively) to  
481 large consumption areas (such as the U.S.A., Asia and Europe), thus shifting the end-use energy consumptions from  
482 fossil fuels to cleanly produced electricity, can be mentioned [53]. Such a configuration could lead to an evolution in  
483 energy security, and could radically change the overall situation. The methodological approach described in this paper  
484 to evaluate supply security could also be adopted in future works to analyse these possible future scenarios and to  
485 compare them with other more traditional ones.

## 487 ACKNOWLEDGEMENTS

488 The authors would like to thank the consortium partners of the FP7 REACCESS project, especially Prof. Evasio  
489 Lavagno, Dr. Raffaella Gerboni and Arch. Laura Schranz.

## 491 REFERENCES

- 492 [1] Kruyt, B., van Vuuren, D.P., de Vries, H.J.M. and Groenenberg, H. (2009): "Indicators for energy security", Energy Policy,  
493 Vol. 37, Iss. 6, pp. 2166-2181.
- 494 [2] Gupta, E. (2008): "Oil vulnerability index of oil-importing countries", Energy Policy, Vol. 36, Iss. 3, pp. 1195-1211.
- 495 [3] Bollen, J. (2008): "Energy security, air pollution, and climate change: an integrated cost-benefit approach", Milieu- en  
496 Natuurplanbureau (MNP), Bilthoven.
- 497 [4] International Energy Agency (2007): "Energy Security and Climate Policy Assessing, Interactions".
- 498 [5] Scheepers, M. J. J., Seebregts, A. J., De Jong, J. J., & Maters, J. M. (2006): "EU Standards for energy security of supply",  
499 Petten, Amsterdam, The Hague: Energy Research Center of the Netherlands and Clingendael International Energy Program.  
500 ECN-C-06-036
- 501 [6] Scheepers, M. J. J., Seebregts, A. J., De Jong, J. J., & Maters, J. M. (2007): "EU standards for energy security of supply –  
502 Updates on the crises capability index and the Supply–Demand Index", Petten, Amsterdam, The Hague: Energy Research  
503 Center of the Netherlands and Clingendael International Energy Program. ECN-C-07-004
- 504 [7] Shannon, C. E. (1948): "A mathematical theory of communication", The Bell System Technical Journal, 27, pp. 379-423.
- 505 [8] Martchamadol, J., Kumar, S. (2013): "An aggregated energy security performance indicator", Applied Energy, Vol. 103, pp.  
506 653-670.
- 507 [9] WEC (2009): "World Energy and Climate Policy: 2009 Assessment", World Energy Council Publication.
- 508 [10] WEC (2010): "Pursuing sustainability: 2010 Assessment of country energy and climate policy", World Energy Council  
509 Publication.
- 510 [11] Asia Pacific Energy Research Centre, A quest for Energy Security in The 21<sup>st</sup> Century Resources and, Constraints; 2007.
- 511 [12] IAEA, UNDESA, IEA, EUROSTAT, EEA, Energy Indicators for Sustainable Development: Guidelines and Methodologies,  
512 International Atomic Energy Agency; 2005.
- 513 [13] Fundación Bariloche (2008): "Energy security and energy efficiency. Global Network on Energy and Sustainable Development  
514 (GNESD)"
- 515 [14] Badea, A. C., Rocco S., C. M., Tarantola, S., Bolado, R. (2011): "Composite indicators for security of energy supply using  
516 ordered weighted averaging", Reliability Engineering and System Safety, Vol. 96, pp. 651-662.
- 517 [15] Capros, P., Mantzos, L., Tasios, N., De Vita, A., Kouvaritakis, N. (2010): "EU energy trends to 2030 », European  
518 Commission, Directorate-General for Energy
- 519 [16] Checchi, A., Behrens, A. and Egenhofer, C. (2009): "Long-term energy security risks for Europe: a sector-specific approach",  
520 Centre for European Policy Studies (CEPS), Working document, No. 309, pp. 8-12.
- 521 [17] Institute for 21st Century Energy, U.S. Chamber of Commerce (2013): "International Index of Energy Security Risk. Assessing  
522 Risk in a Global Energy Market", www.energyxxi.org
- 523 [18] Sovacool, B.K., Mukherjee, I., Drupady, I.M. and D'Agostino, A.L. (2011a): "Evaluating energy security performance from  
524 1990 to 2010 for eighteen Countries", Energy, Vol. 36, Iss. 10, pp. 5846-5853.
- 525 [19] Frondel, M., Ritter, N., Schmidt, C. M. (2009): "Measuring Energy Supply Risks: A G7 Ranking", Ruhr Economic Paper No.  
526 104, Rheinisch-Westfälisches Institut für Wirtschaftsforschung (RWI), Ruhr-University Bochum, TU Dortmund University,  
527 University of Duisburg-Essen.
- 528 [20] Frondel, M., Ritter, N. and Schmidt, C.M. (2012): "Measuring long-term energy supply risks: A G7 ranking", Discussion  
529 Paper, SFB 823, No. 28, Technische Universität, Dortmund.
- 530 [21] Frondel, M., Schmidt, C. M. (2014): "A measure of a nation's physical energy supply risk", The Quarterly Review of  
531 Economics and Finance, Vol. 54, pp. 208-215.
- 532 [22] Herfindahl, O. C. (1950): "Concentration in the steel industry", Columbia University (unpublished doctoral dissertation).
- 533 [23] Guivarch, C., Monjon, S. (2016): "Identifying the main uncertainty drivers of energy security in a low-carbon world: The case  
534 of Europe", Energy Economics, <http://dx.doi.org/10.1016/j.eneco.2016.04.007>

