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Modelling the geopolitical impact on risk assessment of energy supply system: the case of Italian crude oil supply

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Nomenclature

Symbol	Description
$C = \{\dots, c_c, \dots\}, dim(C) = C$	Set of energy commodities
$J = \{\dots, i_i, \dots\}, dim(J) = I$	Set of energy corridors
$K = \{\dots, k_k, \dots\}, dim(K) = K$	Set of countries
$K^i \subseteq K \vee k^i \in K^i$	Set of countries crossed by (captive) corridor i_i
$K'^i \subseteq K' \vee k'^i_k \in K'^i$	Set of sea areas crossed by (maritime) corridor i_i
$\Theta = \{\dots, \theta_\theta, \dots\}, dim(\Theta) = \Theta$	Set of chokepoints
$\Theta^i \subseteq \Theta \vee \theta^i_\theta \in \Theta^i$	Set of chokepoints crossed by corridor i_i
$K'^\theta \subseteq K' \vee k'^\theta_k \in K'^\theta$	Set of coastal countries bordering the chokepoint θ_θ
$\Pi = \{\dots, \pi_\pi, \dots\}, dim(\Pi) = \Pi$	Set of pipelines
$T = \{\dots, \tau_\tau, \dots\}, dim(T) = T$	Set of export port
$\Pi^\tau \subseteq \Pi \ \pi^\tau_\pi \in \Pi^\tau$	Set of pipelines ending on export port τ_τ
γ_π	Capacity of a single pipeline (kbl/d)
Γ^τ	Total capacity of a set of pipelines Π^τ ending in the same port τ_τ (kbl/d)
c_π	Capacity factor of a single pipeline (-)
$L = \{\dots, l_l, \dots\}, dim(L) = L = I$	Set of corridor lengths
$B = \{\dots, b_b, \dots\}, dim(B) = B$	Set of branches lengths
$B^i \subseteq B \vee b^i \in B^i$	Set of lengths of branches of corridor i_i
$M = \{\dots, \mu_{k'}, \dots\}, dim(M) = M$	Set of lengths of maritime branches crossing sea areas k'
$M^i \subseteq B^i \vee \mu^i_{k'} \in M^i$	Set of lengths of maritime branches of corridor i_i crossing sea area k'
$X = \{\dots, \chi_k, \dots\}, dim(X) = X$	Set of captive branches crossing countries k
$X^i \subseteq B^i \vee \chi^i_k \in X^i$	Set of lengths of captive branches of corridor i_i
δ^i_k	Weight (distance) factor of a captive branch of corridor $i_i$crossing the country k (-)
$\delta^i_{k'}$	Weight (distance) factor of a maritime branch of corridor i_i crossing the sea area k' (-)
σ_k	Geopolitical stability index of country k (-)
ρ_k	Geopolitical risk index of country k (-)
$\eta_{k'}$	Piracy index referred to coastal country k' (-)
$\rho_{k'}$	Geopolitical risk index of sea area k' (-)
$\overline{\rho}_{k'}$	Geopolitical risk index of international waters (-)
d	Distance from the coast (km)
λ_θ	Length of a chokepoint (m)
ζ_θ	Width of a chokepoint θ_θ (m)
α_θ	Vulnerability of a chokepoint θ_θ (-)
ρ_θ	Geopolitical risk index of chokepoint θ_θ (-)
ξ_θ	Probability of failure of a single chokepoint θ_θ (-)
ξ^i_θ	Probability of failure of chokepoints along the corridor i_i (-)
ξ^i_μ	Probability of failure of maritime branches of corridor i_i (-)
ξ^i_χ	Probability of failure of captive branches of corridor i_i (-)
ω_i	Probability of success of corridor i_i (-)

ξ_i	Probability of failure of corridor i_i (-)
Q_i^c	Amount of commodity transported by (maritime) corridor i_i (ton)
E_i^c	Energy content of commodity c transported by the corridor i_i (Mtoe)
R_i^c	Energy at risk through the corridor i_i (Mtoe)
R_s^c	Energy at risk to the entire supply system of commodity c

1. Introduction

Ensuring energy availability to meet the national demand is one of the main requirements for the economic growth and social welfare of a country.

The ongoing energy transition policies are favouring the increasing share of renewable resources in the energy mix of many countries, contributing to reduce the fossil consumption, and therefore the dependence on fossil imports. On the other hand, in 2021 fossils still accounted for 82% of global primary energy demand (oil accounted for 31%, coal for 27% and natural gas for 24% [1]). The uneven distribution of oil, gas and coal, coupled with the high demand worldwide, often entails geopolitical instability in the leading producer countries, such as Saudi Arabia and Russia, accounting together for 22% of the global oil demand [2]. Other more geopolitical stable countries such as Norway export fossil resources, but they do not have unlimited availability to meet the global demand.

As shown by the economic crisis following the Russia-Ukraine's war in 2022, geopolitical instability represents a real threat for the security of the energy supply system and deeply affects the global market, leading to intense price volatility. Indeed, the impact of sanctions imposed against Russian crude oil and natural gas, deeply affected the countries importing copious amounts of oil and natural gas from Russia. For instance, European Union (EU-27) has been particularly affected since Russian gas accounted for almost 40% of total EU-27's gas supply in 2021 [3]. Energy crisis forced the European Commission to recalibrate the order of priorities: the former Fit for 55 plan [4] prioritized decarbonisation process, namely reducing European Union's greenhouse gas emissions by 55% by 2030, whereas the REPowerEU plan [5], following the Russian-Ukrainian conflict and designed to address the urgency of energy dependency on Russia, defined as a priority decreasing Russian gas demand even by means of short-terms countermeasures (e.g. gas to coal switching) in contrast with long-term sustainability goals [4] . The REPowerEU plan demonstrates how much geopolitical events, such as the Russia-Ukraine's war can affect not only the reliability of the energy supply-side but also the order of policy priorities, conditioning policymaking and the relevance assigned to each of the three vertices of the so-called "energy trilemma": security, equity, sustainability. Nowadays, EU policies are prioritising energy security and affordability (equity) instead of environmental sustainability, which in previous years has played a leading role in the EU Green Deal and the following agreements ([6]–[8]).

In this context, science-based methodologies become crucial to support policy makers in monitoring the security of energy supply corridors and planning strategies designed to prevent critical situation (prevention strategies) and to intervene promptly to mitigate any loss of energy commodity (protection strategies). This aspect implies the need to transform complex and non-quantitative concept (e.g., the geopolitical security of a country) into numerical information that can be included in a calculation model to estimate the energy supply risk of a country and to implement risk scenario assessment.

