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Modelling the Energy Dimension of the Belt and Road Initiative

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Abstract

The development of modern economies is deeply linked to energy access and availability, which are essential for a country's productivity and social welfare. However, due to uneven distribution of energy resources around the world, many countries are characterized by heavy dependence on external imports, which are subject to geopolitical dynamics, commercial disputes, and infrastructure failure. For these countries, national security is strictly associated with energy security, which can be defined as the capability of ensuring, at an affordable price, the availability of the different energy commodities needed to meet end-use demand.

This thesis aims at developing an integrated tool for modelling energy interdependencies among countries at a multi-regional scale and quantitatively assessing energy security in a multi-dimensional approach, including the physical layer (i.e., energy flows and infrastructure), geopolitical dynamics, the socio-economic level, and the environment. This tool consists of a relational database, a computational kernel capable of performing analyses and calculations, and a web interface for visualizing output and results. The proposed methodology can be used to support the policy decision-making process with scientific evidence based on quantitative models that can simulate the impact of different energy policies and strategies.

The methodology, firstly outlined in general terms, is then applied to the countries involved in the Belt and Road Initiative (BRI) with the aim of analysing the energy dimension of this ambitious Chinese programme, in which energy and energy infrastructure are key factors to foster interregional cooperation and integration. A snapshot of the energy situation of the countries involved in the BRI is provided by analysing energy exchanges and identifying the countries with low levels of self-sufficiency, thus more vulnerable to supply disruption. For them, Shannon diversity indexes are computed for measuring the diversification of energy mix and suppliers. An aggregated indicator for combining the net import dependence, the diversification of supply and the composition of the energy mix is introduced, which can provide an overall measure of the security level. Furthermore, the risk associated to energy supply is calculated taking into consideration the geopolitical situation of suppliers. Focusing on China, an optimization analysis is performed for identifying the energy flows that should be imported from each supplier in order to minimize the supply risk under different constraints. Finally, a scenario analysis is developed with the aim of simulating the impact of possible future events (e.g., unavailability of infrastructure, emergence of geopolitical tensions, and implementation of energy projects) on national energy security in terms of diversification and supply risk. As an example, the effect of the completion of the Power of Siberia gas pipeline, which is one of the main BRI projects, on Chinese energy security is evaluated. This analysis shows that this project allows both to increase diversification and reduce the supply risk, as China could decrease the import from Turkmenistan, its main gas provider, which is characterized by a very high political risk index.

Sommario

Lo sviluppo delle economie moderne è profondamente legato all'accesso e alla disponibilità di energia, che garantiscono la produttività e il benessere sociale del paese. Tuttavia, a causa della distribuzione disomogenea delle risorse energetiche nel mondo, molti paesi sono caratterizzati da una forte dipendenza da importazioni estere, che sono però soggette a dinamiche geopolitiche, controversie commerciali e fallimenti infrastrutturali. Per questi paesi, la sicurezza nazionale è strettamente associata alla sicurezza energetica, che può essere definita come la capacità di garantire, a prezzi accessibili, la disponibilità delle diverse commodity energetiche necessarie per soddisfare la domanda degli usi finali.

Questa tesi ha l'obiettivo di sviluppare uno strumento integrato per modellizzare le interdipendenze energetiche tra paesi su scala multiregionale e valutare quantitativamente la sicurezza energetica in un approccio multi-layer che comprenda una dimensione fisica (cioè flussi energetici e infrastrutture), dinamiche geopolitiche, un livello socio-economico e l'ambiente. Lo strumento è costituito da un database relazionale, un kernel di analisi e un'interfaccia web che permette di visualizzare output e risultati. La metodologia proposta può essere utilizzata per supportare i processi decisionali politici con evidenze scientifiche basate su modelli quantitativi, che permettono di simulare l'impatto di diverse politiche e strategie energetiche.

La metodologia, prima delineata in termini generali, è applicata ai paesi coinvolti nella Belt and Road Initiative (BRI), con l'obiettivo di analizzare la dimensione energetica di questa ambiziosa politica estera cinese, in cui l'energia e le infrastrutture energetiche sono considerati fattori chiave per favorire la cooperazione e l'integrazione interregionale. La situazione energetica dei paesi coinvolti nell'iniziativa viene descritta, analizzando gli scambi energetici e identificando i paesi con bassi livelli di autosufficienza energetica, quindi particolarmente vulnerabili a eventuali interruzioni dell'approvvigionamento. Per questi paesi, gli indici di diversità Shannon sono calcolati al fine di misurare la diversificazione del mix energetico e dei fornitori. Viene introdotto un indicatore aggregato per combinare la dipendenza netta dalle importazioni, la diversificazione dell'approvvigionamento e la composizione del mix energetico, fornendo quindi una misura complessiva del livello di sicurezza. Inoltre, il rischio associato all'approvvigionamento energetico viene calcolato tenendo conto della situazione geopolitica dei fornitori. Concentrandosi sulla Cina, viene eseguita un'analisi di ottimizzazione per identificare i flussi energetici che dovrebbero essere importati da ciascun fornitore per minimizzare il rischio legato all'approvvigionamento. Infine, viene sviluppata un'analisi di scenario con l'obiettivo di simulare l'impatto di possibili eventi futuri (es. indisponibilità dell'infrastrutture, emergere di tensioni geopolitiche, completamento di progetti energetici) sulla sicurezza energetica nazionale in termini di diversificazione e rischio di approvvigionamento. A titolo di esempio, viene valutato l'effetto del completamento del gasdotto "Power of Siberia", uno dei principali progetti BRI, sulla sicurezza energetica cinese. L'analisi mostra che questo progetto permette sia di aumentare la diversificazione che di ridurre il rischio dell'approvvigionamento, in quanto la Cina potrebbe diminuire le importazioni dal Turkmenistan, il suo principale fornitore di gas, che è caratterizzato da un indice di rischio geopolitico molto elevato.

Contents

1 Introduction

1.1 Global energy context and future scenarios

From 2000 to 2016, global energy demand increased by more than 35%, hitting 400 TJ of Total Final Consumption (TFC) in 2016. In 2000, Europe and United States represented almost 40% of the world's energy consumption, and Asia accounted for around 20%. According to the International Energy Agency (IEA), this situation will be completely reversed by 2040, due to the exponential growth of Asian developing economies [1]. In 2016, Asia accounted already for 34% of the total, while the share of Europe and United States declined to 28%. Specifically, China has established itself as a global power and as a leading economy in the energy sector, accounting alone for more than 20% of world energy consumption [2].

The profound shift towards Asia in terms of energy consumption and investments is not the only evolution that the global energy system is experiencing. The transition towards a low-carbon economy represents today a key objective at a global scale and a fundamental strategy in order to limit environmental impacts and climate change, in line with the Paris Agreement goal of keeping the global temperature rise below 2°C above pre-industrial levels. The decarbonisation of the energy sector is enabled by the adoption of renewable energy technologies and by an increasing electrification of final uses. Electricity share in final energy consumption is currently around 19% and it is set to significantly rise. However, fossil fuels are today still essential for guaranteeing the energy system flexibility and for accommodating scarcely predictable and intermittent renewable sources.

Coal represented around 27% of total primary energy demand in 2016 and coal use slightly increased in 2017, after two years of decline, even though investments in new coal-fired plants were significantly reduced in recent years and they are today manly located in the Asia Pacific region. Whereas in Western countries the average age of coal-fired plants is 40 years, for Asian developing economies this is around 15 years, meaning that it is too early to completely phase out coal from the global energy mix and this energy source could be more resilient than expected. Indeed, the IEA New Policies Scenario[1] foresees an overall flat trend for coal demand, since falling consumption in the European Union and United States is balanced by rising demand in India and Southeast Asia.

[1] In the World Energy Outlook, IEA develops three main scenarios: the Current Policies Scenario, if there is no change in policies from today, the New Policies Scenario, which includes policies and targets announced by governments, and the Sustainable Development Scenario, in which accelerated clean energy transitions is implemented for reaching goals related to climate change, pollution and access to energy.

In 2016, oil accounted for roughly 33% of primary energy supply and for more than 90% of final uses in the transport sector. Oil use for cars is expected to peak in the mid-2020s and then start falling, thanks to the spread of electric vehicles. Nonetheless global oil demand is expected to grow steadily until 2040, due to the increasing demand in developing countries.

Natural gas currently represents one of the key commodities for energy systems worldwide. In the last decades, the share of natural gas in the Total Primary Energy Supply (TPES) at global level increased from 16% in 1971 to 22% in 2016, with a growth from 37.4 EJ to 127.1 EJ (i.e., 3.4 times) [2]. Differently from oil and coal, natural gas demand increases not only in the New Policy Scenario, but also in the Sustainable Development Scenario. This trend underlines the crucial role played by this commodity in the mid-, but probably also in the long-term, for accompanying the transition towards decarbonisation. Indeed, natural gas demand is expected to grow not only in the developing countries, as for coal and oil, but also in developed economies such as Europe and North America. The higher share of renewable sources will reduce the utilization factor of gas-fired plants in Europe, and more efficient buildings will probably help to bring down the gas consumption for heating, but gas infrastructure will continue to play a vital role for future economies, in particular in winter, when production from solar PV is limited and the need for heat is especially high. It has to be underlined that natural gas has a lower environmental impact in terms of greenhouse gas (GHG) emissions with respect to the other fossil fuels. Considering CO_2, which has the lower Global Warming Potential[2] (GWP) but the higher concentration and persistence in the atmosphere compared to other GHG, the emissions per unit of energy are equal to about 94.6 t/TJ for steam coal (coal used for power generation), 76.6 t/TJ for combustible oil and 55.9 t/TJ for natural gas [3]. This makes natural gas the ideal candidate to support the transition from fossil fuels to renewables. Finally, the growing natural gas demand is also facilitated by the expansion of Liquefied Natural Gas (LNG) trade (+12% in 2017 with respect to the previous year [4]) which allows for higher flexibility of supply, enabling also spot and medium-term contracts, and it is gradually transforming gas market to a global scale market, similarly to oil.

Data and figures reported above show that fossil fuels are currently still indispensable energy sources for the global economy, accounting together for 82% of TPES, and they will play a crucial role also in the next future, especially for developing countries, and even in an extremely decarbonized energy mix. In addition to causing environmental impacts related to GHG emission and air pollutants, fossil fuels are characterized by an extremely uneven distribution of resources around the world. For instance, almost 50% of global oil reserves are located in the Middle East, mainly in Saudi Arabia, Iran, Iraq, Kuwait and United Arab Emirates. Middle East holds also 41% of natural gas reserves, especially 17% of global reserves are located in Iran and 13% in Qatar. Nonetheless, Russia in the country with the highest amount of gas, accounting alone for roughly 18% of the total [5]. This introduces

[2] The Global Warming Potential (GWP) allows comparisons of the global warming impacts of different greenhouse gases. It measures of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The time period usually used for GWPs is 100 years. CO_2 has a GWP equal to 1, while CH_4 and N_2O have a GWP of 28–36 and 265–298 over 100 years, respectively. (Source: EPA. *Understanding Global Warming Potentials* [https://www.epa.gov/ghgemissions/understanding-global-warming-potentials])

serious geopolitical concerns and security issues for those numerous countries that significantly rely on external energy imports. The risk of supply depends on the assortment of suppliers and on their geopolitical stability and reliability, but also on the diversification level of supply, both in terms of imported commodities and countries of origin. Finally, the transport routes from production areas to national entry points have to be carefully analysed, taking into account the countries crossed and the type of energy corridor, in order to effectively assess the risk associated to the energy supply of each country and evaluate strategical choices, investments and planning.

Due to the different availability of energy sources around the world, global energy trading is fundamental in order to ensure energy access and security to all countries. Today, international energy trade mainly takes place in the fossil fuel sector and it has been steadily increasing due to the highly unbalanced distribution and consumption of fossil fuels, thus requiring optimization of energy resource allocation. In 2017, the trade volumes of oil (crude and products), gas, and coal accounted for 74%, 31%, and 18% of global consumption, respectively [5]. Conversely, transnational and transcontinental electricity trade still operates on a small scale due to grid transmission capacity constraints. International energy trade flows are increasingly converging toward Asia from the Middle East, Russia, Canada, Brazil and the United States, and Asia's share of global oil and gas trade will continue to rise in the future.

Inter-regional interconnections can also play a crucial role in facilitating the integration of renewables, as the European Commission illustrates in its "Energy Union and Climate" program [6]. Among the possible future energy scenarios, the development of electrical UHV super-grids at a global scale can be mentioned, which envisages the construction of extensive interconnections across countries and continents to allocate electricity generated from renewable energy sources, such as solar and wind, on a global scale. Specifically, renewable energy is generated from large production areas (the North Pole for wind and African desert zones for solar photovoltaics) and transmitted towards large consumption areas (United States, Asia and Europe) [7].

The growth in transnational and intercontinental energy trade flows has been made possible by the development and expansion of energy transport networks, namely open-sea and captive corridors (i.e., railways, power lines, oil and gas pipelines). In recent years, a remarkable proliferation of regional integration projects in energy infrastructure has been observed with the aim of improving energy security. However, the complex transport system from production to consumption areas is easily subject to external influences and specifically to geopolitical issues, which have a significant impact on energy security and prices.

One of the most remarkable projects for regional integration is currently carried forward by China, and it is known under the name of Belt and Road Initiative (BRI), New Silk Road or Asian Interconnector. The BRI was launched by the Chinese government in 2013 with the ambition to improve connections and economic integration between Asia, Europe and Africa. It geographically involves more than 80 countries, corresponding to approximately half of word population and of global Gross Domestic Product (GDP). For this strategic initiative, an overall $5000 billion investment is planned. From 2000 to 2017, China has already invested $128 billion in energy projects along the BRI countries, involving exploration and extraction, transmission and distribution, power generation and others [8]. Energy cooperation between China and countries along the BRI is indeed an important component of this strategy which, through overseas energy investment, aims also at securing energy resources needed to satisfy Chinese growing demand.

1.2 Aim of the thesis: science supporting policy decision making

The performance evaluation of energy systems should be developed taking into consideration three domains: security or reliability (which will be analysed in depth in this thesis), sustainability and economic affordability. Any energy strategy, included the energy dimension of the Belt and Road Initiative, must be confronted with these objectives. However, these three areas are closely interlinked and the trade-off between them requires a comprehensive approach to energy policy. In fact, the relationships among these three aspects are constantly evolving and often competing. For instance, the growing penetration of intermittent renewable sources, such as wind and PV, in the global energy mix increases the sustainability of the energy system, but introduces issues related to the reliability of the grid.

In this complex and evolving energy context, the policy choices made by governments across the world are critical for achieving the competing goals of security, sustainability and affordability, and they are decisive for shaping the long-term future of energy systems. Energy systems are complex, dynamic and multilayer systems, in which physical, socio-economic, geopolitical and environmental aspects are closely linked together. In order to grasp and take into account all these aspects and their interactions, science-based approaches can be implemented for supporting the policy decision making process with scientific evidence based on quantitative models and tools that allow to analyse the impact of different decisions and options.

In this framework, this thesis aims to contribute at modelling energy fluxes exchanged at regional and multi-regional scale, taking into consideration physical, economic, geopolitical and environmental factors. In particular, the study of energy supply interdependencies among countries and a quantitative assessment of energy security are developed. In a broader perspective, this thesis aims to develop a methodology for the development of an integrated science-based tool for energy security analysis. The tool is able to query a database which collects the useful data and key performance indicators, perform calculations based on a certain algorithm (e.g., dispatch optimization, minimization of supply cost) and finally produce a result which has to be easily comprehensible for policy decision makers. In particular, the output of the analysis is represented, when possible, on a map, making use of geographic information systems (GIS), for a more effective graphical representation. In this sense, the database collects not only numeric data about energy statistics and flows, but also geographic and spatial information regarding energy infrastructure (e.g., the path of pipelines, the position of LNG terminal etc.) and reserves.

The tool has been tested on the group of countries involved in the Belt and Road Initiative with the aim of analysing, through modelling and quantitative assessment, the energy dimension of this ambitious Chinese program. Specifically, the energy interdependencies, the supply risk and diversification for each nation are evaluated, taking into consideration geopolitical factors. Applying the tool to the BRI countries is particular interesting and relevant due to the evolving nature of the program. In this sense, this tool can be used to compare the consequences and impacts of different policy and investments, helping to choose among competing energy projects in this area and to underline energy issues related to the initiative.

The science-based approach developed in this work can be interesting for answering questions arising from different stakeholders and players: not only policy decision makers but also think tanks, non-governmental organizations, transmission and distribution system operators (TSOs and DSOs), energy companies and financial institutions (insurance companies, banks).

The development of such tool requires intrinsically a multidisciplinary approach with skills in different fields such as Energy, Economics, Computer Science, Geomatics and Policy making.

1.3 Outline of the thesis

In Chapter 1, the global energy context is introduced, underling the trend towards decarbonisation and global interconnection of energy systems. The aim of thesis is explained, including the development of a science-based tool for quantitative energy security assessment.

Chapter 2 describes the Belt and Road Initiative, the ambitious Chinese programme aiming at improving connection and cooperation among Asia, Europe and Africa. The key role played by energy and energy infrastructure in the Belt and Road is underlined, and the main BRI projects in the energy sector are briefly described. Furthermore, Chinese situation in terms of energy consumption, import and supply routes is investigated, with the aim of highlighting China's energy interests in the BRI region.

In Chapter 3, the concept of energy security is introduced, together with its four main dimensions: availability, accessibility, affordability and sustainability. A literature review about the main simple and aggregated indicators for energy security assessment is developed, with particular focus on Shannon diversity indexes, which can be used to measure diversification of energy mix and suppliers. Moreover, three interesting models for energy security assessment in a geopolitical perspective are described, introducing the concept of external supply risk and expected supply.

In Chapter 4, the tool conceptual and IT architecture are explained, underling the attempt to integrated three main elements – data, number, and sign – in a platform able to store useful information in a relational database, perform computational analyses and visualize data on a web interface.

In Chapter 5, the conceptual methodology is applied to the 80 countries involved in the BRI region. Each country is analysed in terms of energy reserves, production, consumption and trade of energy commodities. Furthermore, the energy exchanges among the BRI area are modelled. For a subset of the 80 countries, Shannon diversification indexes are computed and the overall supply risk is measured. The most critical nations in terms of energy security are identified. Finally, further analysis is developed for China, performing optimization analyses for minimizing supply risk with different set of constraints. For each optimized scenario, diversification and supply risk are computed and compared with the reference scenario. Also a scenario analysis is performed, simulating the completion of BRI energy projects, the variation in geopolitical dynamics among countries and the unavailability of import routes, and assessing the impacts on Chinese energy security.

In Chapter 6, a brief summary of the work developed is done, underlining the main results of the analyses on the BRI region. Strengths and limitations of the developed methodology are explained, underling possible future works and improvements.

2 The Belt and Road Initiative

2.1 China's Silk Roads: old and new

Archaeologists have shown that China was in contact with Greece, Rome, Persia and Babylonia already from the 4th-5th century BC, but with limited trades. The true roots of the Silk Road are the mission and explorations to the West carried out by the imperial envoy Zhang Qian in 138 BC, during the Han dynasty (206 BC – 220 AD). His journey lasted thirteen years and the account of what he had seen convinced the Han dynasty of the economic potential associated to the trade routes to the West. For centuries, silk and many other goods were traded along the Silk Road routes, an extensive transcontinental network whose starting point was represented by Xi'an, one of the Chinese ancient capitals. In the 15th century, the Maritime Silk Road replaced the terrestrial one. In addition to economic trade, the Silk Roads enabled also the transmission of ideas, art, culture and religions, acting as a "bridge between East and West" [9].

Despite its ancient history and tradition, the Silk Road is today revived, even if in a different framework and perspective. On September 2013, Chinese President Xi Jinping made a speech titled "Promote People-to-People Friendship and Create a Better Future" at Kazakhstan's Nazarbayev University, in which he proposed to jointly build the "Silk Road Economic Belt" in order to strengthen economic ties and collaboration between Eurasian countries [10]. One month later, on October 2013, during a visit to Southeast Asia, Xi Jinping proposed to the Indonesian parliament the development of a "21st Century Maritime Silk Road" for expanding cooperation between China and ASEAN countries [11]. These two initiatives were later collectively called "One Belt One Road" (OBOR), and, more recently, "Belt and Road Initiative" (BRI). In fact, the Central Compilation and Translation Bureau of the Peoples' Republic of China stated that the "一带一路 [yi dai yi lu]" Chinese term should no longer be translated to "One Belt One Road" in English, but to "Belt and Road Initiative", which better grasp the plurality of routes and economic corridors that the project involves [12] and, moreover, broaden its appeal by dampening its Sino-centric focus [13]. The title "New Silk Road", often used for referring to this Chinese ambitious international project, is never used officially by Beijing, since, in 2011, Secretary of State Hillary Clinton announced under this name a U.S. project for Afghanistan's economic development, which however flopped even before it started [14].

The Silk Road Economic Belt (SREB) indicates a land route that originates in western China and, passing through Central Asia and Middle East, ends in the European Union. The 21st Century Maritime Silk Road (MSR) represents a maritime route that connects Southeast Asia, the Persian Gulf and the Horn of Africa, also ending in Europe [15]. The paths of the land Belt and maritime Road are shown in Fig. 2.1, together with the six economic corridors envisaged by the initiative.

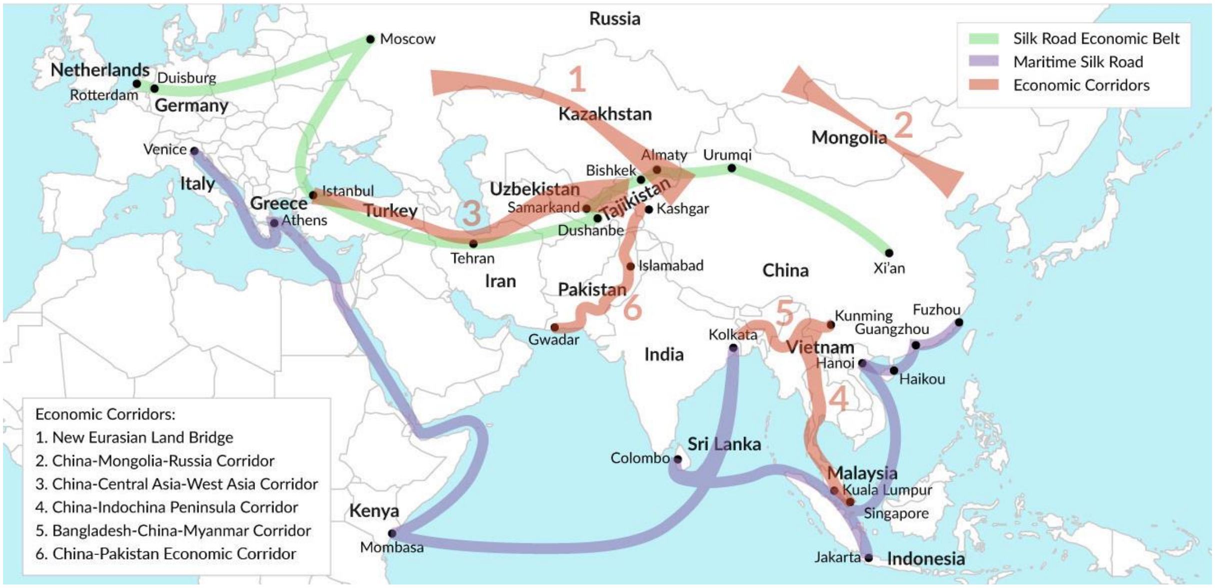


Fig. 2.1 – Routes of the Belt and Road Initiative (Source: Geopolitical Intelligence Service)

In March 2015, Chinese government issued a detailed plan for the Belt and Road Initiative entitled "Vision and Actions on Jointly Building Silk Road Economic Belt and 21st-Century Maritime Silk Road", in which the Belt and Road is described as strategic initiative for promoting economic prosperity, regional cooperation, world peace and development [16]. In this document, the five goals for achieving the often advocated mutual benefit and win-win cooperation among the participants to the BRI are identified: policy coordination, facility connectivity, unimpeded trade, financial integration and people-to-people bond. The five cooperation priorities and their descriptions are reported in Tab. 2.1. In the document, the central role played by infrastructure in pushing economic growth (as "China miracle" clearly exemplifies) is underlined. This aspect, which distinguishes the BRI from other international aid and cooperation mechanisms, is especially important since many countries involved in the initiative are characterized by underdeveloped infrastructure and lack of investments, planning or construction capabilities. Several BRI projects under construction or planned involve the building of cross-border high-speed railways, international oil and gas pipelines, cross-border telecom links and electricity networks [17].

On 14-15 May 2017, the first "Belt and Road Forum for International Cooperation" was held in Beijing with participation of representative from more than 100 countries, including 29 national leaders. The Forum was a chance to demonstrate and point out again China's key role in boosting global connectivity [15]. However, Chinese government carefully monitors how the initiative is perceived by other countries. The Forum was therefore another occasion to stress that BRI does not aim to repeat old geopolitical competition, but promote win-win cooperation and mutual benefits. Xi Jinping reiterated that the BRI covers, but is not limited, to the area of the Ancient Silk Road, underlining that the initiative is inclusive and open to all countries [18].

Tab. 2.1 – Elaboration of the five cooperation priorities of the BRI (Source: [13], [16])

Priority	Actions
Policy coordination	• Promote intergovernmental cooperation and expand shared interest • Enhance mutual political trust • Jointly support large-scale project implementation
Facility connectivity	• Improve the infrastructure network connecting Asia, Europe and Africa • Closer alignment of technical standards and transport rules in order to facilitate international transport • Promote green and low carbon infrastructure construction • Improve connectivity of energy infrastructure, cooperate for ensuring security of energy corridors and build international power networks • Improve international communication connectivity and build cross-border optical cables
Unimpeded trade	• Create mechanisms that facilitate free trade, reducing costs and risks along supply chains • Open free trade areas
Financial integration	• Establish financial institutions for funding BRI projects • Expand local currency swap • Ensure currency stability • Facilitate interbank and multilateral cooperation • Enhance cooperation on financial regulation
People-to-people bond	• Promote cultural and academic exchanges • Promote and facilitate tourism • Increase cooperation in science and technology and develop joint labs and research centres • Encourage cooperation between think tanks and non-governmental organizations

2.2 Geography of the Belt and Road Initiative: countries involved

Due to its open and inclusive nature, there is not an official list stating which countries are exactly included in the initiative. In 2015, a Chinese report identified 65 countries involved in the project, but in three years the number of nations that experienced Chinese investments, bilateral cooperation agreement or simply declared their support to the initiative has grown significantly. In fact, from its initial focus on two specific geographic routes, the Silk Road Economic Belt and the 21st Century Maritime Silk Road, the BRI evolved towards a more global scale. For instance, in 2018, Beijing published the "China's Arctic Policy" in which the building of a "Polar Silk Road" is advocated through the development of the Arctic shipping routes [19], which would significantly shorten the distance between Asia and Europe, and would represent an interesting alternative for avoiding the Malacca choke point. Furthermore, the BRI recently landed in Latin America which, despite its geographical distance from the original land and maritime routes, was appointed by Xi Jinping as "a natural extension of the Maritime Silk Road" during the Belt and Road Forum [20].

Since the identification is not unique and always evolving, the BRI countries analysed in this work are reported in Tab. 2.2, where they are grouped according to the United Nations classification by region, and they are graphically represented in Fig. 2.2. We chose to focus the analyses on the Eurasian continent, thus not including in the list African countries (even if China is financing projects in several nations of this continent, such as Djibouti, Egypt and Ethiopia) and Latin America. India, even if geographically close to the BRI, is not included in the list, being the first country to oppose the initiative and stressing its hostility by not attending the Belt and Road Forum. New Delhi in fact looks suspiciously at Chinese growing presence and influence in its Central Asia immediate neighbourhoods, and expressed strong opposition to the China-Pakistan Economic Corridor (CPEC), which passes through Pakistan Occupied Kashmir.

The area involved in the BRI includes eighty countries covering almost completely two continents, Asia and Europe, for a total surface of 50,984,102 km^2. The population of this area amounts to 3615 million people (48.6% of world population) and its Gross Domestic Product (GDP) equals 38.2 T$, representing 49.2% of the global GDP. Considering GDP based on Purchasing Power Parity[3] (PPP) rates, the share of BRI countries is even higher (54.2%). China alone accounts for almost 20% of global population, 12% of GDP and 18% of GDP PPP, representing the country with the highest GDP PPP in 2016 [21].

The basic geo-economic figures for the eighty BRI countries are reported in Appendix B, Table 1. The set of countries reached by this initiative across two continents is highly diversified, including both developed EU economies and very low-income Asian nations, which have massive potential for economic growth. For instance, in the BRI region, the GDP per capita spans over a range of two orders of magnitude, from around 500 $/capita in South Asian countries, such as Afghanistan and Nepal, to roughly 50,000 $/capita in EU countries, such as Germany and Netherlands.

Tab. 2.2 – BRI countries grouped by region

Region	**Countries**
Central Asia	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
Eastern Asia	China, Mongolia
Europe	Albania, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxemburg, Moldova, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The Former Yugoslav Republic of Macedonia, Ukraine, United Kingdom
Middle East	United Arab Emirates, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Yemen
South Asia	Bhutan, Sri Lanka, Maldives, Nepal, Pakistan, Afghanistan, Bangladesh
Southeast Asia	Brunei Darussalam, Indonesia, Cambodia, Laos, Myanmar, Malaysia, Philippines, Singapore, Thailand, Vietnam
Western Asia	Azerbaijan, Armenia, Georgia, Turkey

[3] GDP PPP is gross domestic product converted to international dollars using purchasing power parity rates instead of market exchange rates. An international dollar has the same purchasing power over GDP as the U.S. dollar has in the United States.

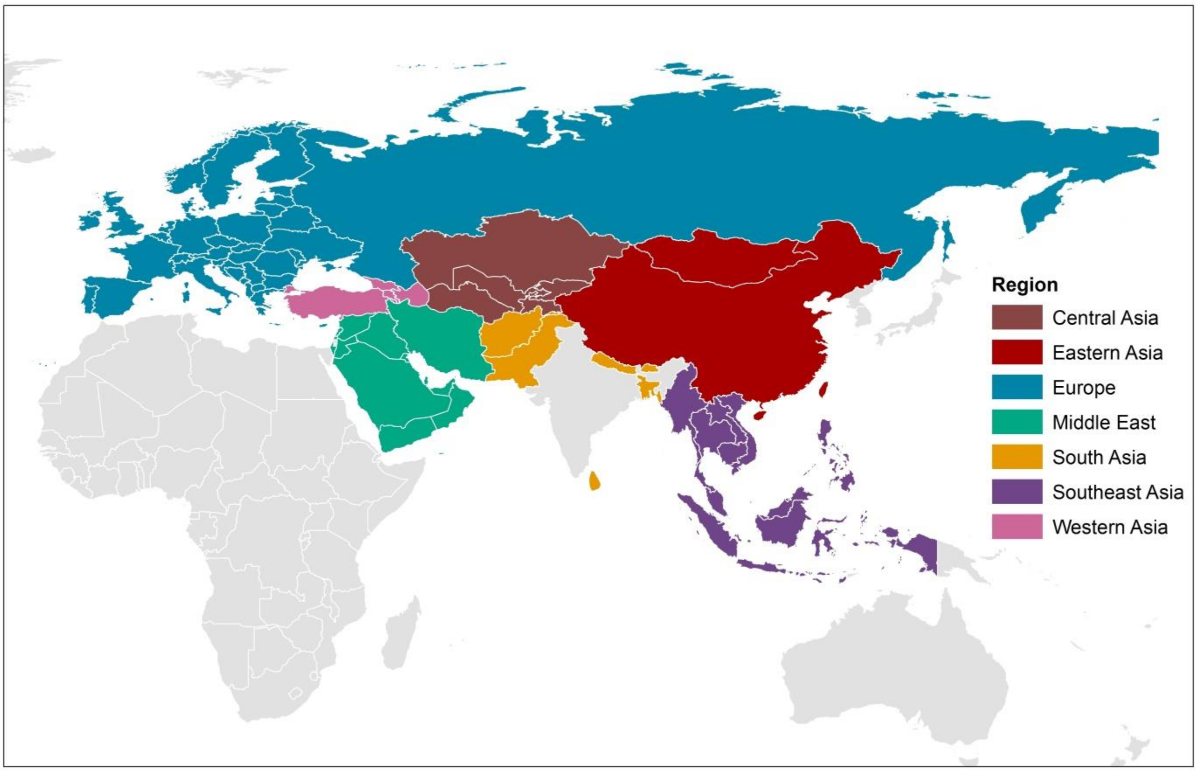


Fig. 2.2 – Map showing the BRI countries (Source: PoliTO)

2.3 The energy dimension of the Belt and Road Initiative

Different drivers lay behind the development of this Chinese foreign policy priority, designated as the "project of the century" by president Xi Jinping. First, the BRI aims at sustaining Chinese economic growth, which significantly slowed down during the last five years, by exploring cooperation with new partners and by finding new destinations for investments and exports for absorbing China's excess capacity. Second, BRI has the potential to increase China's international influence, allowing the country to play a crucial role in reshaping the global economic system [17]. Last but not least, energy security is one of the main drivers of this strategy and investments in infrastructure such as pipeline, railways and ports are often interlinked with Chinese plans of securing resources in line with domestic energy policies [22].

