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Energy Transition in the Euro-Mediterranean area between geopolitics, sustainability and economy

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Summary

The sharply increasing trend of global GHG emissions in the last forty years has urged countries to set increasingly demanding decarbonization targets and place sustainability on top of their 2030 and 2040 agendas. Transitioning towards a decarbonized energy system does not only imply a technological overhaul – with carbon-intensive energy sources that should be replaced by more sustainable alternatives – but also to adequately balance sustainability with energy security and affordability, three attributes better known as the Energy Trilemma.

Simultaneously and effectively accomplishing these attributes is extremely challenging as the paths leading to their improvement are usually diverging and conflicting. Furthermore, energy systems are frequently influenced by external events that may change the prioritization of the attributes.

The Russo-Ukrainian conflict renewed the competition between energy security and sustainability and exhorted European countries to re-think their oil and gas supply systems while struggling to protect final consumers from the price volatility that affected energy supplies and simultaneously work to achieve their decarbonization targets.

Indeed, the decarbonization pathway will be likely pulled by electricity, thanks to the possibility of producing it from renewable energy sources. At the same time, given the unfeasibility of electrifying all the final energy uses, the present energy system is expected to transition towards a multi-commodity framework where electricity will be supported by alternative commodities such as green hydrogen, biofuels and synthetic fuels. From a broader perspective, the concepts of Energy Trilemma and multi-commodity are reciprocally intertwined, because the selection of specific commodities at the policy decision-making level inevitably affects the security, sustainability and affordability of the energy system they are part of.

In this framework, this thesis joins together the concepts of Energy Trilemma and multi-commodity energy systems presenting an optimization framework where

several energy mixes are reciprocally compared with reference to the three Trilemma attributes. More specifically, the work consists in four sections: the first presents the framework of the Energy Trilemma and investigates the tight link between geopolitics, i.e., the study of how geography and socioeconomics influence the processes of policy decision-making, and energy systems, analyzing the impacts of the Russo-Ukrainian and Israeli-Palestinian crises on energy supplies. Then, the reasons behind development of a multi-commodity energy system are introduced and discussed and joined to the idea of Commodity Energy Chains, developed to compare energy commodities in relation to the final energy consuming uses they match and the technologies they are supplied by. The third section analyzes the energy transition in the Mediterranean Basin and its countries: the area, historically characterized by the simultaneous presence of countries with a high dependence on energy imports and oil&gas producers and net exporters, represents the perfect candidate to assess the levers and the bottlenecks of a demographically and socioeconomically tessellated context along its journey towards decarbonization.

In conclusion, the last section illustrates the narrative, the reference system and the main features of the aforementioned energy optimization model. The proposed approach stands out as it effectively integrates the concepts of Energy Trilemma and multi-commodity energy system in a single optimization framework and easily helps to infer what energy commodity mixes are preferable, depending on which is given more relevance among security, sustainability and affordability. Results suggest and confirm that electricity is the energy commodity that will presumably pull the transition thanks to the possibility of exploiting endogenous renewable generation, thus producing carbon-free energy at almost zero cost while improving energy independency and, consequently, security.

Sahlo Folina

List of Acronynms

Abbreviation	Definition
AC	Alternate Current
AFC	Alkaline Fuel Cell
CCUS	Carbon Capture Utilization and Storage
CEC	Commodity Energy Chain
COP	Coefficient of Performance
CRM	Critical Raw Materials
CV	Control Volume
DC	Direct Current
ESOM	Energy System Optimization Model
FC	Fuel Cell
FLT	First Law of Thermodynamics
FSRU	Floating Storage and Regasification Unit
GHG	Greenhouse Gas
GTI	Global Tilted Irradiance
HHI	Herfindal-Hirschman Index
HJT	Hetero-Junction Technology
HVDC	High-Voltage Direct Current
IBC	Interdigitated Back Contact
ICE	Internal Combustion Engine
LCC	Line-Commutated Converter
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MCFC	Molten Carbonates Fuel Cell
MS	Member States
NECP	National Energy and Climate Plan
P2P	Point to Point
PEM	Proton Exchange Membrane
PERC	Passivated Emitter and Rear Cell/Contact
PGM	Platinum Group Metals
PP	Power Plant
PV	Photovoltaic
REEs	Rare-Earth Elements
RES	Renewable Energy Sources
RPP	Refined Petroleum Products
SLT	Second Law of Thermodynamics
SOFC	Solid Oxide Fuel Cell
SRM	Strategic Raw Materials
TPES	Total Primary Energy Supply
TSO	Transmission System Operator
UHVAC	Ultra High-VoltageAlternate Current
VSC	Voltage-Source Converter
WEC	World Energy Council

Contents

List of Tables

List of Figures

Chapter 1

The energy transition amidst geopolitics and global energy crises

1.1 The Energy Trilemma

The process of the energy transition towards the decarbonization of the current energy system does not simply imply a progressive shift in the direction of greener technologies but holistically embraces several domains that are inextricably linked to energy itself. The change of framework required by the energy transition also entails social, economic and environmental structural changes. As such, defining a metric to assess the status of a country and its progress along the path of the energy transition is complicated, due to the multiplicity of involved domains.

To this purpose, in 2010, the World Energy Council (WEC) introduced the concept of Energy Trilemma and released its first *World Energy Trilemma Report*, which is updated annually (World Energy Council, 2024). The Energy Trilemma represents a suitable and robust metric to assess the energy system of a country with respect to the accomplishment of its targets of energy transition while trying to merge several aspects of the domains intercorrelated with energy. The conceptual formulation of the Energy Trilemma is based on the idea that a country should pursue its energy transition balancing the following three attributes: energy security, environmental sustainability and energy equity/affordability.

- **Energy security** measures the ability of a country to match its energy demand continuously, being able to flexibly and resiliently react to any perturbation of energy supplies (both external and internal), as well as to implement preventive measures to promptly face them in the future.
- **Environmental sustainability** defines how a country can meet its current and future energy needs minimizing the harmful effects of energy generation and consumption on the global ecosystem and its inhabitants, such as: emissions of Greenhouse Gases (GHG) and air pollutants, damage to human and natural habitats, excessive water and soil exploitation, etc.
- **Energy equity/affordability** is the attribute measuring the capability of a country to provide easy and affordable access to clean energy to its citizens, as well as to encourage and incentivize energy efficiency while minimizing energy waste.

Each attribute is numerically quantified by an index, the three of which together combined yield the so-called Energy Trilemma Index for each country. The Index is a numerical score from 1 to 100, with 100 being the highest achievable score. This top score indicates that a country has achieved an ideal balance between energy security, energy equity, and environmental sustainability, making it best positioned to succeed in its energy transition.

1.2 The increasing role of energy security

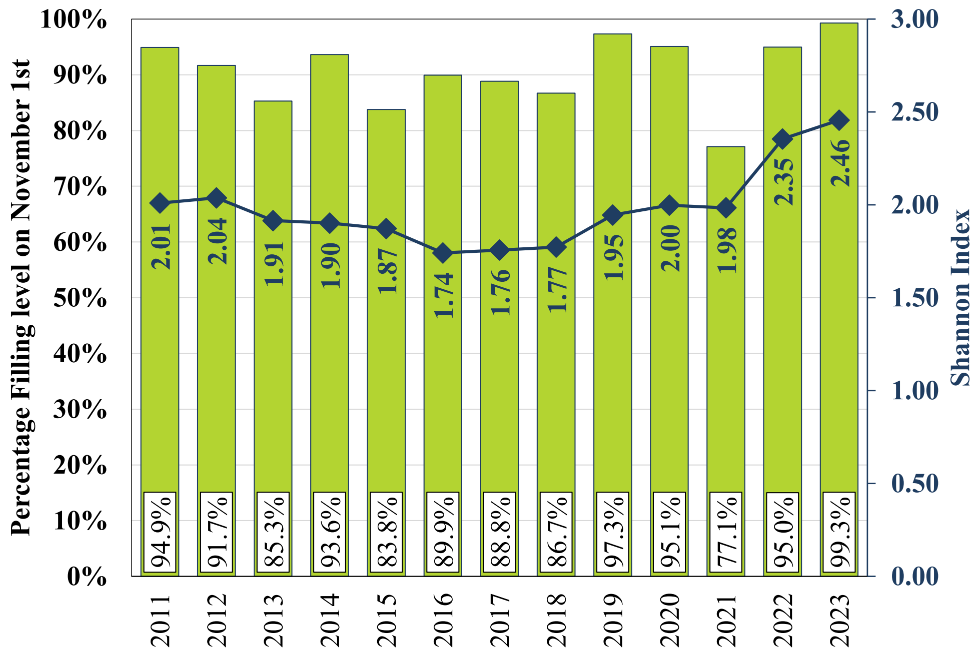
Being able to effectively balance and/or maximize the three attributes of the Trilemma simultaneously is generally complicated, as they reciprocally compete against each other: for example, fuel prices for transport in major oil producing countries are considerably lower when compared to countries with a high oil import dependency, thus they can be afforded by most citizens. On the other hand, encouraging the usage of fossil fuels dramatically drives the country's energy mix away from sustainability.

The aspect of energy security is traditionally linked to the origin of energy supplies and particularly of crude oil and natural gas, due to the combined effects of their large global consumption and their natural reserves being scarcely allocated on Earth. Consequently, any disruption of the supplies interesting either energy corridors (oil pipelines, gas pipelines, maritime shipping routes, etc.) or the origin countries of fossil fuels can severely threaten the security of supply of a country whose fossil fuels reserves are negligible or non-existent. In this context, increasing the penetration of Renewable Energy Sources (RES) not only naturally reduces the carbon intensity of the energy mix but, in addition, replacing a part of the fossil-based electricity generation with internal production from renewables in countries with a marked import dependency on fossil fuels intrinsically increases the security of their supply mix, thanks to the possibility of matching a larger part of their energy demand internally. Nonetheless, the widespread diffusion of non-dispatchable RES gives birth to stability and frequency issues in the power grid, unless this is adequately improved and strengthened. Therefore, not only can security be affected by technology-related issues, but more frequent maintenance also increases the expenses necessary to ensure the proper operation of the electricity transmission and distribution networks and may be bounced back to the final electricity price incurred by final electricity consumers.