International organizations such as World Energy Council and World Economic Forum consider energy security as one of the main domains considered to quantify the energy trilemma index [9] and the energy transition performance [10]. Axon et al. [11] process an extensive review of risks and characterize distinct causes of risk grouped in seven categories but without defining an overall index or model of risk. On the other hand, Augutis et al. [12], coupled an "indicator-based" framework [13] with "model-based" method [14], to forecast the energy security intended as the system's resistance to stochastic disturbances. Several "indicator-based" methodologies can be found in literature: Kisel et al. [15] propose the Energy Security Matrix including electricity, heat and transport indicators; Wang et al. [16] and Radovanovic et al. [17] extend the concept of energy security by including technical, economic and political factors, whereas Zhang et al. [18] adopt a qualitative-quantitative method by employing the hybrid model of GRA-TOPSIS [19]. These studies aim to assess energy risk by means of normalization, weighting, and aggregation of a set of indicators rather than by means of a risk model. Moreover, Abdullah et al. [20] developed Energy Security Of Pakistan (ESIOP) to assess energy security performance; Kitamura et al. [21] analysed the Japan's energy security related to fossil resources' supply system; Iliopoulou et al. [22] adopted a multi-objective problem to assess energy system security of the Aegean archipelago's islands; Erahman et al. [23] assessed Indonesia's Energy Security Index (ESI). These studies delve into specific energy security's aspects (e.g., fossil fuels supply) but they are tailored for the specific case study and cannot be used to assess energy risk of other countries. Similarly, Wang et al. [24] perform a multi-agent game analysis to assess the security of Chinese natural gas supply system; Su et al. [25] adopt the Ecological Network Analysis (ENA) to evaluate and compare the oil and gas supply security in China.

With regards to oil supply, Iqbal et al. [26] focused introduced the Oil supply Vulnerability Index (OVI), an extension of the study carried out by Gupta et al. [27]; Yang et al.[28] propose the Oil Supply Risk Index (ORSI), obtained by the combination of country risk index (International Country Risk Guide, ICRG) with the traditional Herfindahl-Hirschman Index (HHI) and three modified versions of HHI. These "indicator-based" approaches can capture the current and past energy security of one or more countries and can be used to perform ranking, but they cannot provide any evaluation of future scenarios likewise the "modelling-based" approach such as the risk model developed by Bompard et al. [29] based on the geopolitical stability of countries crossed by the natural gas's supply corridors.

Since fossil fuels supply often occurs by sea, especially oil and LNG (Liquefied Natural Gas), the risk related to maritime corridors cannot be ignored. Some studies focused on very specific maritime topics such as Goerlandt et al. [30] and Parviainen et al. [31], evaluated maritime risk by focusing on oil spill, while Zaman et al. [32], and Du et al. [32], [33] used Automatic Identification System (AIS) data to perform maritime risk assessment. In line with maritime risk assessment but focusing on piracy, Tseng et al. [34] adopt fuzzy analytic hierarchy process to prioritize the key defence indicators to plan piracy defence strategies. Moreover, when dealing with the risk related to energy supply by sea, the risk related to straits and chokepoints is crucial. Indeed, given their strategical position and their morphology, chokepoints are characterized by an intense marine traffic and the International Maritime Organization (IMO) [35] included these areas in the Traffic Separation Scheme (TSS) aiming to avoid navigational hazards such as ships collisions. Moreover, straits can be more subjected to terroristic attacks or conflicts among countries bordering the strait which want to establish their authority by imposing restrictions or blocking ships' passage. Many studies are focused on the risk of crossing chokepoints ([36]–[42]), among them, Gao et al. [43] developed a model to assess the impact of strait blockades of the Chinese fleet in terms of transportation costs. However, all these works are too focused on a single commodity (e.g., natural gas) or specific factors (e.g., oil spill risk, piracy, chokepoint blockade) and they do not take into consideration the overall route covered by the commodity from the origin country to the final entry point in the importing country. On the other hand, Sun et al. [44] introduce four factors to assess the risk related to each stage of the Oil Supply Chain (OSC): availability (supply side), accessibility (transportation side), market side (affordability) and acceptability (demand side). The length of corridors (both sea route and pipeline) and the influence of piracy attacks are both included. However, they did not include the impact of the geopolitical stability of countries crossed by pipelines neither of crossed sea areas is not considered. Moreover, the model is designed for a single commodity and it does not track the exact route, but they use a substitution variable of the covered distance. Besides, the model lacks the risk of crossing straits (e.g., Hormuz Strait) or canals (e.g., Suez Canal) even if they are crucial to assess probability of failure of maritime routes.

The literature review highlighted the lack of models assessing the risk of supply for a given energy commodity and for a given importing country by taking into account the entire supply chain from the producer country up to the national entry point, both via pipelines and by sea routes. Many studies focus on specific risk factors (e.g., presence of piracy, crossing chokepoints, etc.) but no one tries to combine them The scope of this work is to bridge this gap, by developing a novel approach to supply system's risk assessment by translating the traditional definition of risk in a geopolitical perspective. Hence, although aware of the variety of risks affecting the security of the national energy system, the model has been focused on the security of the external front of the energy supply system, more affected by the geopolitical stability of suppliers [29]. The evaluation of the threats influencing the security of the internal front [15] (e.g., cyber-attacks, inadequate investment, shortage of skilled labour, etc.), including the availability of local energy resources and the adequacy of national energy infrastructure (e.g., distribution and transmission network), are out of the scope of this paper because more related to the domestic arrangements rather than to the geopolitical risk of third countries [29]. For the same reason, the resilience of the supply system, intended as the capability of the system to react to disturbances [15] and addressed in other studies ([15], [45], [46]) is excluded from the analysis.

The proposed method couples the geopolitical risk of crossed areas (via pipeline and by sea) with spatial and energy factors (e.g., length of the corridor and energy transported by the corridor). Further risk factors related to crossing chokepoint and the presence of piracy areas along the route are included too. or to crossing chokepoints the security of the external supply-front of a given energy system, taking into account also the.

Although aware of the variety of risks related to the domestic arrangements (i.e., internal front) [29] and affecting the security of the national energy security (e.g., inadequate infrastructure, poor policy, shortage of skilled labour, accidents, etc.), the scope of this work is to bridge the gap in literature, by presenting a novel risk model addressing in a geopolitical perspective the security of the external supply-front of a given energy system, taking into account also the spatial and energy dimensions. For this purpose, the probability of failure of each supply corridor is defined as core element of the risk model and then it is used to quantify the overall external energy risk. Moreover, this study aims to support policy makers in risk prevention and impacts mitigation by means of a model able to perform risk scenario analysis and compare impacts of different scenarios and countermeasures.