2.3.1 Domestic drivers of China's energy interests abroad

Within the last twenty years, China has emerged as a dominating global energy actor, becoming a net importer of oil, coal and natural gas. The huge increase in energy imports (in particular oil imports), due to China's rapid economic growth, has raised extreme concern regarding energy security in Chinese regime.

2.3.1.1 China's basic and energy figures

According to the International Energy Agency, in 2009 China surpassed the United States in terms of total final energy consumption, becoming the world's largest energy consumer. In the last twenty years, Chinese total energy consumption has grown almost three times, hitting 1969 Mtoe in 2016. Tab. 2.3 reports the main energy figures for China in 2016 and Tab. 2.4 shows a comparison with the other major world player countries, underling the relative value of each indicator with respect to China. The comparison highlights that in 2016 China was the country with the highest GDP converted to international dollars using purchasing power parity rates. Chinese energy intensity, which measures the energy inefficiency of the economy, is still very high, compared to developed countries such as Europe. China is also the country with the largest carbon dioxide emissions from fuel combustion. In fact, as demonstrated by Fig. 2.3, China energy production still relies considerably on coal. According to BP Energy Outlook 2018, Chinese energy mix will evolve considerably in the next years with coal's dominance declining from more than 60% in 2016 to 36% in 2040 [23]. Conversely, BP forecasts a significant increase in natural gas, renewables and oil consumption.

Tab. 2.3 – China main figures in 2016 (Source: [2], [21])

Population (millions)	1379
Surface (sq. km)	9562911
GDP (billion 2010 USD)	9505
GDP PPP (billion 2011 international $)	19450
Energy production (Mtoe)	2360
Net imports (Mtoe)	559
TPES (Mtoe)	2958
TFC (Mtoe)	1969
CO2 emissions (Mt of CO2)	9057

Tab. 2.4 – Energy indicators: comparison between China and other countries (Source: [2], [21])

	China		**India**		**Russia**		**U.S.**		**EU28**	
Population (millions)	1379	1.00	1324	0.96	144	0.10	323	0.23	511	0.37
Surface (sq. km)	9562911	1.00	3287259	0.34	17098250	1.79	9831510	1.03	4383564	0.46
GDP (billion 2010 USD)	9505	1.00	2465	0.26	1628	0.17	16920	1.78	18308	1.93
GDP PPP (billion 2011international $)	19450	1.00	7905	0.41	3177	0.16	16920	0.87	18136	0.93
TPES (Mtoe)	2958	1.00	862	0.29	732	0.25	2167	0.73	1599	0.54
TFC (Mtoe)	1969	1.00	572	0.29	470	0.24	1515	0.77	1138	0.58
Energy dependence (%)	18.9	-	36.5	-	-85.2	-	12.2	-	56.8	-
Energy intensity with GDP (PJ/billion USD)	13.0	1.00	14.6	1.12	18.8	1.44	5.4	0.41	3.7	0.28
Energy Intensity with GDP PPP (PJ/billion $)	6.4	1.00	4.6	0.72	9.6	1.52	5.4	0.84	3.7	0.58
CO2 emissions (Mt)	9057	1.00	2077	0.23	1439	0.16	4833	0.53	3192	0.35
TFC variation 2000-2015 (%)	150.6%	-	75.9%	-	9.3%	-	-2.5%	-	-5.2%	-

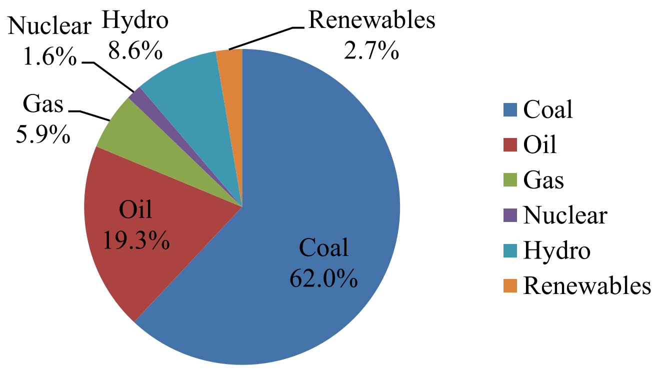


Fig. 2.3 – Chinese energy consumption by source (Source: Elaboration based on [5])

2.3.1.2 China's growing import dependence

Even if the growth in energy demand has slowed down significantly (just +1.24% from 2015 to 2016, compared with roughly +15% per year in the early 2000s [5]), China will still consume almost one quarter of world energy in 2040 and its energy dependence from other countries will constitute more and more a concern for Chinese government. Today, total net energy imports accounts for just 19% of Chinese total primary energy supply, but this figure is expected to increase in the future [23].

China owns approximately 13% of total world's coal reserves (see Tab. 2.5), but, as a result of high production rates, these will cover consumption for less than 40 years. The country used to be a traditional coal exporting country, due to the high availability of this energy source. However, as shown in Fig. 2.4, from 2009 China has become a coal net importing country. Nonetheless, Chinese coal import dependency, calculated as the ratio of coal net imports divided by coal primary energy supply, has always remained far below 10% (see Fig. 2.5). In 2017, China imported coal mainly from Australia, Indonesia, Mongolia and Russia, as Fig. 2.6 shows.

Chinese natural gas reserves are limited, accounting just for 2.8% of the total. Historically, China is not a large natural gas consumer, but natural gas import is significantly growing in the last decade (see Fig. 2.4) and gas dependency reached 32.9% in 2016 (from less than 2% in 2008). In its Energy Outlook 2018, BP forecasts that in 2014 gas dependency will rise to 43%. Tab. 2.6 summarizes Chinese import dependency by commodity for 2016 and 2040. As far as gas is concerned, China relies significantly on Turkmenistan's supply by pipeline via Kazakhstan and Uzbekistan, as shown in Fig. 2.7.

China became a net oil importer in 1993 and today oil is not only the second-largest contributor to China's primary energy consumption, but also the most critical commodity in terms of energy security. Chinese oil proven reserves are extremely limited (1.5% of the world total) and they are expected to satisfy the demand for less than 20 years. In 2016, oil import dependency accounted for more than 65% and this figure is projected to grow to 72% by 2040 [23]. Furthermore, oil imports come largely from politically unstable countries, and nearly three-quarters are shipped through a single checkpoint, the Malacca Strait [24]. Its strategic importance and vulnerability raises major concern in Chinese regime and significant attention has been devoted to the so called “Malacca dilemma”. Fig. 2.8 reports China’s top crude oil suppliers in 2017.

To sum up, future energy demand cannot be covered by China’s own conventional and unconventional sources, and external energy imports will increase more and more in the future [25]. This is forcing China to engage more actively in energy diplomacy and regional cooperation, as also the Belt and Road Initiative demonstrates, with the aim to ensure reliable and diversified energy supply.

Tab. 2.5 – China's proven reserves (Source: [5])

	Reserves at end 2017 in physical units	Reserves at end 2017 (PJ)	Share of Total (%)	R/P ratio (years)
Coal	138819 million tons	3775380	13.4%	39.0
Natural gas	5.5 trillion cubic meters	197877	2.8%	36.7
Crude Oil	25.7 thousands million barrels	147023	1.5%	18.3

Tab. 2.6 – Import dependency by commodity in 2016 vs 2040 (Source: [26], [23])

	Share TPES	Import dependency in 2016	Import dependency in 2040
Coal	64.8%	6.5%	not available
Natural gas	5.8%	32.9%	43%
Crude oil	18.9%	67.4%	72%

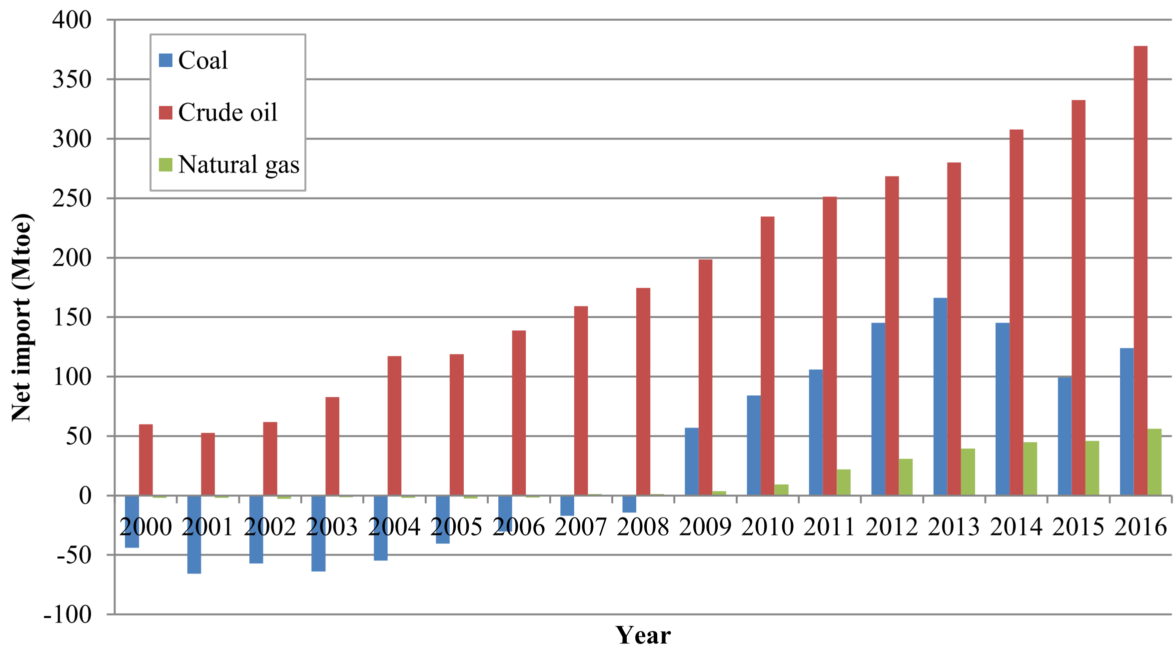


Fig. 2.4 – China net imports from 2000 to 2016 in Mtoe (Source: Elaboration based on [2])

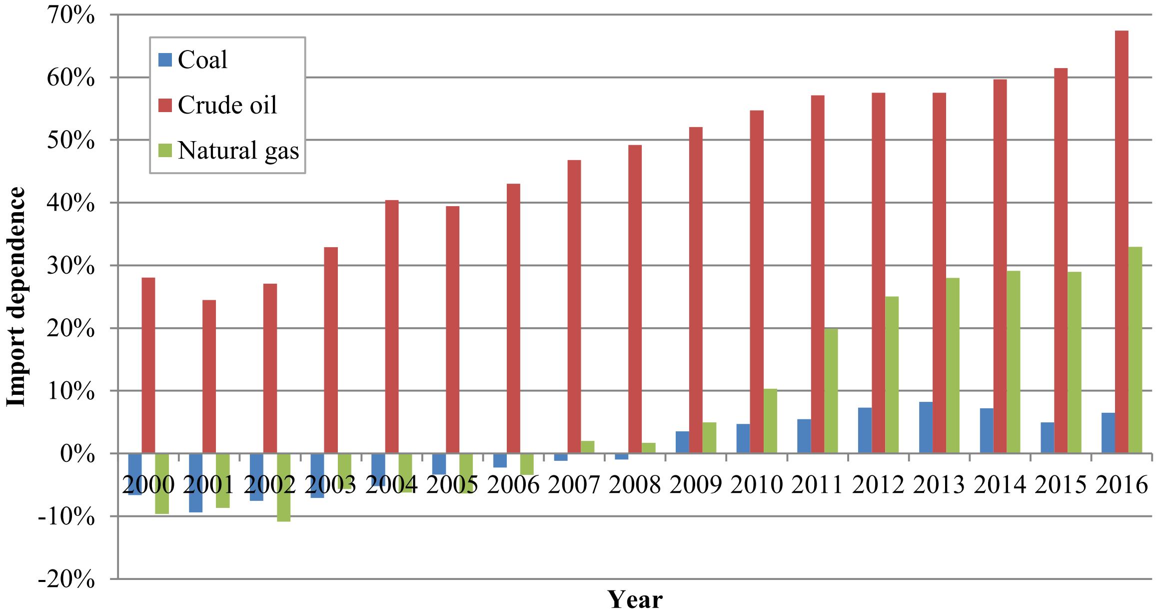


Fig. 2.5 – China’s import dependency from 2000 to 2016 (Source: Elaboration based on [2])

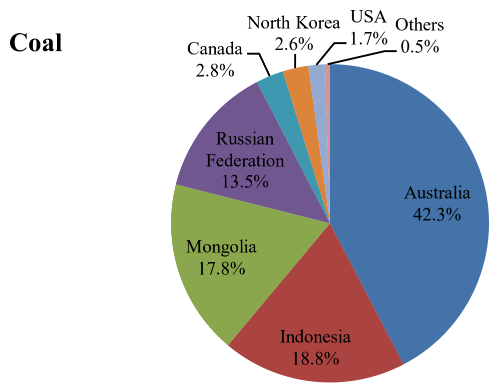


Fig. 2.6 – China's top coal suppliers in 2017 (Source: Elaboration based on [27])

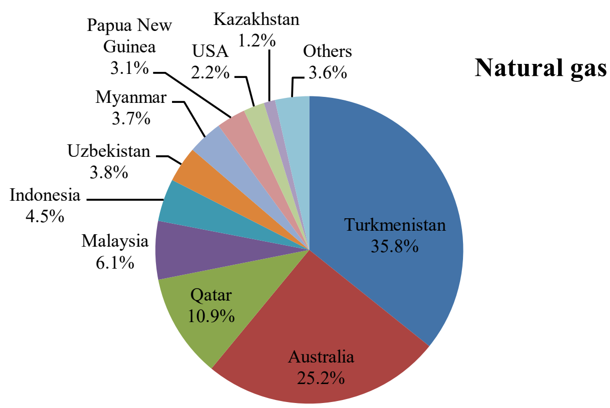


Fig. 2.7 – China's top natural gas suppliers in 2017 (Source: Elaboration based on [27])

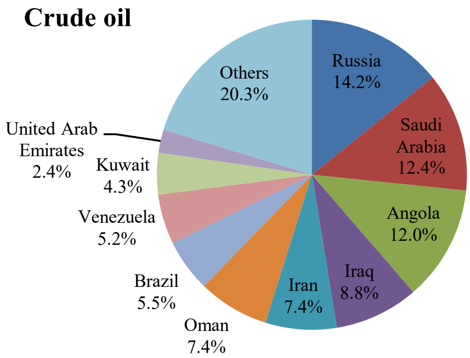


Fig. 2.8 – China's top crude oil suppliers in 2017 (Source: Elaboration based on [27])

2.3.1.3 China's energy supply corridors

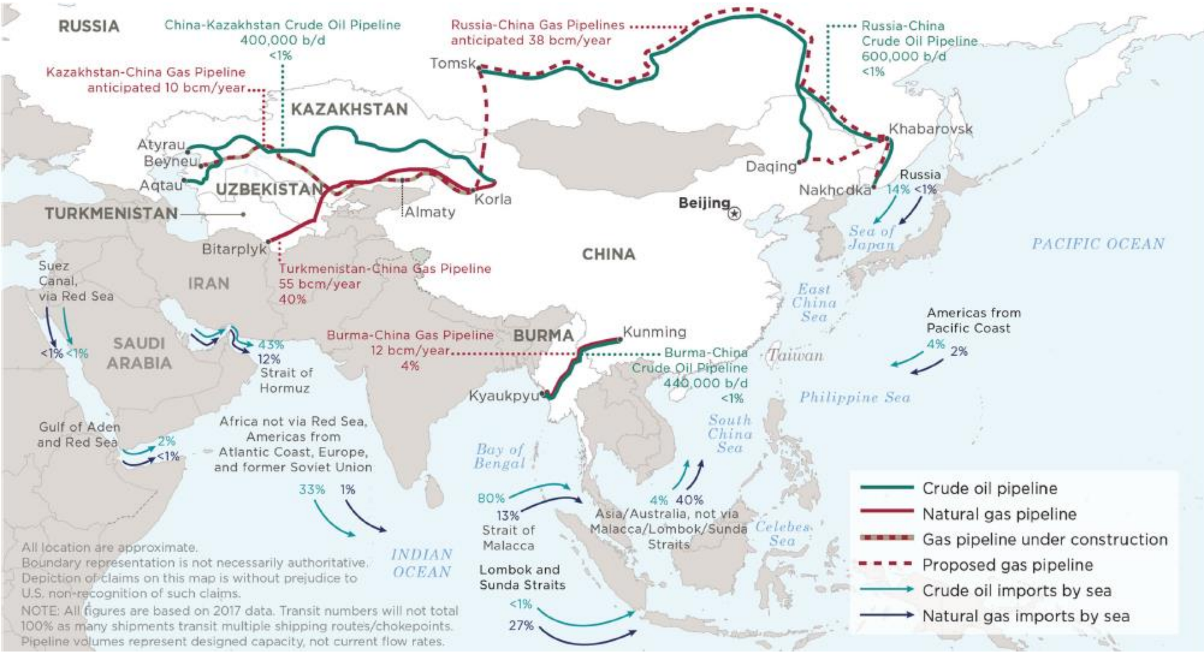


Fig. 2.9 – China's energy import transit routes (Source: [28])

China imports roughly half of its natural gas demand via pipeline. The most important pipelines for Chinese supply of natural gas are:

- The Central Asia-China Gas Pipeline (also named Turkmenistan-China Gas Pipeline in Fig. 2.9), starting at the Turkmen-Uzbek border and running through central Uzbekistan and southern Kazakhstan before reaching Khorgos in China's Xinjiang region. This pipeline is currently composed of three parallel lines (A, B, and C), each 1830 km long, and it is characterized by an overall delivery capacity of 55 billion cubic meters per year. Line A and B, accounting together for 30 billion cubic meters (bcm) per year, are supplied by natural gas from Turkmenistan's fields, whereas Line

C is supplied by natural gas of 10 bcm, 10 bcm, and 5 bcm per year from Turkmenistan, Uzbekistan, and and Kazakhstan respectively. The maximum delivery capacity from Central Asia is expected to increase up to 85 bcm per year, thanks to the construction of line D, as part of the BRI. In fact, an inter-governmental agreement with Uzbekistan, Tajikistan and Kyrgyzstan was signed in 2013 for the Line D project, which will run across these countries towards China for 1000 km, with a capacity of 30 bcm per year. Also Line D will be supplied by Turkmenistan's gas fields [29]. However, at the moment the construction of Line D is stalling and, so far, the project has represented just an unsuccessful attempt of regional integration, with respect to other Belt and Road projects [30]. In Central Asia, also another BRI energy project is currently being developed: the Kazakhstan-China gas pipeline, which, starting from Beyneu (next to the Caspian Sea) and connecting to the Central Asia-China pipeline at Shymken, will supply up to 10 bcm per year of natural gas to China.

- The Bruma-China Gas Pipeline. This pipeline, part of the BRI and designed with maximum capacity of 12 bcm per year, delivered only 3.4 bcm of gas in 2017 [28]. It starts from deep-water port of Kyaukphyu in the Bay of Bengal and it ends at Kunming, in the Yunnan province. It carries natural gas extracted from the offshore fields in Bay of Bengal.
- The Power of Siberia or Russia-China Gas Pipeline. Part of the BRI energy projects and still in its construction phase, this pipeline is expected to supply up to 38 bcm per year by 2035 [28]. According to schedules, it will start delivering Russian gas (extracted in Easter Siberia) in 2019. Russia will be one of the main providers of China's increasing natural gas demand and the two countries are planning to build also another pipeline (called Power of Siberia 2 or Altai) that will deliver other 30 bcm per year from Western Siberia to North-Western China.

Concerning oil supply, China is significantly reliant on Strait of Malacca shipping, as highlighted in the previous paragraph. However, three oil pipelines allow for diversification of import corridors:

- The Eastern Siberia-Pacific Ocean (ESPO) oil pipeline, with a capacity of 600,000 barrels per day, delivers the oil extracted in Western Siberia fields.
- The Kazakhstan-China oil pipeline: this was the first import pipeline from Central Asia to China. It runs from Kazakhstan's Caspian shore to Xinjiang province in China.
- The Bruma-China oil pipeline (or Myanmar-China oil pipeline): this project is part of the BRI and allowed to further diversify China's oil import routes, reducing the reliance on conventional shipping routes across the Malacca Strait, thus increasing energy security. In fact, this pipeline bypasses the Strait of Malacca by transporting crude oil from Kyaukpyu port (Burma) to Kunming (China). Saudi Arabia and other Middle Eastern and African countries supply the crude oil to this pipeline, which runs parallel to the Bruma-China gas pipeline.

Tab. 2.7 and Tab. 2.8 reports the main Chinese gas and oil pipelines, providing geographical information – such as starting and ending point, crossed countries – and physical information, such as maximum capacity.

Tab. 2.7 – China's natural gas import pipelines

Name	From[4]	To	Start point	End point	Crossed countries	Length (km)	Max Capacity (bcm/y)	Max Capacity (PJ/y)	Status[5]
Central Asia-China pipeline (lines A,B,C)	TKM	CHN	Saman-Depe	Khorgos	TKM, UZB, KAZ, CHN	1833	55	2090	O
Central Asia-China pipeline (line D)	TKM	CHN	Galkynysh	Wuqia	TKM, UZB, TJK, KGZ, CHN	1000	30	1140	C
Kazakhstan-China gas pipeline	KAZ	KAZ	Beyneu	Shymkent	KAZ	1400	10	380	C
Bruma-China gas pipeline	MMR	CHN	Kyaukpyu	Kunming	MMR, CHN	793	12	456	O
Power of Siberia	RUS	CHN	Chayanda, Yakutia	Blagoveshchensk (border RU/CN) / Vladivostok (RU)	RUS, CHN	4000	38	1444	C
Power of Siberia 2 (Altai)	RUS	CHN	Urengoy	Xinjiang province	RUS,CHN	2800	30	1140	P

Tab. 2.8 – China's oil import pipelines

Name	From	To	Start point	End point	Crossed countries	Length (km)	Max Capacity (bbl/d)	Max Capacity (PJ/y)	Status
Eastern Siberia–Pacific Ocean (ESPO) oil pipeline	RUS	CHN	Taishet	Daqing	RUS,CHN	4857	1600000	3562	O
Kazakhstan-China oil pipeline	KAZ	CHN	Atyrau	Alashankou	KAZ, CHN	2228	400,000	891	O
Bruma-China pipeline	MMR	CHN	Kyaukpyu	Kunming	MMR, CHN	793	440000	980	O

As far as maritime routes are concerned, China started to import LNG in 2006 [25], due to the increasing natural gas demand. In 2017, the country was the largest contributor to LNG consumption growth (+12.7 Mt with respect to 2016), becoming the second world's bigger LNG importer after Japan [4]. The country's LNG demand is set to further increase and its share in global LNG demand is expected to converge by 2030 with that of Japan, which is at the moment the largest LNG consumer [31]. China counts 17 LNG regasification terminals in operation, for a total capacity around 55 Mtpa (corresponding to roughly 70 bcm/y) which is expected to almost double in the next five years. The regasification utilization rose significantly in 2017, hitting 73% (from 56% in 2016) [4]. Chinese LNG terminals are supplied mainly from Australia, Qatar, Malaysia and Indonesia. In the Belt and Road framework, the Yamal LNG project has to be cited. This is an integrated project for natural gas production, liquefaction and shipping from the South Tambey Field located in the north-eastern part of the Yamal Peninsula (Russia), to both European markets and China. The liquefaction plant came online in 2018 and the terminal can produce 16.5 Mtpa of LNG at full capacity [32]. The Yamal LNG project, a joint-venture of NOVATEK (50.1%), TOTAL

[4] The countries are identified according to the international standard ISO 3166-1 alpha-3.
[5] Status: O = in operation, C = under construction, P = planned

(20%), CNPC (20%) and Silk Road Fund (9.9%), would further strengthen energy ties between China and Russia, together with the two Power of Siberia gas pipelines and the ESPO oil pipeline.

As already highlighted, oil import is the Achilles heel of Chinese energy security. In fact, China imports almost 70% of its oil demand and, furthermore, the country relies significantly on Middle East imports and, thus, on unstable Sea Lines of Communications (SLOCs). Specifically, the congested Malacca Strait, with its minimum width of 3 km, is one of the most important trade routes for China. Beijing is therefore trying to reduce the reliance on maritime shipments and increase diversification of supply through pipelines. Oil imports from Russia almost doubled from 2010 (6%) to 2016 (14%), surpassing Saudi Arabia (12%). As a consequence, the share of oil imports from Middle East and Africa dropped from 76% to 60%, in favour of Russia and Americas (Fig. 2.10). Moreover, oil shipping through the Malacca Strait decreased from roughly 80% to 75% since 2010 [22]. This was made possible also by the completion of the BRI China-Myanmar oil pipeline, which allowed bypassing the Malacca choke point, controlled by US fleet and threatened by piracy.

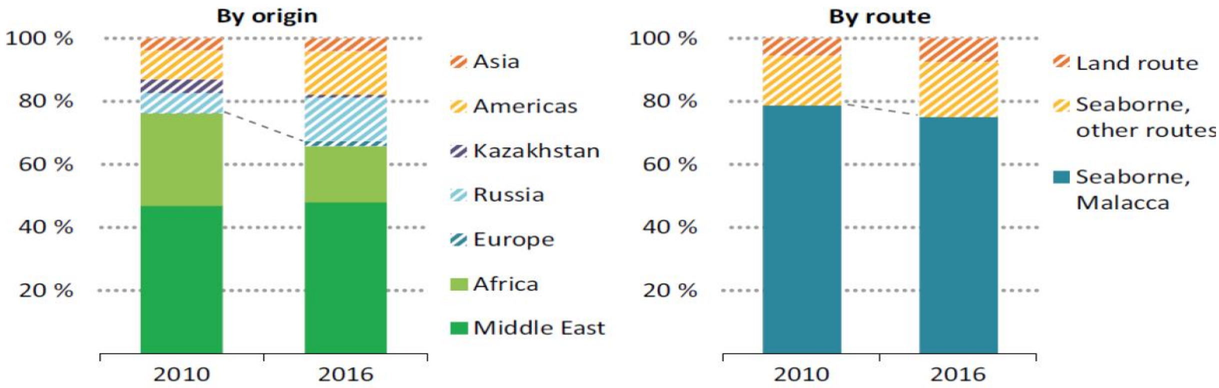


Fig. 2.10 – China's crude oil imports by country of origin and route (Source: [22])

2.3.2 China's energy interests in the BRI region

The previous paragraph highlighted the present situation of Chinese energy mix, underlining future trends and criticalities for the country's energy security. Specifically, one of the major vulnerabilities of Chinese energy supply is represented by the heavy dependence on maritime imports of oil, gas and coal via unstable maritime routes across the Indian Ocean, the Malacca Strait and the South China Sea. Furthermore, the forecasts about growing import dependence enforce China to expand energy cooperation with new partners, with the aim of increasing diversification and guaranteeing security of supply. In this sense, BRI countries can be strategic partners both for providing energy resources and ensuring the safety of new energy corridors routes.

For instance, the Middle East, included in the BRI region, holds almost 48.7% of global oil reserves and accounts for almost half of Chinese crude oil imports. Beijing is expanding bilateral agreements with Saudi Arabia, the major oil exporter of the area, and Iran [22].

In the BRI area, also Central Asia and the Caspian Region are strategic energy partners for China since 1990s. Specifically, Turkmenistan is the country's largest natural gas supplier and the addition of extra pipelines is planned, as part of the BRI (line D of the Central Asia-China pipeline). China is currently the main gas export market for Turkmenistan, which is attempting to increase its diversification level through to the under construction Turkmenistan–Afghanistan–Pakistan–India (TAPI) pipeline [22]. China showed interest in joining TAPI project, which could be used as alternative to the line D of Central Asia-China pipeline, by building a new pipeline linking TAPI Pakistan section to China [33]. However, the implementation of TAPI experienced several delays due to the political instability of the regions crossed and for the hostile relationships between Pakistan and India.

The China-Pakistan Economic Corridor (CPEC) is the flagship of BRI, representing a link between the Economic Silk Belt and the 21st Century Maritime Silk Road. It also constitutes a crucial project for the Chinese energy security. In fact, the construction of the Gwadar port in Pakistan allowed China to receive goods and especially energy resources from the Persian Gulf, Africa and Europe, reducing its dependency on longer maritime routes in the Indian Ocean and Malacca Strait. The shipped good received in Gwadar can then be transported through railways, highways and pipelines to the southwest Chinese provinces [22]. For instance, as part of the CPEC project, the construction of a crude oil pipeline from Gwadar to Kashgar (China) is planned. This pipeline would allow Beijing to increase diversification of crude oil import routes.

Another energy project in the BRI framework is CASA-1000, which aim to link the electricity transmission system of Central Asia and South Asia. The surplus power generated by hydropower resources in Kyrgyzstan and Tajikistan will be used to meet the electricity demand of Pakistan and Afghanistan, where power cuts are frequent [34].

The South China Sea is a crucial maritime route for a decisive part of global trade, and specifically for oil and LNG imports towards China. Beijing is trying to increase its control over the South China Sea, with the aim to improve security of China's energy import routes. As part of the BRI, China is building or buying ports in South Asia, including Myanmar, Bangladesh and Sri Lanka for both commercial and military purposes [22].

Tab. 2.9 reports the main BRI energy projects for transmission of energy commodities and for facilitating international oil, gas and electricity trade, and Fig. 2.11 shows them on the map. Besides these, China funded several projects for power grid extension in rural area or transmission capacity upgrades (e.g., in Cambodia).