Additionally, like fossil fuel resources, many of the raw materials required for the production of renewable energy technologies are also concentrated in a limited number of countries, leading to potential supply chain risks and vulnerabilities. Therefore, this once again underscores how prioritizing one attribute of the Trilemma (sustainability) would give birth to new issues to be tackled and related to another attribute (security).

In the last decades, sustainability has traditionally been the attribute receiving the most attention, following the drastic growth of GHG emissions – 53.0 $GtCO_{2eq}$/y in 2023, compared against 32.7 $GtCO_{2eq}$/y in 1990 (The World Bank, 2024), meaning a 62% increment in slightly more than 30 years. However, the beginning of the Russo-Ukrainian conflict first, and the new phase of the Israeli-Palestinian crisis later, significantly changed the global energy framework and the relevance given to the Trilemma attributes, with security that has been gaining more and more relevance. To corroborate this statement, Figure 1 shows the filling level of natural gas storage systems in the EU27 at the beginning of the withdrawal season[1] (November 1st) and the Shannon Index[2] associated with the EU27's natural gas import mix in the period 2011-2023.

Figure 1 Natural gas storage filling level and Shannon Index of natural gas supplies in the EU27



Source: Elaboration on Gas Infrastructure Europe and IRENA (Gas Infrastructure Europe, 2025; IRENA, 2024b)

The filling level of gas storage systems marked a first, significant peak of 97.3% in 2019, mainly thanks to increased natural gas and LNG supplies, in combination with milder temperatures in winter that reduced the gas demand for heating purposes (Kopalek & Zaretskaya, 2020) in that year. Then, after reaching its minimum of 77.1% in 2021 – because of the energy demand reduction that characterized the COVID-19 pandemic period – gas storages reached a new peak filling level of 95.0% in 2022 and their historical maximum of 99.3% in 2023. This sharp and sudden growth, more than being the natural consequence of the economic

[1] Withdrawal season ranges from November 1st to April 30th, while injection season from May 1st to October 31st.

[2] The Shannon Index is commonly used to quantify the diversification of a generic mix. It ranges from 0 (one-element mix) to 1 (maximum diversification).

and industrial recovery period that followed the end of the pandemic, was caused by the uncertainty that affected natural gas supplies soon after the beginning of the Russo-Ukrainian war. In fact, threatened by a potential, abrupt interruption of Russian natural gas supplies, the EU27 MS imported significant volumes of natural gas in summer to fill storages as much as possible and be able to count on conspicuous reserves during the winter season. Not only, in June 2022 the European Commission released its *Gas Storage Regulation* that enforced MS to ensure a filling level of at least 90% before the beginning of the withdrawal season (European Parliament & Council of the European Union, 2022).

The trend of the Shannon Index provides additional insights to analyze how EU27 MS re-thought their gas import mixes after the Russo-Ukrainian war broke out. In fact, in 2022 and 2023 it registered consequent maxima of respectively 2.35 and 2.46. Consistently, the number of different natural gas suppliers for the EU27 substantially grew after 2021, implying MS sought to increase the diversification of their natural gas import mix to strengthen and improve its security.

The two crises underscored the tight link between geopolitics and energy security and substantially modified the ordinary behavior of energy supplies at the global scale. For this reason, the next sections will analyze their effects and consequences on the supply of crude oil, natural gas and electricity.

1.3 Energy impacts of the Russo-Ukrainian crisis

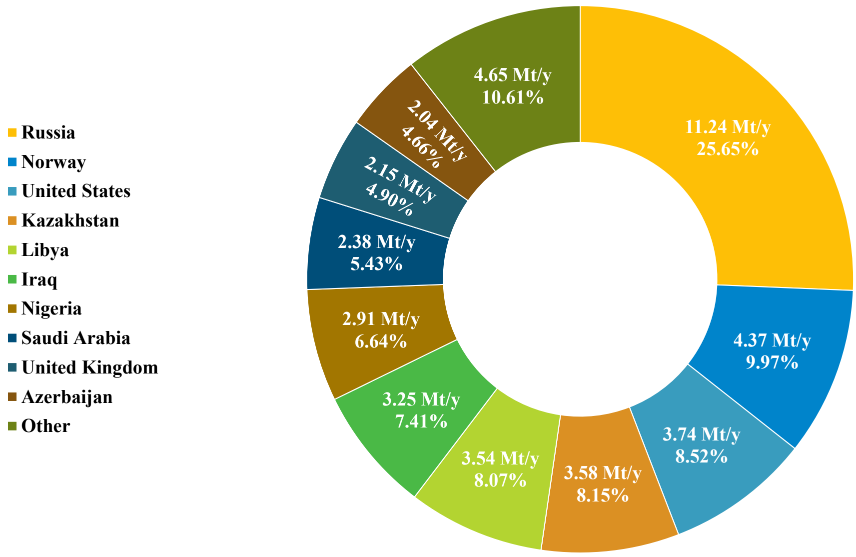
The beginning of the Russo-Ukrainian conflict on February 24th, 2022, posed a severe threat to the crude oil, petroleum products and natural gas supply mixes of member countries of the EU27. In fact, a lot of them relied – with varying levels of import dependency – on Russian supplies of fossil fuels to match a part of their internal oil and gas demand and were forced to unexpectedly re-think their supply import mixes to cope with the fluctuating and unpredictable behavior of Russian exports.

Crude oil supplies

As one of the main global producers and exporters of crude oil (Energy Institute, 2024), Russia has always been a major supplier for the countries of the EU, thanks also to its close geographical position. However, the situation drastically changed from 2023, when the EU27 set severe bans on the imports of Russian crude oil and refined petroleum products: starting from December 5th, 2022, both purchasing, importing and transporting Russian crude oil via maritime routes were officially banned. The same sanctions were applied to certain refined petroleum products, starting from February 5th, 2023 (Council of the European Union, 2024).

Figure 2[3] shows the crude oil import mix of the EU27 in 2021. Russia was by far the largest crude oil supplier to the EU, providing 11.24 Mt/y out of 43.84 Mt/y of total imports. The second supplier in terms of total quantities was Norway, whose crude oil (4.37 Mt/y) did not even account for half the Russian's, with a share of 9.97%. Completing the list of the first five exporting partners there were the USA (3.74 Mt/y, 8.52% of total imports), Kazakhstan (3.58 Mt/y, 8.15% of total imports) and Libya (3.54 Mt/y, 8.07% of total imports).

Figure 2 Imports of crude oil in the EU27 in 2021



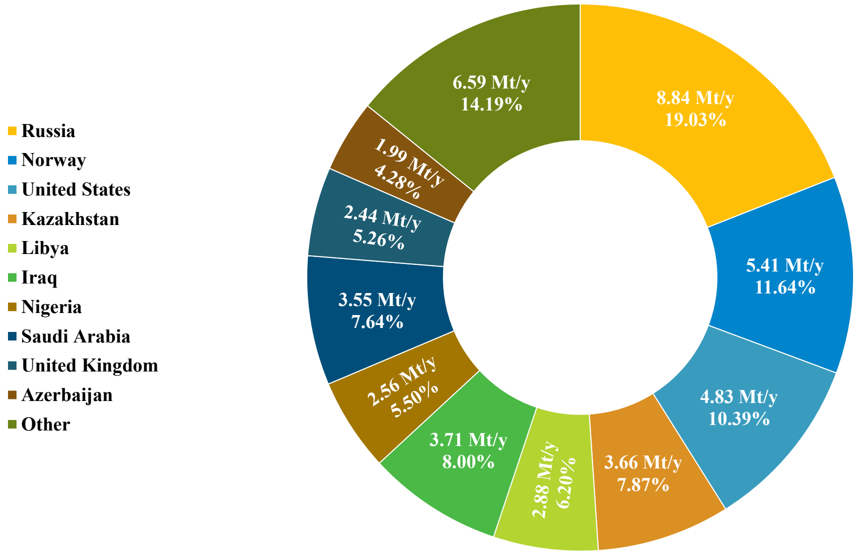
Source: Elaboration on Eurostat (Eurostat, 2025f)

The situation slightly changed in 2022 (Figure 3): in spite of Russia being the leading exporter with 8.84 Mt/y out of 46.46 Mt/y and providing 19.03% of the total EU's crude oil imports, notably these were 27% lower than the previous year. While the composition, as well as the quantities of crude oil exported by the first ten suppliers almost remained unchanged, a considerable 41.7% growth characterized the set of minor exporting countries, represented in the figure under the label *other*. Among these countries, Brazil and Angola are worth mentioning,

[3] Other includes: Algeria, Brazil, Mexico, Canada, Egypt, Cameroon, Equatorial Guinea, Angola, Gabon, Italy, Ghana, Tunisia, Albania, Colombia, Turkmenistan, Croatia, Yemen, Denmark, Congo, Netherlands, Argentina, Trinidad and Tobago, France, Ivory Coast, Poland, Uruguay, Cuba, Ukraine, Curaçao, Lithuania, Bolivia, Slovakia, Moldova, Germany, Kuwait, Latvia, Belgium, Singapore, Ecuador, United Arab Emirates, Türkiye, Israel, Qatar, South Africa, Greece, Venezuela, DRC, Oman, Malaysia. Exports from countries of the EU are mainly re-exports of crude oil originally coming from third, extra-EU countries.

as their relevance grew from 1.81% to 2.73%, and from 0.40% to 2.42%, respectively.