- 535 [24] Matsumoto, K., Andriopoulos, K. (2016): “Energy security in East Asia under climate mitigation scenarios in the 21st  
536 century”, *Omega*, Vol. 59, Part A, pp. 60-71
- 537 [25] Valdés Lucas, J.N., Escribano Francés, G., San Martín González, E. (2016): “Energy security and renewable energy  
538 deployment in the EU: *Liaisons Dangereuses* or Virtuous Circle?”, *Renewable and Sustainable Energy Reviews*, Vol. 62, pp.  
539 1032-1046.
- 540 [26] Biresselioglu, M.E., Yelkenci, T., Oz, I.O. (2015): “Investigating the natural gas supply security: A new perspective”, *Energy*,  
541 Vol. 80, pp. 168-176.
- 542 [27] Flouri, M., Karakosta, C., Kladouchou, C., Psarras, J. (2015): “How does a natural gas supply interruption affect the EU gas  
543 security? A Monte Carlo simulation”, *Renewable and Sustainable Energy Reviews*, Vol. 44, pp. 785-796.
- 544 [28] Kisel, E., Hamburg, A., Härm, M., Leppiman, A., Ots, M. (2016): “Concept for Energy Security Matrix”, *Energy Policy*, Vol.  
545 95, pp. 1-9
- 546 [29] Correlje, A. and van der Linde, C. (2006): “Energy supply security and geopolitics: A European perspective”, *Energy Policy*,  
547 Vol. 34, Iss. 5, pp. 532-543.
- 548 [30] Costantini, V., Gracceva, F., Markandya, A. and Vicini, G. (2007): “Security of energy supply: Comparing scenarios from a  
549 European perspective”, *Energy Policy*, Vol. 35, Iss. 1, pp. 210-226.
- 550 [31] Hedenus, F., Azar, C. and Johansson, D.J.A. (2010): “Energy security policies in EU-25 – The expected cost of oil supply  
551 disruptions”, *Energy Policy*, Vol. 38, Iss. 3, pp. 1241-1250.
- 552 [32] Umbach, F. (2010): “Global energy security and the implications for the EU”, *Energy Policy*, Vol. 38, Iss. 3, pp. 1229-1240.
- 553 [33] Biberacher M., De Miglio R., Gargiulo M., Gerboni R., Lavagno E., Schranz L., Tosato GC. (2011): “Risk of Energy  
554 Availability Common Corridors for Europe Supply Security - Summary Report”, REACCESS Final Workshop, Brussels,  
555 Belgium.
- 556 [34] Loulou R., Labriet M. (2008) ETSAP-TIAM: the TIMES integrated assessment model part I: model structure. *Computational  
557 Management Science* 5: 7–40
- 558 [35] Marín-Quemada, J.M., Velasco, C. and Muñoz, B. (2009a): “Addressing competition in energy supply: weakening the impacts  
559 and improving energy security through complementarities”, Deliverable 4.2 REACCESS Project, Risk of Energy Availability:  
560 Common Corridors for European Security of Supply, EC-FP7 Project Grant Agreement No. 212011.
- 561 [36] Marín-Quemada, J.M., Velasco, C. and Muñoz, B. (2009b): “Competitive and complementary relations of the EU with the  
562 main energy consuming and producing countries”, Technical Note 4.2-1 REACCESS Project, Risk of Energy Availability:  
563 Common Corridors for European Security of Supply, EC-FP7 Project Grant Agreement No. 212011.
- 564 [37] Marín-Quemada, J.M., Velasco, C., García-Verdugo, J., Francés, G., Mahía, R., De Arce, R., San Martín González, E.,  
565 Rodríguez, L. and Muñoz, B. (2009c): “Quantification of socioeconomic risk & proposal for an index of security of energy  
566 supply”, Technical Note 4.5-1 and 4.5-2 REACCESS Project, Risk of Energy Availability: Common Corridors for European  