Tab. 2.9 – Main BRI projects for transmission of energy sources

Corridor name	Commodity	Description	Status
Bruma-China oil pipeline	Oil	Oil pipeline connecting Myanmar to China, with 440,000 bbl/d capacity.	O
Gwadar-Kashgar pipeline	Oil	Oil pipeline connecting the Gwadar port in Pakistan to Kashgar in China with 1,000,000 bbl/d transmission capacity.	P
Central Asia-China pipeline (line D)	Natural Gas	Gas pipeline from Turkmenistan to China, crossing Uzbekistan, Tajikistan and Kyrgyzstan. The expected capacity is 30 bcm/y.	C
Bruma-China gas pipeline	Natural Gas	Gas pipeline connecting Myanmar to China, with 12 bcm/y capacity.	O
Kazakhstan-China gas pipeline	Natural Gas	Gas pipeline that will connect Beyneu (next to the Caspian Sea) to the Central Asia-China pipeline at Shymken. The expected capacity is 10 bcm/y.	C
Power of Siberia	Natural Gas	38 bcm/y gas pipeline from Russia to China.	C
Power of Siberia 2 (Altai)	Natural Gas	30 bcm/y gas pipeline from Russia to China.	P
TAPI pipeline	Natural Gas	Gas pipeline from Turkmenistan to India, crossing Afghanistan and Pakistan. The expected capacity is 33 bcm/y.	C
Yamal LNG	LNG	Maritime Route from Sabetta liquefaction terminal in Russian Yamal peninsula to Europe (westbound from December to June) and China (eastbound from July to November). The total capacity of the LNG terminal is 22 bcm/y (16.5 Mtpa).	O
CASA-1000	Electricity	Electricity transmission network connecting Central and South Asia, with a total capacity of 1300 MW (300 to Afghanistan and 1000 to Pakistan).	C

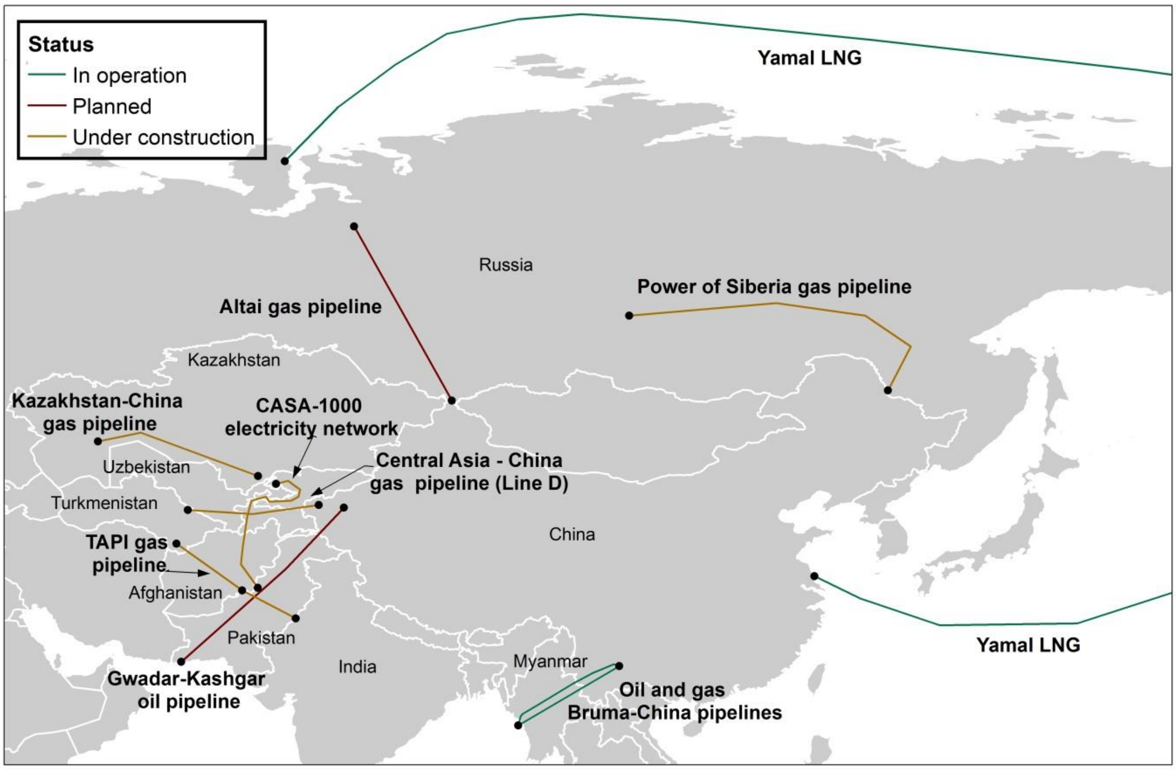


Fig. 2.11 – Main BRI energy projects (Source: PoliTO)

The examples of BRI energy projects reported in Tab. 2.9 refers mainly to infrastructure for transmission and distribution of energy resources across the BRI region. However, China is investing in a much broader set of energy related projects, from exploration and extraction to power generation. According to the China's Global Energy Finance database developed by the Boston University, from 2000 to 2017, Chinese policy banks[6] provided $225.8 billion in financing foreign governments in the energy sector [8]. More than half of this funding was devoted to the construction of energy infrastructure in the nations currently designated to be part of the Belt and Road Initiative. Tab. 2.10 shows that, in the BRI countries, China invested mainly in the power generation sector (50.7%), followed by exploration and extraction (20.5%), and transmission and distribution (16.3%). Investments in fossil fuel technologies still dominates Chinese portfolio with more than two-thirds of the total BRI energy finance. Specifically, more than one-third of investments are in coal-fired power generation (Fig. 2.12). This raises major environmental concerns about the sustainability of the initiative. From a policy point of view, at a global level, acceptability of the BRI might be hindered by the lack of in sustainability of the initiative. From a social point, inside each country, the acceptance of such plants may be opposed. From an economic point of view, the affordability of electricity produced may be highly reduced by international countermeasures to cap the CO2 emissions (e.g., carbon tax or other carbon pricing mechanism).

Tab. 2.10 - Sectoral distribution of Chinese foreign investments in energy from 200 to 2017 in the BRI countries (Source: Elaboration based on [8])

Energy sector	Amount ($m)	% Total
Exploration and Extraction	**26348**	**20.5%**
Gas/LNG	8300	31.5%
Oil	18048	68.5%
Multipurpose	**15954**	**12.4%**
Coal	3260	20.4%
Gas/LNG	12000	75.2%
Oil	694	4.4%
Power Generation	**65121**	**50.7%**
Coal	40861	62.7%
Gas	378	0.6%
Hydropower	11766	18.1%
Nuclear	6692	10.3%
Oil	1590	2.4%
Solar	1626	2.5%
Thermal	515	0.8%
Wind	1693	2.6%
Transmission and Distribution	**20929**	**16.3%**
Gas/LNG	6818.04	32.6%
Hydropower	750	3.6%
Oil	10509	50.2%
Unspecified Source	2852	13.6%
Total	**128352**	**100.0%**

[6] China's Global Energy Finance database tracks financing for energy projects by China's two global policy banks—the China Development Bank and the Export-Import Bank of China.

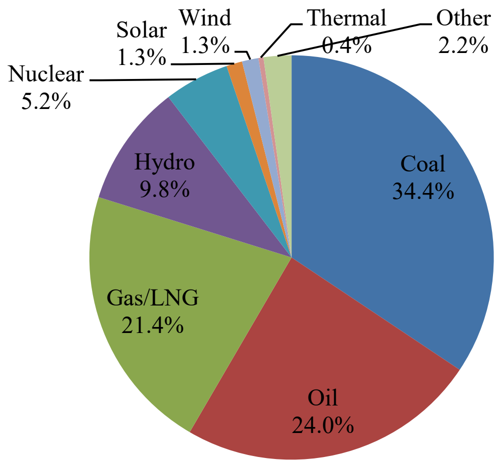


Fig. 2.12 – Chinese energy investments by source from 2000 to 2017 in the BRI countries (Source: Elaboration based on [8])

Sustainability is one of the major criticisms against the Belt and Road Initiative. China has significantly revised its domestic energy policies and, as part of the "Five Year Plan for Power Sector Development (2016-2020)", the share of non-fossil energy in TPES is set to increase to 15% by 2020 and to 20% by 2030 [22]. However, although internal policies are pushing for a reduction of coal consumption and are increasingly addressing issues related to pollution and air quality in major cities, China is still the largest global provider of public financing to foreign coal-fired plants. The concern is that China is just shifting the emission to other regions and countries.

Furthermore, China's energy portfolio is significantly exposed to economic and social risk. The BRI follows the principle of non-interference, differently from other international initiative, being a market-based action based on infrastructure and economically sustainable investments. However, the project involves different political and economic regimes, unstable regions and area in which terrorism is growing. For instance, Afghanistan and Pakistan are extremely critical countries, but also, Xinjiang, China's western province is a crucial area. In the framework of investments in Central Asia, Xinjiang would become the logistic hub of the BRI, bordering with seven countries. However, this province is one of the weaknesses of the initiative. Beijing is indeed worried about the spread of radical Islam in this Muslim-majority province and implements tightly control of its inhabitants.

Another criticism against BRI regards the win-win cooperation often advocated by Chinese leaders. BRI infrastructure projects often lack participation of local workers, with negative impacts on their economy and society. Moreover, some projects led to heavy debt burdens in BRI countries. For example, China became the largest lender for Sri Lanka after building the port of Hambantola. The debt has been written off in exchange of a 99-year long term lease on the port [22]. In order to assess the financial management risk due to high levels of BRI borrowing, two indicators should be carefully analysed: the share of Public and Publicly

Guaranteed (PPG) debt[7] over the country's GDP, and the concentration of this type of debt to China as creditor. If both these indexed are high, the dependence over Chinese lending is worryingly heavy and the project could easily became unsustainable for the country, as happened for Sri Lanka. The Center for Global Development, an American think tank, identified eight counties especially at risk of debt distress, where BRI seems creating significant potential for debt sustainability issues (Fig. 2.13).

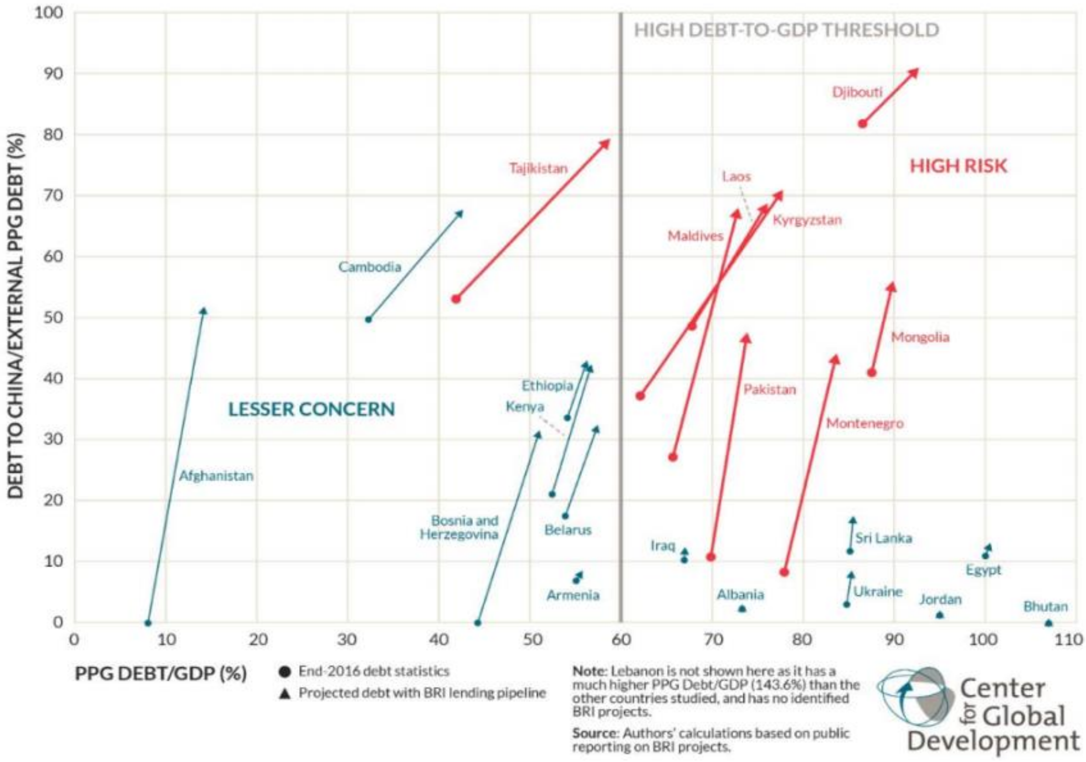


Fig. 2.13 – Impact of Chinese lending on BRI countries (Source: [35])

To sum up, several risk factors hinder the realization of Belt and Road Initiative, but, if successful, this ambitious Chinese international policy initiative could generate important opportunities for China and for the world economy [17]. Energy is a key aspect of the initiative, which aims to facilitate global trade of energy commodities and develop international connections for establishing a "global energy internet"[8]. In this framework, State Grid Corporation (SGCC) of China – the Chinese state-owned electric utility monopoly – conceived a further step for BRI energy dimension: the development of a global electricity network, which, together with electrification of final uses and long-distance transmission, can significantly boost the penetration of Renewable Energy Sources (RES) in the global energy mix. Liu Zhenya, former President of State Grid and now Chairman of Global Energy

[7] Public and Publicly Guaranteed (PPG) is part of the debt that a country owes to foreign creditors. Specifically, it comprises long-term external obligations of public debtors, including the national government, political subdivisions (or an agency of either), and autonomous public bodies, and external obligations of private debtors that are guaranteed for repayment by a public entity. (Source: World Bank)

[8] The phrase "global energy internet" was used by Chinese president Xi Jinping at the General Assembly of the United Nations on Sept. 2015.

Interconnection Development and Cooperation Organization (GEIDCO), developed this concept in his book “Global Energy Interconnection”, explaining that clean electricity will be generated in the Arctic (wind) and Equatorial regions (solar) and transmitted, through UHV DC grids (±800kV / ±1100kV DC), towards large consumption areas (namely, Asia, United Stated and Europe).

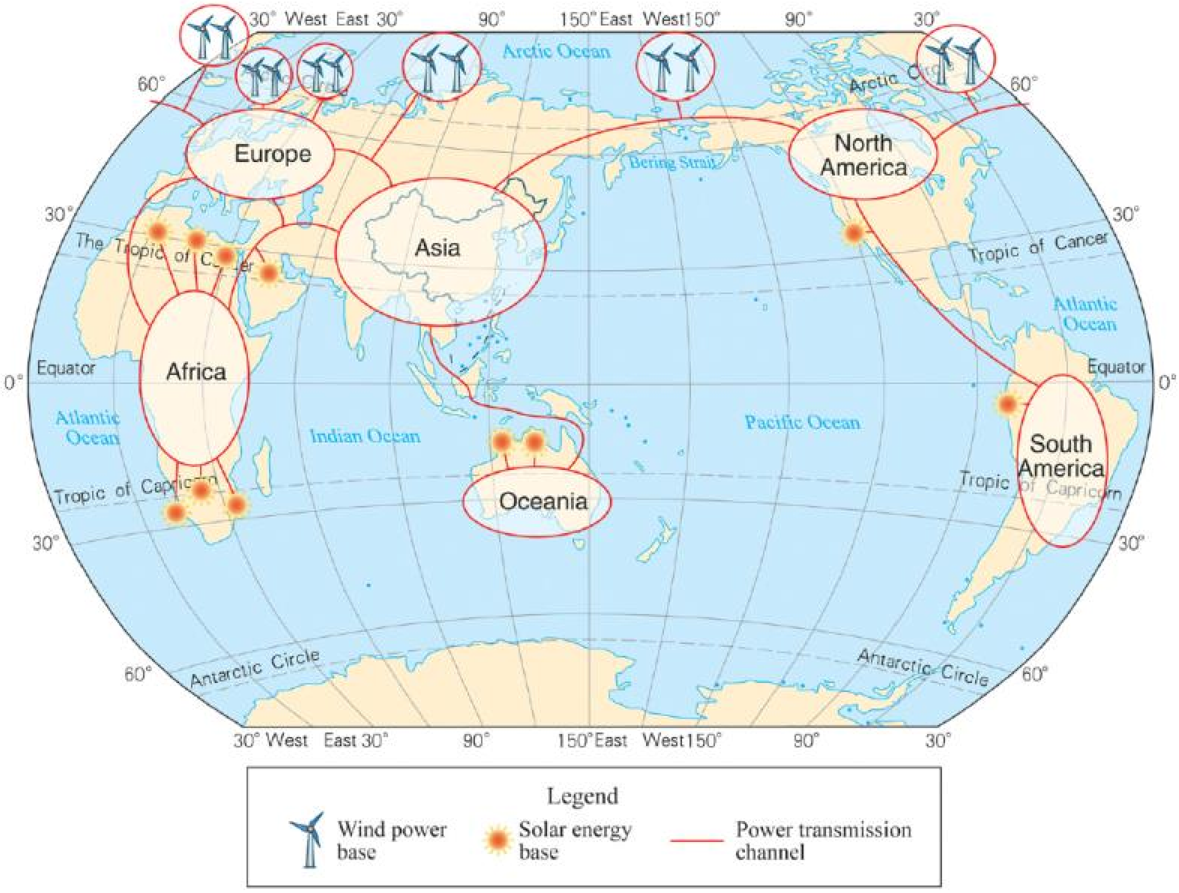


Fig. 2.14 – Global Energy Interconnection: generation and consumption areas (Source: [7])

3 Energy security

Energy access and availability are essential elements for economic growth, human development and social welfare of each country. Energy is indeed one of the four dimensions that identify a superpower, together with financial power, military strength and technology. It is also a major element of each country's security and a fundamental objective of government's energy policies. Christie et al. underlined that "energy security is national security", identifying energy sources as strategic commodities indispensable for the functioning of modern economies [36]. However, due to uneven distribution of energy sources around the world, many countries are characterized by high dependency on external imports and low level of self-sufficiency. The possibility to quantitatively assess the security of energy supply is therefore fundamental for guiding decision makers in selecting the policies to be implemented.

3.1 Definition and dimensions of energy security

A unique and commonly accepted definition of the term is not available in literature, but energy security can be defined as the capability of ensuring, through local production or foreign imports, the energy sources needed to satisfy the demand of final uses. Disruption of supply can occur in any step of the complex energy chain which often stretches over long distances and crosses national borders, involving production, transport, transformation and distribution to final uses.

All energy security definitions include the dominant theme of *availability* of energy sources, related to the geological existence of resources. However, due to the increasing complexity of energy systems, a broader range of vulnerabilities and dimensions have to be taken into account in order to fully grasp and measure a country's overall energy security situation. First, the rising international trade in energy commodities enforced to incorporate the concept of *accessibility* of resources, strictly connected with geopolitical dynamics. Second, the economic dimension or *affordability* is usually enclosed in the energy security concept, referring to the possibility to buy on the market (at market prices) the energy needed to satisfy the users' final consumption, thus sustaining and promoting economic growth. For instance, the IEA defines energy security as uninterrupted availability of energy sources at reasonable and stable prices [37]. Third, the dimension of *sustainability* (or environmental acceptability) of energy systems has to be taken into consideration. Sustainability refers to the opportunity to satisfy present demand without compromising the possibility of satisfying future energy demand, thus ensuring availability and access to energy sources also to next generations. Finally, various studies added new dimensions to the energy security concept, including social acceptability, social development, international relations, human security and energy policy [38]. The four main dimensions of energy security – availability, accessibility, affordability and sustainability – are subject to complex interplay and they are often conflictual [39], [40].

Considering time dimension, many studies make a distinction between sort- and long-term energy security. The former assesses the energy system capability of promptly reacting to unexpected curtailment of energy sources, analysing possible mitigation measures and re-dispatch solutions. The latter regards the development of energy policies for energy security improvement, in line with national environmental plans and international constraints

Furthermore, the assessment of national energy security involves an external front, related to energy imported from abroad, and an internal front, related to domestic production, transformation and distribution inside national borders. The analysis developed in this thesis focuses on the external dimension of energy security, which is especially critical for countries which heavily depend on foreign imports, but it has to be underlined the overall national security is affected by both fronts. The risk associated to the interruption of external energy supply can be related to:

- The geopolitical stability of suppliers.
- The security of the infrastructure which allows the transport of energy commodities from foreign production areas to national entry points. This is heavily dependent on the energy corridor type (namely, captive or open sea corridors) and on the geopolitical stability of crossed countries [41].

Countries are characterized by high external resilience if, in case of disruption of imports from a specific supplier or energy infrastructure unavailability, they are able to promptly cover their demand with energy sources from other suppliers or supply routes. Similarly, domestic resilience regards the ability to respond to disruptions of domestic production, transformation plants or distribution infrastructure. Energy infrastructure, both internal and external, is subject to three types of threads: extreme natural events (such as earthquake, flood or fire), malicious attacks (physical and cyber-attack, sabotage) and accidental failures (due to technical problems).

To sum up, in order to quantitatively assess energy security in a comprehensive view, a multi-perspective approach has to be developed, which has to take into account all the vulnerabilities (such as net import dependency, political stability of suppliers, type of supply corridor and crossed countries) and resilience factors (e.g., number of entry points for a country, storage capacity) of energy systems. Several studies approached the problem of quantitatively assessing energy security, identifying indicators and models which can support science-based policy decision making. The most meaningful indicators and models are reported respectively in Section 3.2 and Section 3.3.

3.2 KPIs for energy security assessment

3.2.1 Simple indicators

Simple indicators for national energy security assessment are obtained through simple elaboration of basic statistics listed in Appendix A. Tab. 3.1 reports the indicators available in literature, underlying in which of the four main dimensions of energy security each metric can be included.

Tab. 3.1 – Simple indicators for energy security assessment

Name	Symbol	Definition	Formula	Unit	Reference	Main dimension[9]			
						Av	Ac	Af	Su
Share of global reserves	$\rho_{\%}$	Share of the country's energy reserves over the world's total (ρ_{tot}). The available domestic resources are a direct indicator of the security of supply, since they are not subject to risk associated with geopolitical tensions and transport across long distances.	$\frac{\rho}{\rho_{tot}}$	%	[39], [42]	x			
R/P ratio	RP	Ratio of energy reserves remaining at the end of a certain year and the energy production (P) in the same year. It gives information about the number of years needed in order to finish all available reserves, assuming that the production rate remains constant with time.	$\frac{\rho}{P}$	%	[39]	x			
Share of source i in TPES	p_i	The information about the TPES composition in terms of energy sources is important because it can capture the dependence on a specific energy commodity. A more diversified energy mix allows for a more flexible response in case of disruption of energy corridors or supply from a certain country.	$\frac{TPES_i}{TPES}$	%		x			x
Import dependence	m	Net energy imports (a negative value means that the country is a net exporter) divided by TPES. Net imports are obtained subtracting exports to imports, thus taking into account countries acting as transport hubs. Import dependence indicates whether resources are domestic or not, which has a significant impact on their accessibility.	$\frac{I-E}{TPES}$	%	[39], [42]		x		
Middle East oil import dependence	$I_{o,ME,\%}$	Measure of a country's dependence on Middle East (ME) oil imports. Similar indicators can be constructed for other energy sources or import areas, but historically oil was the main concern for energy security.	$\frac{I_{oil,ME}}{TPES}$	%	[40]		x		
Self sufficiency	S	Ratio of national energy production and Total Primary Energy Supply. It is the complement of import dependence.	$\frac{P}{TPES}$	%			x		
Geopolitical risk	φ	The political situation of supplier countries and countries crossed during the transport of energy sources is crucial information for assessing the accessibility dimension of energy security. Political risk index can be based on different available datasets[10], for instance: • World Banks's Worldwide Governance Indicators (WGI) • ICRG's Political Risk index developed by PRS group • UNDP's Human Development Indicator (HDI)	-	-	[39]		x		
Non-carbon fuel portfolio	ν	Share of renewable energy sources (RES) and nuclear (N) in TPES. Estimation of an economy's intention to reduce fossil fuels.	$\frac{RES+N}{TPES}$	%	[39]				x
Renewable electricity output	RES	Share of electricity generated by RES in total electricity generated.	$\frac{GEN_{RES}}{GEN}$	%	%				x
Energy intensity	Q	Measure of the energy inefficiency of a nation's economy, calculated as the TPES divided by the GDP. It is a demand-side index which indicates the dependence of economies on energy and therefore also the sensitivity to supply disruption and price changes.	$\frac{TPES}{GDP}$	toe/ USD	[39], [42]			x	
Energy consumption per capita	η	Demand-side indicator measured as gross generation + imports – exports – losses, divided by population.	$\frac{TFC}{POP}$	toe/ capita	[42]			x	
Energy price	μ	The cost of energy sources (oil price in particular) gives indication about supply-demand balance and reflects depletion of energy sources.	-	$/PJ	[39], [42]			x	
CO2 intensity	G	It represents the tons of CO2 per ton of oil equivalent of Total Primary Energy Supply. It is a measure of the sustainability and efficiency of the energy system.	$\frac{CO_2}{TPES}$	ton_{CO2}/ toe	[42]				x

[9] Av= availability, Ac=accessibility, Af=affordability, Su=sustainability
[10] See Section 3.3.1 for further details.

3.2.2 Aggregated indicators

Aggregated indicators are derived from basic statistics or simple indicators, and they are often able to simultaneously capture more than one energy security dimension in a comprehensive approach. The most commonly used aggregated indicators for energy security assessment are the diversity indices. Diversification of energy types and suppliers is in fact one of the major countermeasures to the risk associated with energy supply disruption.

Stirling [43] defined the three basic properties that constitute the concept of diversity:

- *Variety.* It refers to the number of categories into which the elements of the system can be partitioned. In the energy security context, these categories may be related to the type of energy commodities or the supplier countries. The grater the variety, the more diverse is the system.
- *Balance.* It refers to the spread of elements across categories. The more even is the spread, the greater is diversity.
- *Disparity.* It indicates the level of difference between the categories. The more the categories are disparate and distinguishable from each other, the higher the diversity. For instance, a system whose categories in terms of primary energy sources are Oil, Coal and Natural gas is less heterogeneous than a system with Oil, Nuclear and Hydro [44].

Tab. 3.2 reports the question associated to each sub-category of diversity. Diversity indicators should be able to capture all three key elements of diversity. However, due to the difficulty in defining disparity of energy sources and suppliers on a quantitative and objective basis, diversity indicators in the energy security context measure only variety and balance and, for this reason, they are called “indices of dual concept diversity” [39].

Tab. 3.2 – The three properties of diversity (Source: [43])

Name	Question
Variety	How many types of things do we have?
Balance	How much of each type of things do we have?
Disparity	How different from each other are the types of thing that we have?

The mostly used index of dual concept diversity is the Shannon index (or Shannon-Weiner index) defined as [39], [44]:

$$H = -\sum_{i} p_i \ln(p_i) \tag{1}$$

where p_i is the share of the *i-th* category. The higher is the value of H, the higher the diversity, since this indicator increases monotonically with both variety and balance (the latter is shown in Fig. 3.1). The Shannon index is generally normalized[11] on a 0-1 scale:

$$H' = \frac{H}{H_{max}} \tag{2}$$

where:

[11] The prime symbol (‘) is always used in this thesis to identify normalized indicators.

$$H_{max} = -\ln\left(\frac{1}{N}\right) = \ln(N) \quad (3)$$

with N equal to the number of categories. The maximum value is obtained when all the categories have equal share. In this case, H' is equal to one, and the system is highly diversified. Conversely H' is equal to zero when the system is composed of a unique category (i.e., monopoly).

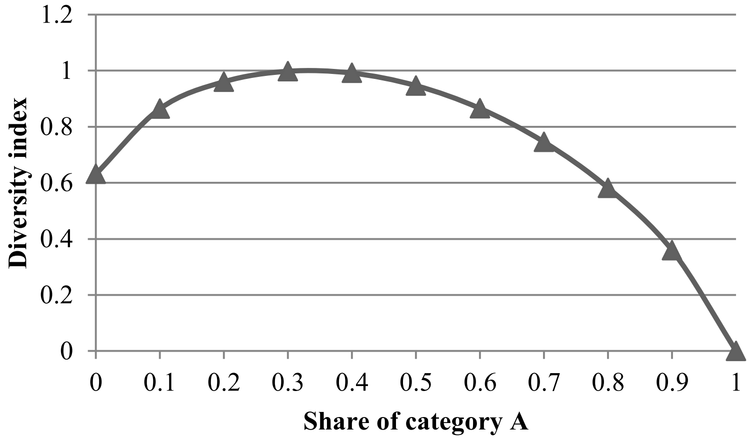


Fig. 3.1 – Normalized Shannon index for a system composed of three categories. Category A is varied and the remainder is split between categories B and C. The highest diversity is obtained when the three categories have equal share (0.33 in this example).

Several studies introduced Shannon index for measuring national energy security. For instance, Jansen [44] proposed four indexes characterized by increasing complexity in order to successively take into consideration more elements and give a more comprehensive view of energy security. He firstly introduced the most basic Shannon indicator, the *diversification of primary energy demand* index, which measures the diversification of a country's energy mix and it is defined as:

$$H_1 = -\sum_{i=1}^{M} p_i \ln(p_i) \quad (4)$$

where p_i is the share of energy commodity i in TPES and M is the number of primary sources. The normalized value is:

$$H_1' = \frac{H_1}{\ln(M)} \quad (5)$$

The lower the value of this indicator, the lower is the energy security, meaning that the country is significantly dependent on a specific energy source. The minimum value is obtained when the energy demand is satisfied by only one primary energy source [40], [44].

A second Shannon index that can be defined in the energy security framework is the *overall diversification* [44]. This index aims at coupling the diversification of primary energy portfolio, the net import dependence, and diversity in geographical sources of energy imports (i.e., diversification of supply). The basic Shannon index H_1 can be modified adding a correction factor, c_i, according to the following relationship:

$$H_2 = -\sum_{i=1}^{M} c_i p_i \ln(p_i) \tag{6}$$

The parameters appearing in the previous formula are:

$$c_i = 1 - m_i \left(1 - \frac{S_i}{S_i^{max}}\right) \tag{7}$$

$$S_i = -\sum_{j=1}^{N} m_{ij} \ln(m_{ij}) \tag{8}$$

$$S_i^{max} = -\ln\left(\frac{1}{N}\right) \tag{9}$$

where m_i represents the share of net imports in PES of source i (net import dependence for source i) and m_{ij} is the share of imports of source i from region j in total import of source i. S_i is the Shannon index for *diversification of supply* for source i and N is the maximum number of regions/countries of origin.

In the case of oil and gas, it is possible to take into account also transport mode – pipeline or open sea corridors (e.g., oil tanker, LNG carrier) – and fictitiously double the number of suppliers [44].

The third diversity indicator is based on H_2, and adjusted in order to take into consideration also the political stability of suppliers. In the definition of H_3 therefore a different correction factor is introduced [44]:

$$H_3 = -\sum_{i=1}^{M} c_i^* p_i \ln(p_i) \tag{10}$$

where:

$$c_i^* = 1 - m_i \left(1 - \frac{S_i^*}{S_i^{*,max}}\right) \tag{11}$$

$$S_i^* = -\sum_{j=1}^{N} h_j m_{ij} \ln(m_{ij}) \tag{12}$$

$$S_i^{*,max} = -\ln\left(\frac{1}{N}\right) \tag{13}$$

In these formulas, all variables are defined as for H_2 indicator. The only difference is represented by h_j, which is the political stability of region j, ranging from 0 (lower) to 1 (higher).

The fourth Shannon index is modified for taking into account the resource depletion, but, due to uncertainty and evolving dynamics of proven resources, the details of calculations are out of the scope of this analysis.

Finally, the Asia Pacific Energy Research Center (APERC) [40] proposed an additional aggregated indicator based on Shannon diversity index, which is a combined measure of primary energy diversification and import dependence, that, however, does not take into consideration the diversification of supply (as H_2) or the political stability of suppliers (as H_3). This is called *overall net energy import dependence* index and it is calculated as:

$$D = -\sum_{i=1}^{M}(1 - m_i)p_i \ln(p_i) \tag{14}$$

where D is the diversification of primary energy demand (H_1) modified for reflecting the level of import.

$$D' = \frac{D}{D_{max}} = \frac{D}{ln(M)} \tag{15}$$

$$H_4 = 1 - \frac{D'}{H_1'} = \frac{\sum_i m_i p_i \ln(p_i)}{\sum_i p_i \ln(p_i)} \tag{16}$$

where p_i and m_i represent respectively the share in TPES and the net import dependence for source i. H_4 measures the country's import dependence weighted by its fuel diversity. Unlike the previous defined indicators, a high H_4 value means that the country has low energy security level, being not only characterized by a limited diversification of its primary energy mix, but also relying significantly on external imports.

To sum up, a literature review was developed in order to identify the most interesting energy security indicators, both simple and aggregated, for supporting science-based policy decision making. The indicators introduced are characterized by some limitations and could hinder peculiar energy dynamics. For instance, considering the simple import dependence indicator, this is sometimes unable to capture crucial issues related to energy security. Iran is a striking example of this, being a net oil exporter, but, due to insufficient transformation capacity, importing a significant amount of the gasoline needed to satisfy its internal demand [39]. Nonetheless, these metrics can be particularly useful for highlighting trends and supporting comparative scenario analyses, rather than focusing on their specific absolute values. Moreover, they can help policy makers to get a comprehensive view of the different dimensions of energy security. In Fig. 3.2, the indicators considered in this section are plotted in relation to the four main dimensions of energy security, with the aim of underlining again the complex interplay and relationships among them.