Figure 3 Imports of crude oil in the EU27 in 2022



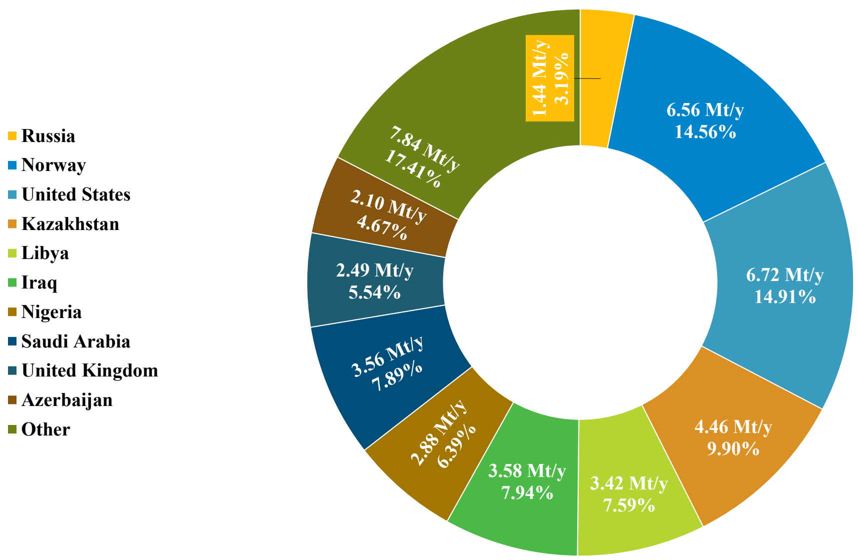
Source: Elaboration on Eurostat (Eurostat, 2025f)

Following the activation of the EU's sanctions, the 2023 crude oil import mix (Figure 4) experienced the most significant changes.

- *Imports from Russia*: they shrank to only 1.44 Mt/y and accounted only for 3.19% (despite the sanctions were issued at the end of 2022, some quantities are still present due to exemptions for certain countries that do not have any alternative but to import Russian crude to match their total internal demand – Germany and Poland among the others).
- *Imports from other major suppliers*: Norway and the USA became the main suppliers for the EU, each of which accounting for almost 15% and matching 13.28 Mt/y out of 45.05 Mt/y of its total demand. Kazakh imports grew to 4.46 Mt/y, increasing their share from 8.15% in 2021 to 9.90% in 2023. A non-negligible growth characterized Saudi Arabian crude too, which passed from 2.38 Mt/y in 2021 to 3.56 Mt/y in 2023 – meaning its weight increased from 5.43% to 7.89%.
- *Imports from minor suppliers*: also in 2023, minor suppliers experienced the largest increments: their quantities reached 7.84 Mt/y and weighed 17.41%. The relevance of Brazilian crude increased even more and stood at 3.97%, more than doubling with respect to 2021; crude imported from Angola also increased – yet less markedly – to 2.86%. 2023 even saw the introduction of new exporting partners in the

EU27 supply mix, such as the United Arab Emirates, which carved a tiny 0.78% share in the European composition of crude supplies.

Figure 4 Imports of crude oil in the EU27 in 2023



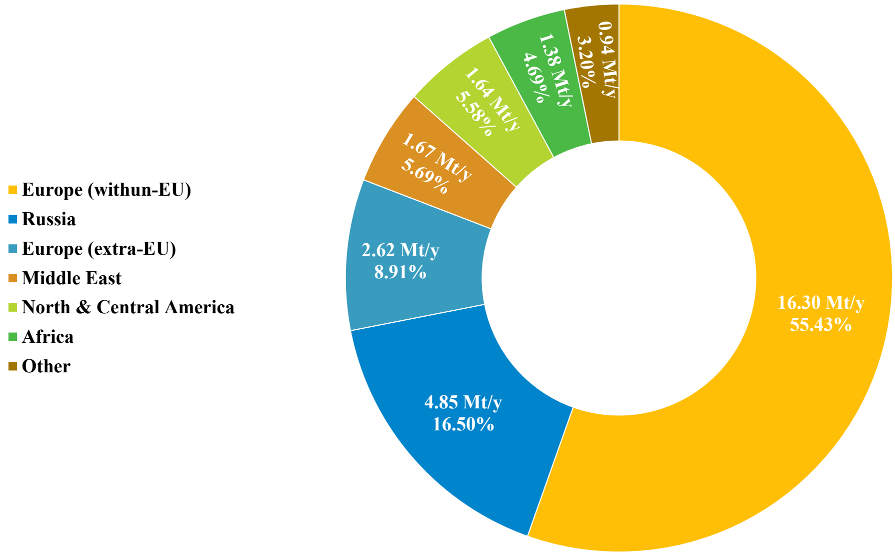
Source: Elaboration on Eurostat (Eurostat, 2025f)

In general, the need to abandon Russian crude oil supplies boosted the diversification of the European supply mix, which benefitted in terms of its energy security. In fact, being able to rely on more exporting partners implies a reduced relevance of the larger ones on the overall import mix. Consequently, in the case of sudden and/or unexpected disruptions of their supplies, the quantity that needs to be replaced would be lower, partially relieving the stress on the receiving country's import infrastructure.

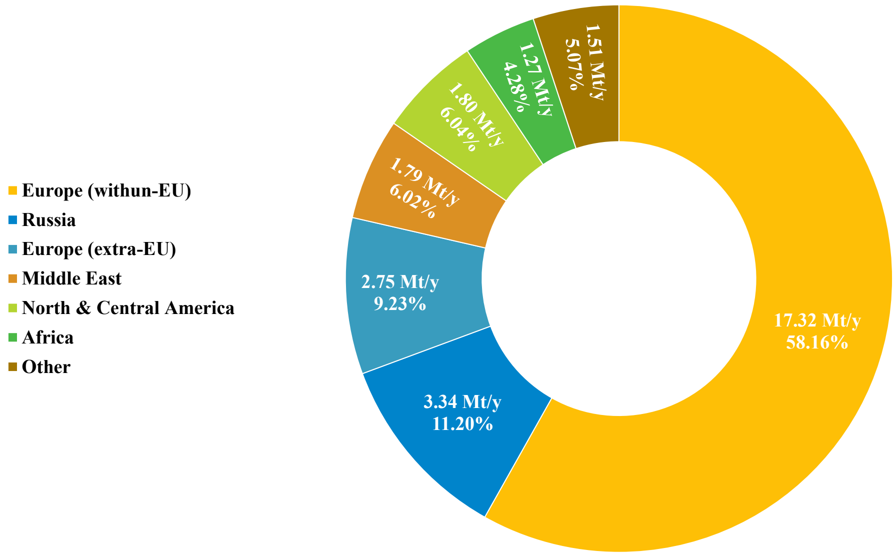
Petroleum products supplies

The main difference between the imports of petroleum products and those of crude oil is that most of the EU27's supply of the first is produced in refineries within the EU27 itself, therefore making the import mix of refined petroleum products intrinsically more secure (Eurostat, 2025a). Despite this, the role of Russia as an exporter of refined products also has heavily changed in the three years. The composition of the import mix of refined petroleum products in the EU27 for the three years is shown in Figure 5 (given the much wider range of suppliers with a non-negligible weight over the total EU277 imports, results were aggregated by macro-areas[4]).

Figure 5 Imports of petroleum products in the EU27 in 2021, 2022 and 2023

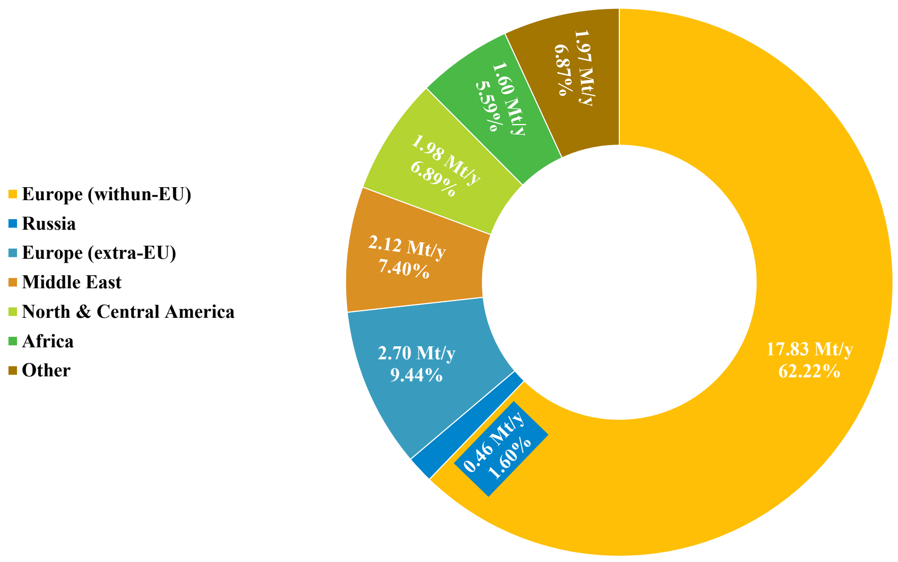


2021



2022

[4] Middle East includes United Arab Emirates, Israel, Oman, Iraq, Iran, Qatar, Saudi Arabia, Yemen, Bahrain, Jordan, Lebanon, Syria. Other includes Argentina, Bolivia, Brazil, Colombia, Ecuador, Kazakhstan, Malaysia, Singapore, Turkmenistan, Uruguay, Venezuela, Australia, Bangladesh, Chile, China, Hong Kong, Indonesia, India, Japan, Kyrgyzstan, North Korea, South Korea, Sri Lanka, Marshall Islands, New Zealand, Peru, Philippines, Pakistan, Thailand, Taiwan, Uzbekistan, British Virgin Islands, and Vietnam.



2023

Source: Elaboration on Eurostat (Eurostat, 2025f)

The EU27 self-produced more than half its demand of petroleum products each year, also registering a steadily increasing trend: 16.30 Mt/y out of 29.40 Mt/y in 2021 (55.43%), 17.32 Mt/y out of 29.78 Mt/y in 2022 (58.16%) and 17.83 Mt/y out of 28.66 Mt/y in 2023 (62.22%). Conversely, Russia's share decreased from 16.50% in 2021 (4.85 Mt/y) to only 1.60% in 2023 (0.46 Mt/y), shrinking by more than five times. Supplies coming from all the other areas grew from year to year, the most relevant increment being that of minor exporting areas: in fact, their share more than doubled from only 3.04% in 2021 to 6.87% in 2023, corresponding to exports of 0.94 Mt/y and 1.97 Mt/y, respectively. Country-specific figures show that India and China appeared as two new trading partners for the EU. In fact, the share of petroleum products exported from India increased from 1.15% in 2021, to 1.54% in 2022, to 3.09% in 2023; China's more than tripled, growing from 0.29% in 2021 to 1.01% in 2023.