567 Security of Supply, EC-FP7 Project Grant Agreement No.: 212011.
- 568 [38] Gerboni, R., Grosso, D., Lavagno, E., Kanudia, A., Tosato, GC. (2015): “Coupling World and European models: energy trade  
569 and energy security in Europe”, in: “Informing Energy and Climate Policies Using Energy Systems Models” / Giannakidis G.,  
570 Labriet M., Ó Gallachóir B., Tosato, GC., Springer International Publishing Switzerland, pp. 411-426, ISBN 9783319165394.
- 571 [39] Doukas, H., Flamos, A., Karakosta, C., Flouri, M. and Psarras, J. (2010): “Web tool for the quantification of oil and gas  
572 corridors’ socio-economic risks. The case of Greece”, *International Journal of Energy Sector Management*, Vol. 4, No. 2, pp.  
573 213-235.
- 574 [40] Muñoz, B., García-Verdugo, J. and San-Martín, E. (2015): “Quantifying the geopolitical dimension of energy risks: A tool for  
575 energy modelling and planning”, *Energy*, Vol. 82, pp. 479-500.
- 576 [41] Carpignano, A., Nironi, C., Ganci, F. (2011): “Technological risk: a criterion for the optimisation of future EU energy supply  
577 scenarios”, *International Journal of Energy Sector Management*, Vol. 5, Iss. 1, pp. 81-100.
- 578 [42] Jun, E., Kim, W., Chang, S.H. (2009): “The analysis of security cost for different energy sources”, *Applied Energy*, Vol. 86,  
579 pp. 1894-1901.
- 580 [43] Ministero dello Sviluppo Economico - DGSAIE - Statistiche ed analisi energetiche e minerarie,  
581 <http://dgsaie.mise.gov.it/dgerm/>
- 582 [44] Eurostat Energy Statistical Database, <http://ec.europa.eu/eurostat/web/energy/data/database>
- 583 [45] Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal  
584 market in natural gas and repealing Directive 2003/55/EC
- 585 [46] Ministry of Economic Development, natural gas balance, <http://dgsaie.mise.gov.it/dgerm/bilanciogas.asp>
- 586 [47] Geng, J.B., Ji, Q. (2014): “Multi-perspective analysis of China’s energy supply security”, *Energy*, Vol. 64, pp. 541-550.
- 587 [48] Bambawale, M.J., Sovacool, B.K. (2011): “India’s energy security: A sample of business, government, civil society, and  
588 university perspectives”, *Energy Policy*, Vol. 39, pp. 1254-1264.
- 589 [49] International Energy Agency Statistical Database, <http://www.iea.org/statistics/>
- 590 [50] Prael, A., Weingartner, K. (2016): “Chapter 3 - A Study of Russia as Key Natural Gas Supplier to Europe in Terms of Security  
591 of Supply and Market Power”, in *Low-carbon Energy Security from a European Perspective* (Lombardi, P., Gruenig, M. Eds.),  
592 Academic Press, Oxford, pp. 43-79.
- 593 [51] Purvins, A., Fulli, G., Covrig, C.F., Chaouachi, A., Bompard, E.F., Carpaneto, E., Huang, T., Pi, R.J., Mutule, A., Oleinikova,  
594 I., Obushevs, A. (2016): “The Baltic power system between East and West interconnections”, JRC Science for Policy report,  
595 doi:10.2790/41165
- 596 [52] Cassen, C., Gracceva, F. (2016): “Chapter 7 - Energy Security in Low-Carbon Pathways”, in *Low-carbon Energy Security  
597 from a European Perspective* (Lombardi, P., Gruenig, M. Eds.), Academic Press, Oxford, pp. 181-205.
- 598 [53] Liu, Z. (2015): “Global Energy Interconnection”, Academic Press, pp. 396.
- 599  
600  
601  
602  
603