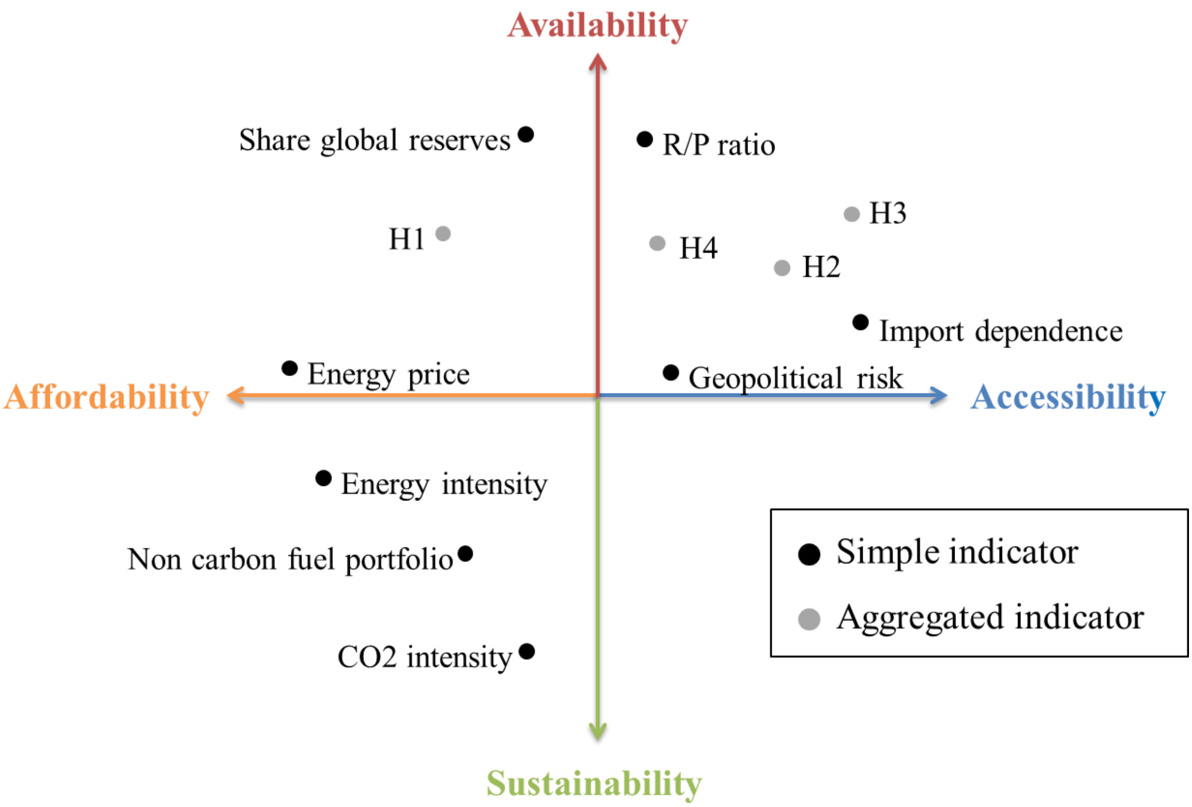


Fig. 3.2 – Indicators and energy security dimensions

3.3 Models and algorithms for energy security assessment

Different types of models have been devised for analysing national energy security in a science-based approach. The mathematical models most frequently adopted are:

- *Physical flow modelling*. It allows physical modelling of energy flows for different energy commodities, taking into account operational limits (e.g., pipeline maximum capacity, maximum pressure or voltage, etc.). These models involve equations for physical and thermo-hydraulic representation. They can be applied for analysing normal operation or re-dispatch problems in case of failure. An example is the EUGas model of the European gas transmission pipeline network, developed by JRC-IET (Joint Research Centre - Institute for Energy and Transport).
- *Game theory*. It allows to model strategic interactions among different players with conflictual interests. The payoff of each player depends on its actions, but also on the strategy implemented by other players. This approach can be applied to many fields in science and also to energy security, allowing for modelling geopolitical interactions among countries and probability of terroristic attacks.
- *Optimization and simulation approaches*. They are generally used for mid- and long-term planning of energy systems. Simulation models are able to assess the system response to the values assumed by a given set of variables, and the cost/benefits of a given system configuration, allowing comparison among different options.

Optimization models (e.g., TIMES model) find the optimal values of all the system variables, which allow minimizing or maximizing a given objective function, taking into account constraints (e.g., maximum capacity of a pipeline) and targets (e.g., reduction of CO2 emissions under a certain threshold).

- *Reliability, Availability, Maintainability, Safety (RAMS) analysis*. It allows assessing the risk associated to energy supply through a probabilistic approach. Risk is in fact the product of the probability of occurring and the damage (physical or economic) of an event. This approach can be used for assessing either safety of energy systems (related to accidental or technical risk) either security (related to malicious attacks or geopolitical events). RAMS analyses can also be applied at the infrastructure level.

According to the model adopted, different time scales of energy security can be analyzed. For instance, physical flow models are suitable to perform short-term analysis (e.g., the unexpected disruption of energy infrastructure, interruption of supply from a certain country). Conversely, optimization and simulation approaches are linked to long-term planning, allowing for comparison among different future scenarios. They can be applied in order to assess the impacts of different strategic energy policies. For example, they could support the construction of energy corridors involving new suppliers, with the aim of increasing diversification of supply and minimizing the geopolitical risk.

3.3.1 Energy security assessment in a geopolitical perspective

In this section, three models (see Tab. 3.3) are presented in which the focus is the assessment of the external dimension of energy security (i.e., from production areas to national entry points) in a geopolitical perspective. In this sense, the geopolitical situation of suppliers and countries crossed by energy corridors is especially important to be quantified. This can be done by referring to indicators which provide a quantitative assessment of the socio-political dimensions related to the governance of each country. The datasets mostly used in literature are:

- *The PRS Group International Country Risk Guide (ICRG) political risk rating*[12]. The ICRG political risk rating is published annually and it ranges from 0 (high risk) to 100 (low risk). It is calculated using 17 risk components including turmoil, financial transfer, direct investment, and export markets. The average ICGR political risk index was used, for example, by the IEA for assessing energy security [45].
- *The World Banks's Worldwide Governance Indicators (WGI)*[13]. The WGI is published annually and it measures the different dimensions of governance through 6 composite indicators: Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law and Control of Corruption. A variety of different data sources from surveys, nongovernmental organizations and public sector providers are collected, rescaled from 0 (high risk) to 1 (low risk), and finally combined to build the six indicators [46]. Each indicator is available either on scale from -2.5 (weak governance performance)

[12] Regional Political Risk Index, The PRS Group [https://www.prsgroup.com/regional-political-risk-index-4/]
[13] Worldwide Governance Indicators, The World Bank [http://info.worldbank.org/governance/wgi/#home]

to 2.5 (strong) and on a scale from 0 (weak) to 100 (strong), as a percentile rank among all countries. The IEA adopted the average of the first two WGI indicators (Voice and Accountability and Political Stability, and Absence of Violence/Terrorism), which are the more related to the energy security perspective, in order to estimate each country's political stability [47].

- *UNDP's Human Development Index (HDI)*[14]. HDI is a composed index which takes into consideration life expectancy, education and standard of living (i.e., income per capita). It ranks from 0 (low human development) to 1 (very high human development). Even if this indicator is not directly built considering country's governance performances, Jansen et al. [44] based their quantitative measure of political stability on HDI for calculating an energy security diversity index which takes into account also the geopolitical perspective (see Section 3.2.2).

It has to be emphasised, however, that geopolitical relationships are extremely difficult to be quantified. All the political stability indicators introduced above should be used with caution, taking into consideration that they could not perfectly reflect the political situation of a country. Furthermore, it has to be underlined that geopolitical situations and relationships among countries can experience sudden disruptive changes, due to socio-political events. Nonetheless, the political stability is commonly assumed constant when developing comparative scenario analyses, due to the impossibility to forecast future trends for these types of indicators.

Tab. 3.3 – Models for energy security assessment in a geopolitical perspective

N.	Name	Type	Focus	Source
1	Supply risk due to corridor unavailability	RAMS	Infrastructure	[41]
2	Supply risk due to supplier unavailability	RAMS	Suppliers	-
3	Supply optimization in a geopolitical perspective	Optimization	Suppliers	-

3.3.1.1 Model 1: Supply risk due to corridor unavailability

This model allows for assessing the external supply risk, considering the political stability of the countries crossed by the energy corridors which connect the source countries and the national entry points [41]. The following input data are necessary:

- Country geopolitical risk index (φ_k): it is an indicator of the political instability of country k, ranging from 0 (lower risk) to 100 (higher risk). This can be obtained as the complement of the ICRG index or the average WGI.
- Length of energy corridor in each country crossed (l): the failure probability of the corridor due to geopolitical reasons in a certain crossed county is proportional to the length of the corridor in that country.
- Energy flow transported through each corridor j (E_j): the higher is the energy transported, the higher is the damage for the importing country when the corridor is unavailable.

[14] Human Development Report, UNDP [http://hdr.undp.org/en/content/human-development-index-hdi]

The country geopolitical risk and the corridor length in each crossed country are used to calculate the probability of failure for corridor j, ξ_j. Each corridor is composed by several branches[15] in series. Therefore, assuming that the failure of each branch is independent from the others, the probability of failure of the entire corridor is obtained as:

$$\xi_j = 100 * \left[1 - \prod_{k_j} \left(1 - \frac{\gamma_k \varphi_k}{100}\right)\right] \tag{17}$$

where k_j refers to all countries crossed by corridor j and γ_k is an empirical weighting function that allows taking into account the length of the branch. γ_k is a function of the ratio between the length of the branch b_b and the average corridor branches, $\bar{b}_j$ (equal to the total corridor length divided by the number of crossed countries). When $b_b/\bar{b}_j$ >1, meaning that the branch is longer than the average, γ_k is greater than 1 so that the probability of failure of that branch is increased. Conversely, when $b_b/\bar{b}_j$ <1, γ_k is lower than one, since it is less probable that a failure occurs in a shorter branch. For details about the values assumed by the weighting function γ_k, you can refer to [41]. The term $(\gamma_k \varphi_k)/100$ represents the probability of failure for the branch crossing country k, due to geopolitical tensions or national instabilities.

The risk associated to energy corridor j, is obtained multiplying the previously defined corridor failure probability and the damage, which can be expressed as physical damage (loss of energy supply in TJ) or economic damage (loss of GDP output in $).

$$R_j = \sum_{c_j} \frac{\xi_j}{100} * E_{c,j} \tag{18}$$

$$R_{j,econ} = \frac{R_j}{Q} \tag{19}$$

where $E_{c,j}$ (TJ) is the energy flow of commodity c transported through corridor j, and Q is the energy intensity of the economy (TJ/G$). $R_{j,econ}$ allows measuring the economic impact in terms of reduction of GDP as a consequence of the corridor unavailability.

The overall external risk for the country, considering all the supplying corridors is calculated as:

$$R_{ext} = \sum_j R_j \tag{20}$$

$$R_{ext,econ} = \sum_j R_{j,econ} \tag{21}$$

Another indicator that can be obtained from this procedure is the expected supply, S_{ext} (TJ), which is the difference between the total energy imported, E, and the overall external risk, R_{ext}:

[15] A branch identifies the portion of a corridor inside a specific country: the number of branches is equal to the number of countries that the corridor crosses. The total length of the corridor is equal to the sum of the lengths of all branches.

$$S_{ext} = E - R_{ext} \quad (22)$$

S_{ext} represents the expected value of energy supplied from each country, taking into consideration the geopolitical situation of crossed nations.

The proposed model allows for a quantitative evaluation of supply risk and expected supply. More than focusing on the exact values obtained by this model, the results of this type of analysis are especially useful for highlighting criticalities and suggesting energy policies aimed at improving diversification of supply. It has to be underlined, however, that this methodology presents some limitations:

- As mentioned in Section 3.3.1, the quantitative evaluation of a country's geopolitical risk based on available datasets is challenging and often unable to capture complex socio-political dynamics or particular relationships among countries.
- This methodology is unable to fully take into consideration differences in transport mode and, specifically, between captive and open sea corridors (see Tab. 3.4). For open sea corridors, it is possible to estimate an average transport route and apply the some country risk also to territorial waters. However, the intrinsic flexibility of maritime routes is not taken into account. For instance, considering natural gas, the presence of LNG regasification terminals allows for short-term contracts and can help to significantly increase diversification of supply. In this model, by contrast, LNG routes and gas pipelines are treated in the same way.
- Finally, this model does not make a distinction between suppliers and crossed countries. It is therefore good at assessing the probability of failure of energy corridors due to political instabilities in crossed countries; however, disruption of supply due to tensions in supplier countries is not fully captured. In order to better explain this point, the case of Central Asia-China gas pipeline can be reported. This starts at the Turkmenistan/Uzbekistan border and the length of the Turkmen branch is very short compared to the Uzbek branch. For this reason, the γ_k value for the Turkmen branch operates in the direction of reducing the weight of Turkmen risk index (γ_k<1), even if the political situation of the energy producing country is especially critical for the security of supply. A possible solution to this issue could be setting γ_k to its maximum value for supplier countries.

Tab. 3.4 – Energy corridor types

Corridor Type	Examples	Description
Captive	• Oil pipelines • Gas pipelines • Railways • Power lines	Captive corridors refer to spatially fixed infrastructure.
Open sea	• Oil tanker • LNG tanker • Coal tanker • Biomass tanker	Open sea corridors are maritime routes connecting two ports. They allow for a higher flexibility in terms of routes and they can be defined within a certain spatial range.
Other	• Road freight transport	

3.3.1.2 *Model 2: Supply risk due to supplier unavailability*

This model is similar to the one described in Section 3.3.1.1, except that the focus is not on the geopolitical situation of crossed countries, which could lead to the unavailability of energy corridors, but on the geopolitical situation of suppliers, which could nonetheless determine the disruption of supply. In this sense, the probability of successfully crossing all the countries along the corridor transit routes is assumed equal to one, and only the geopolitical risk of suppliers is taken into consideration. The risk associated to supplier *j* and the overall external risk can thus be calculated as:

$$R_j = \sum_{c_j} \frac{\varphi_j}{100} * E_{c,j} \tag{23}$$

$$R_{ext} = \sum_j R_j \tag{24}$$

where *j* and *c* are respectively the index referring to the suppliers and the energy commodities imported from country *j*. As done before, the physical external risk can be converted into monetary terms using the energy intensity.

Model 1 and 2 allow highlighting criticalities and weak points related to supplier countries and to the energy import infrastructure. They can be applied for performing comparative scenario analyses and guiding investments aiming at improving energy security. For instance, the current overall external risk can be compared with the risk obtained including a new energy corridor (under construction or planned) or a new supplier. Furthermore, the variation of one or more political risk indexes for the countries involved in the national energy supply can be assessed, calculating a new overall external risk and comparing it with the reference scenario.

However, it is also possible to use the previously defined indicators, or a combination of them, in order to perform optimization analyses and, for example, minimizing the risk associated to national energy supply.

3.3.1.3 *Model 3: Supply optimization in a geopolitical perspective*

Optimizations analyses allow finding the optimal set of the system variables which minimize (or maximize) a given objective function, subject to equality and/or inequality constraints. The more general formalization of an optimization problem is:

$$\begin{aligned} &\textit{minimize} && f(x) \\ &\textit{subject to} && g_i(x) \leq 0 \quad i=1,\dots,m \\ & && h_j(x) = 0 \quad j=1,\dots,p \end{aligned}$$

where *x* is a n-variable vector which represents the system variables to be optimized. In our case, the variables are the energy fluxes imported from abroad in order to satisfy the national demand. Optimization analyses give therefore suggestions about the quantity of commodities that should be imported from each supplier in order to minimize a given objective function, which can be:

- The overall external risk, calculated according to Model 1 or Model 2. For instance, focusing on supplier countries (for nomenclature, see Tab. 3.5):

$$\min f_1 = \min(R_{ext}) = \min\left(\sum_j \sum_{c_j} \varphi_j * e_{j,c}\right) \quad (25)$$

- The total cost of energy imports, calculated, for each commodity, as the product of the unit energy cost ($/PJ) for the different corridors or suppliers and the corresponding energy fluxes transported:

$$\min f_2 = \min(Cost) = min\left(\sum_j \sum_{c_j} \mu_{j,c} * e_{j,c}\right) \quad (26)$$

- A function taking into account both the external risk and the total cost of energy imports:

$$\min f_3 = \min\left(\sum_j \sum_{c_j} \varphi_j * \mu_{j,c} * e_{j,c}\right) \quad (27)$$

In all three cases, the equality constraint is represented by the necessity to satisfy the internal energy demand, therefore:

$$\sum_j \sum_{c_j} e_{j,c} = I_{tot} \quad (28)$$

Inequality constraints regard:

- The maximum capacity of energy corridors, which upper bounds the energy flow transported. For LNG exchanges, the maximum capacity is the minimum between the regasification capacity of the importing country, and the liquefaction capacity of the exporting country.

$$e_{j,c} \leq E_{c,j,max} \quad (29)$$

$$E_{LNG,j,max} = \min\left(C_{reg}, C_{liq,j}\right) \quad (30)$$

- The minimum capacity of energy corridors, related to contracts between countries.

$$e_{j,c} \geq E_{c,j,min} \quad (31)$$

- The sum of all LNG imports must be lower or equal to the country’s regasification capacity.

$$\sum_j e_{j,LNG} \leq C_{reg} \quad (32)$$

- Further constraints can be added in order to take into account that, in a short term-scenario, energy commodities are not interchangeable (i.e., if 50% of imports is represented by oil, this cannot be completely substituted by gas, due to system and final uses requirements). For instance, it could be set that, for each commodity, the total import variation is limited inside a certain percentage, α (e.g., α = 20%), with respect to the reference scenario:

$$(1 - \alpha) * I_c \leq \sum_j e_{j,c} \leq (1 + \alpha) * I_c \qquad (33)$$

Tab. 3.5 – Nomenclature for optimization problem

Name	Description	Symbol
Supplier countries	Set of countries from which energy commodities are imported.	j
Commodities	Set of energy commodities considered in the analysis (e.g., coal, crude oil, natural gas, electricity).	c
Energy fluxes	Variables of the optimization problem: energy import of commodity c from country j.	$e_{j,c}$
Geopolitical risk index	Probability of supply failure due to geopolitical tensions in country j. Ranging from 0 (low risk) to 100 (high risk).	φ_j
Energy price	Unit energy cost for commodity c, imported from country j.	$\mu_{j,c}$
Total import	Total import required to satisfy the internal demand.	I_{tot}
Import by commodity	Import of commodity c in the reference scenario.	I_c
Regasification capacity	Maximum amount of LNG that can be regasified and inserted into the gas grid.	C_{reg}
Liquefaction capacity	Maximum amount of LNG that can be liquefied and exported.	C_{liq}

The three optimization problems defined in this section are linear (i.e., the objective function, the equality and inequality constraints are all linear) and static (i.e., constraints and variables appearing in the objective function are constant with time).

The approach described can be used to find the quantities of different commodities which minimize the overall external supply risk, the overall supply cost, or both. However, it should be underlined that the result of the optimization could imply a reduction in diversification, which is a critical measure of energy security, since the model tends to favour the most stable or inexpensive supply countries, or the less expensive energy sources. A solution to this could be the definition of a multi-objective function which aims at minimizing the cost or risk, but maximizing the diversification of supply (using, for instance, the Shannon index introduced in Section 3.2.2). Since Shannon diversity indexes are nonlinear, the optimization would not be linear anymore, and more complex solution algorithms have to be introduced for solving the problem.

4 Integrated tool for science-based policy decision making in the energy sector

In this chapter, a science-based tool for analysis, through modelling, simulation and quantitative assessment, the energy dimension of an interconnected set of countries at a regional or multi-regional scale is proposed. The developed tool aims at taking into consideration, in a comprehensive approach, different interacting layers:

- *Physical*: energy resources, energy balances at national scale, energy exchanges and trade among countries, energy infrastructure and corridors.
- *Economic*: related to the impacts of energy policy implementation and investments on countries' economies.
- *Environmental*: impacts of energy projects on the environment in terms of emissions of greenhouse gases (CO_2, CH_4, N_2O, HFC, PFC) and air pollutants (SO_x, NO_x, NO_2, PM, VOCs, CO, NH3, O_3).
- *Social*: acceptance of energy projects and policies by national communities; effects on social employment, social welfare and energy access.
- *Geopolitical*: international relations among a broad set of countries, in which different cultures, political and economic regimes co-exist.

This multi-layer analysis can be adopted for supporting, with quantitative indicators and mathematical models, science-based policy decision making in the energy security field.

4.1 Vision: data, numbers, signs

The concept of energy security can be analysed from two different and complementary perspectives:

- The humanistic approach, able to grasp relationships among socio-political systems on the basis of geopolitical dynamics and historical events.
- The scientific approach, based on mathematical models, and able to provide quantitative information, ranking actions and investments to be implemented.

The dialogue between different knowledge and the integration of complementary skills can lead to a holistic and comprehensive analysis of energy security. In this sense, three elements have to be integrated in order to make an effort in coupling humanistic and scientific approach:

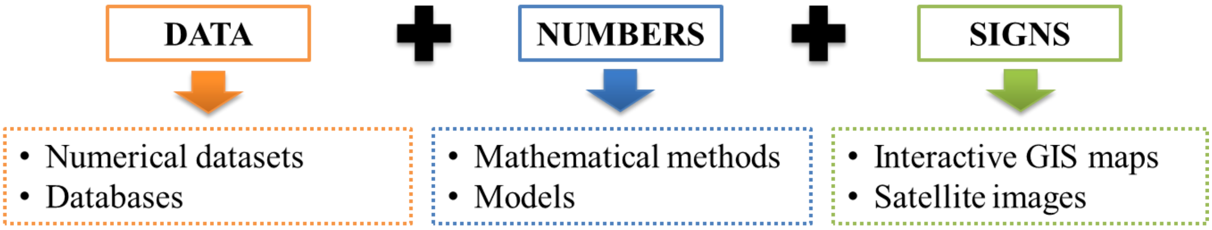


Fig. 4.1 – Integrated perspective: data, numbers, signs

- ***Data***: numerical data are based on available statistical information. Qualitative concepts (e.g. geopolitical factors and interrelationships) have to be converted into quantitative information.
- ***Numbers***: models can capture the behaviour of physical systems, the multilayer dynamics and quantitatively implement narrative scenarios (i.e. from policy visions to numerical targets and constrains). For the approach that we want to implement, "numbers" are fundamental and should guide the decisions and policy choices.
- ***Signs***: maps and graphical output can add a visual perspective to numerical analyses.

Each element is connected with one of the blocks constituting the tool architecture: data collection and processing (data), analysis (numbers) and representation of obtained results (signs).

The developed science-based approach for energy security assessment in a multi-layer perspective is able to answer to different questions related to energy security, investments in international energy projects and infrastructure. These answers can be of interest for several players and stakeholders, from energy companies to think tanks (see Tab. 4.1).

Tab. 4.1 – Example of questions that the tool can help to answer and interested stakeholders

Questions	**Stakeholders**					
	Research centers, Universities	Policy decision makers (supranational, national, local)	Think tanks	NGOs	TSOs/ DSOs, energy companies	Financial institutions (insurance companies, banks)
How the development of a new energy infrastructure affects national energy security?	✖	✖	✖			
Which is the investment that maximizes the improvement in terms of energy security?		✖	✖			
Which are the major criticalities in the national energy security?	✖	✖	✖		✖	
Which is the investment that allows maximising the IRR taking into account risk assessment analysis in geopolitical perspective?						✖
Which is the path for a planned energy corridor that minimises the risk?					✖	
Which infrastructure minimises the environmental impact?		✖	✖	✖		

4.2 Conceptual tool architecture

Fig. 4.2 represents a schematic of the different elements and blocks that conceptually compose the tool. Each of them will be briefly explained in the following sections.

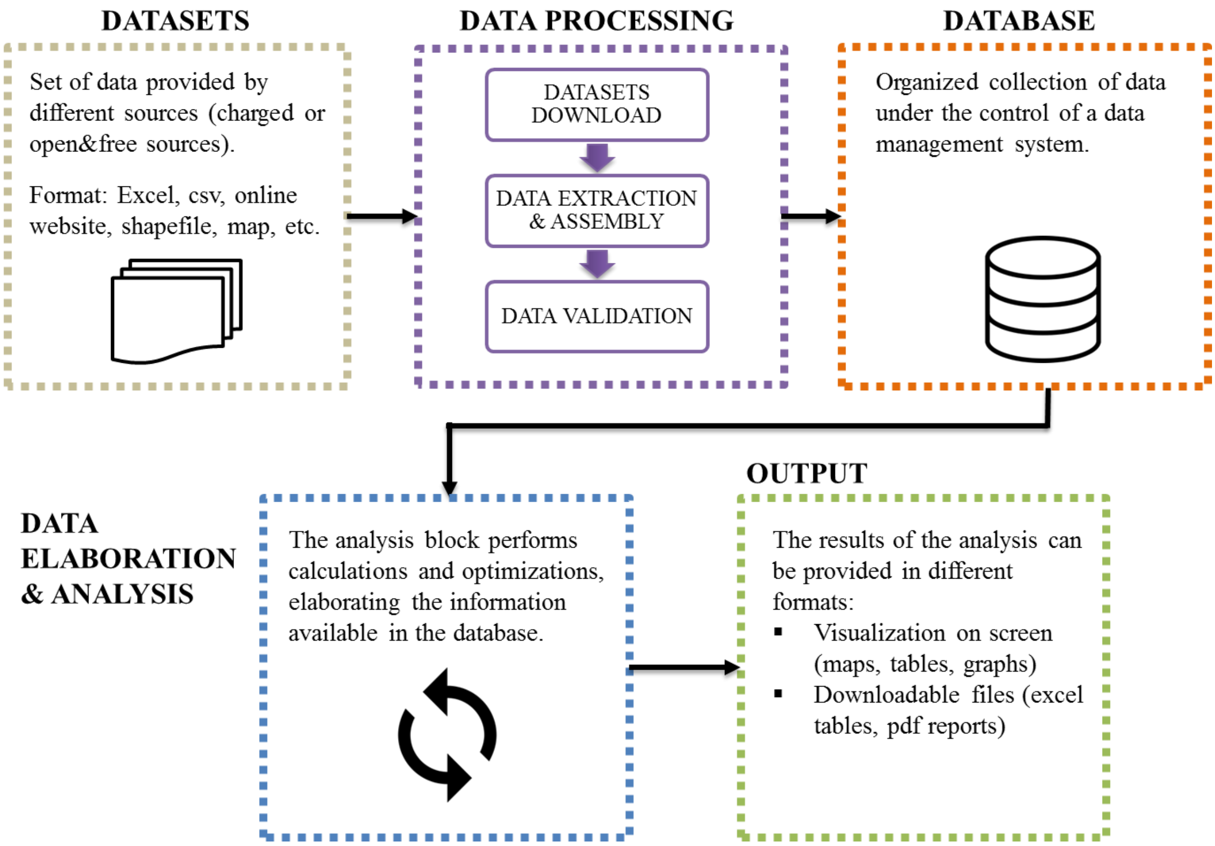


Fig. 4.2 – Tool structure

4.2.1 Data: from datasets to database

Datasets are unstructured set of data provided by different sources (charged or free of charge), which are needed to build the database and perform the desired analyses. In our case, useful data can be grouped in the following categories:

- *Geo-economic data*: macroeconomic indicators that characterize each country involved in the analysis in terms of population, surface, GDP, and population growth.
- *Geopolitical data*: data about the socio-political dimension related to the governance of each country involved in the analysis (necessary for performing energy security assessment in a geopolitical perspective).
- *Energy data*:
  - Energy balances: data that characterizes each country in terms of energy reserves, production, TPES, TFC, import and export. Also the information about the energy mix composition is crucial in the framework of energy security.

- Energy indicators: derived metrics from energy and geo-economic data, such as share of each commodity in TPES, net import dependence, energy intensity, and consumption per capita.
- Trade by origin and destination: information about the energy exchanges in the considered geographic region.

- *Data about energy corridors and infrastructure*:
  - Physical characteristics: commodity transported, type of corridor (open sea or captive), length, maximum capacity, operating capacity, status (existing, under construction or planned).
  - Georeferenced characteristics: path of the energy corridors, staring point, entry point. This information can be provided through maps, which have to be geo-referenced, or GIS data, which already have embedded the spatial information.
- *Social data*: information about the situation of society in terms of income, occupation, energy access and education level (e.g., Human Development Index, GINI coefficient[16], energy access, share of energy in household expenditure etc.).
- *Environmental data*: data about the sustainability of the energy system, such as the share of RES in the TPES, CO_2 intensity of the energy mix or CO_2 emissions per capita.

In Tab. 4.2 the main online available datasets are listed in relation to the type of data that they provide, to the cost and the geographic coverage.

Tab. 4.2 – Main datasets and information provided

Dataset	**Free**	**Coverage**	**Data provided**				
			Geo-economic/ Social/ Env.	**Geopolitical**	**Energy balance**	**Energy Trade**	**Corridors**
World Bank	✓	World	×	×			
IEA	✓	World			×		
Eurostat	✓	Europe			×	×	
BP	✓	World			×	×	
eia	✓	World			×		
UN Comtrade	✓	World				×	
ENTSO-G/ ENTSO-E	✓	Europe					×
Open Street Map	✓	World					×
Enipedia	✓	World					×
Petroleum Economist		World					×
Platts		World			×		×
IHS Markit		World			×	×	
marinetraffic		World					×

[16] The GINI coefficient measures the distance between a country's distribution of income among individuals and a perfectly equal distribution. The GINI index is equal to 0 in case of perfect equality.

Datasets are usually available in disparate formats (.xlsx, .csv, online website, .shp[17], maps, etc.) and unit of measurement. Useful information has to be extracted, aggregated if necessary and converted into a coherent unit of measurement. Data are then assembled into a relational database, a structured collection of tables consisting in a set of rows and columns. The data stored have to undergo a validation process. This can be done, when possible, through comparison of available datasets that provide the same type of information.

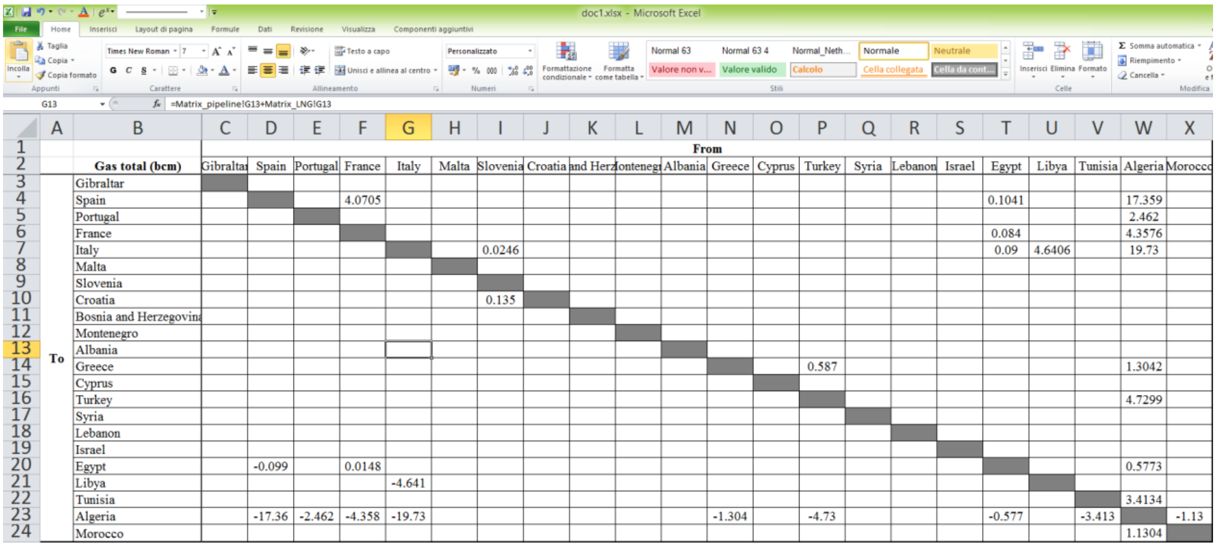
4.2.2 Numbers: analyses

Once the database is completed, it is possible to start with the analysis phase, related to the "numbers" dimension, which involves:

- *Current scenario analysis*: it is the first step of the analysis and it consists in analysing the current geo-economic and geopolitical situation in the countries of interest.
- *Energy analysis*: analysis of countries' energy balances, TPES and TFC composition in terms of energy sources. Calculation of energy indicators (energy intensity, energy consumption per capita, CO_2 intensity) and basic energy security indicators (see Section 3.2.1). Also the energy interdependencies among the considered geographic area have to be assessed, and the matrix of energy exchanges is built reporting, for each commodity, trade flows by origin and destination (see Fig. 4.3 for an example).
- *Diversification assessment*: calculation of aggregated energy security indicators (see Section 3.2.2) for assessing security in terms of diversification of energy mix and suppliers, highlighting the countries characterized by critical situations and that are particularly vulnerable to supply disruption.
- *Supply risk/Economic risk assessment*: energy security assessment in a geopolitical perspective, calculating the supply risk and the expected value of energy supplied for each country. The supply risk can be converted into monetary terms, as explained in Section 3.3.1.
- *Cost of energy imports*: calculation of the total supply cost, taking into consideration, for each commodity and each supplier, the unit energy cost and the flow imported.
- *Optimization of supply*: calculation of the quantity of energy commodities that should be imported from each supplier in order to minimize the supply risk or the total supply cost.
- *Energy corridors analysis*: calculation of the risk associated to each energy corridor, according to the procedure developed in Section 3.3.1.1, for finding the most critical import routes.
- *Sustainability assessment*: analysis of current situation in terms of GHG and air pollutants emissions, and carbon intensity.