The ban on imports of Russian crude oil and petroleum products naturally affected Russia as a supplier. Its exports inevitably had to be rerouted mitigate the lost income that had come from the EU27 before the sanctions came into effect. In this framework, two countries emerged as the new dominating destinations of Russian oil: India and China. In India, crude oil imported from Russia grew from 4.45 Mt/y in 2021 (2.14% of total imports), to 34.40 Mt/y in 2022 (15.23%) and to 75.43 Mt/y in 2023, when it accounted for 33.13%. Besides, in 2023 Russia became the first Indian crude oil supplier. The same increasing trend characterized Chinese crude oil imports from Russia, which increased from 34.40 Mt/y in 2021, to 45.95 Mt/y in 2022 and 62.96 Mt/y in 2023, with a corresponding share of 12.79%.

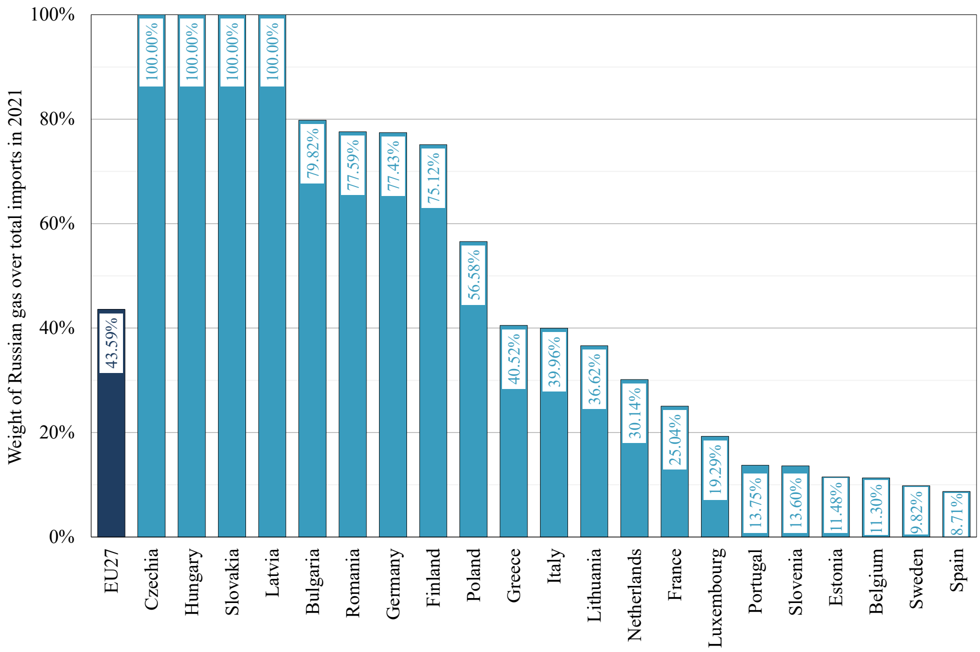
Russian supplies of petroleum products to the two countries followed a similar increasing trend: in India, their 2021 share of 8.90% reached 19.97% and 32.36%

in 2022 and 2023, respectively – more than triplicating with respect to two years before. A significant growth characterized Chinese imports of Russian products, which accounted for just 2.77% in 2021 but surged to 15.81% two years later, marking a more than five times larger percentage increment (AXSMarine, 2025).

Natural gas supplies

The beginning of the Russo-Ukrainian conflict substantially altered the ordinary behavior of the natural gas (hereafter meant as the mix of pipeline gas and Liquefied Natural Gas – LNG) supplies of EU27 Member States (MS). In fact, most of them had relied on Russian gas supplies to match their internal demand until the end of 2021. To this purpose, Figure 6 shows the 2021 share of Russian in total gas imports for EU27 countries.

Figure 6 Share of the imports of Russian gas for EU27 MS in 2021



Source: Elaboration on Eurostat (Eurostat, 2025e)

The EU27 imported 43.59% of its natural gas from Russia, highlighting the significant challenge of phasing out Russian gas completely. In general, most countries depended on Russian imports for more than half their respective totals, with some showing even larger values. Czechia, Hungary and Slovakia imported Russian gas only, mainly due to being landlocked and therefore having no alternative but to import gas via pipelines. Latvia also relied solely on Russian imports, reasonably due to being geographically close. These countries were followed by Romania (88.33%) and Bulgaria (68.54%). In Germany, the largest European energy and gas consumer, connected to Russia via the *NordStream* and

Yamal gas pipelines, Russian gas accounted for 77.43% of the total German gas imports. Among the other largest European energy consumers, Poland relied on Russian gas for 56.58% and Italy for 39.96%, while both France and Spain were considerably less dependent on Russian gas – the second having a share of just 8.71%.

Although officially the EU27 never applied sanctions to the purchase, import and trade of Russian natural gas, it encouraged its member countries to progressively phase-out its imports, especially after the *REPowerEU* set of measures was issued on June 18th, 2022 (European Commission Secretariat-General, 2022). Indeed, the plan was purposely thought to end the EU's dependency on Russian fossil fuels and increase the diversification of its energy mix, while improving its energy efficiency to speed up the process of the energy transition.

Figure 7 displays the EU27's import mixes of natural gas in 2021, 2022 and 2023[5].

As mentioned, in 2021 Russia accounted for 43.59% of EU27's total natural gas imports, to which it sent 153.23 Gm^3/y, obviously also representing its main supplier. The second and third main exporters to the EU27 were Norway with 59.19 Gm^3/y (16.84%) and Algeria with 42.82 Gm^3/y (12.18%), which mainly exported pipeline gas to Spain and Italy, which jointly received 34.92 Gm^3/y.

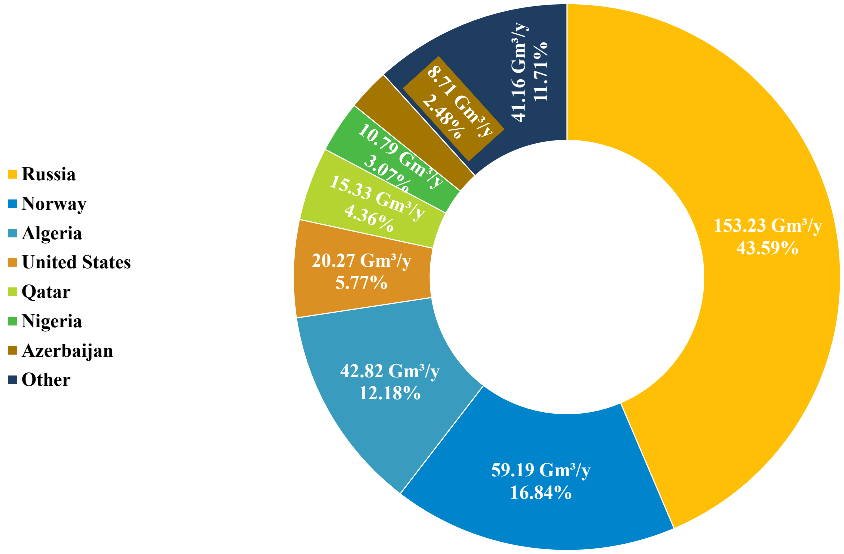
2022 not only saw a first significant reduction of Russian imports – which almost halved to 83.82 Gm^3/y and decreased their share to 24.05% – but more importantly saw the steep growth of American LNG imports and the consequent rise of the USA as one of the main exporters of natural gas for the EU: if in 2021 the USA had exported 20.27 Gm^3/y, in 2022 volumes grew to 53.00 Gm^3/y and accounted for 15.21%. A significant growth also characterized imports from Norway (70.70 Gm^3/y), whose share increased to 20.29%.

Similarly to what happened with crude oil, in 2022 other natural gas exporters that had had an almost negligible relevance carved a significant share of the EU27 natural gas market for themselves: the first of these was Egypt, whose exports of LNG to the EU27 grew from 0.97 Gm^3/y to 3.77 Gm^3/y; imports from Trinidad and Tobago almost doubled from 1.81 Gm^3/y to 3.09 Gm^3/y, while those from Angola more than doubled from 0.85 Gm^3/y to 1.75 Gm^3/y. The UK's natural gas exports to the EU27 also saw a remarkable increase, rising from 5.53 Gm^3/y to 12.53 Gm^3/y, more than doubling its previous volume and solidifying its position as a significant supplier to the region. However, considering the modest British gas

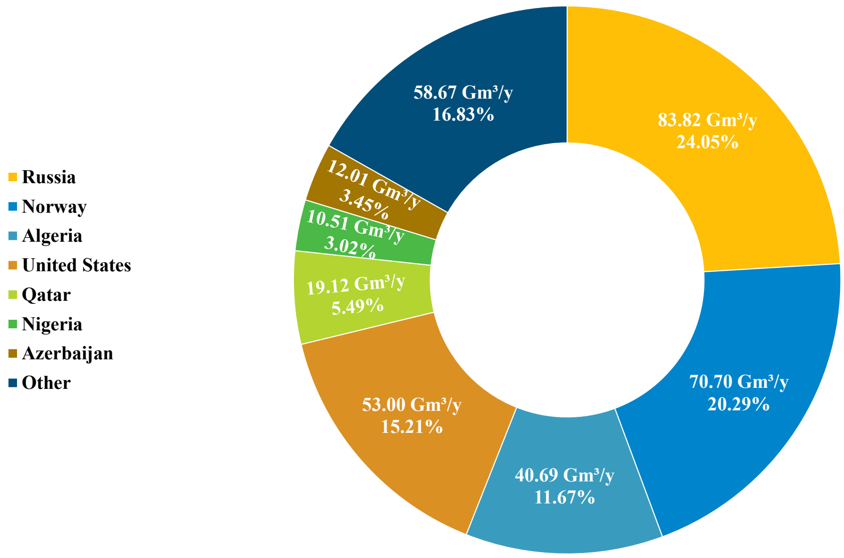
[5] Other includes: Netherlands, Libya, Egypt, Germany, United Kingdom, France, Belgium, Trinidad and Tobago, Denmark, Equatorial Guinea, Austria, Spain, Angola, Bulgaria, Estonia, Hungary, Czechia, Latvia, Greece, Türkiye, Ukraine, Peru, Portugal, Slovenia, Finland, Lithuania, India, Switzerland, Gibraltar, Romania, Croatia, Papua New Guinea, Luxembourg, Poland, Italy, South Korea, Indonesia, Mozambique, Moldova, Slovakia, Australia, United Arab Emirates, Malaysia, Cameroon, Oman, Guinea-Bissau, Jamaica. Exports from EU MS are mainly re-exports of natural gas originally coming from third, extra-EU countries, either via pipeline or in the form of LNG.

reserves (Energy Institute, 2024), this quantity could reasonably be biased by re-exports of gas, rather than domestic UK production.