The proposed methodology is here illustrated with reference to crude oil supply to Italy: the developed risk model is applied to assess both the current Italian energy security related to crude supply and to evaluate the impacts on oil supply system of alternative risk scenarios (potential and actual) in terms of energy at risk.

The paper is structured as follows. The adopted model is described in section 0; the results of case study are discussed in section 3; limitations, conclusions and future work are reported in section 4.

2. Risk model

The traditional definition of risk, intended as the product of probability of occurrence (p) with the entity of the damage (D), is translated into energy terms by adopting a geopolitical perspective in order to assess the security of the external front of the energy supply system. The geopolitical dimension is measured by means of a geopolitical risk assigned to all countries and sea areas crossed by corridors. Moreover, a piracy risk indicator is allocated to sea areas subjected to piracy attacks and a further risk is assigned to maritime routes crossing one or more chokepoints. The spatial dimension is included in the model by considering the length and pathway covered by corridor i from the origin country to the national entry point. The energy dimension is instead represented by the energy content of the flow of commodity transported by the corridor.
The probability of failure of each corridor ξ_i, obtained by the aggregation of geopolitical and spatial factors, is combined with the energy flow E_i^c to quantify the energy risk of the single corridor R_i^c. In the end, the energy risk of the entire supply system of a certain commodity R_s^c, is obtained by aggregating the energy risk of all corridors.

$$R_s^c = \sum_i^I R_i^c \qquad (1)$$

A corridor i_i is defined as:

$$\forall i_i \in J : i_i = \{c_c, l_l, K_i, K'_i\} | c = l = i$$

Corridor $i_i \in J$is characterized by a length $l_i \in L$, a commodity $c_c \in C$, a set of crossed countries K_i (including the country of origin) and a set of crossed sea areas K'_i.

Each corridor is composed by several segments ("branches") distinguished into two categories: "captive branches" when crossing countries overland through pipelines, and "maritime branches" when the corridor crosses sea areas. The total length of a given corridor i_i is obtained by the sum of all branches (both captive and maritime).

$$l_i = \sum_{k'} \mu_{k'}^i + \sum_k \chi_k^i \qquad (2)$$

where $\mu_{k'}^i \in i_i$ and $\chi_k^i \in i_i$

Shape and length of each branch is obtained by adopting a geographic information system (GIS) approach. Each maritime and captive branch is then characterized by a probability of failure, ranging between 0 and 1 depending on geopolitical and spatial features: 0 means successful branch crossing and 1 refers to failed branch crossing. Risk assessment is performed with a conservative approach by considering branch crossings as stochastically independent events (occurrence of one event does not affect the probability of the others), leading to higher risk values [29]. Then, the overall probability of disruption of a given corridor ξ_i is obtained by combining the failure probabilities of all branches composing it. Unsuccessful crossing of a single branch is sufficient to disrupt supply from the entire corridor as a result of combination of independents event.

The traditional definition of risk is adapted in terms of energy as follow:

$$R_i^c = \xi_i E_i^c \qquad (3)$$

Where $\xi_i$is the probability of failure of the corridor (-), E_i^c is the energy content of commodity transported, R_i^crepresents the amount of energy at risk.

2.1. *Probability of failure assessment*

The probability of failure of a single corridor ξ_i is defined as a function of the geopolitical stability of countries and sea areas crossed, weighted according to lengths of maritime and captive branches. Moreover,$\xi_i$increases in case of crossing chokepoints and piracy zones.

$$\xi_i = f\left(\rho_k, \eta_{k'}, \lambda_\theta, \zeta_\theta, \chi_k^i, \mu_{k'}^i \overline{\mu}_{k'}^i\right) \qquad (4)$$

The spatial dimension is included in the risk model by means of a weight factor defined for all branches of corridor i_i, respectively δ_k^i for captive branches and $\delta_{k'}^i$ for maritime branches, obtained by the ratio between the branch's length and the total length $l_i$of the corridor i_i:

$$\delta_k^i = \frac{\chi_k^i}{l_i} \chi_k^i \in i_i \qquad (5)$$

$$\delta_{k'}^i = \frac{\mu_{k'}^i}{l_i} \mu_{k'}^i \in i_i \qquad (6)$$

2.1.1. Captive branches

The probability of failure of each captive branch ($\xi_{\chi,k}^i$) belonging to corridor i_i, is defined as a combination of geopolitical dimension (the geopolitical risk $\rho_k$of crossed country k) and the spatial dimension (weight factor δ_k):

$$\xi_{\chi,k}^i = \rho_k \delta_k \qquad (7)$$

2.1.2. Maritime branches

Likewise, the probability of failure of maritime branch ($\xi_{\mu,k'}^i$) is defined as a function of the weight factor $\delta_{k'}$ and the geopolitical risk $\rho_{k'}$of crossed sea areas k'but, in addition to this, two different formulations are introduced to calculate $\rho_{k'}$ according to Exclusive Economic Zone (EEZ) subdivision [47], which gives to coastal countries sovereign jurisdiction of sea areas within 200 Nautic Miles (NM), i.e. about 370 km from their coast. Above EEZ boundaries, sea areas are defined international waters, in contrast, within EEZ boundaries sea areas are defined national waters. The geopolitical risk of national waters is obtained by the mean of geopolitical risk of coastal country with the piracy index ($\eta_{k'}$), while in international waters the average value of geopolitical risks ($\overline{\rho}_{k'}$) of all sea areas K' is used.

$$\rho_{k'} = \begin{cases} \frac{\rho_k + \eta_{k'}}{2} & d < 370km \\ \overline{\rho}_{k'} & d > 370km \end{cases} \qquad (8)$$

where:

$$\overline{\rho}_{k'} = \frac{\sum_{k'}^{K'} \rho_{k'}}{K'} \qquad (9)$$

The probability of failure of each maritime branch $\xi_{\mu,k'}$ is defined as follow:

$$\xi_{\mu,k'} = \rho_{k'} \delta_{k'} \qquad (10)$$

2.1.3. Chokepoints

When considering the risk related to the presence of chokepoints along the route, two categories are taken into consideration [48]:

1. straits and canals: narrow channel characterized by physical borders (natural or artificial) that connect two larger areas of sea (e.g., Bosporus and Dardanelles connecting Black Sea with Mediterranean Sea and Suez Canal connecting Red Sea with Mediterranean Sea)
2. borderless chokepoints, characterized by high vessel traffic due to their strategic position (e.g., Cape Horn in south America, Cape Town in south Africa, Kattegat between Denmark and Sweden).