604 TABLES  
 605  
 606

Table 1: Weighting function  $\gamma_k$

$b/\bar{b}_i$	$\gamma_k$
0-0.2	0.90
0.2-0.5	0.93
0.5-0.9	0.96
0.9-1.1	1.00
1.1-1.5	1.04
1.5-2.0	1.07
>2.0	1.10

607  
 608

Table 2: Nomenclature

Set / Parameter	Description
$\mathcal{C} = \{\dots, c_c, \dots\}, \dim(\mathcal{C}) = C$	Set of energy commodities
$\mathcal{J} = \{\dots, i_i, \dots\}, \dim(\mathcal{J}) = I$	Set of energy corridors
$\mathcal{C}_i \subseteq \mathcal{C} \mid c_i \in \mathcal{C}_i$	Commodity delivered by corridor $i_i$
$\mathcal{K} = \{\dots, k_k, \dots\}, \dim(\mathcal{K}) = K$	Set of countries (both source and corridor)
$\mathcal{K}^i \subseteq \mathcal{K} \mid k_h \in \mathcal{K}^i$	Country crossed by corridor $i_i$
$\mathcal{L} = \{\dots, l_i, \dots\}, \dim(\mathcal{L}) = L=I$	Set of corridor lengths (km)
$\mathcal{B}^i = \{\dots, b_{b_i}, \dots\}, \dim(\mathcal{B}) = B^i$	Set of the lengths of branches of corridor $i_i$
$\mathcal{D} = \{\dots, d_d, \dots\}, \dim(\mathcal{D}) = D$	Set of distribution / transmission infrastructures
$\gamma_k$	Geopolitical country index weight for Country $k$ , depending on the length of each corridor branch
$\vartheta_{c,d}$	Resilience index for the internal distribution network $d$ carrying commodity $c$
$\xi_i$	Risk index of corridor $i$
$\phi_k$	Geopolitical country index for country $k$
$\lambda$	Import dependency (%)
$\omega_i$	Probability of success of corridor $i$
$Q$	Energy Intensity of the Economy
$w_1$	Weight coefficient for the internal risk
$w_2$	Weight coefficient for the external risk
$R_i$	Risk of corridor $i$
$R_{int( ext)}$	Overall internal (external) risk value
$R_{int( ext),m}$	Overall internal (external) risk, monetary units
$S_i$	Expected supply of corridor $i$
$S_{int( ext)}$	Overall internal (external) expected supply
$E$	Total energy supply
$E_{c,i}$	Energy flow of commodity $c$ carried by corridor $i$
$R_n$	National Energy Security Index

609  
 610  
 611  
 612  
 613  
 614  
 615  
 616  
 617  
 618  
 619  
 620  
 621  
 622  
 623  
 624