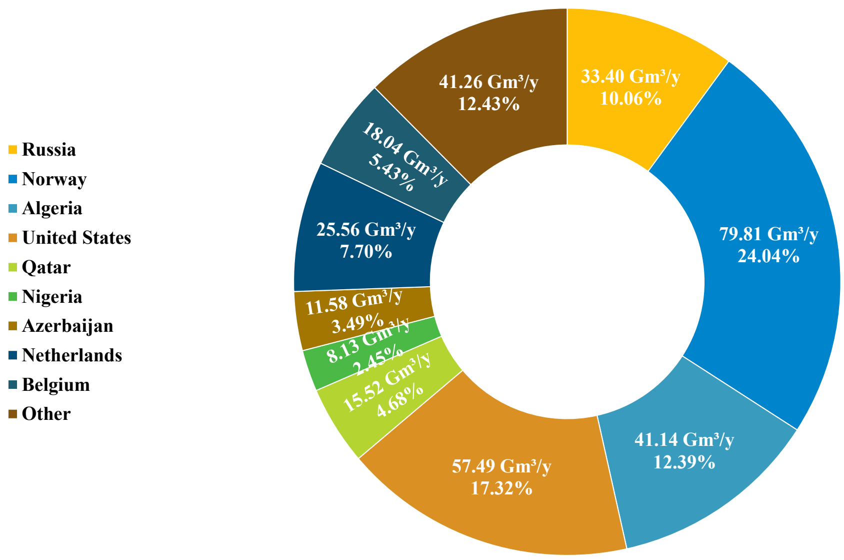
Figure 7 Imports of natural gas in the EU27 in 2021, 2022 and 2023



2021



2022



2023

Source: Elaboration on Eurostat (Eurostat, 2025f)

In 2023, Russian gas decreased to only 33.40 Gm^3/y, namely 10.06% of the total EU27 MS imports. Germany, Poland and Romania, among the countries that depended on Russia the most, completely abandoned its supplies. Remarkable reductions characterized Italy (from 58.34 Gm^3/y to 5.86 Gm^3/y), Czechia (from 17.44 Gm^3/y to 1.10 Gm^3/y) and the Netherlands (from 18.35 Gm^3/y to 2.72 Gm^3/y) too. On the contrary, from 2021 to 2023, Belgium, France and Spain increased their LNG imports from Russia: in Belgium, they more than tripled, growing from 1.34 Gm^3/y to 4.01 Gm^3/y; in Spain from 3.22 Gm^3/y to 6.47 Gm^3/y; in France from 3.46 Gm^3/y to 6.47 Gm^3/y. The reason behind such a countertendency relates to transshipments[6] occurred at the terminals of Zeerbrugge (Belgium), Montoir-de-Bretagne (France) and Bilbao (Spain) (Jaller-Makarewicz, 2023), the first two of which imported significant volumes of LNG from the Yamal Russian liquefaction terminal. About 37% of Russian LNG delivered to Belgium and France was transshipped and exported – mostly to extra-EU27 countries – in the first three quarters of 2023. Although defining where Spanish re-exports of LNG came from is uncertain, it is presumable that a considerable amount had come from Russia too.

In the same year, the USA consolidated their role as a major exporter of LNG for the EU27: in fact, exports further grew and stood at 57.49 Gm^3/y, meaning 17.32% of the total. Large increases interested both Dutch and Belgian exports too,

[6] The transfer of LNG between two tanker ships, without necessarily having them docked at the regasification terminals and/or discharging any gas in the transmission network. Transshipments differ from re-exports as the second are such if LNG is bought by another company before being reloaded and sent to third countries.

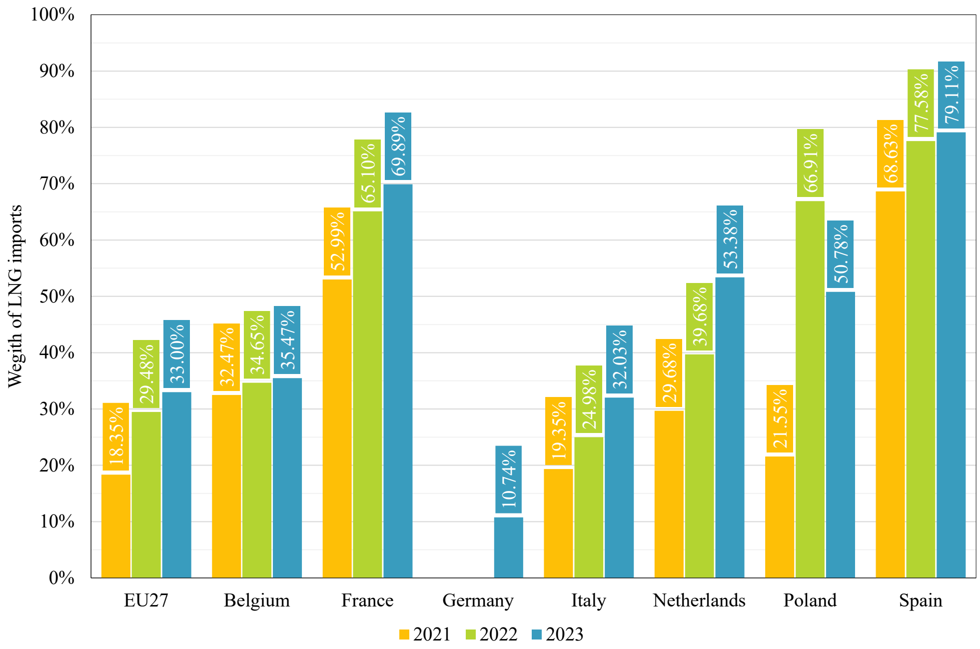
although it is reasonable that neither of them was the ultimate origin country of natural gas, rather than the landing point of LNG coming from third countries and re-injected into the European gas transmission network.

Generally, the interruption of Russian gas supplies not only urged the EU27 to diversify its import mix but sensibly increased the relevance of LNG to match its gas demand too, thanks to the possibility of importing it from a wider set of suppliers. Therefore, it represented an effective way to increase the diversification and, consequently, the security of the EU27's natural gas supply system.

The effects are clear when observing how much LNG imports to the EU27 have grown after 2021, when they were equal to 72.39 Gm^3/y and to 20.60% of the overall EU27's gas imports. Two years later, they rose to 125.54 Gm^3/y and so rose their share, reaching 37.82%.

Figure 8 shows the maximum values – on a monthly basis – of the share of LNG imports over the total natural gas imports in the EU27 and other six countries, in the period 2021-2023.

Figure 8 Share of LNG imports over total natural gas imports in the EU27 and specific EU27 countries in 2021-2023



Source: Elaboration on JODI (Joint Organizations Data Initiative (JODI), 2025)

In the EU27, the share of LNG almost doubled as it grew from 18.35% to 33.00%, corresponding to a 2021-2023 growth of 79.88%. The largest increase was registered in Poland from 2021 to 2022, when it more than triplicated from 21.55% to 66.91%. Remarkable growths from 2021 to 2023 also interested Italy (65.57%) and the Netherlands (79.90%). France and Spain, despite already used to importing significant quantities of LNG even before the beginning of the conflict, registered a more modest – yet non-negligible – increment: 31.89% and 15.27%, respectively. Germany, which had not even exploited LNG until the end of 2022, started operating LNG regasification terminals in 2023, which supplied 10.74% of its total natural gas imports in 2023.

LNG helps a country to immediately counteract sudden disruptions of natural gas supplies, but its effectiveness is limited to the country's overall regasification capacity. For this reason, the Russo-Ukrainian crisis also urged some European countries to either increase their existing regasification capacity, or to equip themselves with LNG regasification infrastructures like Germany did. In fact, thanks to the possibility of broadening the range of natural gas importing corridors, LNG imports jointly improve diversification and preventively strengthen the natural gas import and transmission infrastructures.

A significant boost in the integration of new regasification terminals in a country's natural gas network was given by the opportunity of purchasing Floating Storage and Regasification Units (FSRU): these are ships simultaneously capable of transporting, storing and regasifying LNG, with significantly lower lead times with respect to onshore regasification terminals. In fact, the ship only needs to reach its docking location right after having been purchased.

Table 1 lists the currently operational (OP) and under construction (UC) LNG regasification terminals in the EU27, also specifying whether they are onshore (O) or floating (F) units, their yearly overall regasification capacity and their start year (expected, in the case of UC terminals).

Overall, the EU27 can count on a total LNG regasification capacity of 215.4 Gm^3/y (71% of which onshore and 29% floating), with further 30.7 Gm^3/y under construction. Spain is the country with both the largest overall capacity, 64.7 Gm^3/y, and the biggest regasification terminal – Barcelona LNG – 16.4 Gm^3/y. Out of the 32 operational terminals in the EU27, 11 started their commercial operation from 2022 onwards, granting an additional capacity of 64.9 Gm^3/y. More specifically, nine of them are floating regasification units, and so are all of those under construction (with the only exceptions of Fos Cavaou 2 and Swinoujscie-phase 2, both capacity expansion projects of existing onshore terminals), underscoring the key role of FSRUs in a context of emergency and uncertainty.

Despite a country's natural gas supply infrastructure would sensibly benefit from the availability of one more LNG receiving terminals, solely relying on maritime gas imports could threaten its security of supply as well.