To measure the chokepoint (and strait) risk factor, both geopolitical and spatial dimensions are considered: respectively, the geopolitical risk, as a function of the geopolitical security of coastal countries neighbouring the chokepoint, and the intrinsic vulnerability (α_θ) factor, affected by the morphological characteristics, namely length (λ_θ) and width (ζ_θ), of the chokepoint θ_θ.

The geopolitical risk $\rho'_\theta$of each chokepoint is formulated as follow:

$$\rho'_\theta = \frac{\sum_{k'}^{K'^\theta} \rho_{k'}}{K'^\theta} \qquad (11)$$

Where: $k' \in K'^\theta$ and K'^θ is the number of coastal countries bordering the chokepoint.

The vulnerability indicator α_θ, relevant only for confined chokepoints (straits and canals), measures the intrinsic tendency of the chokepoint to be less or more susceptible to blockade due to its morphological constitution: wider is the strait, the less likely will be the total blockade of ships passage; on the contrary, longer is the channel, higher will be the probability of ship accidents, piracy occurrence, terroristic attacks or other adverse events.

$$\alpha_\theta = \frac{\lambda_\theta}{\zeta_\theta} \qquad (12)$$

However, vulnerability index cannot be used in combination with ρ'_θwithout a previous normalization. Hence, a logarithmic normalization is performed:

$$\dot{\alpha}_\theta = \frac{ln(\alpha_\theta + 1) - ln\left(\alpha_{\theta_{min}} + 1\right)}{ln(\alpha_{\theta_{max}} + 1)} \qquad (13)$$

Where $\dot{\alpha}_\theta$ ranges between 0 and 1

The probability of failure of the chokepoint $\xi_\theta \xi_\theta = \rho'_\theta \dot{\alpha}_\theta$ (14) is finally formulated as follow:

$$\xi_\theta = \rho'_\theta \dot{\alpha}_\theta \qquad (14)$$

2.1.4. Aggregation

Before calculating the probability of failure ξ_i of the entire corridor, contributions of individual branches and chokepoints are aggregated as a combination of independent events [29] by using the complement of ξ_i, corresponding to the probability of success ω_i, defined as follow:

$$\omega_i = 1 - \xi_i \qquad (15)$$

For a given corridor i_i, the total probability of failure of captive branches is formulated as follow:

$$\xi_\chi^i = 1 - \left(\prod_{\chi_k^i}^{X^i} (1 - \xi_{\chi,k}^i)\right) \qquad (16)$$

The total probability of failure of maritime branches belonging to corridor i_i is instead defined as:

$$\xi_\mu^i = 1 - \left(\prod_{\mu_{k'}^i}^{M^i} \left(1 - \xi_{\mu,k'}^i\right)\right) \qquad (17)$$

Finally, the probability of failure of any chokepoint along the route of corridor i_i is defined as:

$$\psi^i = 1 - \left(\prod_{\theta^i}^{\Theta^i} \left(1 - \xi_\theta^i\right)\right) \quad (18)$$

Likewise, χ_i, μ_i andψ_i are aggregated as independent events to obtain the probability of failure related to the entire corridor:

$$\xi_i = 1 - \left[(1 - \xi_\chi^i)(1 - \xi_\mu^i)(1 - \psi^i)\right] \qquad (19)$$

2.2. Energy risk calculation

The overall energy risk R_i of a given corridor (equation 3) is calculated as the product between the probability of failure ξ_i and the corresponding entity of damage, expressed in terms of energy E_i^c. The value of E_i^c corresponds to the energy content of commodity *c* transported by the corridor in the considered time frame (e.g., one month or one year). The overall risk R_S^c is then obtained by adding the contribution of all the corridors i_i supplying the energy commodity c_c. It corresponds to the amount of energy at risk and can be calculated with reference to different time horizons: a past period (e.g., last year, last six months), as showed in section 3, or a period in the future, by defining possible risk scenarios, as discussed in section 2.3.

To summarise the logic and the setup adopted in this work, Figure 1 illustrates the main elements included in the model.

2.3. Risk scenario assessment

The developed risk model allows to perform risk scenario analyses by quantifying and comparing their impact on the energy risk of supply system. Two main categories of risk scenarios are introduced: potential risk scenarios, based on the assumption of the worsening of geopolitical stability of one or more countries or sea areas, but without an effective loss of energy; actual risk scenarios, which take into consideration events that really occur and cause an effective loss of energy from one or more supply corridors (e.g. strait blockade or corridor disruption due to accidents, attack or policy action). In this case, mitigation countermeasures are required to limit the negative impacts on energy system and alternative corridors have to be identified to recover the lost amount of commodity.