[17] The shapefile format (.shp) is a commonly used geospatial vector data format for geographic information system (GIS) software.

- *Scenario definition*: definition of a set of scenarios (e.g., construction or completion of energy infrastructure, variation in the geopolitical situation of one or more countries, introduction of energy policies, introduction of carbon tax) and re-application of the previous defined analysis tools in order to assess the impacts on the different countries in terms of energy security.
- *Financial risk analysis*: quantification of financial risk for the energy investments in the area studied, taking into account economic and geopolitical situation of the countries involved.



		From																					
	Gas total (bcm)	Gibralta	Spain	Portugal	France	Italy	Malta	Slovenia	Croatia	and Herz	ontenegr	Albania	Greece	Cyprus	Turkey	Syria	Lebanon	Israel	Egypt	Libya	Tunisia	Algeria	Morocco
	Gibraltar																						
	Spain				4.0705														0.1041			17.359	
	Portugal																					2.462	
	France																		0.084			4.3576	
	Italy							0.0246											0.09	4.6406		19.73	
	Malta																						
	Slovenia																						
	Croatia							0.135															
	Bosnia and Herzegovina																						
	Montenegro																						
To	Albania																						
	Greece														0.587							1.3042	
	Cyprus																						
	Turkey																					4.7299	
	Syria																						
	Lebanon																						
	Israel																						
	Egypt		-0.099		0.0148																	0.5773	
	Libya					-4.641																	
	Tunisia																					3.4134	
	Algeria		-17.36	-2.462	-4.358	-19.73							-1.304		-4.73				-0.577		-3.413		-1.13
	Morocco																					1.1304	

Fig. 4.3 – Example of matrix of exchanges for natural gas in the Mediterranean area (negative values mean that the flow is in the opposite direction)

4.2.3 Signs: output

Output and result representation is related to the "signs" dimension of the integrated science-based vision. The results of the analyses can be provided in the form of tables, graphs but also GIS maps or satellite images. These can be shown to the users through a web interface, which allows them to perform the desired analysis and visualize the results.

Fig. 4.4 is a screenshot of the web interface developed for studying the energy dimension of the Belt and Road Initiative. On the left, the list of buttons for displaying on the map the useful indicators stored in the database is located. Just below, the buttons for performing the different analysis are available. On the right, the output is presented on a map and the most relevant features are reported also in a table or on a graph. A small tab provides also the satellite vision of the critical energy infrastructure.

Finally, the web interface is not just the instrument which provides output representation, but it can also become input, allowing the user to directly interact with the map in order to simulate the implementation of a specific policy action, investment in energy infrastructure or the unavailability of energy corridors.

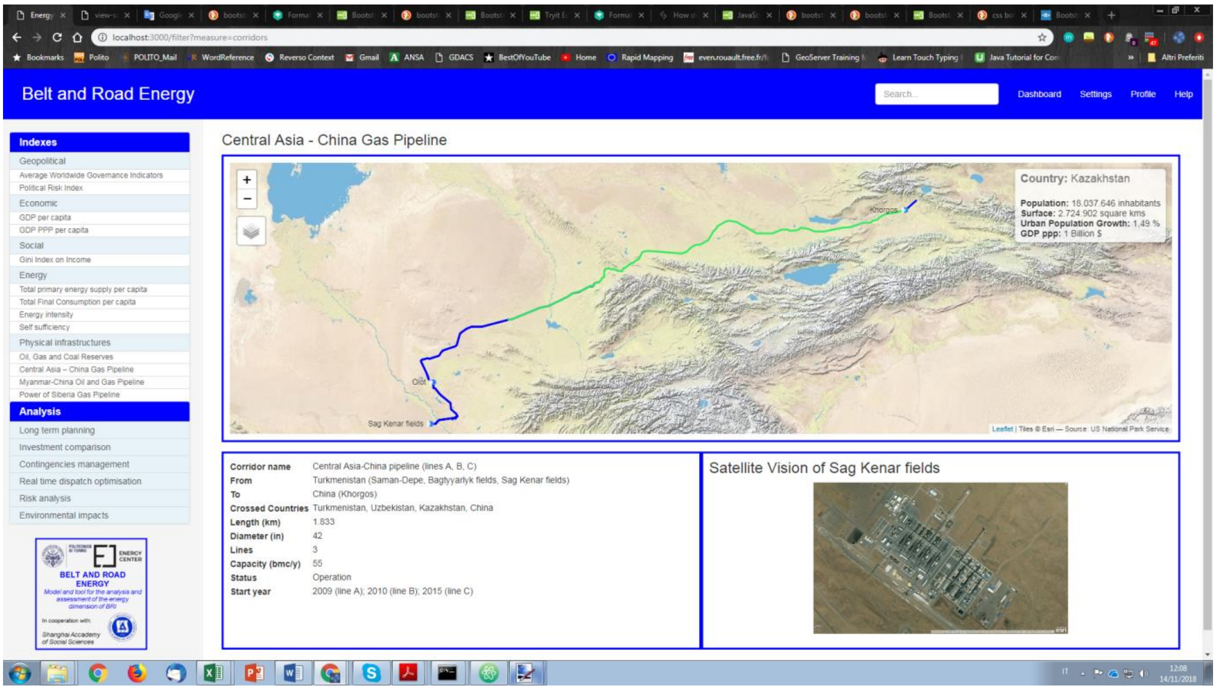


Fig. 4.4 – Example of the web interface developed, showing the technical characteristics, the spatial dimension and a satellite image of the Central Asia - China gas pipeline

4.3 Tool IT architecture

The tool is implemented using three main IT components:

- *Python*: a general-purpose programming language, used for writing software in a broad variety of application domains. Python's implementations (e.g., CPython, the reference one, written in C and Python) are open source.
- *PostgreSQL*: an open source relational database management system (RDBMS), which allows including also spatial data thanks to the PostGIS extension. An RDBMS stores and retrieves data that are organized into a collection of interrelated tables, made up of rows (features) and columns (attributes). Each column contains a specific datatype (e.g., integer, text, double). In each table contained in a relational database, there is at least one column that is the primary key (or unique ID). This is the column that uniquely identifies each row of the table. Through PostGIS, geographical objects can be included and a spatial database is created. This permits, for instance, to create tables which contain a column (with "geometry" datatype) reporting the location of LNG plants (point geometry), or the path of pipelines (line geometry), as Fig. 4.5 shows. The database is managed and queried using statement written in SQL language.
- *Node.js*: open source runtime environment able to execute programs written in JavaScript. It can be used for both server- and client-side scripting. Specifically, the Express.js framework for Node.js provides a robust set of features for developing web applications. It allows the development of interactive web-based maps able to visualize, explore and manipulate spatial data.

All three components are open source, which guarantees a more flexible application of the tool.

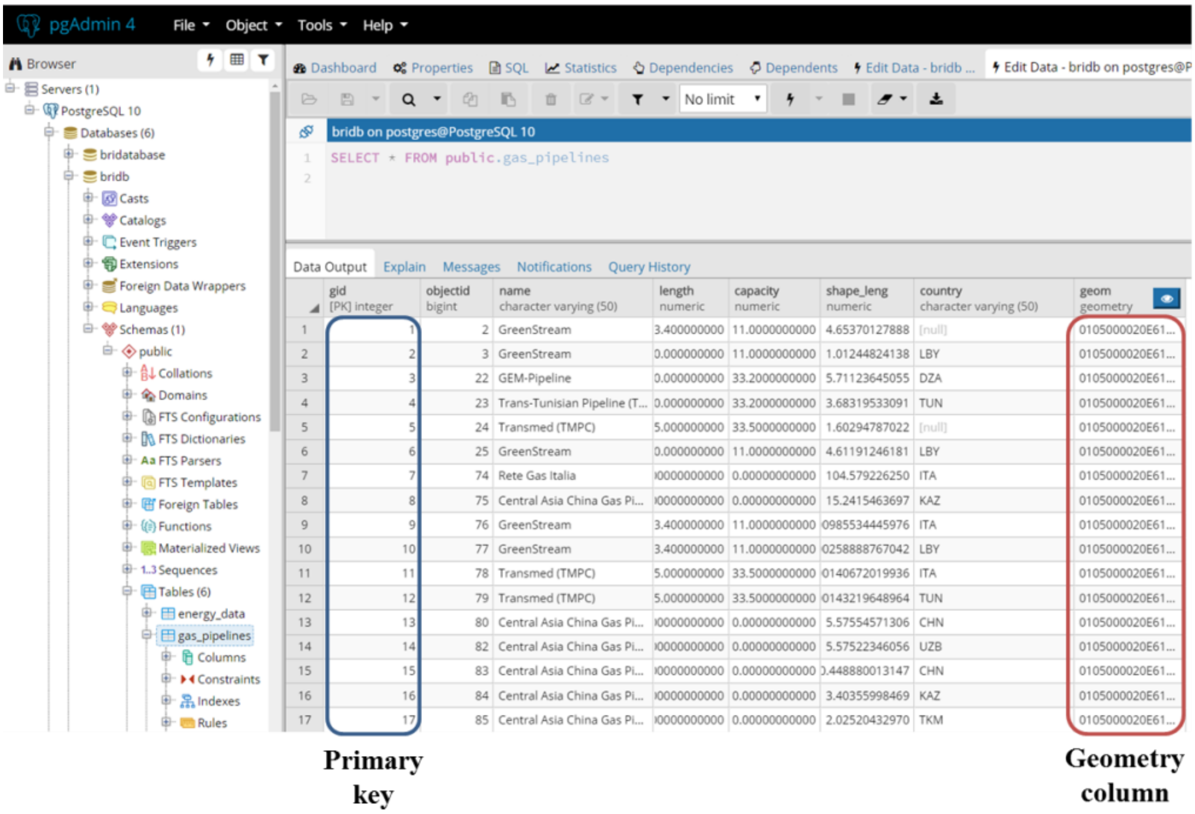


Fig. 4.5 – Example of table containing spatial data (path of gas pipelines) in PgAdmin, the most popular administration and development platform for PostgreSQL

These three elements have to interact and integrate in order to perform all the tool tasks: database management, computational analysis and representation of results on the web interface (see Tab. 4.3). The interaction between the database and the computational block (see Fig. 4.6) is possible thanks to the use of psycopg2, a Python's package that allows adapting PostgreSQL database for the Python scripting language. This Python library permits to connect to the database and perform SQL queries, as shown in Fig. 4.7, so that data are available in the Python environment. In this way, a Python script can be implemented for each mathematical model corresponding to one of the analysis functions listed in Section 4.2.2. The Python scripts can then be integrated into the JavaScript environment, and called when the user requires, through the web interface, to perform one of the available analysis.

Tab. 4.3 – Main IT elements and their functions

Function	Software	Language	Description
Database management	PostgreSQL	SQL	• Store data into organized tables • PostGIS extension allows to include in the DB also spatial data (e.g. shapefiles) • Perform query and extract data useful for the analyses
Computational analysis	Python	Python	• Perform simple calculations (risk assessment, indicators etc.) • Perform optimization analysis • Implement complex mathematical models
Web interface/output	Node.js	JavaScript	• Provide graphical user interface • Visualize output and results of the analyses (maps, tables, graphs) • Allow for results' download in excel or pdf format • Allow for interactive interface (the map is both input and output)

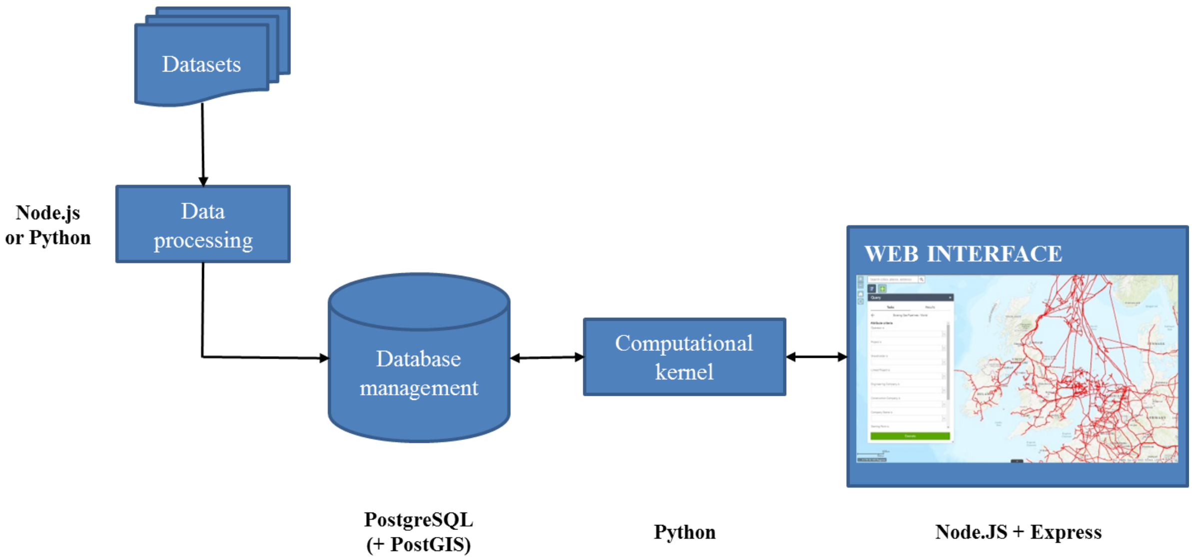


Fig. 4.6 – Tool IT architecture

```python
import psycopg2

# Connection to PostgreSQL
con = psycopg2.connect(
    host="localhost",
    database="bridatabase",
    user="postgres",
    password="postgres",
    port=5432
)

# Choose country of interest
focus = 'ITA'

# DB Query
cur = con.cursor()
comm = 'LNG'
cur.execute("SELECT partcode, quantity FROM energyex WHERE countrycode= %s AND comm = %s", (focus, comm))
rows_pipe = cur.fetchall()
suppliers_lng = [x[0] for x in rows_pipe]
import_lng = [x[1] for x in rows_pipe]
cur.close()
```

Fig. 4.7 – Connection and query of PostgreSQL DB through psycopg2 in Python

5 Case study: the Belt and Road energy dimension

The general framework described in Chapter 4 for the development of a science-based tool for energy security assessment is here applied to the countries involved in the Belt and Road Initiative. A prototype for the tool is implemented with the aim of analysing the energy dimension and the security of supply for each country, and highlighting the presence of energy interdependencies in this vast geographic region, which covers almost completely the Eurasian continent. The analyses performed for the BRI region are:

- *Geopolitical analysis*: assessment of the political stability for the countries involved in the BRI.
- *Energy analysis*: evaluate the energy situation in terms of reserves, production, TPES, TFC, import and export for each primary energy source considered (i.e., coal, crude oil and natural gas). Furthermore, simple indicators for energy security assessment are calculated for each country.
- *Diversification assessment*: calculation of Shannon diversity indexes for each country.
- *Supply risk and expected supply*: calculation of the overall external supply risk for each country, based on the geopolitical stability of suppliers.

Focusing on China, further analyses are developed:

- *Minimization of supply risk:* optimization that allow finding, for each commodity, the quantity that should be imported from each supplier in order to minimize the overall external supply risk.
- *Scenario definition:* scenario analyses allow assessing the impact of possible future events on the energy security of a nation. These events include the increase in the geopolitical risk index of one of the supplier countries, the implementation of a specific energy project or policy, and the unavailability of an energy corridor.

Quantitative analyses on the Belt and Road area are limited in literature. The majority of researches and studies about the BRI are characterized by a more qualitative approach, aiming to underline the economic and international dimension of the project [13], the security issues and challenges [15] or the motivations that pushed China to develop this ambitious programme [17]. With a more quantitative approach, Umbach [22] analysed the relationships between BRI and China's energy security, but he focused mainly on the Chinese perspective. Conversely, this thesis aims at considering the BRI region as an interconnected system. In this respect, Duan et al. [48] developed a quantitative methodology for assessing the risk associated to foreign investments along the BRI countries, proposing a new indicator based on six dimensions.

5.1 Extended energy database

Fig. 5.1 shows the main datasets used for the analyses on the BRI region and their relationship with the tables that constitute the database. A brief description of the datasets is reported in Tab. 5.1, and the list of all tables that constitute the database is reported in Tab. 5.2, together with the content of rows (index) and columns (fields). The relational database was build using PostgreSQL, as explained in Section 4.3. The views are virtual tables (or "second level" tables) obtained from simple calculations on data contained in the database. For instance, the net import dependence for each BRI country is reported in the view "Energy indicators", and it is obtained as the ratio of the net imports and the TPES (both contained in the "Energy data" table).

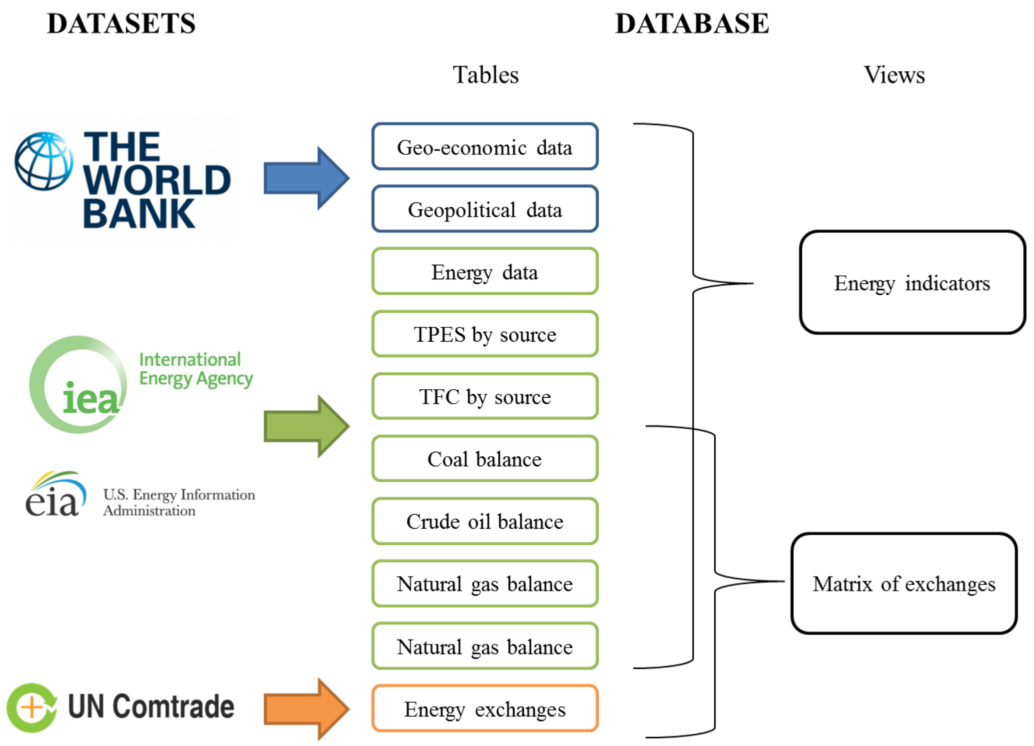


Fig. 5.1 – From datasets to database for analysing the energy dimension of the BRI region

Tab. 5.1 – Datasets used for the database construction

Name	Source nature	Datasets	Description
The World Bank	International financial institution	Online Databank, Worldwide Governance Indicators	Statistics and indicators on a global scale about different aspects including energy, economics, environment and geopolitics.
IEA	Intergovernmental organization	Online statistics (Energy balances and Key Indicators)	Indicators and energy balances for more than 150 countries and regional aggregates.
eia	U.S. Federal Statistical System responsible for collecting and analysing energy information	International Energy Statistics	Energy statistics on a global scale about production, consumption, and energy reserves.
UN Comtrade	United Nations International Trade Statistics Database	UN Comtrade Database	Import and export by origin and destination for gas, LNG, crude oil, oil products, coal, and electricity.

Tab. 5.2 – BRI database structure

Name	Description	Index	Fields	Dataset
Geo-economic data	Macroeconomic indicators that characterize each country in terms of population, surface, GDP and population growth.	BRI countries	Surface, Population, GDP, GDP PPP, population growth	World Bank
Geopolitical data	Data about the socio-political dimension related to the governance of each country.	BRI countries	Voice and accountability, Political stability and absence of violence, Government effectiveness, Regulatory quality, Rule of law and control of corruption, Average WGI	World Bank
Energy data	Data that characterizes the country in terms of energy reserves, production, TPES, TFC, import.	BRI countries	Energy reserves, oil reserves, coal reserves, oil reserves, energy production, net imports, TPES, TFC	IEA, eia
TPES by source	Data about the contribution of the different energy sources to TPES.	BRI countries	Coal, Crude oil, Oil products, Natural gas, Nuclear, Hydro, Geothermal, solar, etc., Biofuels and waste, Electricity, Heat, TPES total	IEA
TFC by source	Data about the contribution of the different energy sources to TFC.	BRI countries	Coal, Crude oil, Oil products, Natural gas, Nuclear, Hydro, Geothermal, solar, etc., Biofuels and waste, Electricity, Heat, TFC total	IEA
Coal balance	Data about production, trade and consumption of coal.	BRI countries	Coal Production, Import, Export, TPES_coal, TFC_coal	IEA
Crude oil balance	Data about production, trade and consumption of crude oil.	BRI countries	Gas Production, Import, Export, TPES_oil, TFC_oil	IEA
Gas balance	Data about production, trade and consumption of natural gas.	BRI countries	Gas Production, Import, Export, TPES_gas, TFC_gas	IEA
Energy exchanges	Data about trade by origin and destination	BRI Countries	Partner, Import/Export, Commodity, Commodity Code, Quantity (kg), Value ($), Year	UN Comtrade
Energy indicators (view)	Metrics derived from geo-economic data, energy data and information about the energy mix of each country.	BRI countries	Import dependency, Coal import dependency, Crude oil import dependency, Gas import dependency, Coal share in TPES, Crude oil share in TPES, Gas share in TPES, TPES per capita, TFC per capita, Energy intensity	
Matrix of exchanges (view)	Three matrixes, one for each commodity, with energy flows exchanges among countries. They are built from the “Energy exchanges” table.	BRI countries	Suppliers (all countries of the world)	

5.2 Energy security of BRI countries

5.2.1 Geopolitical analysis

The analysis of the political stability of the countries involved in the initiative is critical for assessing the energy security in a geopolitical perspective. However, as already mentioned in Section 3.3.1, the socio-political dimensions related to the governance of each country are extremely difficult to be quantified. Among the available indexes, the six governance indicators – voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption – provided by World Bank's Worldwide Governance Indicators (WGI) for year 2017 are adopted in this analysis. The average among the six governance dimensions for the percentile rank among all countries – ranging from 0 (lower stability) to 100 (highest stability) – was performed. The WGI dataset was chosen because available online without restrictions and built using a transparent methodology, developed in the '90s but continually revised and improved. Furthermore, the indicators are available for more than 200 countries, which well suits the broad country level analysis proposed in this work.

In Fig. 5.2 the geopolitical risk, calculated as the complementary of the average percentile rank WGI, for each BRI country is displayed on a map.

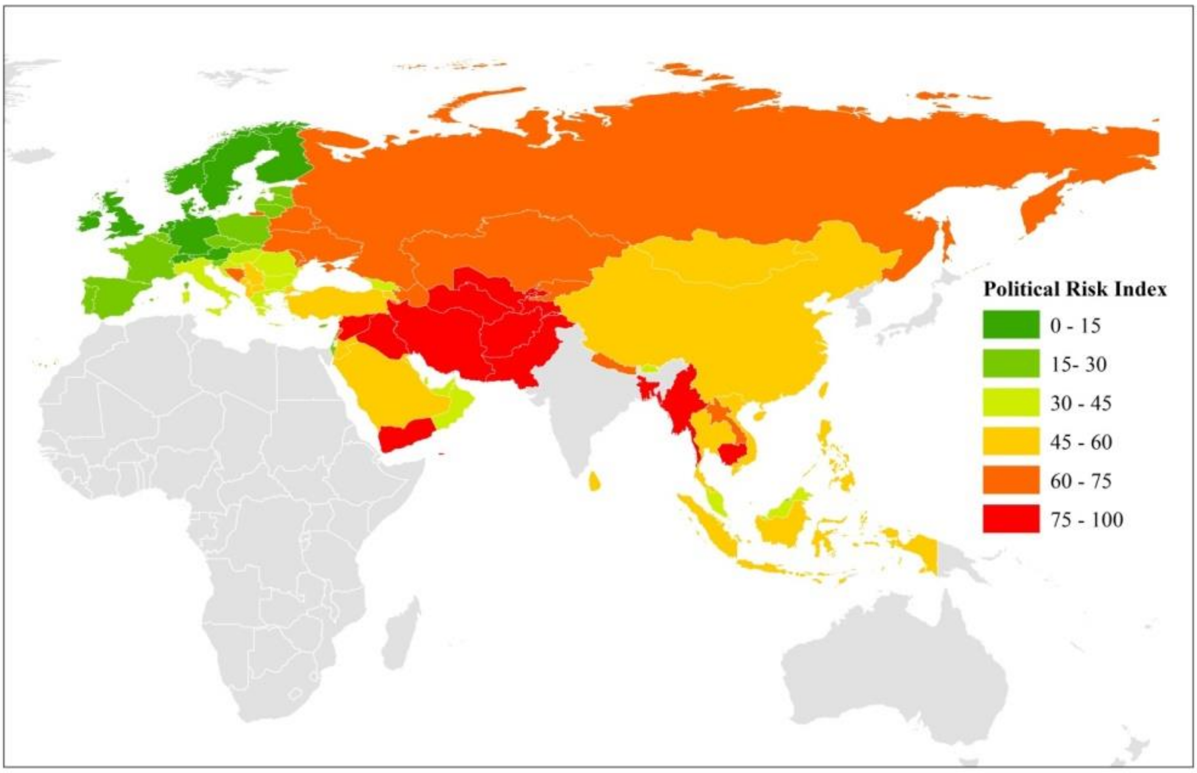


Fig. 5.2 – Political risk index for the BRI countries in 2017 (Source: PoliTO elaboration based on Worldwide Governance Indicators)

The BRI region includes very stable countries (mainly in Western Europe and Scandinavia) and high risk areas. For instance, Central Asia, the core region of the whole BRI, is characterized by an average risk around 79. Specifically, Turkmenistan, China's main natural gas supplier has a risk index of 89, the highest in Central Asia. Also the Middle East is a critical region, with Syria ranking last in terms of political stability of the whole BRI area. Finally, in South Asia, countries such as Afghanistan and Pakistan are scene of conflicts and undermined political stability. For instance, tensions in the Kashmir region, disputed by India and Pakistan, broke out again in February 2019.

5.2.2 Energy analysis

The BRI area includes several regions and countries owing large amounts of primary energy sources, thus behaving as key players in the international trade of energy commodities. The BRI area holds in fact 55.2% of global energy reserves and, specifically, 80.9% of natural gas, 58.9% of crude oil and 47.7% of coal [49]. The energy reserves of the countries involved in the initiative are reported in Appendix B, Table 2, and they are graphically displayed in Fig. 5.3 and Fig. 5.4, where the share of reserves for each country over the world's total is shown for each commodity[18].

The Middle East is the region with the highest amount of energy reserves in the BRI area with 4605 EJ of oil and 2880 EJ of gas, corresponding respectively to 48.7% and 41.0% of the world's total. In this region, Saudi Arabia owns alone 1530 EJ of crude oil, amounting to 16.2% of the world's total and ranking second for oil reserves in 2016. Iran holds considerable amounts of both natural gas and oil (17.5% and 9.6% of global reserves). In this area, other significant oil reserves are located in Iraq (8.7%), Kuwait (6.2%) and United Arab Emirates (5.9%). As far as natural gas is concerned, a key player is represented by Qatar, which ranks third worldwide, with 12.6% of global reserves. Moreover, Qatar is currenlty the world's leading exporter of LNG by a large margin, with a total liquefaction capacity of 77 Mtpa [4]. Finally, coal is almost absent in the Middle East region, except for limited reserves in Iran.

In Central Asia, natural gas is mainly concentrated in Turkmenistan (3.9% of the world's total), but all the countries of this region own limited reserves of this energy commodity. Kazakhstan holds also a significant amount of oil and coal.

In Western Asia, the major country for energy reserves is Azerbaijan, which owns both natural gas and oil fields. Eastern Asia is rich in coal reserves, both in China (13.0% of the global coal) and Mongolia. South Asia hols limited amount of reserves (located mainly in Pakistan, Bangladesh and Afghanistan), and the same is true for Southeast Asia, where, Indonesia is the major resource owner, with 2.5% of global coal reserves and 1.5% of natural gas.

In Europe, Russia is by far the major player in terms of energy reserves, owing 24.5% of global natural gas reserves (and ranking first for gas reserves worldwide), 15.6% of coal and 4.8% of crude oil. Oil reserves are situated in Norway and United Kingdom, whereas coal reserves are located mainly in Germany, Ukraine and Poland.

[18] All data about energy reserves are taken from EIA (Energy Information Administration) [49] and they refer to year 2016 for oil and natural gas, and to 2015 for coal.

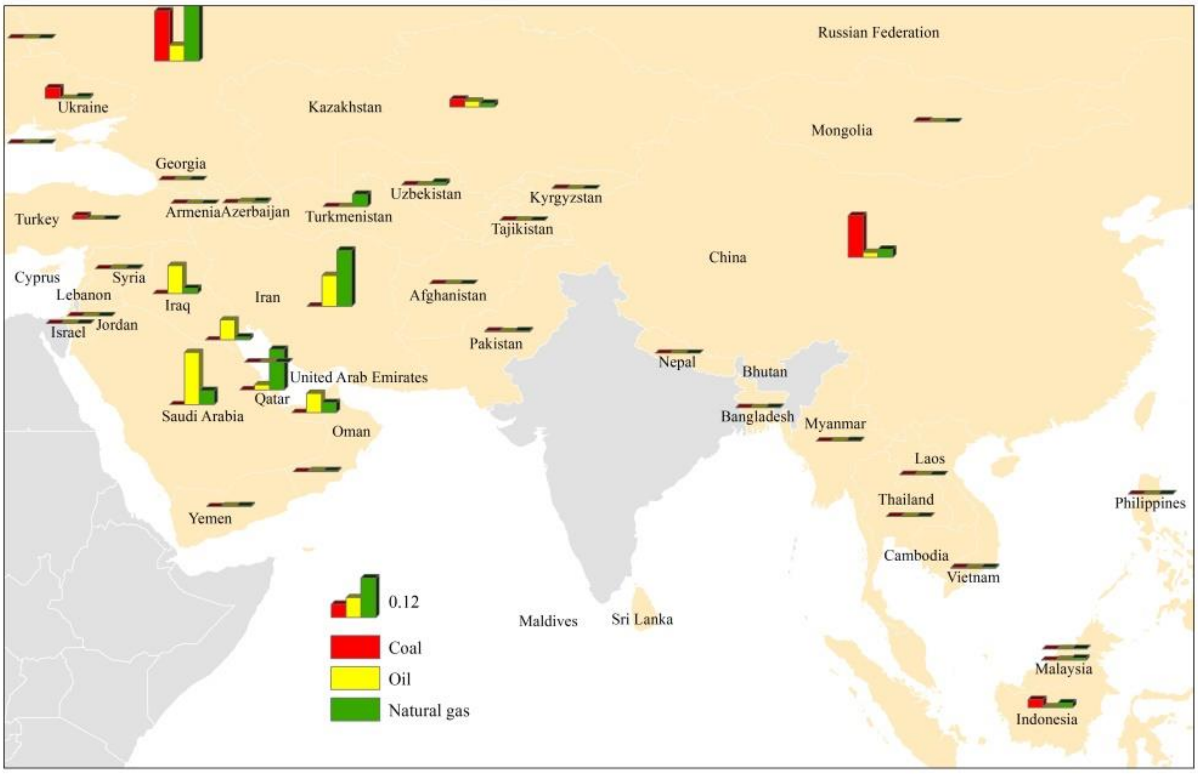


Fig. 5.3 – Share of coal, oil and natural gas reserves over the world's total in BRI Asian countries (Source: PoliTO elaboration based on [49])

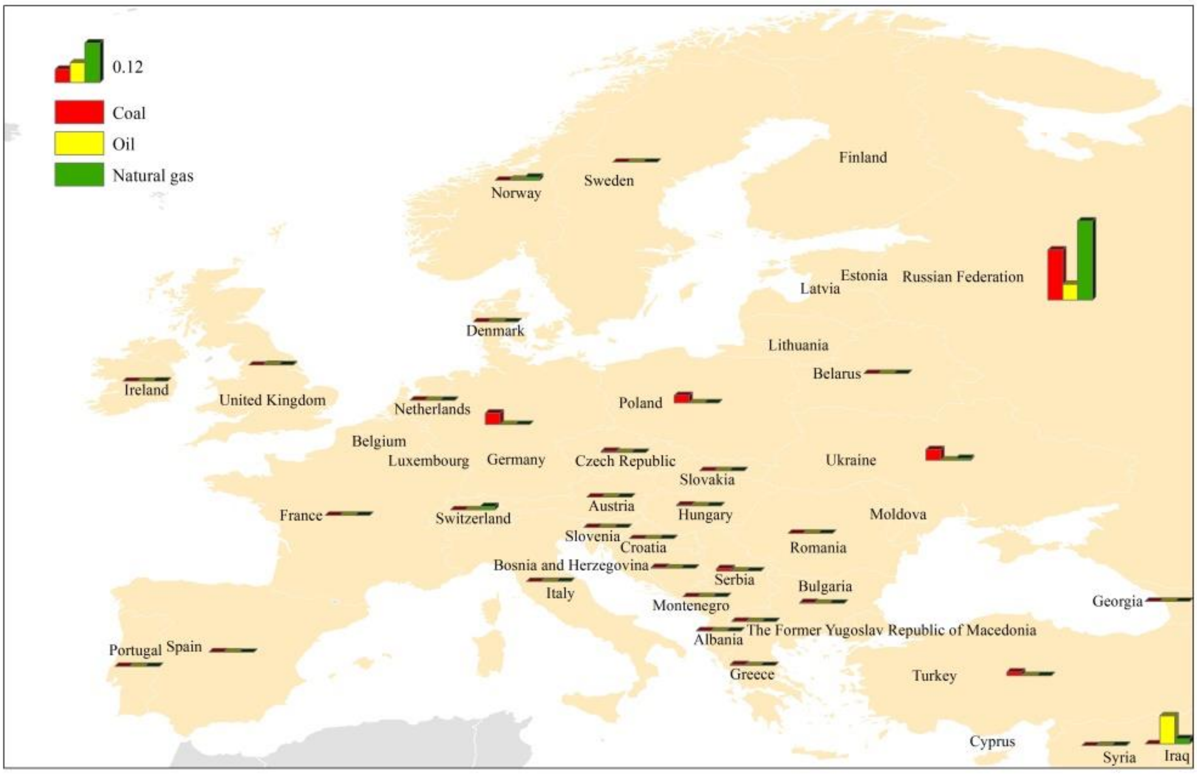


Fig. 5.4 – Share of coal, oil and natural gas reserves over the world's total in BRI European countries (Source: PoliTO elaboration based on [49])

In 2016, the final energy consumption of the entire BRI region was equal to roughly 209 EJ, corresponding to 52.3% of the world energy consumption [2][19]. The energy consumption is shown in Fig. 5.5, where the dimension of the circle is proportional to the country's TFC. The huge difference between China and all the other BRI countries in terms of absolute energy consumption is evident. China in fact has an energy demand (82 EJ) four times larger than Russia (20 EJ), the second consumer in the BRI area, and 1.6 times larger than the entire European continent (not including Russia), equal to 53 EJ. Nonetheless, if the energy consumption per capita is taken into consideration, China is just slightly above the mean per capita consumption of Central Asia and Southeast Asia (both around 56 GJ/person), and considerably lower than Wester Europe and Middle East levels (both roughly 120 GJ/person), and Russia (almost 140 GJ/person). The region characterized by the lowest energy availability per person in the BRI area is however South Asia, where average consumption is around 16 GJ/person, as reported in Tab. 5.3.