Table 1 Operational and under construction LNG receiving terminals in the EU27

Country	Terminal Name	Start Year	Regasification Capacity [Gm^3/y]	Type	Status
Belgium	Zeerbrugge	1987	8.6	O	OP
Croatia	Krk LNG Terminal	2021	2.8	F	OP
Cyprus	Cyprus LNG	2025	0.8	F	UC
Estonia	Paldiski LNG	2024	2.3	F	UC
Finland	Hamina LNG Terminal	2022	0.2	O	OP
	Inkoo FSRU	2023	4.8	F	OP
France	Dunkirk	2017	12.5	O	OP
	Fos Cavaou	2010	7.8	O	OP
	Fos Tonkin	1972	1.4	O	OP
	Le Havre FSRU	2023	4.8	F	OP
	Montoir-de-Bretagne	1980	10.4	O	OP
	Fos Cavaou 2	2026	2.6	O	UC
Germany	Elbehafen LNG (Brunsbüttel)	2023	4.8	F	OP
	Lubmin LNG	2023	5.0	F	OP
	Mukran LNG	2024	12.9	F	OP
	Wilhelmshaven LNG	2022	7.2	F	OP
	Elbehafen LNG 2	2026	7.6	F	UC
	Stade LNG	2024	4.8	F	UC
Greece	Alexandropoulis LNG	2024	5.3	F	OP
	Revithoussa	2000	6.4	O	OP
Italy	Adriatic LNG	2009	8.6	O	OP
	Paningaglia LNG	1971	3.4	O	OP
	Piombino FSRU	2023	4.8	F	OP
	Toscana FSRU	2013	3.5	F	OP
	Ravenna FSRU	2025	4.8	F	UC
Lithuania	Klaipeda LNG	2014	3.8	F	OP
Malta	Electrogas Malta	2017	0.5	F	OP
Netherlands	Eemshaven FSRU	2022	7.6	F	OP
	LNG Rotterdam	2011	15.3	O	OP
Poland	Swinoujscie LNG	2016	6.2	O	OP
	Swinoujscie LNG-phase 2	2024	2.5	O	UC
Portugal	Sines LNG Terminal	2004	7.5	O	OP
Spain	Bahia de Bizkaia Gas	2003	6.6	O	OP
	Barcelona LNG	1969	16.4	O	OP
	Cartagena	1989	11.2	O	OP
	El Musel	2023	7.6	O	OP
	Huelva	1988	11.2	O	OP
	Mugardos LNG	2007	3.4	O	OP
	Sagunto	2006	8.3	O	OP
EU	*Operational*		*215.4*		
	Under Construction		*30.7*		

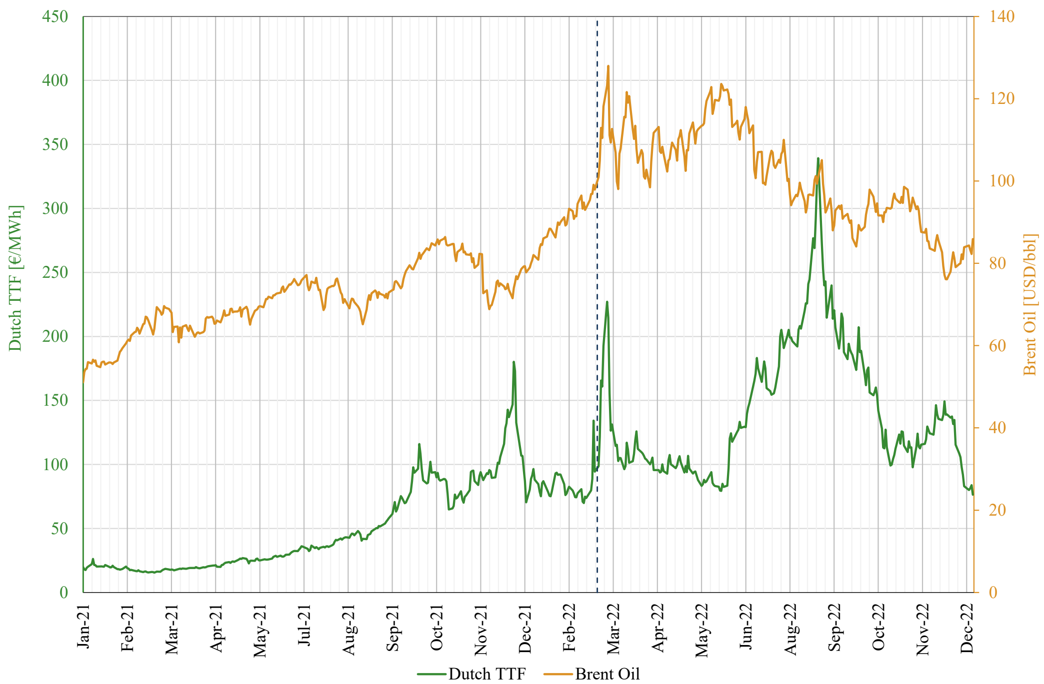
Source: Elaboration on IGU (International Gas Union, 2025)

Energy prices

The Russo-Ukrainian crisis not only urged EU27 MS to implement safeguarding and preventive measures to tackle the sudden absence of Russian oil and gas but, given their significant dependency on Russia's energy supplies, exposed them to the effects of price volatility and speculation on the main energy markets.

To this purpose, Figure 9 displays the daily values of the Dutch TTF and Brent Oil spot price indexes – two among the main price benchmarks for the European natural gas and crude oil markets, respectively – in the period 2021-2022 (the chart also highlights the date the war began – on February 24th, 2022 – with a dashed line).

Figure 9 Daily trends of the Dutch TTF and Brent Oil commodity price indexes in the period 2021-2022



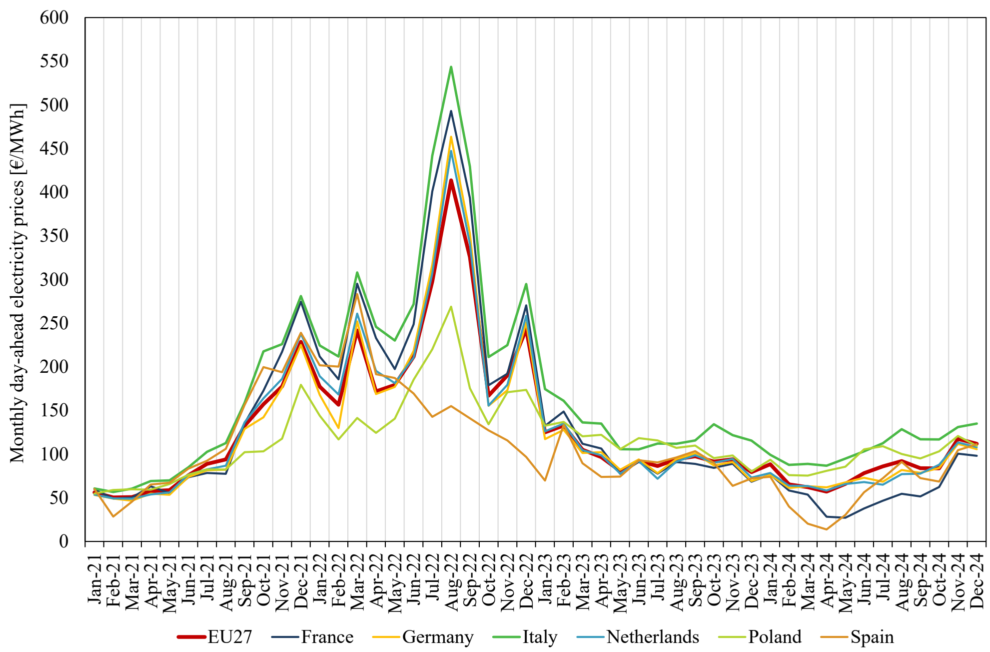
Source: Elaboration of CME Group and ICE (CME Group, 2025; ICE, 2025)

Both indexes started ramping from between November and December 2021, when rumors about a potential Russian invasion became more and more insistent (Adolfsen et al., 2022). The Dutch TTF registered a first peak on March 7th, 2022, when gas prices went up to 227.20 €/MWh; similarly, Brent Oil reached its peak of 127.98 USD/bbl the following day. Until the end of the first semester of 2022 commodity prices steadily increased, likely because of the uncertainties associated with a potential phase-out of Russian supplies (Troderman, 2023). Then, while oil prices started decreasing, the Dutch TTF reached its maximum of

339.16 €/MWh on August 26th (17 times larger than January 2021), presumably because of competition and speculation in gas markets that followed the release of the *Gas Storage Regulation* (European Parliament & Council of the European Union, 2022) by the European Commission in June, which bound member countries to ensure a minimum 90% percentage filling level of their natural gas storage systems by November 1st.

The fluctuations in fuel commodity prices were inevitably transmitted to those of electricity as well. In fact, because the EU's electricity market is based on a marginal pricing model, electricity produced from natural gas in thermal power plants usually sets its market price. Consequently, the price oscillations that affected the natural gas market also affected the electricity one. Figure 10 displays the trend of monthly electricity prices on the day-ahead market in the EU27 and some selected countries, from 2021 to 2024.

Figure 10 Day-ahead market electricity prices (monthly averages) in the EU27 and selected countries in the period 2021-2024



Source: Elaboration on ENTSOE (ENTSOE, 2025)

In 2021, prices steadily grew, presumably due to the progressive recovery of industrial and commercial activities that followed the end of the COVID-19 pandemic period: in the EU, the average electricity price rose from 56.05 €/MWh in January to 228.67 €/MWh in December. Just like fuel commodity prices did, soon after the conflict broke out electricity prices experienced a sudden peak in March 2022, after a period characterized by a decreasing trend. The most affected countries were Italy and France, where they respectively reached 307.97 €/MWh and 295.17 €/MWh. The biggest price peaks were registered in August of that year, (European Parliament & Council of the European Union, 2022) due to the aforementioned need to urgently fill natural gas storages. In the EU, electricity prices peaked at 413.58 €/MWh, while they surged to 463.59 €/MWh in Germany, 493.08 €/MWh in France, and to 543.55 €/MWh in Italy. At the beginning of the 2022 Autumn season, also thanks to warmer temperatures that reduced the demand of both natural gas and electricity for air conditioning purposes, prices fell again and even reached pre-crisis values. Additionally, in Summer 2022, MS voluntarily agreed on implementing measures to reduce their natural gas demand by 15% in the period August 2022-March 2023, as compared to the average registered during the previous five years. The joint effect of milder temperatures and the countries' commitment had achieved a 19% reduction in the natural gas demand already by the end of January 2023 (European Council, 2025). However, regardless of the collective efforts, the increased energy demand for heating in winter was responsible for a third price peak in December 2022: prices grew to 243.10€/MWh in the EU, to 294.82 €/MWh in Italy and to 270.49 €/MWh in France.