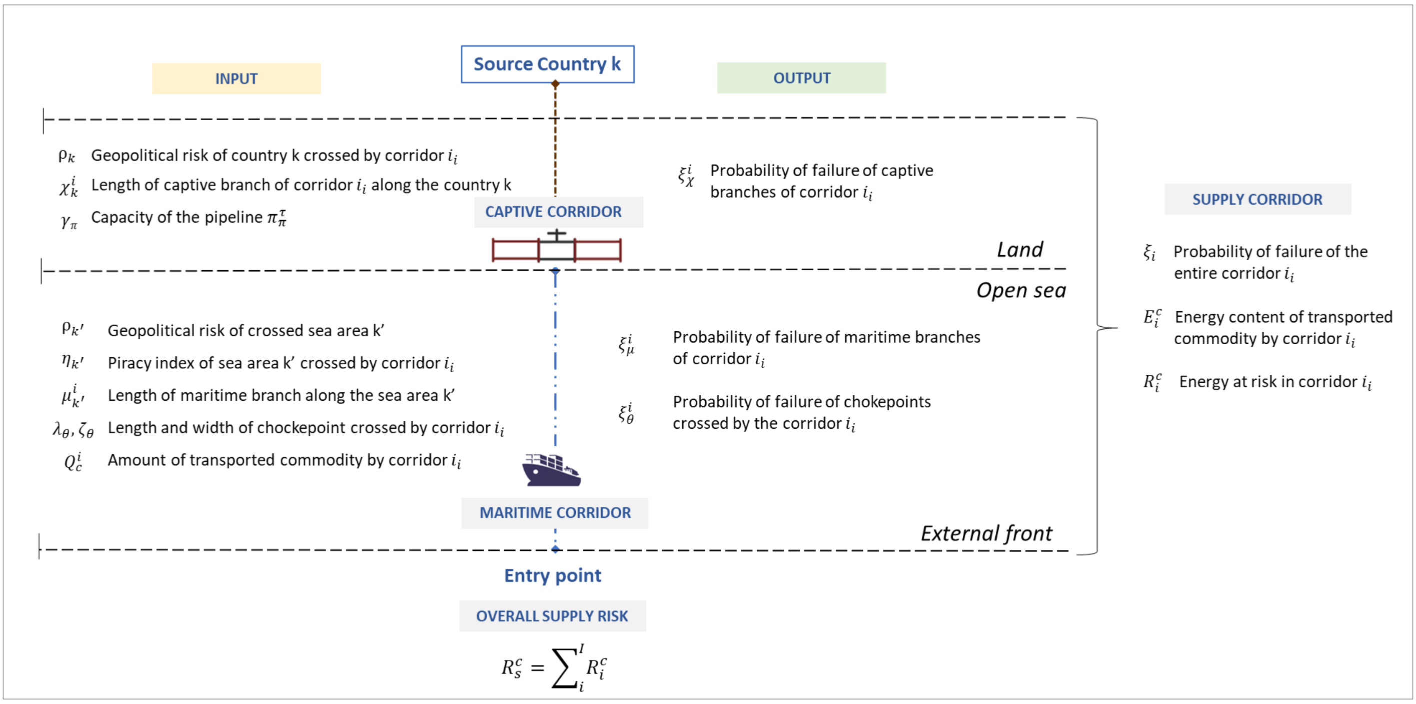

Figure 1: Conceptual map of the risk assessment model

3. Case study

In order to test the developed methodology, Italy has been selected as case study since it is one of the EU countries with the highest energy dependency (73%) [49]. Despite Italian government is trying to enhance diversification in the energy mix, oil and gas still account for the majority of Italian energy import: LNG and oil supply occurs mainly by sea whereas natural gas is transported through pipelines.

The case study deals with crude oil supply, more relevant for the Italian energy mix. In 2021 refined products import amounted to 13.3 Mton, far less than crude oil equal to 57 Mton [50]). Compared to natural gas, which is directly delivered by producer countries to importing countries via pipelines, crude oil supply is more complex. Indeed, many crude oil producing countries (e.g., Azerbaijan) miss a direct access to sea, therefore, crude is firstly transferred via pipelines to the ports of third countries and then exported by sea. Azerbaijan, Kazakhstan and Saudi Arabia, three of the main crude oil suppliers for Italy, use foreign ports (e.g., Turkish, Russian, Egyptian and Libyan) to export crude oil to Mediterranean Sea. Since crude exchanges between countries are generally difficult to be detected, specific backward analyses (from the national entry point back to the origin site) are performed, by using a maritime oil trade database [51] and the national database [50].

3.1. *Backward analysis*

Starting from the national entry points (ports), crude supply corridors and exporting ports are identified. Then, the risk assessment is extended to the entire supply corridor. To meet this need, pipeline name, producing country and capacity of pipeline are gathered by pipeline database [52] used as integration of oil maritime trade database [51]. Since direction and actual flow of crude through pipelines are missing, the directions are derived by cross-checking national datasets [50] with maritime information [51] and other international sources on oil trade ([53]–[61]); the flow is derived by multiplying the amount of crude departed from the port τ_τ (Q_i^c) with the pipeline's capacity factor c_π. If the exporting port is not connected to any pipeline or in case of several pipelines belonging to the same country of port τ_τ, the capacity factor is set equal to 1. If among the pipelines at least one comes from a different country, it is calculated as follow:

$$c_\pi = \frac{\gamma_\pi^\tau}{\Gamma^\tau} \qquad (20)$$

Where: γ_π^τ is the capacity of pipeline π ending in the export port τ (kbl/d); Γ^τ is the total capacity of the set of pipelines Π^τ ending in the same exporting port τ_τ (kbl/d).

3.2. *Geopolitical indicators*

The Worldwide Governance Indicators (WGIs) provided by World Bank [62] are used as reference values for assessing the geopolitical stability of each country [48]. These indicators, ranging from 0 (low stability) to 100 (high stability), quantify the geopolitical stability of a country by considering six main aspects: Voice and Accountability, Political stability and absence of violence, Government effectiveness, Regulatory quality, Rule of law, Control of corruption. The geopolitical stability σ_k of each country is obtained by normalizing and averaging the six WGIs:

$$\sigma_k = \frac{\sum_{j=1}^{6} \frac{WGI_{j,k}}{100}}{6} \quad (21)$$

Syria (1.52), South Sudan (1.59) and Somalia (1.84) resulted the least stable countries, on the contrary, New Zealand (97.76), Norway (97.61) and Switzerland (96.65) the most stable countries. Then, the geopolitical risk ρ_k of a given country is obtained from the complementary value of geopolitical stability.

$$\rho_k = 1 - \sigma_k \qquad (22)$$

Piracy and Armed Robbery Index (PARI) provided by Maritime Security Indexes [63] is used as reference index to quantify the maritime security of sea areas k' according to piracy occurrences. The value ranges between 0 (low security, high presence of piracy and armed robbery) and 100 (high security, low presence of piracy and armed robbery). The corresponding piracy index $\eta_{k'}$ ranging between 0 (low risk) and 1 (high risk) is obtained from the complementary value of PARI normalized as follow:

$$\eta_{k'} = 1 - \frac{PARI}{100} \quad (23)$$

Then, the overall geopolitical risk index of each sea area k' is calculated by the mean of piracy index $\eta_{k'}$ with the geopolitical risk country k according to the EEZ subdivision as formulated in equation 8.

3.3. Energy risk

Once completed the backward tracing of the entire corridor from the national entry point up to the origin location, the energy risk is calculated as follow:

$$E_i^c = Q_i^c c_f \lambda_c f \qquad (24)$$

Where Q_i^c is the amount (ton) of crude oil transported through maritime corridor in 2021 [51], c_f is the pipeline's capacity factor, λ_c is the Low Heat Value (LHV) [64]) and f is the conversion factor to obtain the energy risk in the chosen unit of measurement. In this study, the adopted unit of measure for E_i^c is tonnes of oil equivalent (toe) and the commodity is crude oil, therefore f is equal to 1.

3.4. Energy risk assessment of Italian crude oil's supply system

As regards 2021, 11 Italian ports, 70 exporting ports and 966 maritime voyages travelled by 353 vessels have been tracked. Then, by tracing back the corridors from the Italian ports up to the producing countries, a total of 32 corridors were identified (Table 10 in Appendix A: Corridors for crude oil supply to Italy). The total amount of crude oil discharged in Italian ports in 2021 resulted equal to 93.2 Mt/y, of which about two-thirds coming from Turkey (25.7%), from Russia (23.4%) and Libya (18.1%). Almost 40% of 93.2 Mt/y was discharged in the Trieste port and exported to eight European refineries (in Germany, in Austria and in the Czech Republic [65]) through the TAL oil pipeline, whereas the remaining crude goes to refining, as for crude discharged in Sarroch and Augusta ports, sent to the refineries of Saras (Sardinia), Isab and Sonatrach (Sicily).