625

**Table 3: Geopolitical country index  $\varphi_k$** 

Source Country	$\varphi$	Source Country	$\varphi$
Algeria	44.7	Mexico	31.7
Angola	61.7	the Netherlands	10.5
Australia	12.5	Nigeria	48.0
Austria	22.0	Norway	0.4
Azerbaijan	43.9	Qatar	44.2
Belgium	25.8	Russia	34.0
Canada	9.9	Saudi Arabia	47.9
China	44.1	Slovenia	28.7
Colombia	39.9	South Africa	36.1
Congo	55.0	Spain	24.1
Egypt	47.0	Switzerland	22.8
France	23.0	Syria	52.5
Gabon	44.5	Thailand	40.1
Germany	12.3	Tunisia	44.7
Ghana	52.7	Turkey	41.8
Greece	30.2	Turkmenistan	52.3
India	38.3	the Ukraine	35.9
Indonesia	46.0	the UAE	43.1
Iran	50.4	the USA	5.9
Iraq	67.9	Venezuela	39.9
Kazakhstan	38.3		
Kuwait	38.5		
Libya	47.5		

626  
627  
628**Table 4: Scenarios for the energy security analysis**

S	Description	Country risk $\varphi_k$	Corridor disruption
S1	Increased activity of terroristic groups in NA	+15% Algeria, Egypt, Libya, Tunisia	-
S2	Deterioration of the Italian/Qatari relations	-	Unavailability of all the Qatari LNG corridors (4)
S3	Antagonistic actions in Libya	-	Disruption of the NG Greenstream corridor (1)
S4	Increase in contrast between Russia and the Ukraine	+10% Russia, Ukraine	Closure of the NG/Oil pipelines in the Ukraine (3 +1)
S5	Simultaneous Scenarios 1 + 4	+15% Algeria, Egypt, Libya, Tunisia; +10% Russia, Ukraine	Closure of NG/Oil pipelines in the Ukraine (3 +1)

629

630

**Table 5: Impact analysis for various scenarios, all commodities (reference 2014)**

	Total Supply		
	Energy risk [TJ/y]	Economic risk [G€/y]	Percentage variation
REF	3320988,0	848,9	-
S1	3421496,4	874,6	+ 3,03%
S2	3402748,3	869,8	+ 2,46%
S3	3437896,7	878,7	+ 3,52%
S4	3609261,2	922,6	+ 8,68%
S5	3709769,6	948,2	+ 11,70%

631

632

633

634

**Table 6: Impact analysis for various scenarios - only NG (reference 2014)**

	Natural Gas Supply		
	Energy risk [TJ/y]	Economic risk [G€/y]	Percentage variation
<i>REF</i>	1412834,3	361,1	-
<i>S1</i>	1470743,8	375,9	+ 4,10%
<i>S2</i>	1494594,5	382,0	+ 5,79%
<i>S3</i>	1529742,9	391,0	+ 8,27%
<i>S4</i>	1643575,4	420,1	+ 16,33%
<i>S5</i>	1701484,9	434,9	+ 20,40%

635  
636**Table 7: Monthly energy and economic risk variation for *S1***

	Energy risk [TJ/month]		Economic risk [G€/month]		% variation
	REF	S1	REF	S1	
January	326301,9	335475,6	83,4	85,7	+ 2,8%
February	266461,9	275681,2	68,1	70,5	+ 3,5%
March	285720,8	292396,6	73,0	74,7	+ 2,3%
April	271453,4	280431,3	69,4	71,7	+ 3,3%
May	303996,6	313961,8	77,7	80,3	+ 3,3%
June	260970,7	267085,1	66,7	68,3	+ 2,3%
July	290410,6	297436,9	74,2	76,0	+ 2,4%
August	259432,6	268039,6	66,3	68,5	+ 3,3%
September	246424,2	255304,8	63,0	65,3	+ 3,6%
October	264644,3	271567,0	67,6	69,4	+ 2,6%
November	266992,5	276374,6	68,2	70,6	+ 3,5%
December	278178,6	287741,8	71,1	73,5	+ 3,4%