In this framework, the EU27 intervened to shield its consumers from soaring energy prices, and, in October 2022, it proposed a set of emergency measures that came into effect starting from December 1st, 2022, and lasted until March 31st, 2023 (Council of the European Union, 2022). The measures mainly addressed three areas of action:

- Reducing overall electricity consumption by means of voluntary, arbitrary austerity measures to be implemented by member countries: these had to ensure an overall 10% reduction of electricity consumption by March 2023 and mandatorily reduce consumption during peak hours by at least 5%.
- Capping revenues of electricity producers with lower marginal costs, namely renewables, lignite and nuclear, and redistribute surplus profits to end consumers.
- Redistributing the additional income obtained by companies operating in the coal, oil and gas sectors – which considerably benefitted from the increased prices of fossil fuels – to the hardest-hit end consumers.

Thanks to the implementation of emergency measures and with energy markets progressively reaching a new, stable equilibrium, electricity prices started to decrease from 2023 onwards: in fact, the EU's average yearly prices were equal to 97.93 €/MWh in 2023 and to 82.67€/MWh in 2024 – even lower than in 2021 when they averaged at 102.31€/MWh.

1.4 Energy impacts of the Israeli-Palestinian crisis

The Mediterranean Basin has historically played a relevant role for the energy supplies of European countries[7]. In fact, a considerably large amount of both crude oil and natural gas delivered by ship to European countries was unloaded at Mediterranean ports before being either consumed locally, re-exported or converted into refined petroleum products. For example, both in 2023 and 2024 around 30% of the total European maritime imports of crude oil and LNG were unloaded at Mediterranean ports (AXSMarine, 2025).

For this reason, ensuring a constant supply to and from Mediterranean ports is fundamental to keep the security of the European oil and gas supplies at a proper level. Among the most crucial and delicate Mediterranean entry points of tanker ships there is the Suez Canal, where most of the supplies coming from the Middle East and South-East Asia travel through, shortcutting shipping routes to avoid circumnavigating the African continent. Therefore, if the access to the Suez Canal were suspended or, even worse, disrupted, the ordinary maritime supplies of oil and gas could be heavily affected.

The beginning of the most recent phase of the Israeli-Palestinian conflict on October 7th, 2023, and the geopolitical tensions it gave birth to in the area of the Gulf of Aden posed a severe threat to the transit of oil and gas tankers through the Red Sea and, consequently, through the Suez Canal too.

Effects of the tensions in the Red Sea on Mediterranean crude oil supplies

Table 2 shows the maritime crude oil imports of some Mediterranean countries in the period 2021-2023, detailing the amounts shipped through the Suez Canal and their weight over the total imports.

If the total crude oil imports coming from the Suez Canal were below 30.0 Mt/y both in 2021 and 2022, they significantly increased in 2023 when they reached 40.1 Mt/y, also as a consequence of the Russo-Ukrainian conflict. In terms of relevance, crude oil imports shipped through the Suez Canal weighed between around 10% and 15%, but significant differences can be found when looking at specific countries. In fact, Greece and Türkiye imported more than one quarter of their crude oil from the Suez Canal in all the three years, respectively reaching a maximum import dependency of 33.3% in 2023 and 33.0% in 2021.

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[7] Hereafter meant as EU countries plus the UK, Norway, Ukraine, Iceland, Albania, Bosnia-Herzegovina, Montenegro and Türkiye.

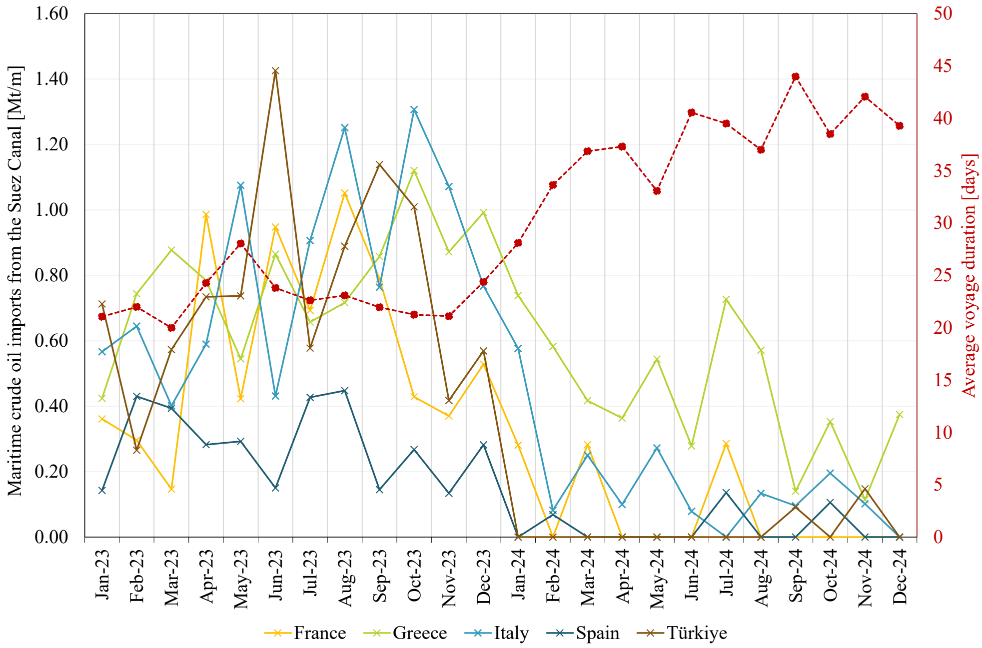
Table 2 Weight of Mediterranean maritime crude oil imports through the Suez Canal in the period 2021-2023

Country	Imports from Suez Canal [Mt/y]			Total imports [Mt/y]			Weight of Suez Canal imports [%]		
	2021	2022	2023	2021	2022	2023	2021	2022	2023
Croatia		0.1	1.0	6.3	6.0	6.0	0.0	1.7	16.7
Cyprus			0.3	0.2	0.5	1.8	0.0	0.0	16.7
France	4.6	4.6	7.0	34.3	40.2	44.7	13.4	11.4	15.7
Greece	6.3	5.8	9.5	24.4	24.2	28.5	25.8	24.0	33.3
Italy	4.1	5.3	9.8	93.7	95.8	92.8	4.4	5.5	10.6
Malta	1.1		0.2	4.0	2.1	1.8	27.5	0.0	11.1
Portugal		0.2	0.1	9.1	10.0	10.1	0.0	2.0	1.0
Spain	1.4	3.9	3.4	54.1	62.4	59.2	2.6	6.3	5.7
Türkiye	8.9	8.3	9.1	27.0	29.9	30.5	33.0	27.8	29.8
Total	*26.4*	*28.2*	*40.1*	*252.9*	*270.6*	*273.6*	*10.4*	*10.4*	*14.7*

Source: Elaboration from (AXSMarine, 2025)

Italy, the country with the largest total crude oil supply among those listed in the table (Eurostat, 2025a), relied on maritime imports from the Suez Canal more limitedly, reaching a maximum dependency of 10.6% only in 2023. Croatia and Cyprus, instead, started registering non-negligible imports of crude oil travelling through the Suez Canal in 2023 only, each of which showing a share of 16.7%.
The situation drastically changed after piracy attacks perpetrated by Houthi rebel groups began, off the coast of the Gulf of Aden, on November 19th, 2023 (Scarr et al., 2024).To better illustrate their effects, Figure 11 shows the monthly maritime imports of crude oil of some countries in the Mediterranean in 2023 and 2024.

Figure 11 Monthly crude oil imports of Mediterranean countries from the Suez Canal and average voyage duration in 2023 and 2024



Source: Elaboration from (AXSMarine, 2025)

The figure also displays the average voyage duration of trips leaving from crude oil exporting countries[8] that had traditionally relied on the Suez Canal to enter the Mediterranean Sea.

Quantities of crude oil shipped through the Suez Canal and the average duration of trips followed an inverse behavior. In fact, while the first progressively declined, the second started increasing.

If, until the end of 2023, it took a ship around 20-25 days to reach its destination port in the Mediterranean Sea, the average voyage duration almost doubled the following year, averaging at 37 days and topping at 44 days in September.

In Türkiye, France and Spain, trips through the Suez Canal stopped during most months of 2024, with non-null values several times smaller than the corresponding months of 2023: for example, French and Spanish imports in July 2024 respectively decreased by 59% and 68% with respect to July 2023. Trips crossing the Suez Canal and reaching Italy and Greece did not completely stop in 2024, yet their number drastically decreased, as it can be implied by the exported quantities: if Italian and Greek maritime imports from the Suez Canal in 2023 averaged at 0.80 Mt/m and 0.78 Mt/m, they shrank to 0.12 Mt/m and 0.41 Mt/m, respectively.

The reason why the average duration of trips grew this much is that, in order to avoid risks associated with the ongoing tensions in the Red Sea, shipping routes were rescheduled and started rounding the Cape of Good Hope instead of the Gulf of Aden, entering the Mediterranean Sea from the Gibraltar Strait: Iraqi and Kuwaiti ships, to which it took about 23 and 26 days to reach the Mediterranean in 2023, saw their trips delayed by around 16-18 days in 2024.