Among the 32 corridors identified, Iraq-Italy resulted the most critical with an average probability of failure equal to 0.89, followed by United Arab Emirates – Italy (0.88) and Saudi Arabia - Italy (0.88). Those corridors, indeed, have both geopolitical and spatial risk factors: long distances to be covered, crossed areas with low geopolitical stability, presence of piracy and chokepoints along the route. In particular, the Iraq-Italy covers the longest distance, by crossing Hormuz and Bāb el-Mandeb straits, passing close to Somalia, Yemen, Eritrea and Sudan (with high presence of piracy and low geopolitical stability), and crossing the Suez Canal up to the Mediterranean Sea. However, the impact on the overall energy risk in 2021 results modest due to the relatively low amount imported: 3 Mt/y from Iraq (3.2% of total crude import), 0.1 Mt/y from United Arab Emirates and 0.1 Mt/y from Saudi Arabia. By considering the contributions of all 32 supply corridors, the overall energy risk resulted equal to 42.3 Mtoe/y, corresponding to 45.4% of annual crude import: the most affecting corridors in terms of energy risk were Russia-Italy with 11.5 Mtoe/y (27.1% of total energy risk), Turkey-Italy with 9.5 Mtoe/y (22.4%) and Libya-Italy with 6.8 Mtoe/y (16.1%).

3.5. Risk scenarios analysis

The energy risk of the Italian crude oil supply in 2021 has been adopted as reference case to compare risk scenarios. Five risk scenarios are defined (Table 1): two potential risk scenarios (SC1, SC2) and three actual risk scenarios (SC3, SC4, SC5). Furthermore, for SC3 three countermeasures (M1, M2, M3), aiming at replacing the lost amount of crude, have been discussed and compared.

Table 1: Potential and actual risk scenarios

Scenario	Category	Description	σ_k variation (%)	Loss of crude (Mt)
SC1	Potential risk	Russia's invasion of Ukraine leads to a worsening of Russian geopolitical stability.	-40% of the geopolitical stability of Russia	-
SC2	Potential risk	Civil War in Libya degenerates leading to an overall decrease of geopolitical stability in	-20% of the geopolitical stability of Morocco, Algeria, Libya,	-

		North-Africa countries.	Tunisia and Egypt	
SC3	Actual risk	Worsening Turkish-Russian tensions cause closure of the Turkish Straits (Bosporus and Dardanelles), impacting on supplying corridors coming from the Black Sea	-	17.6
SC4	Actual risk	Further worsening of US-Iran tensions, causes a blockade of the Strait of Hormuz by Iran, impacting on corridors from the Persian Gulf.	-	3.1
SC5	Actual risk	Suez Canal blockade due to ship stuck leads to disruption of all corridors coming from Persian Gulf, Arabian Peninsula and Red Sea.	-	4.0

The model assumes that the higher the geopolitical stability of a country, the more critical its worsening is. Therefore, in case of worsening of geopolitical stability of countries recognised as stable and reliable, as Norway (σ_k equal to 97.6 in reference scenario), it results more impactful. Hence, since Russia is already characterized by a low geopolitical stability σ_k (28.9 in the reference scenario), the variation (-40%) on its geopolitical stability assumed in SC1 results to a relatively limited increase of the probability of failure of Russia-Italy's corridor (+2.70%) with respect to the reference case (REF). By assumption, SC1 does not involve any supply disruption therefore the quantity of crude oil from Russian corridors remains the same of REF (21.8 Mt/y) and the corresponding energy risk of Russia-Italy corridor is equal to 11.8 Mtoe, +0.3 Mtoe compared to REF (11.5 Mtoe). Since SC1 affects just a single country (Russia) which is not crossed by other relevant corridors from other countries, the overall energy risk is equal to 42.7 Mtoe (45.8% of total crude import in REF) and the increase on the total energy risk results moderate, +0.75% with respect to REF. In SC2 there is no supply interruption, but it is assumed a decrease of geopolitical stability (-20%) of several countries simultaneously (Algeria, Egypt, Libya, Morocco[1] and Tunisia). The worsening of geopolitical stability impacted mostly Tunisia in terms of probability of failure increase (Table 2) since it is the most stable among the North African countries. All the 32 corridors supplying crude oil to Italy, except for Croatia-Italy's corridor, register an increase in their probability of failure since they cross sea areas allocated to EEZ of these North African countries. For this reason, even if σ_k variation is lower (-20%) compared to SC1, the overall energy risk resulted similar to SC1: 42.6 Mtoe/y (45.7% of crude import in REF case), corresponding to +0.68% compared to REF.

Table 2: Probability of failure of Nord African countries in SC2

Corridors	ξ_i			σ_k		
	SC2	**REF**	**VAR %**	**SC2**	**REF**	**VAR %**
Algeria	0.46	0.45	+2.50%	17.15	21.43	-20%
Egypt	0.45	0.44	+1.44%	18.57	23.21	-20%
Libya	0.40	0.40	+0.61%	2.82	3.53	-20%
Tunisia	0.39	0.37	+6.26%	36.64	45.80	-20%

The blockade of Bosporus and Dardanelles straits in SC3 led to the disruption of all corridors from the Black Sea. Unlike SC1 and SC2, SC3 includes an effective loss of crude oil (actual risk scenario) equal to 17.6 Mt/y (18.9% of Italian crude import in REF case), coming from Novorossiysk and CPC terminal (Russia) and from Supsa Marine terminal (Georgia). The impact on the overall energy risk results equal to 49.6 Mtoe/y (53.2% of total crude import in 2021), +17.1% compared to the reference case.

Due to the relevance of Hormuz Strait to the global seaborne traded oil [66], SC4 assumes its blockade and evaluates its impact on crude supply system of Italy. The loss of crude results equal to 3.1 Mt/y (3 Mt/y from Iraq and 0.1 Mt/y from United Arab Emirates), corresponding to 3.3% of Italian crude import in REF case, far less impactful than the blockade of Turkish Straits (SC3). The blockade of Hormuz Strait would affect only two supply corridors: one from Al Basrah Oil Terminal (ABOT) in Iraq and one from Ruwais port in United Arab Emirates. The amount of crudes from the Persian Gulf imported by Italy is higher than 3.3% (Iraqi and Saudi Arabian crudes covered 24.1% of Italian crude demand in 2021 [50]) but it mostly comes from alternative corridors that circumvent the Strait of Hormuz. Saudi Arabia uses the East-West pipeline (also known as Petroline) and Egyptian ports to export crude in Mediterranean Sea. Similarly, as alternative to ABOT, Iraq uses the Iraq-Turkey pipeline to transport Kirkuk crude towards Ceyhan port (Turkey) in the Mediterranean Sea, bypassing the Strait of Hormuz. The impact of SC4 on the overall energy risk is equal to 42.7 Mtoe/y (45.8% of total crude import in REF case), corresponding to +0.84% compared to the reference scenario.