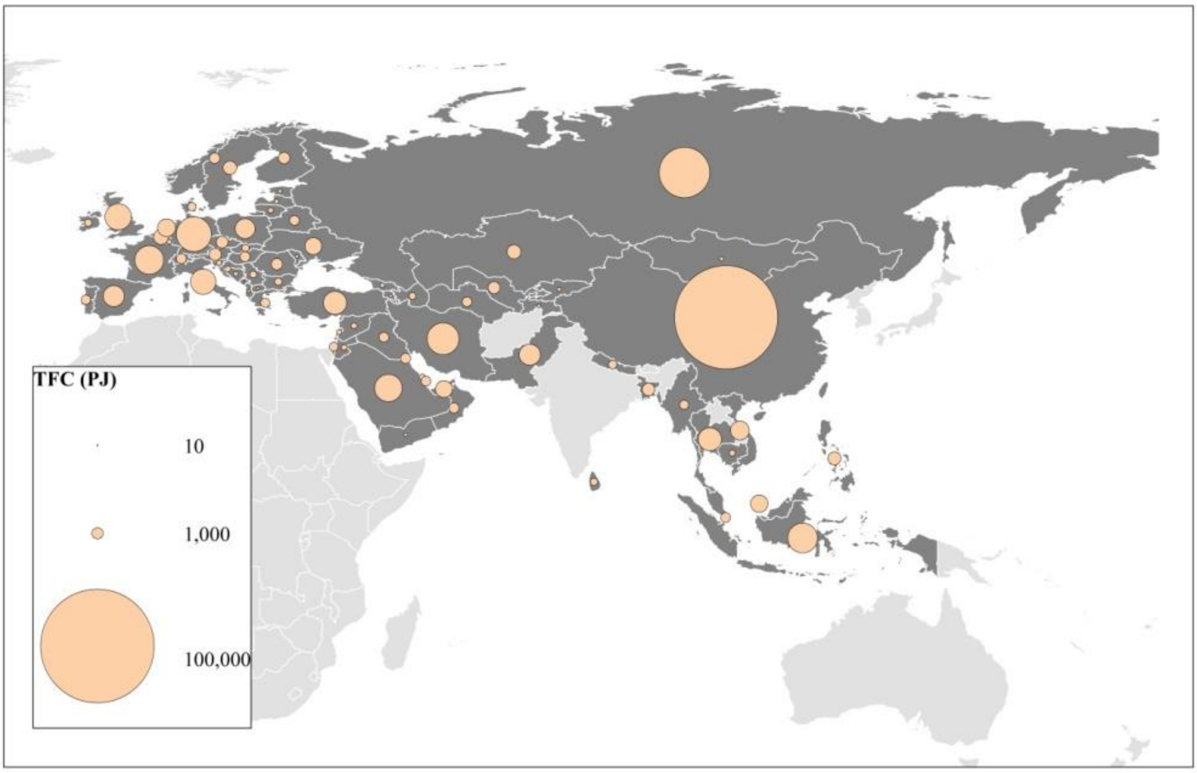


Fig. 5.5 – Total final consumption in BRI region (Source: PoliTO elaboration based on [2])

[19] IEA Online Statistics do not provide data about five countries included in the BRI region - namely Liechtenstein, Afghanistan, Bhutan, Maldives, and Laos – which are therefore neglected in this study.

Tab. 5.3 – Average TFC per capita in the BRI regions (Source: [2], [21])

Region	Average TFC per capita (GJ/pers)
Central Asia	58.5
China	59.8
Western Europe	124.8
Eastern Europe	65.5
Russia	136.3
Middle East	120.2
South Asia	15.7
Southeast Asia	55.7
Western Asia	42.3

Aiming to study the energy interdependencies among BRI region, it is important to identify, for each energy commodity, net importing and exporting countries. In this study, we focus on three energy commodities: coal, crude oil and natural gas. Electricity and oil products, despite being critical commodities in the global energy market, are not analysed in this thesis. However, the proposed methodology can easily be extended for including them in the analysis.

As introduced in Section 3.2, two indicators have to be coupled together in order to quantitatively assess the energy security of the BRI countries:

- The *net import dependence*, calculated, for each commodity, as the ratio of net imports and TPES (negative values are obtained for net exporting countries).
- The *share in TPES*, calculated as the ratio of the primary energy supply of each commodity divided by the TPES.

The first index gives information about the level of self-sufficiency of the country, and the second about the energy mix composition. The higher is the contribution of an energy source in the TPES, the higher is the damage for the economy in case of disruption of supply. If both net import dependence and share in TPES are high, that commodity is especially critical for the country's energy supply and security.

Referring to coal, this energy commodity still gives the major contribution to the TPES of the whole BRI region, accounting for 34.4% and followed by crude oil with 31.9%, and natural gas with 23.3%. However, significant differences exist in the energy mix of the countries involved in the BRI. China and Mongolia, the two Eastern Asian countries, relies on coal for more than 60% of their TPES. Coal gives a contribution greater than 40% to TPES in Kazakhstan and in many Eastern Europe countries (i.e., Bosnia, Estonia, Poland and Serbia) characterized by significant reserves of this primary source. In Southeast Asia, coal is a crucial energy source for Vietnam, Philippines, Malaysia and Indonesia, where it accounts for more than 20% of TPES. Conversely, coal is almost absent in all the Middle East countries, where the great availability of oil and natural gas in this region is evident looking at the composition of their energy mix.

Coal production in the BRI region represents more than two-thirds of the global coal production. The main producer of the area is China, with 72 EJ of coal extracted in 2016. Despite the large domestic availability of reserves and high production rates, in 2009 China became a net coal importer. The country uses its coal production mainly for satisfying its huge internal demand, which relies significantly on this primary energy source (64.8% of

TPES). The second producer in the area is Indonesia (more than 10 EJ in 2016), that, unlike China, exports the vast majority of the coal extracted in its mines. Indeed, the 83.7% of the Indonesian coal is exported, resulting in a net import dependency of -474.5%, which indicates that coal exports are almost 5 times bigger than the domestic coal demand. Although Indonesia is a major coal producer, the contribution of this energy commodity in its energy mix is relatively limited compared, for instance, to other producers such as China and Mongolia, and it accounts for less than 20%. Mongolia is another key player for coal production. There, coal is used both for domestic consumption – Mongolia ranks first for contribution of coal in TPES in the whole BRI area, with a share of 73.8%, even higher than China – and export. The net import dependency is extremely negative, as for Indonesia, and equal to -439.2%. Other coal net exporting countries are Russia (-83.9%), Kazakhstan (-30.6%) and Poland (-11.8%). The other coal producers of the area use their limited amount of resources almost exclusively for satisfying internal demand, thus resulting in a net import dependency around zero. This is the case for many of the Eastern Europe countries which own coal reserves, such as Bosnia, Bulgaria, Czech Republic, Estonia, Greece, Romania and Serbia. Conversely, other countries – such as Germany, Ukraine, United Kingdom, Turkey and some Southeast Asian countries (Philippines, Thailand and Vietnam) – despite considerable coal production, are not able to fully cover internal demand with their resources and are characterized by positive net import dependences. Finally, the BRI region includes also many countries that own null or negligible coal reserves and rely significantly on external imports. Many European countries, such as Albania, Austria, Belgium, Croatia, France, Italy, Netherlands, Portugal and Sweden have a dependency greater than 90%. However, these countries are usually characterized by low share of coal in TPES (generally well below 15%), which makes the dependence on external supply less critical.

To sum up, coal is a critical commodity for the BRI region, especially for Eastern Asia, Southeast Asia and Eastern Europe. The entire BRI region accounts for 68% of global coal demand and some major producer and exporter are included in this geographic area. However, also countries characterized by very low level of coal self-sufficiency are present, with issues related to energy security. The risk associated to energy supply for these countries will be further investigated in the next sections, where the diversification of supply and the expected supply value are calculated. Fig. 5.6 summarizes the results obtained in terms of coal net import dependency for the BRI countries.

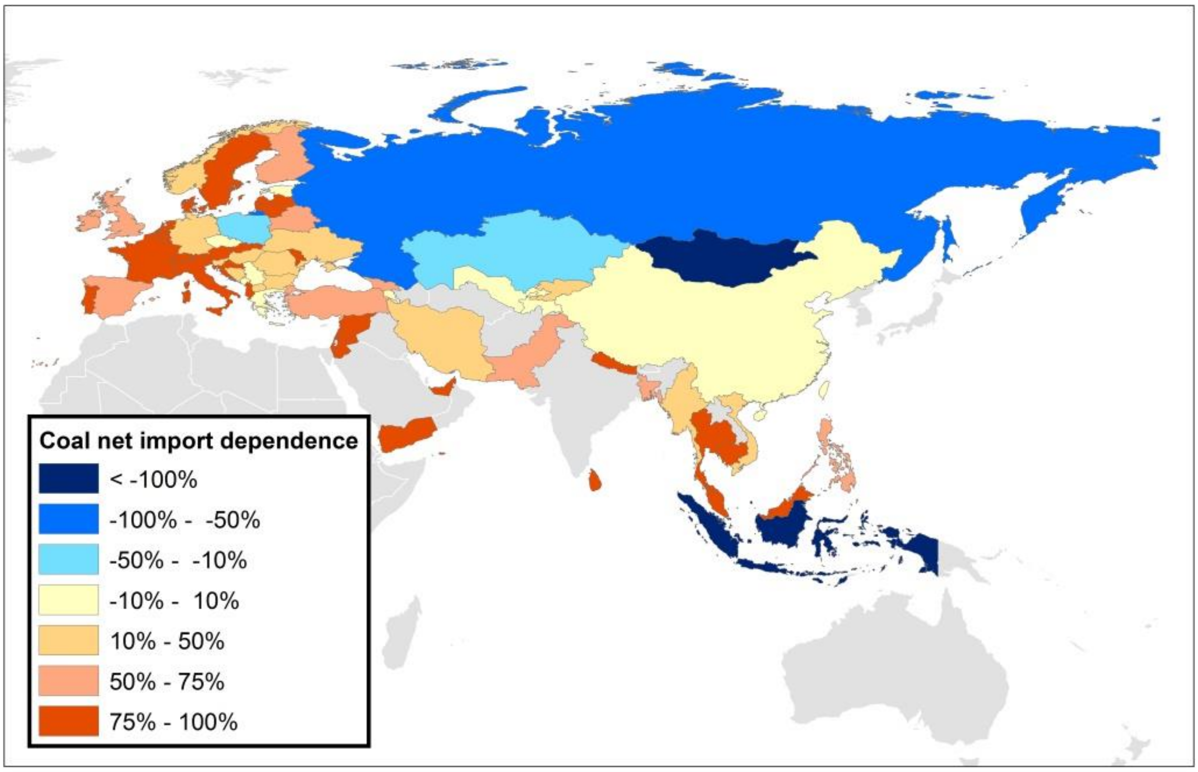


Fig. 5.6 – Coal net import dependence in BRI countries. Negative values are for net exporting countries. (Source: PoliTO elaboration based on [2])

Crude oil is the second energy source in the TPES of the BRI area, accounting for 31.9% of the total energy demand. Oil production from BRI countries represents 60.8% of global oil production, with Middle East accounting alone for one-third of the total. The BRI region includes major oil producer and exporter, such as Saudi Arabia and Russia. Saudi Arabia is the major producer with 25 EJ of oil extracted in 2016 and -180.6% of net import dependence. Russia ranks second in the BRI region for oil production with 23 EJ and -86.7% net import dependence. In addition to Saudi Arabia, other major producers in the Middle East region are Iraq, Iran, United Arab Emirates and Kuwait, Qatar and Oman. All these countries use their oil reserves to satisfy both internal demand – crude oil share in TPES is very high for them – and export. In Western Asia, Azerbaijan is the main producer and exporter, sending abroad almost the totality of the extracted oil. In Southeast Asia, Indonesia and Malaysia are the main producer of the area in absolute terms, but they use their production mainly to satisfy internal demand. Conversely, Vietnam is a net exporter (-66.8% import dependence) and Thailand, despite a considerable domestic production, relies significantly on external imports (61.7%). In Central Asia, Kazakhstan is the key producer and exports more than three times its oil demand. Chinese oil imports are approximately two-times the internal production (8 EJ) and they represent the highest oil import in absolute terms of the whole BRI region. China relies on external import for 67.4% of its internal demand and, as already explained in Section 2.3.1.2, oil is the most critical commodity for the national energy security. Finally, in the European continent, besides Russia, oil is produced in Norway, which is also a net exporter (-326.3%) and in the United Kingdom, which, conversely, is a net importing country. The majority of the other European countries are characterized by oil net import dependence greater than 90%, as shown in Fig. 5.7.

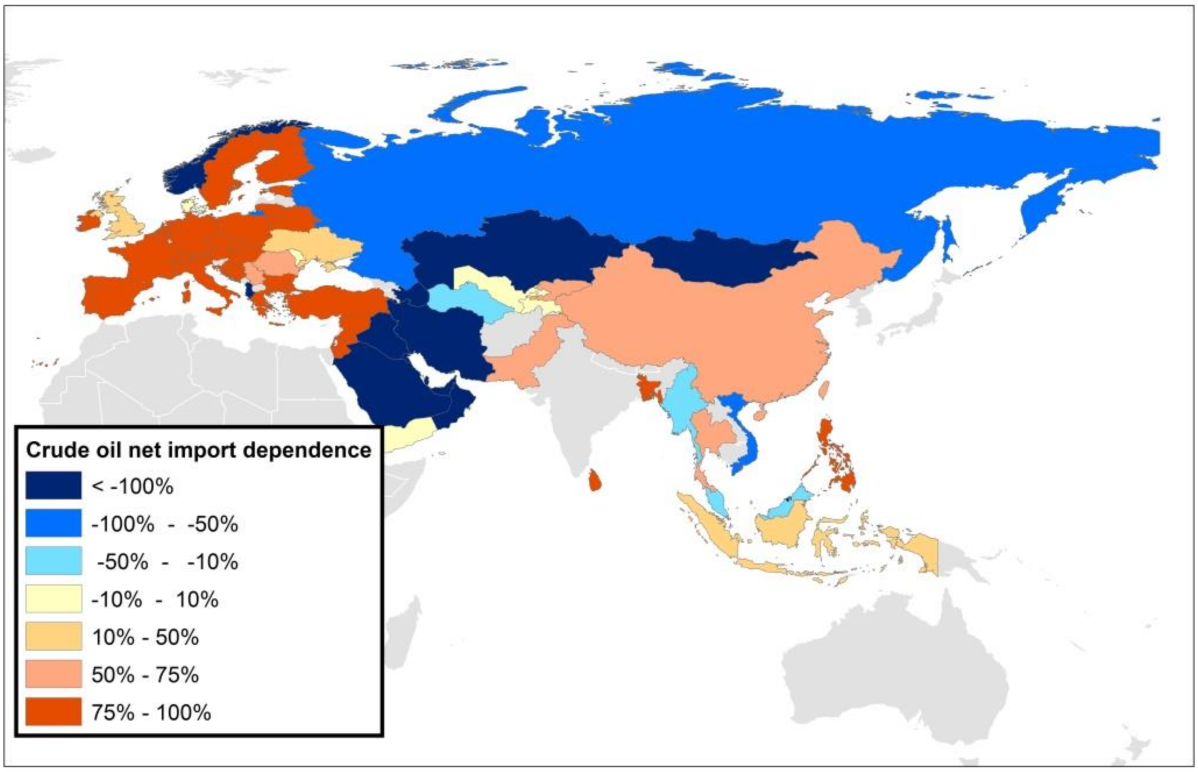


Fig. 5.7 – Crude oil net import dependence in BRI countries. Negative values are for net exporting countries. (Source: PoliTO elaboration based on [2])

Roughly 60% of natural gas extracted worldwide is produced in the BRI region, and this commodity represents the 23.3% of the TPES of this area. The main producer of the area is by far Russia, which has a net import dependency equal to -42.5%. In the Middle East, almost all the countries have a considerable or limited gas production. However, unlike oil, gas production is mainly use to meet internal demand (e.g., this is the case of Iran, the main producer in the Middle East region). However, this is not true for Qatar, which exports almost three-quarters of its production. Other major gas producers and exporters are:

- Turkmenistan in Central Asia
- Norway and Netherlands in Europe
- Brunei, Indonesia, Malaysia and Myanmar in Southeast Asia
- Azerbaijan in Western Asia.

Natural gas is a critical commodity for many Western Europe countries which rely significantly on external imports and are characterized by net import dependence above 90%. This is the case of Belgium (100%), Sweden (100%), Switzerland (100%), Portugal (99.1%), France (99.0%), Greece (99.2%), Spain (98.7%), and Italy (91.8%). The situation for Italy is especially critical since this country is characterized by the highest contribution of natural gas to TPES (38.5%) in the group, and the highest import in absolute values (2239 PJ in 2016).

Italy is the third importer in the entire BRI region, preceded just by Germany (3417 PJ and 88.6% of net import dependence) and China (2473 PJ), which, however, thanks to considerable internal production has a much lower import dependence (32.9%). Spain and Turkey are in a condition similar to Italy, with considerable gas import (1180 and 1598 PJ, respectively) and high share in TPES (20.9% and 28%, respectively). The gas net import dependence of the BRI countries is summarized in Fig. 5.8.

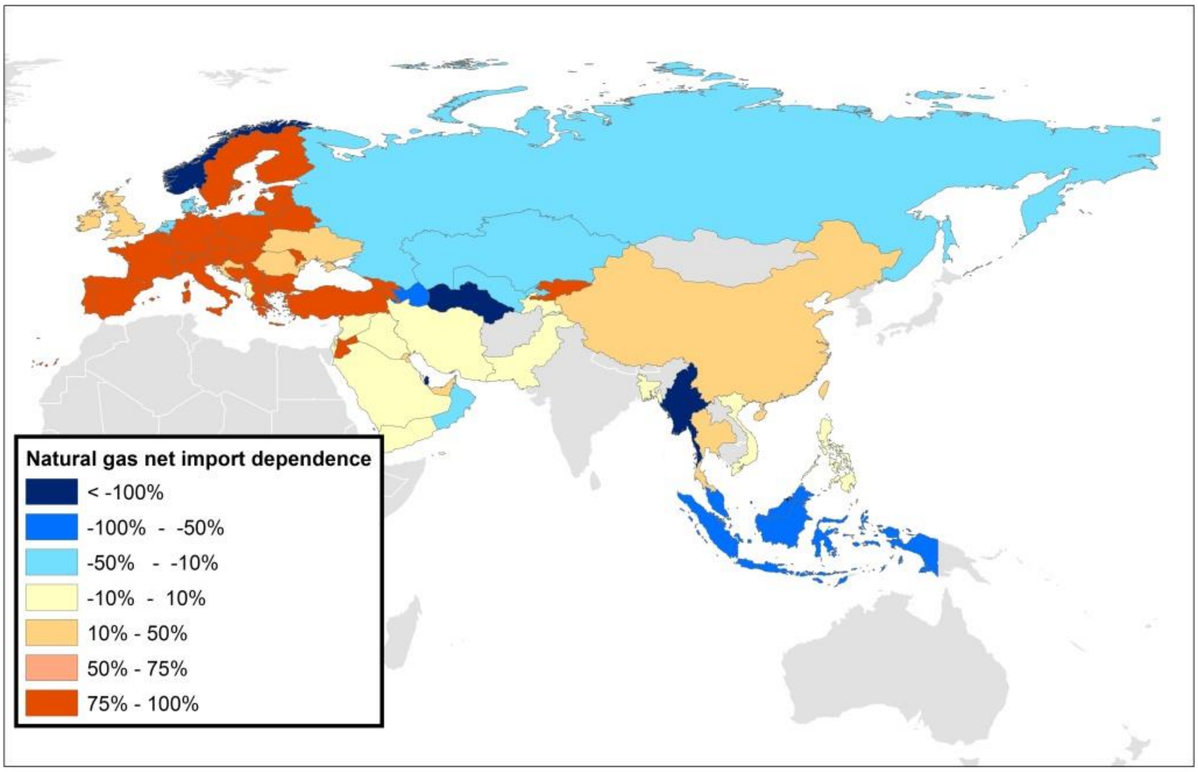


Fig. 5.8 – Natural gas net import dependence in BRI countries. Negative values are for net exporting countries. (Source: PoliTO elaboration based on [2])

To conclude, this section gives a snapshot of the energy situation for the BRI countries, focusing on reserves availability (in absolute terms and as a fraction of global reserves), import dependence, energy mix composition and consumption per capita. These are some of the simple energy security indicators introduced in Section 3.2.1. The energy analysis allows identifying the major exporter and importer in the BRI region. For instance, Fig. 5.6, Fig. 5.7 and Fig. 5.8 show that the majority of Western Europe countries are characterized by an import dependence greater than 75% for all primary energy commodities, which introduces significant issues related to security. The level of energy security for net importing countries is further investigated in the following sections, where Shannon indexes are calculated in order to assess the diversification of energy mix and supply.

5.2.3 Diversification assessment

We now want to assess the diversification of energy mix and supply for the BRI countries, using respectively the diversity index H_1 and H_2 introduced in Section 3.2.2. To accomplish this, the input data required for each country are:

- p_i, the contribution of coal, oil and natural gas in the energy mix
- m_i, the net import dependency for energy source *i*
- m_{ij}, the share of imports of source *i* from country *j* in total import of source *i.*

As already mentioned, the energy commodities considered in this study are coal, crude oil and natural gas. Therefore, the number of primary energy sources, *M*, in eq. (4), eq. (5) and eq. (6) is equal to three. The index p_i can thus be calculated as the ratio of the primary energy supply of source *i* and the primary energy supply of the three commodities considered:

$$p_i = \frac{TPES_i}{TPES_{coal} + TPES_{oil} + TPES_{gas}} \tag{34}$$

The index p_i is therefore slightly different from the share in TPES considered in Section 5.2.2, where all the ten commodities of IEA Online Statistics [2] are taken into account. However, the aim of the Shannon indicators is to make a comparison among countries. Since the comparison is made taking into account just three energy sources, it is not necessary to consider the others when p_i is calculated. The index m_i conversely is exactly the net import dependency introduced before:

$$m_i = \frac{I_i - E_i}{TPES_i} \tag{35}$$

The first two indicators – p_i and m_i – can easily be calculated from IEA Online Statistics [2]. However, for assessing m_{ij}, information about trade by origin and destination is necessary. This can be extracted from UN Comtrade [27], the international trade statistics dataset provided by the United Nations. This dataset contains information about the trade of a broad number of commodities, including also energy commodities. Each commodity is associated to a code of the Harmonized System (HS). The commodities of interest in this thesis and their HS code are:

- Coal (2701)
- Crude oil (2709)
- Natural gas, in gaseous form (271121)
- Natural gas, liquefied (271111).

Trade data provided by national authorities are standardized and then added to the UN Comtrade database. Trade flows are reported in monetary units (US dollars) and, when possible, in metric units (kg). The dataset is completely available for free, but it has some limitations. For instance, UN Comtrade declares that imports received by one country do not coincide with exports reported by its trading countries. Moreover, we performed some checks comparing data provided by UN Comtrade for EU countries and Eurostat, finding out that several inconsistencies in terms of absolute trade values exist. Finally, for commodities transported via pipeline, it is not stated if the country of origin is the real supplier of that commodity, or the country bordering to the national entry point. Despite limitations and incoherencies, the UN Comtrade dataset has been used anyway, being the only one providing information about trade by origin and destination for the vast geographic area involved in the BRI. The results of the analyses therefore have to be read with caution, but the methodology developed here can easily be applied to other input data, if available. In order to reduce the error on the absolute values of traded flows, UN Comtrade was used only to calculate the share of each supplier over the total import for each commodity (m_{ij}). The flows in absolute values were than obtained multiplying the share from country j and the total import for each commodity, provided by IEA.

Putting together the UN Comtrade and the IEA datasets, it is possible to build, for each commodity, the matrix of exchanges in 2016 for the BRI area, which provide information about the energy suppliers of each country. Each matrix is composed of 80 rows, representing the 80 BRI countries, and 236 columns, referring to the 236 partners included in the UN Comtrade dataset, from which the BRI countries can import energy. However, these matrixes are highly sparse, since many countries are not involved in the energy trade with the BRI region. Furthermore, data about some BRI countries are not available for year 2016, but only very outdated trade statistics are provided and not considered in this analysis.

Once the energy exchanges among the BRI countries are known, it is possible to calculate the diversity indexes H_1 and H_2, through an algorithm developed in Python, which is able to query the PostgreSQL database, perform the required calculations and finally print the results on an Excel file. It is especially interesting to investigate the situation of countries which significantly rely on external import for all three commodities (i.e., positive net import dependence for coal, oil and gas). In fact, the index H_2 is able to modify the net import dependence indicator for taking into account also the diversification of suppliers of each commodity, and diversification of the energy mix composition. The normalized index H_2 is equal to one in the ideal situation in which:

- Each of the three commodities has the same share in the TPES meaning that $p_{coal} = p_{oil} = p_{gas} = 0.33$ (in this case, also the normalized index H_1 is equal to one).
- Each commodity is imported in equal share form the maximum possible number of suppliers ($N_{max,coal}$ = 153, $N_{max,oil}$ = 157, $N_{max,gas}$ = 24, according to the data provided by UN Comtrade). In this case,
$$S_i = S_i^{max}$$
and the correction factor c_i in eq. (6) becomes equal to one, for any value of import dependence.

Tab. 5.4 reports the normalized index H_1 and H_2 and the diversification of supply for each commodity (S') for the BRI countries with positive net import dependence for coal, oil and gas. They are ordered with increasing normalized index H_2, so that the more critical countries are at the top of the table.

Tab. 5.4 – Diversification of supply by commodity and index H_2 for the BRI countries with positive net import dependence for all primary energy sources

Country	Region	p_{coal}	p_{oil}	p_{gas}	m_{coal}	m_{oil}	m_{gas}	S'_{coal}	S'_{oil}	S'_{gas}	H'_1	H'_2
Belarus	Europe	0.02	0.54	0.44	0.51	0.89	0.98	0.14	0.00	0	0.70	0.08
Lithuania	Europe	0.02	0.83	0.15	0.89	0.99	1.01	0.00	0.10	0.23	0.47	0.08
Sweden	Europe	0.09	0.87	0.04	1.08	1.00	1.00	0.26	0.33	0.30	0.42	0.11
Bosnia	Europe	0.80	0.17	0.04	0.15	1.09	1.00	0.22	0.00	0.00	0.55	0.12
Singapore	Southeast Asia	0.01	0.84	0.15	1.00	1.00	1.00	0.03	0.39	0.37	0.43	0.15
Switzerland	Europe	0.02	0.50	0.48	0.99	0.99	1.00	0.32	0.33	0.28	0.71	0.22
Belgium	Europe	0.06	0.64	0.29	0.95	1.00	1.01	0.33	0.13	0.42	0.74	0.22
Jordan	Middle East	0.03	0.45	0.51	1.00	0.99	0.97	0.13	0.00	0.67	0.74	0.23
Finland	Europe	0.24	0.65	0.11	0.60	1.00	1.00	0.23	0.09	0.19	0.79	0.23
Pakistan	South Asia	0.12	0.32	0.57	0.66	0.66	0.00	0.20	0.14		0.86	0.25
Slovakia	Europe	0.25	0.46	0.30	0.83	0.97	0.93	0.34	0.07	0.42	0.97	0.32
France	Europe	0.08	0.56	0.36	0.93	0.97	0.99	0.35	0.51	0.32	0.81	0.34
Greece	Europe	0.12	0.78	0.10	0.04	1.01	0.99	0.01	0.34	0.30	0.62	0.35
Bulgaria	Europe	0.37	0.46	0.17	0.10	0.99	0.96	0.26	0.13	0.00	0.93	0.37
Spain	Europe	0.10	0.65	0.25	0.74	0.99	0.99	0.35	0.57	0.43	0.78	0.39
Ireland	Europe	0.22	0.34	0.44	0.55	1.00	0.40	0.19	0.14	0.00	0.97	0.41
Kyrgyzstan	Central Asia	0.59	0.25	0.16	0.28	0.63	0.91	0.00	0.00	0.29	0.87	0.41
Italy	Europe	0.08	0.50	0.42	0.98	0.93	0.92	0.36	0.54	0.49	0.83	0.42
Hungary	Europe	0.13	0.41	0.46	0.34	0.86	0.79	0.30	0.15	0.33	0.90	0.43
Croatia	Europe	0.10	0.57	0.33	1.02	0.80	0.33	0.14	0.37	0.34	0.83	0.43
Serbia	Europe	0.60	0.26	0.14	0.08	0.70	0.76	0.13	0.18	0.00	0.85	0.46
Thailand	Southeast Asia	0.13	0.57	0.30	0.92	0.62	0.32	0.15	0.43	0.18	0.86	0.48
China	Eastern Asia	0.72	0.21	0.06	0.06	0.67	0.33	0.32	0.55	0.59	0.67	0.55
United Kingdom	Europe	0.08	0.44	0.48	0.51	0.22	0.47	0.36	0.30	0.30	0.83	0.62
Ukraine	Europe	0.53	0.05	0.42	0.31	0.18	0.34	0.19	0.02	0.60	0.77	0.63
Romania	Europe	0.20	0.45	0.34	0.20	0.68	0.13	0.15	0.26	0.02	0.95	0.70

In Central Asia, the most critical country in terms of energy security is Kyrgyzstan. This country imports almost the totality of coal and the totality of oil from one single country, the neighbouring Kazakhstan. Due to this, the *S'* index for coal and oil is almost zero, indicating an almost absent diversification of supply (i.e., monopoly) for both energy sources. Considering natural gas, the situation for Kyrgyzstan is slightly better than for the other two commodities, but still critical. The country in fact imports gas from only three suppliers: Russia (50.7%), Kazakhstan (41.6%) and Uzbekistan (7.8%). The dependence on a single supplier, Kazakhstan, is evident for this country. Furthermore, Kazakhstan is characterized by a low political stability (the average WGI is equal 38.7), which makes this dependence even more critical. Nonetheless, the comprehensive H_2 index is relatively high, compared to other countries reported in Tab. 5.4. This is due to the relatively low import dependence for coal and oil, which are the major contributors to TPES for the country. Conversely, the high import dependence on foreign natural gas is counterbalanced by a limited share of this commodity in TPES.