637  
638**Table 8: Energy and economic risk variation for mitigation actions to *S2***

	Energy risk [TJ/y]	Economic risk [G€/y]	Percentage variation
<i>S2</i>	3353434,3	857,2	-
<i>MA1-S2</i>	3360660,8	859,0	-1,21%
<i>MA2-S2</i>	3329944,1	851,2	-2,10%
<i>MA3-S2</i>	3319985,2	848,6	-2,39%

639  
640**Table 9: Energy and economic risk variation for mitigation actions to *S3***

	Energy risk [TJ/y]	Economic risk [G€/y]	Percentage variation
<i>S3</i>	3387423,0	865,8	-
<i>MA1-S3</i>	3334651,4	852,4	-1,56%
<i>MA2-S3</i>	3269333,4	835,7	-3,49%

641  
642**Table 10: Energy and economic risk variation for the *S4* mitigation actions**

	Energy risk [TJ/y]	Economic risk [G€/y]	Percentage variation
<i>S4</i>	3555031,6	908,7	-
<i>MA1-S4</i>	3203725,9	818,9	-9,88%
<i>MA2-S4</i>	3196688,0	817,1	-10,08%

643  
644  
645  
646  
647  
648  
649  
650

651 FIGURES  
 652  
 653

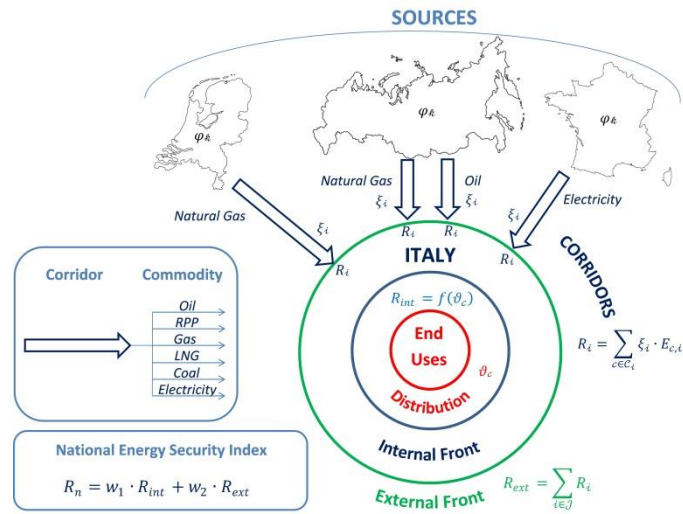


Fig. 1 – “Fronts” and risk indexes in a national energy security assessment

654  
 655  
 656  
 657

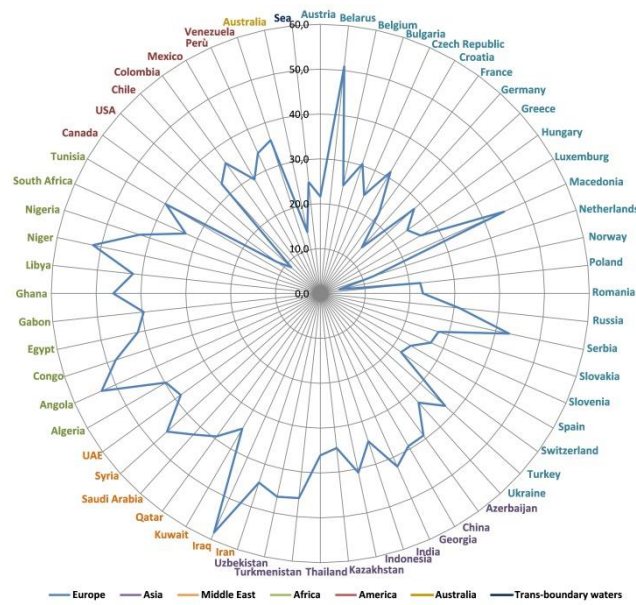


Fig. 2 – Polar representation of the geopolitical country index  $\phi_k$

658  
 659  
 660  
 661  
 662