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[1] Morocco is no part of crude oil supply system to Italy

The blockade of Suez Canal in SC5 represents another potential criticality for crude oil coming from Iraq, United Arab Emirates, Saudi Arabia, Yemen and Sudan. However, for Italian crude supply system, Suez Canal's closure does not represent a relevant issue: the effective loss of crude resulted equal to 4.0 Mt, corresponding to 4.3% of total import in 2021 (REF case). Indeed, Iraqi crude (accounting for 14.4% of Italian crude demand in 2021 [50]) is mainly imported from Turkey-Italy corridor (with an average probability of failure equal to 0.39) rather than Iraq-Italy corridor (0.88). Overall impact of SC5 in terms of energy risk resulted equal to 42.8 Mtoe/y (45.9% of total import in 2021), corresponding to +1.17% compared to the REF case.

Table 3: Impacts of risk scenarios

Code	Energy risk (Mtoe/y)	Var% w.r.t. REF
REF	42.35	-
SC1	42.67	+0.75%
SC2	42.61	+0.68%
SC3	49.57	+17.06%
SC4	42.70	+0.84%
SC5	42.84	+1.20%

Since SC3 scenario resulted the most impacting scenario (Table 3), three countermeasures aimed at replacing the amount of lost crude have been evaluated, starting from a backward analysis up to the oil fields to identify the crude qualities exported by each port (Table 4).

Table 4: Results of backward analysis

Export port	Crude name	Origin country	σ_k of origin country[2]
CPC Terminal	CPC blend	Kazakhstan	41.87
Novorossiysk	Soviet blend (URALS)	Russia	28.88
Supsa Marine Terminal	Azeri light	Azerbaijan	25.74

Depending on the site of origin, the chemical properties, and the value of crude oil change too. When evaluating alternative corridors, the quality of crude cannot be neglected. Two key factors are used to categorise the vast variety of crudes (qualities) are: the API gravity and the sulphur content. In this case, the crude quality's analysis covered the Italy's crude import between 2019 and 2021 [50]: 108 imported crudes have been identified and distinguished through a set of attributes [50]: identification code (ID), origin country, API gravity (°), sulphur content (%) and price ($/bl). Averages of API gravity, sulphur content and price, over the period 2019 to 2021 are used to characterize each crude. The characteristics of CPC blend, Soviet blend and Azeri light (Table 5) are used as benchmark.

Table 5: Characteristics of reference crudes

Crude name	ID	API gravity [°]		Sulphur content [%]		Cost [$/bl]
		min	max	min	max	average
Azeri light	41	34.48	37.81	0.13%	0.18%	62.1
Soviet blend	3580	29.92	31.00	1.20%	1.78%	58.8
CPC blend	9363	42.02	46.82	0.36%	0.96%	59.3

Each reference crude is therefore characterized by replaceability benchmarks summarized in (Table 6).

Table 6: Replaceability benchmarks

	Min API gravity [°]	Min threshold (-5%)	Max Sulphur content [%]	Max threshold (+5%)
Alternatives to Azeri light	32.76	31.12	0.19%	0.20%
Alternative to Soviet blend	28.42	27,00	1.87%	1.96%
Alternatives to CPC blend	39.92	37.92	1.01%	1.06%

Firstly, hardly imported crudes (with an average share lower than 1.5% to the annual crude demand) are excluded. Only 11 qualities among 108 crude qualities fulfilled this condition (14 if also considering CPC blend, Azeri light and Soviet blend). As shown in Table 6, each benchmark crude (Azeri, Soviet and CPC) is characterized by two replaceability benchmarks: the minimum API gravity and the maximum sulphur content recorded between 2019 and 2021. A further selection of alternative crudes is performed by comparing the properties of the 11 preselected crudes with the accepted thresholds reported in Table 6. Crudes characterized by an API gravity higher than the minimum threshold and with a sulphur content lower than the maximum threshold are selected. Just one quality resulted suitable to replace CPC blend, three qualities suitable to replace Azeri light and five qualities suitable to replace Soviet blend. In case of more than one suitable alternative, priority is given to crudes with stricter constraints. Hence, priority is given to the CPC crude's replaceability, since only one crude (Saharan blend) fulfilled all the replaceability conditions. By excluding the Saharan blend, two crudes remain to replace Azeri Light crude. As for the Soviet blend, by prioritising CPC and Azeri crudes, among the five suitable crudes, only two alternatives remain: Es Sider crude and Arabian Light (Table 7).

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[2] Origin country is intended as the country where oil fields are located and crude oil is extracted.

Table 7: Alternative crudes to replace CPC blend, Azeri light and Soviet blend

	Alternative crude	**Origin country**	**API[3] gravity [°]**	**Sulphur content[3] [%]**	**Price[3] [$/bl]**
CPC blend	Saharan Blend	Algeria	44.4	0.1%	61.9
Azeri light	Azeri Blend	Azerbaijan	38.0	0.2%	62.2
	Amna	Libya	37.2	0.1%	61.6
Soviet blend	Arabian Light	Saudi Arabia	32.9	1.8%	58.1
	Es Sider	Libya	36.6	0.4%	60.9

Three countermeasures to mitigate the impacts of SC3 are defined (Table 8) by adopting three main criteria (in case of several alternatives available): lowest crude price (SC3-M1), highest geopolitical stability of producing country (SC3-M2) and keeping the same crude coming from alternative export port (SC3-M3).

Table 8: Countermeasures to mitigate the impacts of SC3

Code	**Description**	**Maritime supply corridor**
SC3-M1	Replacing CPC blend with Saharan blend	Algeria - Italy
	Replacing Azeri light with AMNA crude	Libya - Italy
	Replacing Soviet blend with Arabian light	Egypt[4]- Italy
SC3-M2	Replacing CPC with Saharan blend	Algeria - Italy
	Replacing Azeri light with Azeri blend	Turkey[5] - Italy
	Replacing Soviet blend with Arabian light	Egypt[4]- Italy
SC3-M3	Replacing CPC with Saharan blend	Algeria - Italy
	Replacing Azeri light with Azeri blend	Turkey[5] - Italy
	Keeping Soviet blend coming from Russian ports in the Baltic Sea	Russia (Baltic Sea) - Italy

Finally, the identification of the best countermeasure is based on the lowest energy risk criterion. Hence, among the three alternatives, SC3-M3 resulted the best one to replace the loss of crude simulated in SC3. Indeed, using SC3-M3 configuration, the lost crude is recovered, and the overall energy risk is reduced: -20.4% concerning the SC3 and nearly -7% compared to REF case.