In Eastern Asia, China is the only net importer. Mongolia, on the other hand, it is a net coal and oil exporter, almost exclusively to China. Despite, the energy security issues described in Section 2.3.1, China is among the countries with the highest H_2 normalized index (around 0.55). This indicator in fact does not grasp the risk associated to the transport of energy commodities along import routes. For instance, according to S' index, Chinese crude oil imports are highly diversified in terms of countries of origin (Russia, Saudi Arabia, Angola, Iraq, Oman, Iran, Venezuela, Brazil, Kuwait, United Arab Emirates, Colombia, Congo, etc.). However, this indicator is not able to take into consideration that many of these suppliers are distant geographically, but the sea routes from these countries to China all converge in the Malacca Strait, as Fig. 5.9 shows, with significant energy security issues. If the diversification of import routes instead of suppliers was calculated, a much lower value would be obtained, since more than two-third of Chinese oil import passes through the Malacca Strait. This example demonstrates that diversity indexes should always be coupled with an in-depth analysis of the energy situation of the country, taking into consideration also energy infrastructure and import corridors.

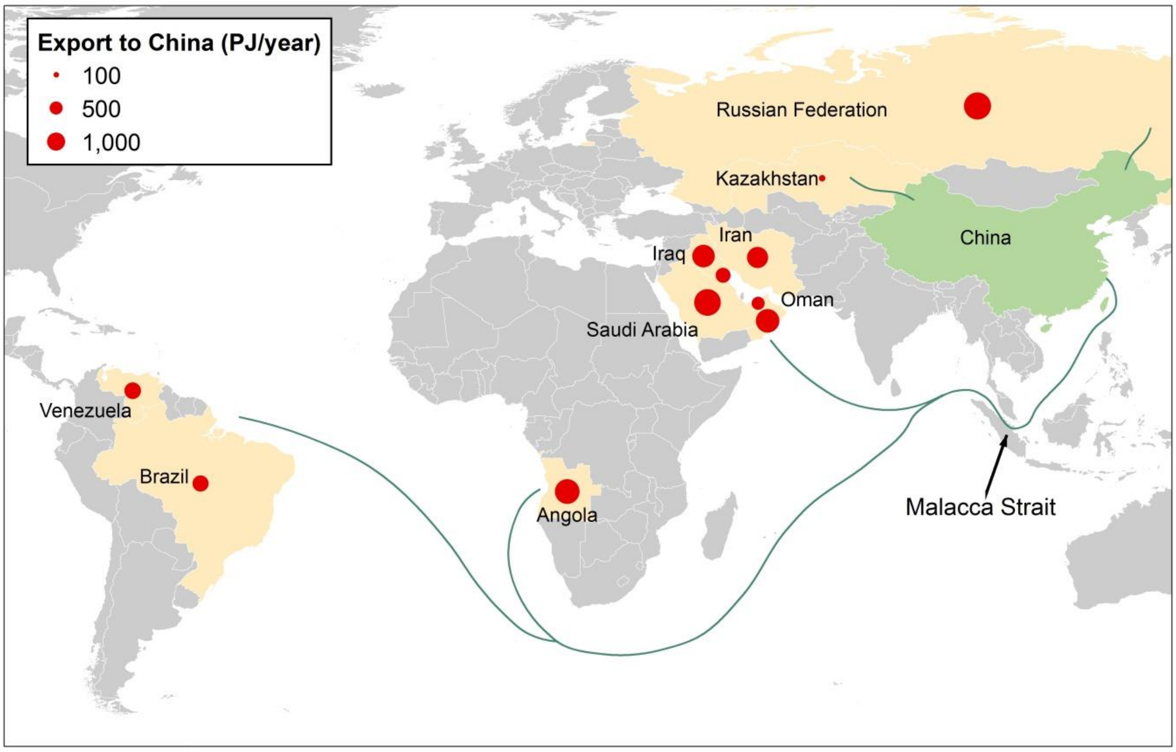


Fig. 5.9 – Chinese oil suppliers and import routes in 2016 (Source: PoliTO elaboration based on [27])

In South Asia, many countries were excluded from calculations due to lack of data in the IEA or in the UN Comtrade datasets (or both). For instance, IEA does not provide data about three out of the seven countries included in this region (namely, Afghanistan, Bhutan, and Maldives). For Bangladesh and Sri Lanka, both characterized by significant import dependence on coal and oil, no information about import by origin is provided by UN Comtrade. Regarding the other two countries belonging to the South Asian region, Nepal and

Pakistan, considerable security issues can be underlined. Nepal has a low diversification of the primary energy supply portfolio and, furthermore, relies for 98% on foreign coal imports, mainly from three suppliers – India (49.0% of imports), South Africa (33.2%), and Indonesia (15.2%) – that together cover more than 97% of total imports. Pakistan, conversely, is characterized by a very low diversification of oil suppliers. The 99.3% of total oil imports comes from only two countries, United Arab Emirates and Saudi Arabia.

In Southeast Asia, Cambodia relies for 100% on external imports to satisfy its coal demand and it is characterized by a diversity index for coal suppliers equal to zero. In fact, coal is provided by a single country, Indonesia, which is the major provider also for Philippines, Laos, Malaysia and Thailand. Thailand has a very limited diversification also regarding natural gas suppliers, which are basically only two: Myanmar, accounting for 75.9% of imports and Qatar, with 23.6%. Conversely, Thai imports of oil – the main contributor to the TPES of the country – are much more diversified, and this determines that the overall H_2 normalized index is relatively high. Finally, in the Southeast Asian region, Singapore is the country with the lowest normalized H_2 index. Singapore, indeed, imports the totality of its coal, oil and gas demand ($m_{coal} = m_{oil} = m_{gas} = 1$). Furthermore, it relies significantly on a single primary energy source, oil, and in fact the H_1 normalized value, which measures the diversification of the primary energy mix, is one of the lowest in the analysed group of countries. Oil is imported mainly from the Middle East region (Saudi Arabia, United Arab Emirates, Qatar, and Kuwait), which accounts for 86.6% of the total. As many other countries belonging to this region, Singapore imports coal essentially from a single supplier, Indonesia (for 97.6%).

Europe is the region with the highest number of countries which rely on external imports for coal, oil and natural gas. This region includes the countries with the lowest H_2 normalized index: Belarus and Lithuania ($H_2 = 0.08$). The first depends totally on Russia for gas and oil imports (i.e., S' for gas and oil equal to zero). Also the S' index for coal is extremely low, since this commodity is imported from only two countries, Russia (56.1%) and Kazakhstan (43.9%). The situation of Lithuania is very similar to Belarus. The country, in fact, relies almost completely on Russia for coal and oil imports, whereas gas is imported from Norway and Russia. The heavy dependence on Russian energy resources is common to many European countries. Russia is in fact often the major provider of gas and, less prominently, of oil and coal for many European countries. In Bosnia and Herzegovina, almost 100% of oil and gas is imported from Russia. Russia provides gas for more than 70% of total imports also to other Eastern Europe countries, such as Czech Republic, Estonia, Latvia, Serbia and Macedonia. Lower dependence on Russian gas, but still critical, is present in Greece (65.4%), Hungary (49.9%), Slovakia (48.8%) and Slovenia (44.3%). In Western Europe, Italy is the country with the highest dependence on Russia (42.0% of total gas imports).

To sum up, the diversification of supply and of the primary energy portfolio has been quantitatively assessed for the most critical countries in terms of energy security of the BRI area. Some general patterns and interdependencies in this area can be summarized:

- Oil is the most traded primary energy source among the BRI countries. The 80 countries analysed in fact imported – from other BRI countries or external suppliers – 50.6 EJ of crude oil, 23.5 EJ of natural gas and 16.4 EJ of coal.

- The Middle East is the principal oil provider for the majority of the BRI countries, covering 32.3% of all imports of this commodity, which, in absolute terms correspond to 16.4 EJ. The Middle East exports mainly to China, Europe, South and Southeast Asia. The second oil supplier is Russia that exports 10.1 EJ, corresponding to 19.9% of the total BRI oil imports, mainly to Europe and China. Finally, Norway and the Netherlands are important suppliers for Northern and Western Europe countries, accounting together for 9.1% of BRI oil imports.
- Russia is a major provider also of gas for several BRI countries. Russian gas imports amount to 11.5% of the total traded gas towards the BRI region and they are directed mainly to Europe. Norway and the Netherland cover another 9.4%, exporting mainly to European Countries. In the international gas trade, Qatar plays a major role being the principal LNG exporter worldwide. Qatar sends gas to a very broad range of countries, including China, Southeast Asian countries (e.g., Thailand, Singapore and Malaysia) and Europe (mainly Italy, Spain, France and UK).
- Australia is the major coal provider for the BRI area, sending this commodity to all the different BRI regions and covering 20.6% of the demand. Inside the BRI area, the major coal suppliers are Russia and Indonesia. The first accounts for 19.2% of the total BRI coal imports, being a key supplier for the majority of European countries. The latter represents the 17.5% and is the main coal provider for China, South and Southeast Asia. Finally, 10.3% of BRI coal demand is satisfied by Colombia.

The results of this analysis show that the BRI region owns a considerable amount of energy reserves and accounts for more than half of world's energy consumption. This area includes both major energy producers and exporters, and countries relying heavily on foreign imports. The energy trade among the BRI countries is significant, resulting in a highly interconnected system. The 73.7% of the crude oil imported by BRI countries is provided by other BRI countries. The share is slightly lower for coal and natural gas, but also for these two commodities more than half of imports are supplied by other BRI countries. However, the BRI area is not a closed system from an energy perspective. The major energy exporters towards the BRI region and not included themselves in this area are:

- Algeria, an important gas provider for all the European, African and Asian countries bordering the Mediterranean Sea. It exports gas both via pipeline to Europe through three international pipelines – the Transmed ending in Italy, and the Maghreb-Europe and Medgaz gas pipeline towards Spain – and in the liquefied form through two liquefaction plants (Arzew LNG and Skikda), for a total capacity of around 34 billion cubic metres per year [50], [51]. Algeria covers 6.8% of the gas imported by the BRI countries.
- In Africa, another relevant gas exporter to the BRI region is Nigeria, which was the fourth country in the world for LNG exports in 2017 [4]. Nigeria exports both towards China and the European markets. This country is also a significant oil exporter. Oil is exported towards the BRI region also from Angola.

- In Latin America, a relevant LNG exporter is Trinidad and Tobago, and Venezuela is a major oil provider for the BRI region. Moreover, Colombian coal is sent to both European and Asian markets.
- Finally, as already underlined, Australia is a key coal exporter for China and Southeast Asia, but also for many European countries.

In this section, the focus was on the diversification of energy suppliers for net importing countries. However, the diversity index can be applied also to net exporting countries, in order to assess the diversification of energy exports. In fact, energy exporters often rely significantly on the sales revenues of energy commodities. The dependence on a single energy buyer or on a single export route can be a significant risk factor for the economy of these countries. The case of Turkmenistan, already cited, is emblematic: the country in fact exports the totality of its gas to one single country, China, and it is trying to develop the TAPI project (refer to Section 2.3.2) in order to increase its export diversification. In the same framework, Russia is currently investing to increase exports towards China, as a measure of diversification away from Europe.

The methodology developed in this section has some limitations. Firstly, the Shannon index, being a "dual concept diversity index" (see Section 3.2.2), is intrinsically not able to take into account the disparity among the suppliers. For instance, if nation A imports half of its energy demand from country B, and half from country C, with B and C belonging to the same geographic region (e.g., two Middle East countries), it has the same diversification of a country importing from B and D, where D is geographically distant from B. The two suppliers B and C, however, could be subject to the same geopolitical dynamics or external events which can cause interruption of supply. Furthermore, the trade routes from B and C towards country A, could converge at a certain point and run together. This last case is perfectly exemplified by the Chinese oil supply, as already shown in Fig. 5.9. The calculated indicators in fact are not able to capture differences in transport modes and routes, and, furthermore, they do not take into account geopolitical relations. As explained in Section 3.2.2, the index H_2 could be further modified for taking into account the political risk index of suppliers. However, the construction of more and more complex indexes can lead to missing out the capacity to identify the real causes of low energy security levels (e.g., the energy security is low because the energy mix is not diversified? Or is it low due to limited diversification of suppliers? Or the suppliers are geopolitically unstable? Or is it a mix of the previous options?).

Despite limitations, the proposed methodology can be particularly useful to bring out critical situations in terms of energy security, for which further investigations (e.g., geopolitical analysis, study of existing energy infrastructure and supply routes) is necessary.

5.2.4 Supply risk and expected supply

In this section, the overall external risk associated to energy supply is calculated, taking into account the geopolitical situation of energy providers, as explained in Section 3.3.1. The input data for the algorithm are:

- The geopolitical risk of suppliers (φ_j), calculated as the complement of the average WGI (see Section 5.2.1). The values of this index are between 0 (for the most stable country) and 1 (most unstable). The vector $\vec{\varphi}$ of dimension 236 x 1 contains the risk for each country of the world from which it is possible to import energy.

- The matrixes of energy exchanges in PJ for year 2016, for each commodity *i*. The matrixes are three, one for each commodity considered: coal, crude oil, and natural gas. Each matrix $\overrightarrow{E_i}$ has dimensions 80 x 236, and, for each commodity, the element e_{kj} is the energy flow imported by the BRI country *k* from supplier *j*.
- The energy intensity of the economy (Q_k), in PJ/G$, which measures the energy inefficiency of a country (the higher the intensity, the lower is the energy efficiency since more energy is needed in order to produce a unit of GDP). This indicator can be used to "translate" the physical damage associated to supply disruption, expressed in PJ/y, into monetary terms (i.e., G$/y). The vector $\vec{Q}$ has dimensions 80 x 1, corresponding to the energy intensity of each BRI country.

For each commodity, the overall supply risk, in PJ/year, can be calculated as a matrix product between the matrix of exchanges $\overrightarrow{E_i}$ and the vector of geopolitical risk index $\vec{\varphi}$:

$$\overrightarrow{R_i} = \overrightarrow{E_i} * \vec{\varphi} \tag{36}$$

$\overrightarrow{R_i}$ is an 80 x 1 vector containing the risk for each BRI country. The total risk can be then calculated as the sum of the risk associated to the import of each commodity. Finally, the expected supply is the difference between the total import required by the country and the flow at risk due to geopolitical stability of suppliers.

Tab. 5.5 reports the risk per commodity, the overall risk, and the expected supply for the main importer of the BRI area. The table is ordered so that the countries with higher percentage of import at risk over the total are on the top.

Greece is the country with the highest risk in relative terms among the analysed countries. Greece in fact imports oil from very unstable countries such as Iraq, Iran, Kazakhstan, Russia and Saudi Arabia; gas from Russia and Algeria; and coal almost exclusively from Russia. All these countries are characterized by φ values above 0.5 (see Tab. 5.7). Iraq, in particular, is the main oil supplier for Greece, accounting for more than 40% of total oil imports, and it has also one of the highest political risk indexes among the main energy exporter toward the BRI area (φ=0.91). Many Eastern Europe countries, such as Belarus, are characterized both by high supply risk and limited diversification, due to the heavy dependence on Russia, whose φ value amounts to 0.73. In Western Europe, the most critical countries are Italy and Spain, which are characterized by a relatively high diversification, but also by a high supply risk (both in relative and absolute terms) due to the instability of suppliers. Specifically, Italy imports both oil and gas from Libya, one of the most unstable countries in the world (φ=0.97). Belgium is the country with the lowest risk, thanks to the high share of Norway and Netherlands in its oil and gas imports, which are the most stable countries among the main exporters towards BRI area (see Tab. 5.7).

Also China, despite the high diversification of supply (see Tab. 5.4), presents an overall supply risk around 60% of total import. Chinese situation will be further investigated in Section 5.3.

In Tab. 5.6, the supply risk is converted into monetary terms through the energy intensity of the economy, according to eq. (19). It is evident that the energy intensity of BRI countries is highly diversified, ranging from less than 5 PJ/G$ in Western Europe countries, to more than 20 PJ/G$ in Eastern Europe and Central Asia.

The analysis developed in this section focuses on the risk of suppliers neglecting the risk associated to geopolitical tensions along import routes. Nonetheless, it is significantly useful, especially if coupled with the analysis of energy mix and supply diversification, for identifying criticalities in terms of energy security in a vast area such as the one involved in the BRI. The countries with the lowest level of energy security are the ones characterized both by a limited diversification and a high supply risk.

Tab. 5.5 – Supply risk and expected supply for the BRI countries with positive net import dependence for all primary energy sources

Country	Region	Coal		Crude oil		Natural gas		Total import [PJ/y]	Total risk [PJ/y]	Expected supply [PJ/y]	Supply at risk %
		Import [PJ/y]	R [PJ/y]	Import [PJ/y]	R [PJ/y]	Import [PJ/y]	R [PJ/y]				
Greece	Europe	8.0	5.8	1178.0	914.4	145.0	101.7	1331.0	1021.9	309.1	76.8%
Serbia	Europe	27.0	15.9	101.0	79.1	60.0	43.6	188.0	138.6	49.4	73.7%
Belarus	Europe	20.0	13.4	779.0	567.5	648.0	472.2	1447.0	1053.2	393.8	72.8%
Bulgaria	Europe	24.0	15.2	291.0	210.9	109.0	79.1	424.0	305.3	118.7	72.0%
Romania	Europe	43.0	27.4	338.0	234.2	49.0	35.7	430.0	297.2	132.8	69.1%
Italy	Europe	459.0	232.0	2817.0	2049.5	2239.0	1454.7	5515.0	3736.2	1778.8	67.7%
Spain	Europe	339.0	165.3	2865.0	1966.4	1180.0	782.9	4384.0	2914.6	1469.4	66.5%
Lithuania	Europe	7.0	5.0	420.0	297.4	79.0	24.9	506.0	327.4	178.6	64.7%
Croatia	Europe	28.0	18.6	128.0	97.9	44.0	9.9	200.0	126.3	73.7	63.1%
Kyrgyzstan	Central Asia	17.0	10.2	11.0	6.4	9.0	6.3	37.0	22.9	14.1	61.9%
China	Eastern Asia	5696.0	2332.6	15952.0	10656.2	2473.0	1471.1	24121.0	14459.9	9661.1	59.9%
Hungary	Europe	48.0	7.8	263.0	195.4	302.0	154.2	613.0	357.5	255.5	58.3%
Finland	Europe	117.0	62.3	520.0	343.1	86.0	10.1	723.0	415.5	307.5	57.5%
Jordan	Middle East	9.0	3.5	125.0	68.6	167.0	95.6	301.0	167.7	133.3	55.7%
Slovakia	Europe	115.0	44.5	243.0	164.9	151.0	65.8	509.0	275.2	233.8	54.1%
Thailand	Southeast Asia	597.0	278.4	1852.0	811.6	488.0	340.8	2937.0	1430.8	1506.2	48.7%
Bosnia	Europe	39.0	7.5	40.0	29.0	8.0	5.6	87.0	42.1	44.9	48.4%
Singapore	Southeast Asia	18.0	9.7	2047.0	947.3	365.0	165.7	2430.0	1122.7	1307.3	46.2%
France	Europe	338.0	132.0	2367.0	1482.6	1726.0	404.0	4431.0	2018.6	2412.4	45.6%
Sweden	Europe	94.0	21.2	852.0	421.0	34.0	2.6	980.0	444.8	535.2	45.4%
Pakistan	South Asia	143.0	75.0	400.0	166.7	0.0	0.0	543.0	241.7	301.3	44.5%
Ukraine	Europe	445.0	273.7	22.0	13.4	369.0	46.2	836.0	333.3	502.7	39.9%
Switzerland	Europe	5.0	1.6	130.0	83.2	125.0	14.2	260.0	99.0	161.0	38.1%
Ireland	Europe	48.0	24.3	137.0	20.9	71.0	9.2	256.0	54.4	201.6	21.3%
United Kingdom	Europe	266.0	124.2	2110.0	559.0	1706.0	181.8	4082.0	865.0	3217.0	21.2%
Belgium	Europe	120.0	44.8	1419.0	216.4	626.0	46.5	2165.0	307.7	1857.3	14.2%

Tab. 5.6 – Energy intensity and supply risk converted into monetary terms for the BRI countries with positive net import dependence for all primary energy sources

Country	**Region**	**Energy intensity (PJ/G$)**	**Economic risk (G$/y)**
Kyrgyzstan	Central Asia	25.5	0.9
China	Eastern Asia	13	1112.3
Belarus	Europe	17.7	59.5
Belgium	Europe	4.6	66.9
Bosnia and Herzegovina	Europe	14.9	2.8
Bulgaria	Europe	13.4	22.8
Croatia	Europe	5.8	21.8
Finland	Europe	5.6	74.2
France	Europe	3.6	560.7
Greece	Europe	3.9	262.0
Hungary	Europe	7.3	49.0
Ireland	Europe	1.8	30.2
Italy	Europe	3	1245.4
Lithuania	Europe	6.6	49.6
Romania	Europe	6.6	45.0
Serbia	Europe	15.5	8.9
Slovakia	Europe	6.6	41.7
Spain	Europe	3.4	857.2
Sweden	Europe	3.7	120.2
Switzerland	Europe	1.6	61.9
Ukraine	Europe	31.9	10.4
United Kingdom	Europe	2.7	320.4
Jordan	Middle East	12.2	13.7
Pakistan	South Asia	17.6	13.7
Singapore	Southeast Asia	3.8	295.5
Thailand	Southeast Asia	14.2	100.8

Tab. 5.7 – Political risk index for the main energy exporter towards the BRI region, ordered by decreasing φ

Country	**φ**
Libya	0.97
Venezuela	0.93
Iraq	0.91
Turkmenistan	0.89
Angola	0.84
Nigeria	0.83
Algeria	0.79
Iran	0.78
Russian Federation	0.73
Azerbaijan	0.72
Kazakhstan	0.61
China	0.58
Brazil	0.56
Colombia	0.55
Saudi Arabia	0.55
Indonesia	0.54
Kuwait	0.54
Peru	0.53
Trinidad and Tobago	0.43
South Africa	0.43
Oman	0.42
Qatar	0.37
United Arab Emirates	0.30
United States	0.15
United Kingdom	0.13
Australia	0.09
Netherlands	0.06
Norway	0.03

5.3 A focus on Chinese energy security

This section focuses on the strategic assessment of Chinese energy supply, quantifying the current level of expected supply in a geopolitical perspective and analysing the optimal re-despatching of energy fluxes with the aim of minimizing the risk associated to supply. The developed methodology and algorithms can however be applied to any other BRI country.

The main questions that we want to answer are:

- Which is the current level of Chinese energy security in terms of supply risk?
- Which are the quantities of the different commodities that should be imported from the different suppliers in order to minimize the supply risk?

The first question was already answered in Section 5.2.4, when the supply risk for all BRI countries was calculated. Although China has a relatively high diversification of supply for all primary sources ($S_{coal}{}' = 0.32$, $S_{oil}{}' = 0.55$, $S_{gas}{}' = 0.59$), the security and stability of suppliers is a critical issue for Chinese regime. In year 2016, which is assumed as reference year, China imported 24,121 PJ of primary sources (coal, crude oil and gas). Of these, 14,460 PJ were at risk due to geopolitical tensions in supplier countries, corresponding to 59.9% of total imports. The expected supply value was therefore very low compared to the demand, amounting to just 9,661 PJ.

The most critical commodity in terms of geopolitical stability of suppliers is represented by crude oil, which is also the commodity for which the country has the higher import dependency. China in fact imports more than two-third of its crude oil demand from abroad, mainly from Russia (13.8%), Saudi Arabia (13.4%), Angola (11.5%), Iraq (9.5%), Oman (9.2%), Iran (8.2%), Venezuela (5.3%), Brazil (5.0%), Kuwait (4.3%) and United Arab Emirates (3.2%) and others (14.9%).

For natural gas, Turkmenistan is by far the main provider (40.0%), followed by Australia (22.2%), Qatar (9.2%), Uzbekistan (5.9%), Myanmar (5.3%), Indonesia (5.2%), Malaysia (4.8%), Papua New Guinea (3.9%), Kazakhstan (0.6%), Nigeria (0.5%), Russia (0.5%), Peru (0.5%) and USA (0.4%) and others (2.5%).

Finally, coal is the commodity with the highest share in TPES and the lowest diversification of supply. However, thanks to the considerable domestic production, Chinese import dependence for coal is limited. The main coal providers for China are: Australia (38.5%), Indonesia (21.3%), Mongolia (14.4%), Democratic People's Republic of Korea (12.2%), Russia (10.1%), Canada (2.8%), and others (0.7%).

In order to answer to the second question, a linear optimization problem can be set, as explained in the following section.

5.3.1 Minimization of supply risk

The objective function to minimize in the optimization problem is the total external risk for Chinese supply, which is the product of suppliers risk indexes and the energy flow imported. The following simplifying assumptions are made:

- China imports crude oil from more than 20 countries, but only the top ten suppliers are taken into consideration: Russia, Saudi Arabia, Angola, Iraq, Oman, Iran, Venezuela, Brazil, Kuwait and United Arab Emirates, accounting together for 85.1% of total oil imports.
- For natural gas 13 suppliers are considered, which represents 98.8% of gas imports: Turkmenistan, Australia, Qatar, Uzbekistan, Myanmar, Indonesia, Malaysia, Papua New Guinea, Kazakhstan, Nigeria, Russia, Peru and USA.
- Regarding coal, the importing countries taken into account are six (for 99.3% of total imports): Australia, Indonesia, Mongolia, Democratic People's Republic of Korea, Russia and Canada.

- For all commodities, the imports from countries which were not cited before are assumed constant and labelled as import from "Others".

The objective function can be written as:

$$\min f = \min(R_{ext}) = \min\left(\sum_{c}\sum_{j}\varphi_j * e_{j,c}\right) \tag{37}$$

where subscript *c* refers to the commodity, and *j* to the supplier countries. The indicator φ represents again the political risk index, calculated as the complement of the average WGI. The system variables are the $e_{j,c}$ values, which represent the energy fluxes of commodity *c* imported from country j, and they are expressed in PJ/year.

The equality constraints that must be satisfied are:

- Scenario SC1: the sum of energy imports from all suppliers for each commodity must be equal to the total import of that commodity in 2016 (i.e., it is assumed that the demand of each commodity and the share in TPES remains unchanged).

$$\sum_{j}\varphi_j * e_{j,coal} = I_{coal} \tag{38}$$

$$\sum_{j}\varphi_j * e_{oil} = I_{oil} \tag{39}$$

$$\sum_{j}\varphi_j * e_{j,gas} = I_{gas} \tag{40}$$

  In the equations, I_{coal}, I_{oil}, I_{gas} represent respectively the import of coal, oil and natural gas, in PJ/y. It is therefore possible to solve three independent optimization problems separately, one for each commodity.

- Scenario SC2: the sum of energy imports must be equal to the total value of imports in 2016 (i.e., the total import demand is unchanged, but the energy mix portfolio is flexible):

$$\sum_{c}\sum_{j}\varphi_j * e_{j,c} = I_{tot} \tag{41}$$

  where I_{tot} is the total import of coal, oil and natural gas.

The inequality constraints that must be satisfied are:

- The energy fluxes transported through each energy corridor must be lower than the maximum capacity. For captive corridors, this is equal to the nominal capacity. For LNG, this is equal to the minimum between China's regasification capacity (C_{reg}) and the liquefaction capacity of the supplier country ($C_{liq,j}$). The minimum is further multiplied for 0.5 in order to guarantee a minimum diversification for both importer and exporter. For crude oil and coal, it is assumed that the maximum capacity is equal to 1.6 times the import of that commodity.

$$e_{j,c} \leq E_{j,c,max} \tag{42}$$

$$E_{j,LNG,max} = 0.5 * \min\left(C_{reg}, C_{liq,j}\right) \tag{43}$$

- The energy fluxes transported through each energy corridor must be higher than a minimum contract value. The minimum is assumed equal to 40% of the reference value, as a simplifying assumption.

$$e_{j,c} \geq E_{j,c,min} \tag{44}$$

- For LNG, a further constraint must be added: the sum of all LNG imports must be lower or equal to the country's regasification capacity.

$$\sum_j e_{j,LNG} \leq C_{reg} \tag{45}$$

For each case, the algorithm was developed in Python using the *linprog* function of the Scipy optimization library, based on the Simplex method.

Fig. 5.11, Fig. 5.12, and Fig. 5.13 represent the results of the two optimization problems, comparing them with the reference scenario. In scenario SC1, the contribution of Australian gas increases significantly from 22.2% to 57.5% at the detriment of Turkmenistan that experiences a reduction in imported flow of 60% (the minimum for the constraints adopted). A considerable drop is evident in all the others gas suppliers except USA, which pass from less than 1% to more than 10% of total gas imports. In this case, the risk associated to gas supply is almost halved with respect to the reference scenario. However, the reduction in supply risk is achieved at the cost of a significant reduction in the diversification of gas suppliers. The normalized Shannon index for gas in fact drops from 0.70 to 0.56. Concerning oil, Chinese imports experience a slightly increase in dependence from the Middle East, even if favouring the most stable countries, such as Saudi Arabia, Oman, Kuwait and United Arab Emirates, instead of Iraq and Iran. The risk for oil import does not decrease substantially in the optimized scenario (only -13.4%) as for gas, and, furthermore, the diversification is slightly reduced from 0.95 to 0.91. Finally, the optimal re-dispatch for coal favours again Australia, the most stable supplier among Chinese energy providers, which passes from 38.5% to 61.5%. This is obviously followed by a significant reduction in diversification from 0.82 to 0.64, although the risk is reduced of more than one-third. Comparing scenario SC1 with the reference scenario, it becomes evident that risk minimization and diversification are competing objectives, since the optimization tends to favour significantly one, or two, countries, the most stable ones.

In scenario SC2, the energy mix changes in favour of gas (+36.8% of imports with respect to the reference scenario) and coal (+32.7%). Conversely, oil imports are reduced of -17.4%. Indeed, oil suppliers include many unstable countries and the optimization for SC1 led to the lowest risk reduction. Natural gas imports from Australia grow also in scenario SC2, together with USA. Furthermore, Qatar experiences a considerable expansion from 9.2% to 23.0%. The reduction in diversification with respect to the reference scenario is lower with respect to SC1, but still significant (0.61 vs. 0.7). For crude oil, the trend is the same as for SC1, but the reduction in total import leads to a further reduction of the risk associated to this commodity. As far as coal is concerned, imports from Australia, Indonesia and Mongolia rise considerably. The growth in total coal import increases the security of the country, and also the economic sustainability of the energy import, due to the low prices of this commodity. However, an increase in the share of coal in the energy mix introduces issues related sustainability.

Overall, SC2 is characterized by a higher risk reduction (-25.7% instead of -21.7%), and by a lower drop in diversification with respect to SC1. Tab. 5.9 summarizes the comparison among the reference scenario, and the two optimized results.

5.4 Scenario definition

Scenario analyses allow assessing the impact of possible future events on the energy security of a nation. These events include the increase in the geopolitical risk index of one of the supplier countries, the implementation of a specific energy project or policy, and the unavailability of an energy corridor. In this section, different scenarios are defined and compared with the reference and optimized scenarios in terms of supply risk and diversification of supply. Two types of scenarios analysis can be developed: the first regards the impact assessment of potential criticalities (e.g., variation in geopolitical dynamics among countries), the second is related to the contingency management in case of supply disruption or corridor failure. In Tab. 5.8, the analysed scenarios are briefly described.