Table 9: Impacts of countermeasures on overall energy risk

Code	Intake (Mt/y)	Extra[6] intake (Mt/y)	Extra[6] energy risk (Mt/y)	Energy risk (Mt/y)	Var % w.r.t. SC3	Var% w.r.t. REF
REF	93.2	-	-	42.35	-	-
SC3	75.7	-	-	49.57	-	+17.1%
M1	75.7	17.6	7.85	39.83	-19.6%	-5.9%
M2			7.84	39.82	-19.7%	-6-0%
M3			7.50	39.48	-20.4%	-6.8%

4. Conclusion

The paper proposes a new model that extends the classical risk analysis approach to incorporate the geopolitical dimension in the risk assessment of the external front of a country's energy supply system. By coupling the geopolitical dimension with the energy flows and spatial features of supply corridors, the model allows for the evaluation of energy risk of each corridor supplying a given energy commodity. Although the case study addresses the supply risk of a given commodity (crude oil) for a given importing country (Italy), the proposed approach can be applied to any country and to any energy commodity transported through captive (e.g., oil and gas pipelines) and maritime corridors. The flexibility and wide applicability make the model valuable for policymaking in the international context. In particular, as shown in the case study, the methodology provides a comprehensive view of the risk related to supply corridors, including vulnerabilities and strengths, allowing for analyzing different types of risk scenarios (i.e. actual and potential ones) and evaluating the impacts of mitigation actions in case of supply disruption.

Policymakers can therefore utilize this model to better understand and monitor the risk associated to the supply of the imported energy commodities and to devise strategies to address eventual risk scenarios by mitigating their impact. For instance, the application of this methodology to the crude oil supply system in Italy, highlighted some relevant strengths: specifically, to meet Iraqi crudes demand, Italy has already adopted the strategy of importing most crude from the Turkey-Italy corridor rather than directly from the Iraq-Italy corridor, which have the highest probability of failure of all the 32 identified supply corridors. Furthermore, unlike many other countries which import crude from Iraq, the closure of Hormuz Strait and Suez Canal is not critical for the current Italian supply system. On the other hand, the risk scenario analysis showed a certain vulnerability in the event of closure of the Turkish straits (Bosporus and Dardanelles straits), owing to the limited replaceability of the CPC blend. Indeed, from the replaceability analysis resulted that the CPC blend has just one alternative crude (Saharan blend) fulfilling all the replaceability requirements (section 3.5). Furthermore, CPC blend is one of the most imported crudes in Italy, but it is exported just through a single corridor (from the CPC port, in the Black Sea) crossing the Turkish straits,

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[3] Average vale over the period 2019-2021

[4] Saudi Arabia's crude is shipped to Italy from Egyptian ports

[5] Azeri blend comes from Ceyhan (Turkey) port despite Azeri Light coming from Supsa port (Georgia) and Novorossiysk (Russia)

[6] Additional amount coming from alternative corridors to recover the missing amount resulting from supply interruption

without any alternative corridors. However, a set of alternative solutions to recover the amount of lost crude from other corridors have been identified and discussed.

As shown in the case study, the amount and, especially, the physical/chemical properties of the needed commodity limit the choice of the alternative suppliers, and the availability of import (e.g., presence of oil pipeline networks, capacity of the available pipelines) further reduces the set of possible alternative supply corridors. Due to these constraints, importing from more geopolitical stable countries is not always a feasible option. In this case, the importing country should improve the diversification of suppliers, monitor the geopolitical stability of the main suppliers, and evaluate in advance compatible alternatives in case of unavailability of one or more of the main supply flows.

As regards the current Italian configuration of crude oil supply, it could be further enhanced by decreasing the share of the Kazakh CPC crude and by differentiating the mix of crudes; in this way, the extent of the loss in case of supply disruption would be less critical and the crude replacement would be easier to be implemented.

However, since the security of the national energy system depends not only on the external front but also on the internal one, in order to enhance the overall energy security, a country should invest resources to improve the internal front and the domestic energy arrangement.

With reference to possible future development of the presented methodological approach, in the perspective of performing a systematic assessment of the overall energy supply security of a given country, an application of the proposed model to all the imported energy commodities could be planned. Moreover, the inclusion of the risk factors related to the internal front and the integration into the model of a quantitative assessment of the resilience of the supply system could be taken into consideration.

Appendix A: Corridors for crude oil supply to Italy

Table 10: Supply corridors of crude oil to Italy in 2021: export country, intake (%), probability of failure (-), energy at risk (toe)

Export Country	Share Intake	Average Probability of failure (-)	Energy risk (toe)
Algeria	1.57%	0.45	662,143
Angola	0.29%	0.41	111,043
Brazil	0.45%	0.39	162,295
Cameroon	0.52%	0.42	200,830
Canada	0.21%	0.43	84,061
Croatia	0.08%	0.31	21,951
Denmark	0.30%	0.29	81,968
Egypt	7.10%	0.44	2,920,687
Equatorial Guinea	0.21%	0.42	83,566
Gabon	0.23%	0.41	87,923
Georgia	1.57%	0.46	671,060
Ghana	0.28%	0.40	102,136
Guyana	0.15%	0.49	69,339
Iraq	3.21%	0.89	2,653,188
Ireland	0.09%	0.28	23,841
Libya	18.08%	0.40	6,834,566
Malaysia	0.35%	0.87	282,516
Malta	0.96%	0.29	253,192
Netherlands	0.08%	0.34	24,618
Nigeria	4.23%	0.40	1,591,795
Norway	1.62%	0.30	448,089
Republic of Congo	0.13%	0.41	49,090
Russia	23.36%	0.55	11,497,706
Saudi Arabia	0.11%	0.88	92,756
Sudan	0.43%	0.85	338,528
Tunisia	0.29%	0.37	99,218
Turkey	25.72%	0.39	9,476,314
United Arab Emirates	0.11%	0.88	92,261
United Kingdom	2.18%	0.31	635,862
United States	5.52%	0.44	2,288,775
Venezuela	0.09%	0.36	31,292
Yemen	0.47%	0.85	373,569
Total			42,346,175

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