Tab. 5.8 – Scenarios definition

Code	Name	Type	Description
REF	Reference	-	In the reference scenario, the energy flows from Chinese suppliers corresponds to the actual situation of imports in year 2016.
SC1	Optimization 1	Potential criticality analysis	Re-despatch at minimum supply risk assuming that the total imports of each commodity are unchanged with respect to the reference scenario.
SC2	Optimization 2	Potential criticality analysis	Re-despatch at minimum supply risk assuming that the total import is unchanged with respect to the reference scenario, but the import per commodity can change (variation of energy mix composition allowed).
SC3	Power of Siberia	Potential criticality analysis	The Power of Siberia gas pipeline, connecting Russia to China, is completed.
SC4	Increase in Russian risk	Potential criticality analysis	The political risk index of Russia increases by 30%.
SC5	Russia out	Contingency management	Re-dispatch at minimum risk assuming that Russia stops exports towards China, due to geopolitical tensions.

Scenario SC1 and SC2 are formally defined in Section 5.3. For scenario SC3, the risk and diversification of supply for China is calculated after the completion of one of the BRI energy project, the Power of Siberia gas pipeline.

The Power of Siberia is an under construction gas pipeline which will deliver the gas extracted in Eastern Siberia to China. The expected capacity is 1444 PJ/y (corresponding to 38 bcm/y) by year 2035. This would significantly increase the share of Russia in Chinese gas imports. The following simplifying assumptions are made:

- The pipeline operates with a utilization factor of 40%, meaning that 578 PJ/y are delivered from Russia to China through the Power of Siberia.
- The flow from Russia is increased of 578 PJ/y, corresponding to the import through the Power of Siberia.
- The increase in imports from Russia is counterbalanced by a reduction in imports from Turkmenistan, so that the total gas import is constant.
- All the other import flows are kept constant and equal to the reference scenario.

In this scenario, the share of Russian imports raises from less than 1% to more than 20%, and Turkmenistan drops from 40% to 17%. Since Russia has a political risk index lower than Turkmenistan (0.73 vs. 0.89), security is improved and the risk of gas supply is reduced by 6%, passing from 1461 PJ/y to 1369 PJ/y. Furthermore, the Shannon index for diversification of gas supply increases from 0.7 to 0.79, since the system becomes more balanced among gas providers, as figure Fig. 5.10 shows.

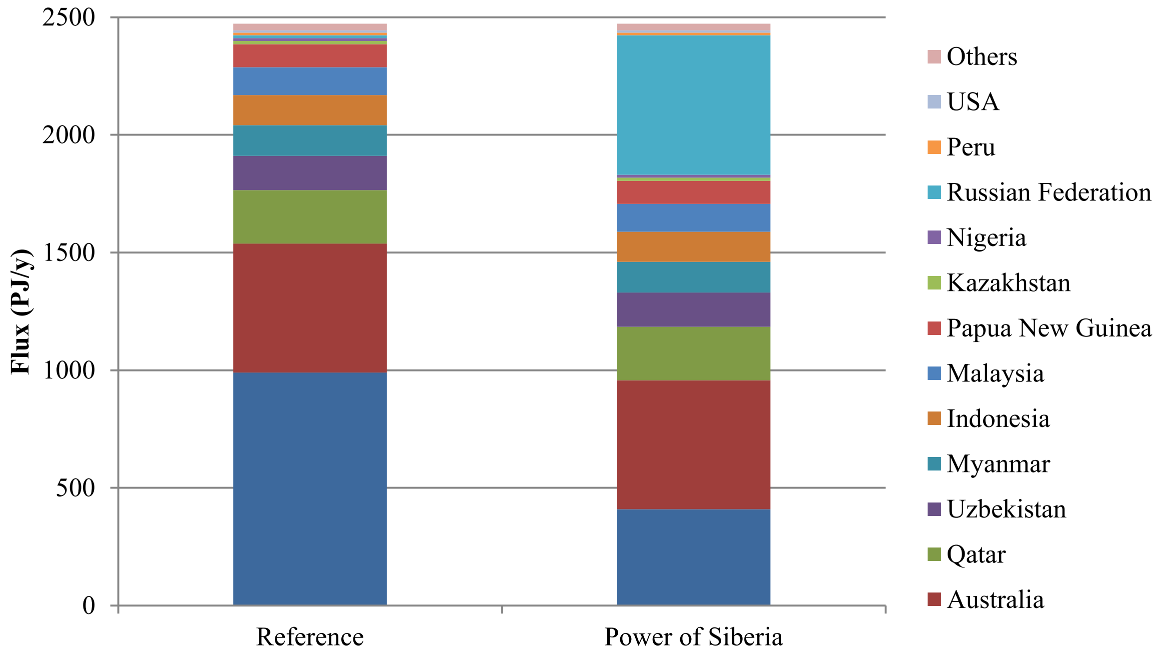


Fig. 5.10 – Comparison of gas flows between the SC3 and reference scenario

In scenario SC4, the political risk index of Russia is assumed to increase by 30%, passing from 0.73 to 0.95. It is assumed that the import flows from Russia and all the other suppliers remain unchanged. In this case, the risk of supply increases of roughly 4.7%, passing from 12,883 PJ to 13,494 PJ, due to the Chinese dependence on Russia for both oil and coal. However, the variation is much lower with respect to other BRI countries that, as a consequence of an increase in Russia's political risk index, experience a growth in supply risk up to 15%. This is the case of countries that significantly rely on Russia, such as the majority of Eastern Europe countries. The impact of Russian political stability on China is slightly higher (5.0%) if the scenario SC3 and SC4 are combined, but still much lower with respect to other BRI countries, such as Belarus, Estonia etc.

In scenario SC5, the optimization algorithm is run again imposing that all import flows from Russia are null, and adopting the same constraints of optimization SC2. It is interesting to notice that, in this scenario, the overall risk actually decreases with respect to the reference one. It is furthermore the highest risk reduction among all the considered scenarios (-27.2%) In this scenario, introduced as adverse scenario, Chinese security seems actually to improve. This apparent contradiction shows one of the limitations of the model adopted. An in-depth analysis of energy corridors and supply contract among countries is missing, and, therefore, the upper and lower bounds for the variables of the optimization problems are assumed arbitrary as percentage of the flow in the reference scenario. In the considered scenario, the loss of supply from Russia is easily replaced by other, more stable, suppliers, such as Australia and USA. The import composition is very similar to scenario SC2.

The comparison among the system variables (i.e., the flow imported from each supplier) in the different scenarios is reported in Fig. 5.11, Fig. 5.12, and Fig. 5.13. The composition of SC4 is identical to the reference scenario, since just the political risk index of Russia is varied, however, the overall risk is different. Tab. 5.9 summarizes the external risk and the diversification of supply for each scenario analysed.

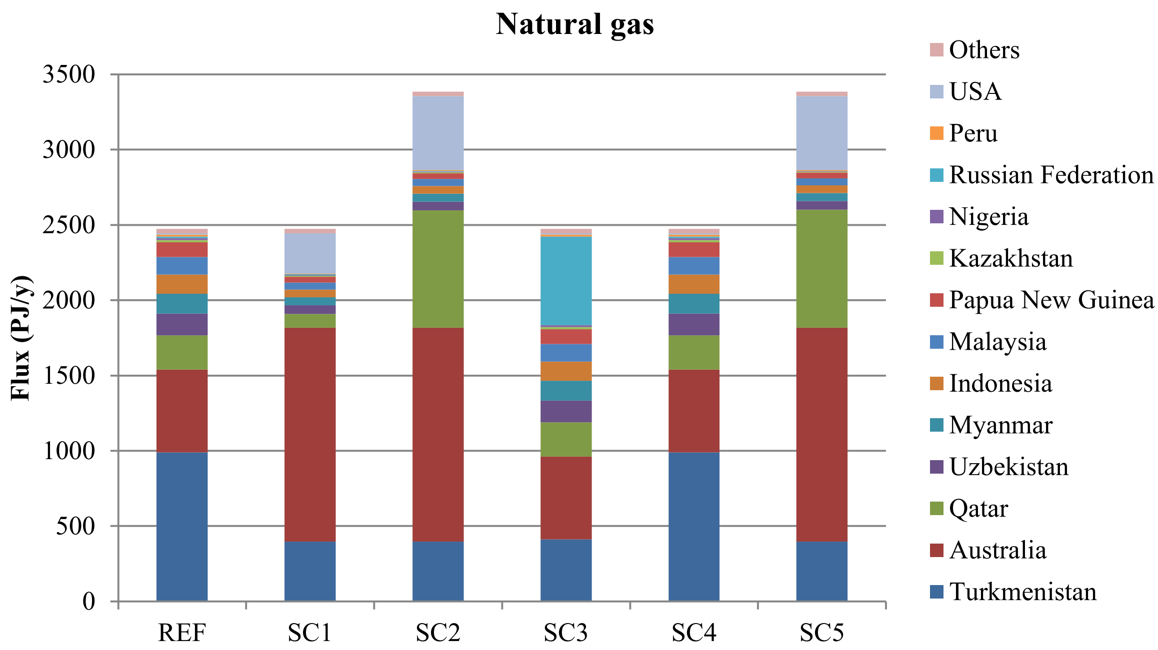


Fig. 5.11 – Scenario comparison: natural gas

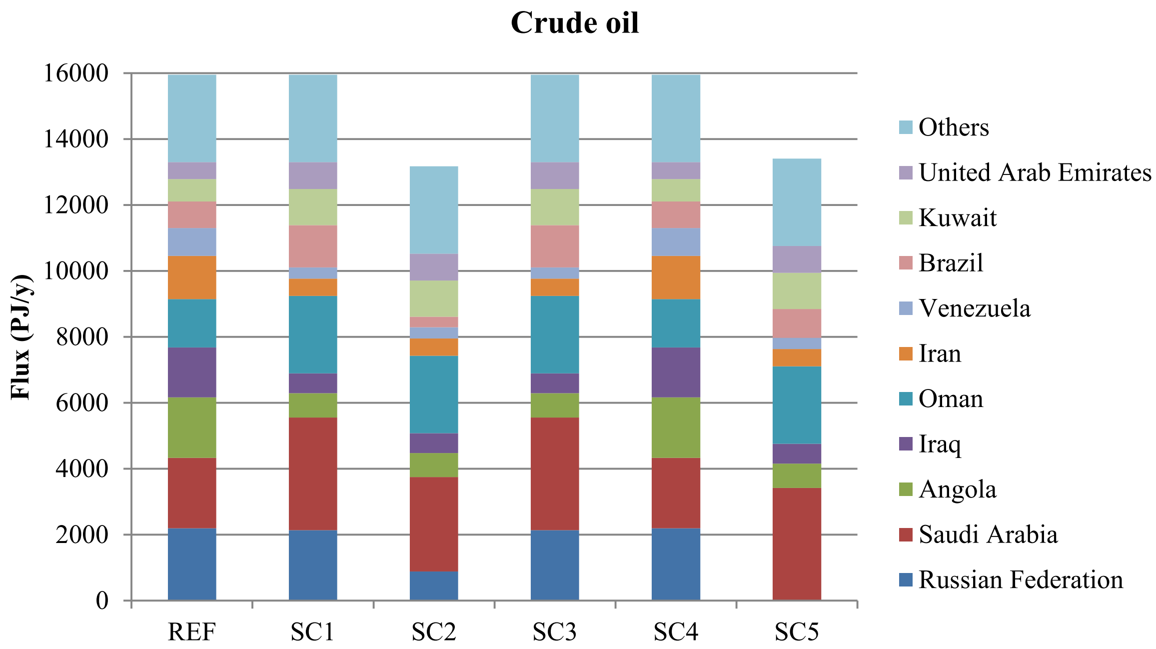


Fig. 5.12 – Scenario comparison: crude oil

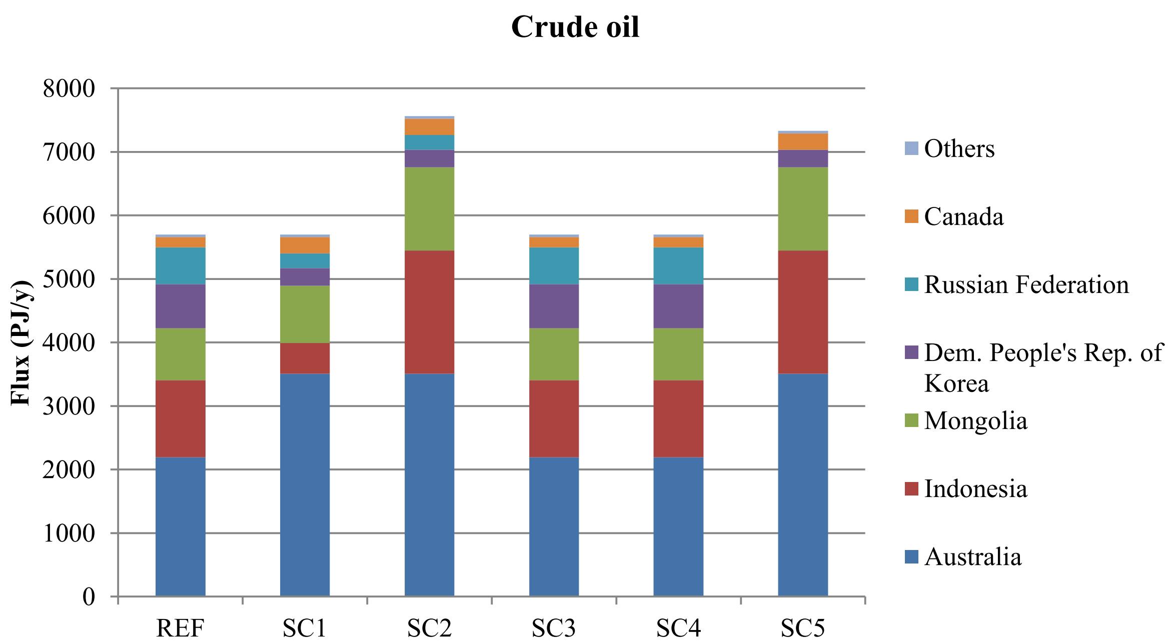


Fig. 5.13 – Scenario comparison: coal

Tab. 5.9 – External risk and diversification of supply for different scenarios

	Natural gas		Crude oil		Coal		Total risk (PJ/y)	% variation wrt REF
	Risk (PJ/y)	S’	Risk (PJ/y)	S’	Risk (PJ/y)	S’		
REF	1461.0	0.70	9091.2	0.95	2331.2	0.82	12883.4	-
SC1	732.2	0.56	7871.0	0.91	1459.3	0.64	10062.5	-21.9%
SC2	1020.1	0.61	6107.9	0.89	2446.0	0.71	9574.1	-25.7%
SC3	1368.6	0.79	9091.2	0.95	2331.2	0.82	12791.0	-0.7%
SC4	1464	0.70	9572	0.95	2458	0.82	13493.6	+4.7%
SC5	1018	0.61	6082	0.85	2277	0.66	9378.2	-27.2%

6 Conclusions and future work

Energy plays a crucial role in the national security of each country, constituting the engine for the functioning of modern economies. However, many countries are characterized by limited or null availability of energy sources and rely significantly on foreign imports, which are subject to geopolitical dynamics, commercial disputes, and infrastructure failure.

This work aimed at developing an integrated tool for supporting science-based policy decision making, quantitatively assessing energy security, and modelling the energy interdependencies among countries at a multi-regional scale. The quantitative assessment of energy security is especially important for those countries that have low level of self-sufficiency and are thus particularly vulnerable to supply disruption. The proposed tool can be useful for guiding energy policies and strategies in the short- and long-term, and for selecting investments and projects in the energy sector.

The methodology has been applied to a specific case study: the Belt and Road Initiative, the ambitious Chinese project for improving cooperation and connectivity among Asia and Europe, and involving 80 countries. Energy and energy infrastructure is one of the key theme of the initiative. Pipelines, electricity networks and power generation plants are extensively being built in the countries involved, thanks to Chinese investments, with the aim of increasing energy trade and cooperation.

A tool prototype has been developed, which includes the construction of a relational database in PostgreSQL, the development of algorithms in Python for performing the desired analyses, and the visualization of results on a web interface. The main analyses that the prototype can implement are:

- The analysis of the energy situation and the flows exchanged among the BRI countries or towards the BRI region. The main energy producers and exporter of the BRI region were identified.
- The calculation, for each importing country, of Shannon indexes for measuring the diversification of the energy mix and the diversification of suppliers from which energy is imported. An aggregated indicator is introduced measuring an overall diversification index, which includes the energy mix composition, the import dependence per commodity, and the diversification of suppliers. This analysis allows identifying the countries characterized by major criticalities in terms of energy security (e.g., the ones relying considerably on a single supplier or on a single energy commodity).
- The quantitative assessment of the risk associated to supply for each country, taking into consideration the geopolitical risk of supplier countries.

Furthermore, an optimization for minimizing the supply risk was developed for China. The results indicate the energy quantities that should be imported from each supplier for minimizing the supply risk. The outcomes of the analysis showed, however, that often risk minimization and supply diversification are competing objectives. In the future, therefore, it could be interesting to perform a multi-objective optimization aiming to minimize supply risk, and maximize diversification. Nonetheless, the results of the optimizations can be a guideline for Chinese government, showing the directions for future investments and projects in the energy sector. Finally, a scenario analysis for China was developed for assessing the impact of future events on the national supply risk, simulating supply disruption, variation in geopolitical dynamics or implementation of energy projects. For instance, the effect of the completion of the Power of Siberia gas pipeline, which is one of the main BRI projects, on Chinese energy security is evaluated, showing that the project allows to both increase diversification and reduce the supply risk, decreasing the import from Turkmenistan, China's main gas provider at the moment, which is characterized by a very high political risk index.

Up to now, the physical layer regarding energy flows among countries and the geopolitical layer were implemented. However, the complete assessment of energy security in a comprehensive approach requires the addition of other interconnected layers:

- Information about the energy infrastructure and corridors should be added to the physical layer, for building the spatial database of the BRI countries, and introducing the assessment of risk associated to the transport of energy commodities along import routes.
- Economic layer, which allow assessing the impacts of the BRI energy projects on the economy of countries involved, and performing re-despatch optimizations at minimum cost (i.e., the objective function to be minimized is the total cost of imported energy commodities) or aiming to find a balance between supply cost and risk.
- Social layer, for assessing the impact of BRI projects on local communities touched by the initiative (e.g., on job creation and access to energy).
- Environmental layer, for assessing the sustainability of the initiative. This layer is especially important since many concerns arose about Chinese investments in coal-fired plants in several BRI countries. The tool should be able to evaluate the impacts on the environment of the BRI, both at local and global scale, and to assess the effects of the introduction of carbon pricing mechanisms (e.g., carbon tax).

In addition to that, the geopolitical layer can be refined and improved. In fact, geopolitical relationships are extremely difficult to be quantified. At this stage, Worldwide Governance Indicators provided by World Bank were adopted to calculate the country's political risk index. However, the security of supply is affected by the presence of bilateral agreements and energy contracts between exporting and importing countries. For this reason, the risk index is more a parameter that depends on the considered couple of exporter-importer, than a country's intrinsic characteristic.

To sum up, the modelling of the energy dimension of the BRI was developed focusing mainly on two layers (physical and geopolitical) and three primary energy commodities (coal, crude oil and natural gas). Future works should be developed for integrating in the model the other commodities, such as electricity, oil products, which are both critical energy commodities. The introduction of electricity is especially important due to the trend towards decarbonisation and electrification of final uses. Furthermore, the problem of data validation should be addressed, with the aim of developing automated processed able to compare different datasets. Further improvements of the model regards the development of algorithms able to take into consideration the interaction and complex interplay among the different layers and assessing competing objectives such as security, affordability and sustainability. Finally, besides models and algorithms, the development of a suitable web interface is crucial for the purpose of building a tool able to support policy decision making in the energy sector. The web interface is not only the platform where data and results are displayed, but it is also an interactive platform which allows the user to interactively build new scenarios and customize the analysis to be developed.

To conclude, the proposed methodology, refined for integrating the different layers, allows assessing the energy security of the countries involved in the Belt and Road Initiative in a comprehensive and quantitative approach, highlighting the presence of criticalities and pointing the way towards energy strategies and investments aiming at improving national security.

List of Acronyms

ASEAN	Association of Southeast Asian Nations
bcm	Billion Cubic Metres
BRI	Belt and Road Initiative
CPEC	China Pakistan Economic Corridor
DB	Database
DC	Direct Current
DSO	Distribution System Operator
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographic Information System
GWP	Global Warming Potential
HDI	Human Development Index
IRR	Internal Rate of Return
LNG	Liquefied Natural Gas
MSR	Maritime Silk Road
NGO	Non-Governmental Organization
OBOR	One Belt One Road
PV	Photovoltaic
RDBMS	Relational Database Management System
RES	Renewable Energy Sources
SREB	Silk Road Economic Belt
TFC	Total Final Consumption
TPES	Total Primary Energy Supply
TSO	Transmission System Operator
UHV	Ultra-High Voltage

Appendix A: Glossary and definitions

The following table contains the definition of basic figures which cannot be calculated with mathematical formulas, but they have to be collected from available online datasets and sources.

Name	Symbol	Definition	Unit	Source
CO_2 emissions	CO_2	Annual carbon dioxide emissions originated by burning of fossil fuels and by the manufacture of cement.	Mt	World Bank, IEA
CO2 equivalent emissions	CO_2^{eq}	Annual equivalent carbon dioxide emissions originated by burning of fossil fuels and by the manufacture of cement. The CO_2 equivalent of a greenhouse gas is the amount of CO2 that would have an equivalent global warming impact.	Mt	World Bank, IEA
Electrical Installed Capacity	CAP	Also known as nameplate capacity, rated capacity, nominal capacity, it is the intended full-load sustained output of a facility such as a power plant.	GW	IEA
Electricity consumption	EL	Electricity generation less power plants' own use and transmission, distribution, and transformation losses less export plus import.	TWh	IEA
Electricity Generation	GEN	Total amount of electricity generated by power only or combined heat and power plants including generation required for own-use. This is also referred to as gross generation.	TWh	IEA
Energy Export	E	Exports comprise amounts having crossed the national territorial boundaries of the country leaving the country or area.	ktoe	IEA
Energy Import	I	Imports comprise amounts having crossed the national territorial boundaries of the country entering the country or area.	ktoe	IEA
Energy Production	P	Production of primary energy (i.e. hard coal, lignite, peat, crude oil, NGL, natural gas, combustible renewables and waste, nuclear, hydro, geothermal, solar and the heat from heat pumps that is extracted from the ambient environment).	ktoe	IEA
Energy Reserves	ρ	Estimated quantity of energy source (i.e., coal, natural gas, oil) that can be extracted with currently available technology at an economically viable cost.	PJ	BP, EIA

Gross Domestic Product	GDP	GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. Dollar figures for GDP are converted from domestic currencies using single year official exchange rates.	USD	World Bank, IEA
Gross Domestic Product based on purchasing power parity	GDP PPP	GDP PPP is gross domestic product converted to international dollars using purchasing power parity rates (PPP) instead of market exchange rates. An international dollar has the same purchasing power over GDP as the U.S. dollar has in the United States.	USD	World Bank
Population	POP	Total population counts all residents regardless of legal status or citizenship. The values shown are midyear estimates from UN statistics division.		World Bank, IEA
Surface	A	Surface area is a country's total area, including areas under inland bodies of water and some coastal waterways.	km^2	World Bank
Total Final Consumption	TFC	Amount of primary and secondary energy commodities directly consumed in the end-use sectors in order to fulfil the so-called energy services demands (i.e. space heating and cooling, water heating production, lighting, cooking, use of electrical appliances for the residential and commercial sectors, industrial production, mobility of passengers and goods, etc.)	ktoe	IEA
Total Primary Energy Supply	TPES	Overall internal energy needs of a given country or area, requested to satisfy its consumption. This is also referred to as Gross Inland Consumption. It represents domestic demand only and is broken down into power generation, other energy sector and total final consumption and it excludes international marine and aviation bunkers.	ktoe	IEA

Appendix B: Geo-economic and energy figures

Table 1 – Geo-economic figures for the BRI countries (Source: [21])

Region	**Country**	**Surface (km2)**	**Population (million)**	**GDP (billion 2010 USD)**	**GDP PPP (billion 2011 international $)**
Central Asia	Kazakhstan	2724902	17.8	188.3	417.2
	Kyrgyzstan	199949	6.1	6.3	20.1
	Tajikistan	141376	8.7	8.5	24.1
	Turkmenistan	488100	5.7	39.6	88.6
	Uzbekistan	447400	31.8	62.5	192.3
Eastern Asia	China	9562911	1378.7	9505.2	19854.0
	Mongolia	1564120	3.0	11.8	34.4
Europe	Albania	28750	2.9	13.5	32.7
	Austria	83879	8.7	420.0	388.5
	Belarus	207600	9.5	59.2	159.3
	Belgium	30530	11.3	515.1	476.9
	Bosnia and Herzegovina	51210	3.5	18.9	39.9
	Bulgaria	111000	7.1	56.8	126.8
	Croatia	56590	4.2	61.1	91.5
	Cyprus	9250	1.2	24.3	27.3
	Czech Republic	78870	10.6	231.3	331.1
	Denmark	42922	5.7	347.5	263.4
	Estonia	45230	1.3	23.8	37.0
	Finland	338420	5.5	252.7	217.9
	France	549087	66.9	2806.0	2544.9
	Germany	357380	82.3	3781.7	3658.9
	Greece	131960	10.8	244.5	260.9
	Hungary	93030	9.8	147.2	251.9
	Ireland	70280	4.8	332.4	300.7
	Italy	301340	60.6	2080.6	2101.1
	Latvia	64490	2.0	28.9	46.5
	Liechtenstein	160	0.0	5.2	5.3
	Lithuania	65286	2.9	45.7	80.4
	Luxemburg	2590	0.6	63.2	55.2
	Moldova	33850	3.6	7.4	17.6
	Montenegro	13810	0.6	4.7	9.8
	Netherlands	41540	17.0	890.1	805.0
	Norway	385178	5.2	472.8	335.8
	Poland	312680	38.0	572.1	990.8
	Portugal	92225	10.3	231.7	280.1
	Romania	238390	19.7	200.2	429.2
	Russian Federation	17098250	144.3	1654.4	3581.3
	Serbia	88360	7.1	41.3	96.8
	Slovakia	49035	5.4	104.7	158.6
	Slovenia	20270	2.1	50.5	61.8

	Spain	505940	46.5	1464.5	1548.9
	Sweden	447420	9.9	560.4	462.1
	Switzerland	41290	8.4	642.1	480.8
	Macedonia	25710	2.1	10.9	27.3
	Ukraine	603550	45.0	124.0	327.6
	United Kingdom	243610	65.6	2757.6	2578.5
Middle East	Bahrain	771	1.4	31.8	62.2
	Iran	1745150	80.3	540.6	1484.9
	Iraq	435050	37.2	213.9	601.6
	Israel	22070	8.5	287.8	279.4
	Jordan	89320	9.5	30.8	79.3
	Kuwait	17820	4.1	142.9	279.1
	Lebanon	10450	6.0	42.9	79.0
	Oman	309500	4.4	75.1	176.5
	Qatar	11610	2.6	170.7	303.8
	Saudi Arabia	2149690	32.3	690.1	1627.4
	Syria	185180	18.4	15.0	34.0
	United Arab Emirates	83600	9.3	384.2	627.6
	Yemen	527970	27.6	11.9	71.2
South Asia	Afghanistan	652860	34.7	21.4	62.2
	Bangladesh	147630	163.0	167.8	540.9
	Bhutan	38394	0.8	2.2	6.6
	Maldives	300	0.4	3.6	6.2
	Nepal	147180	29.0	19.9	66.7
	Pakistan	796100	193.2	227.9	938.4
	Sri Lanka	65610	21.2	79.9	242.7
Southeast Asia	Brunei Darussalam	5770	0.4	13.3	30.4
	Cambodia	181040	15.8	17.0	54.6
	Indonesia	1910931	261.1	1037.9	2811.3
	Laos	236800	6.8	11.1	41.0
	Malaysia	330800	31.2	344.1	801.1
	Myanmar	676590	52.9	74.5	280.5
	Philippines	300000	103.3	284.3	747.3
	Singapore	719	5.6	299.2	463.3
	Thailand	513120	68.9	407.0	1081.6
	Vietnam	330967	94.6	164.1	552.1
Western Asia	Armenia	29740	2.9	11.5	24.0
	Azerbaijan	86600	9.8	57.2	156.1
	Georgia	69700	3.7	15.2	34.5
	Turkey	785350	79.5	1122.5	1888.9
	Total BRI	50984102	3615	38190	60857
	World	134325130	7444	77631	112333
	Share BRI %	38.0%	48.6%	49.2%	54.2%

Table 2 – Energy reserves in the BRI countries (Source: [49])

Country	Coal reserves (PJ)	Oil reserves (PJ)	Natural Gas reserves (PJ)	Total energy reserves (PJ)
Central Asia	**792965**	**178739**	**424544**	**1396247**
Kazakhstan	716802	171864	86871	975537
Kyrgyzstan	27174	0	204	27378
Tajikistan	10489	0	204	10693
Turkmenistan	0	3437	270833	274270
Uzbekistan	38500	3437	66431	108368
Eastern Asia	**3812701**	**143220**	**178852**	**4134774**
China	3742151	143220	178852	4064223
Mongolia	70550	0	0	70550
Europe	**7847778**	**520748**	**1929968**	**10298493**
Albania	14603	1146	0	15748
Austria	0	0	307	307
Belarus	0	1146	102	1248
Belgium	0	0	0	0
Bosnia	63388	0	0	63388
Bulgaria	66233	0	204	66437
Croatia	0	0	920	920
Cyprus	0	0	0	0
Czech Republic	102905	0	102	103007
Denmark	0	3437	1124	4561
Estonia	0	0	0	0
Finland	0	0	0	0
France	0	0	307	307
Germany	1013732	573	1737	1016042
Greece	80505	0	0	80505
Hungary	81445	0	307	81752
Ireland	381	0	409	790
Italy	483	3437	1942	5862
Latvia	0	0	0	0
Liechtenstein	0	0	0	0
Lithuania	0	0	0	0
Luxemburg	0	0	0	0
Moldova	0	0	0	0
Montenegro	3987	0	0	3987
Netherlands	13917	0	0	13917
Norway	56	29217	69497	98770
Poland	676372	573	2964	679908
Portugal	1016	0	0	1016
Romania	8152	3437	3781	15371
Russia	4489276	458304	1725156	6672737
Serbia	210355	0	1737	212092
Slovakia	3784	0	511	4295
Slovenia	10387	0	0	10387
Spain	33218	1146	0	34364
Sweden	28	0	0	28
Switzerland	0	0	71541	71541
Macedonia	9295	0	0	9295
Ukraine	962305	2292	39858	1004455
United Kingdom	1955	16041	7461	25457
Middle East	**33675**	**4605382**	**2880030**	**7519087**
Bahrain	0	573	3373	3946
Iran	33675	905150	1227436	2166262
Iraq	0	819218	114465	933684
Israel	0	0	7154	7154

Jordan	0	0	204	204
Kuwait	0	584338	65409	649746
Lebanon	0	0	0	0
Oman	0	30363	24528	54891
Qatar	0	143220	885062	1028282
Saudi Arabia	0	1529590	306604	1836193
Syria	0	14322	8687	23009
United Arab Emirates	0	561422	219733	781155
Yemen	0	17186	17374	34561
South Asia	**95847**	**2292**	**34748**	**132887**
Afghanistan	1854	0	1840	3694
Bangladesh	8203	0	8380	16583
Bhutan	0	0	0	0
Maldives	0	0	0	0
Nepal	28	0	0	28
Pakistan	85762	2292	24528	112582
Sri Lanka	0	0	0	0
Southeast Asia	**867822**	**76193**	**205731**	**1149746**
Brunei Darussalam	0	6302	11242	17544
Cambodia	0	0	0	0
Indonesia	715888	21197	104245	841330
Laos	14069	0	0	14069
Malaysia	5028	20624	42925	68577
Myanmar	168	0	10220	10388
Philippines	8838	573	3577	12988
Singapore	0	0	0	0
Thailand	29764	2292	7972	40027
Vietnam	94067	25207	25550	144824
Western Asia	**328040**	**41820**	**36281**	**406142**
Armenia	4571	0	0	4571
Azerbaijan	0	40102	35770	75872
Georgia	5638	0	307	5945
Turkey	317831	1719	204	319754
Total BRI	**13778828**	**5568394**	**5690154**	**25037376**

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