Effects of the tensions in the Red Sea on Mediterranean LNG supplies

Table 3 illustrates the quantities of LNG imported by some Mediterranean countries in the period 2021-2023, detailing those that travelled through the Suez Canal and their corresponding weight over total imports.

Overall, the importance of the Suez Canal for LNG is comparable to that of crude oil, as its weight oscillated between around 11% and 15%. However, country-specific values show significant differences. In fact, if Türkiye and Greece were the most Suez-dependent countries for the imports of crude oil, they showed almost null values in the case of LNG – with Greece having phased them out after 2021.

[8] Bahrain, Iran, Iraq, Kuwait, Oman, Saudi Arabia, United Arab Emirates

Table 3 Weight of Mediterranean LNG imports through the Suez Canal in the period 2021-2023

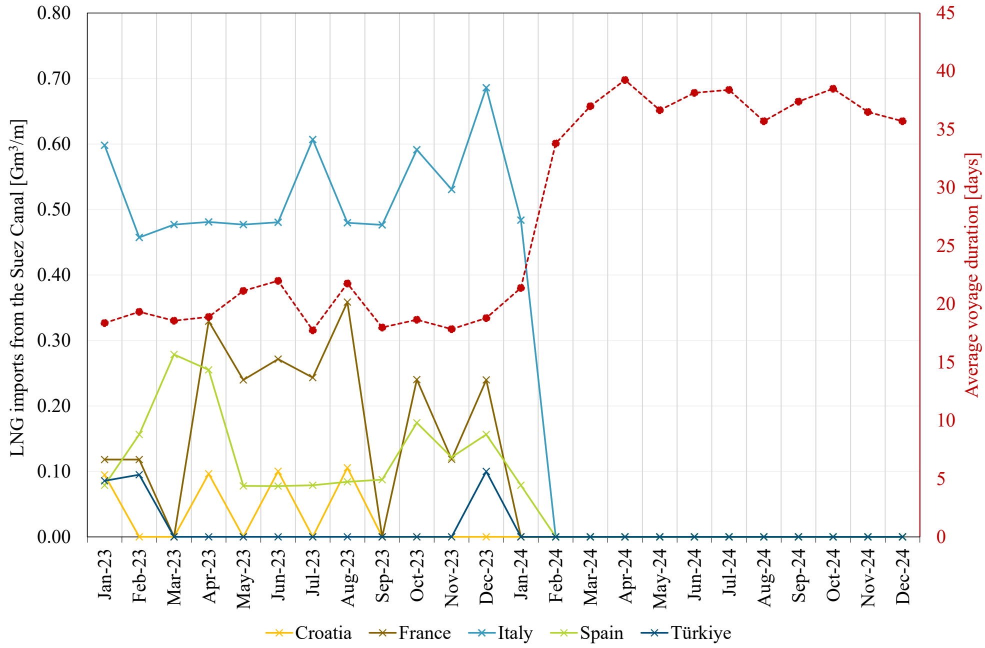
	Imports from Suez Canal [Gm^3/y]			Total imports [Gm^3/y]			Weight of Suez Canal imports [%]		
Country	2021	2022	2023	2021	2022	2023	2021	2022	2023
Croatia	0.30	0.09	0.40	1.73	2.25	2.54	17.3	4.0	15.7
France	0.53	2.26	2.28	18.28	34.51	29.41	2.9	6.5	7.8
Greece	0.66	0.09		2.57	4.34	2.99	25.7	2.1	0.0
Italy	6.50	7.17	6.34	9.39	14.10	15.38	69.2	50.9	41.2
Malta				0.44	0.45	0.48	0.0	0.0	0.0
Portugal	0.40			5.39	5.81	4.57	7.4	0.0	0.0
Spain	2.31	2.10	1.63	19.64	28.62	24.92	11.8	7.3	6.5
Türkiye	0.30	0.28	0.28	13.28	14.90	12.20	2.3	1.9	2.3
Total	*11.00*	*12.00*	*10.93*	*71.08*	*105.40*	*92.74*	*15.5*	*11.4*	*11.8*

Source: Elaboration on (AXSMarine, 2025)

On the contrary, Italy stood out as the country importing the most LNG from ships travelling through the Suez Canal. In 2021, 69.2% of the Italian imports of LNG came from Qatar only; their incidence in 2022 (50.9%) and 2023 (41.2%) decreased, but simply because of the sharp growth of the total LNG supplies that followed the abandonment of Russia gas. Indeed, Qatari imports in 2023 (6.34 Gm^3/y) were comparable to those in 2021 (6.50 Gm^3/y).

Errore. L'origine riferimento non è stata trovata. shows the monthly imports of LNG of countries listed in Table 3.

Figure 12 Monthly LNG imports of Mediterranean countries from the Suez Canal and average voyage duration in 2023 and 2024.



Source: Elaboration on (AXSMarine, 2025)

Suppliers include natural gas exporting countries[9] whose gas tankers were used to crossing the Suez Canal, as well as the average duration of the trips (importing countries displayed in the table and not present in the figure did not register any imports at all).

Differently from what happened for crude oil, in whose case imports from the Suez Canal heavily decreased but never completely stopped, no ship carrying LNG was tracked travelling through the Suez Canal after February 2024. Naturally, exports themselves did not stop (Italy, for instance, imported other 6.2 Gm^3/y of LNG from Qatar in 2024) but, as it happened for crude oil, also gas tankers had to start circumnavigating Africa to not face any risks along their routes. Quantitatively, the average duration of trips in 2023 was 19 days and rose to 36 days the following year.

The geopolitical tensions that led to the rerouting of oil and gas ships around the Cape of Good Hope showed that a disruption in the ordinary behavior of energy supplies can not only interest oil and/or gas producing countries, but also specific supply corridors. In the proposed analysis, the blockage of the Suez Canal naturally imposed considerable delays, forcing shipping companies to reschedule the routes of their entire fleet. This affected some among the world's leading ones such as CGM, Equinor, BP, and Maersk, the last of which even introduced additional surcharges to account for additional risks in case ships had to travel through the Red Sea (Cooban, 2023; LaRocco, 2023; Staffetta Quotidiana, 2024).

On top of that, longer trips implied longer shipping costs: according to estimates, a Qatari LNG tanker travelling to the Mediterranean Sea would spend on fuel between 30,000 $/d and 35,000$/d; therefore, considering the average shipping times recorded in 2023, the total fuel costs amounted to around 570,000 US$/trip-665,000 US$/trip. However, because of the increased shipping times, it took the same ship between 1,080,000 US$/trip and 1,260,000 US$/trip to reach its destination (U.S. Energy Information Administration (EIA), 2024).

Red Sea tensions did not only affect oil and gas exporting countries and shipping companies but, among their impacts, they also deprived Egypt of the revenues coming from the tolls it had collected from ships travelling through the Suez Canal until the end of 2023. Egypt's President al-Sisi stated that uncollected payments costed the country around 8 billion US$ of lost revenues in 2024 and, by the end of March 2025, other 800 million US$ (Taha, 2025).

1.5 Conclusions

This chapter introduced the concept of the Energy Trilemma as an instrument to quantitatively assess the status of a country with respect to achieving satisfactory

[9] Oman, Qatar

levels of energy security, environmental sustainability and energy equity and affordability. The Trilemma framework is particularly important in the context of the energy transition towards decarbonization, as its successful accomplishment does not simply mean reducing the carbon footprint of a country's energy mix but to also build a socially and economically just and balanced system, as these two domains are strictly intertwined with energy and the environment.

The analyses discussed in the previous sections highlighted how extremely sensitive energy systems are with regards to apparently uncorrelated events such as geopolitical crises. Abrupt and unexpected disruptions in the ordinary behavior of a country's energy system can drastically alter the relevance given to the three Trilemma attributes. For example, the Russo-Ukrainian conflict substantially increased the importance attributed to energy security in the EU27. The most tangible effect of the crisis is represented by the increase of the overall LNG regasification capacity in the EU27, which increased from 156 Gm^3/y to 221 Gm^3/y (a 42% growth) in only three years from 2021 to 2024 and is projected to reach 246 Gm^3/y in the near-future. Maritime supplies of LNG not only have been a "just-in-time" solution to promptly face the absence of Russian gas but are also a way to preventively strengthen the security of the national natural gas import network.

On the other hand, the uncertainty associated with energy supplies that characterized the months that followed the beginning of the war dramatically exposed final energy consumers to speculation and price volatility on the main energy markets, with spot electricity that almost quintuplicated from March 2021 to March 2022.

If the Russo-Ukrainian crisis interested one major oil and gas exporting country, the Israeli-Palestinian conflict and its related geopolitical tensions in the Red Sea posed serious problems to the security of supply through the Suez Canal, one of the most crucial transit corridors of oil and gas tanker ships. In this case, the composition of neither the oil nor the natural gas import mixes were tangibly affected. However, the ongoing tensions in the Red Sea heavily influenced the affordability of fossil fuels shipped to the EU27, because of the higher shipping costs incurred by shipping companies. In junction, delivery times of both oil and gas tankers that were used to enter the Mediterranean Basin from the Suez Canal increased from about 20-25 days to 35-40 days, being forced to round the Cape of Good Hope to prevent risks associated with the Red Sea tensions.

The tight link between geopolitics and energy systems positions the second ones in a delicate position where they can be heavily influenced by the consequences of events of geopolitical nature. In the framework of the energy transition, this could slow down the pace at which the gap between the current situation and decarbonization targets is bridged, as sustainability may be outranked by both security and affordability.

Chapter 2

Competing energy commodities for the energy transition and the primary role of electricity

The previous chapter introduced the topic of energy transition towards the decarbonization of the current energy system, presenting the concept of Energy Trilemma as a valuable tool to holistically quantify the positioning of countries along their decarbonization paths. More specifically, it casted the light on the new role attributed to energy security after the outbreak of the Russo-Ukrainian war and the latest phase of the Israeli-Palestinian crisis.

The Trilemma Index and, in general, the concept of the Energy Trilemma itself helps to assess the energy transition from the policy decision-maker perspective. In junction with its analysis, this chapter presents the concept of Commodity Energy Chain (CEC), another flexible and handy tool to carry out a quantitative evaluation of the energy transition, this time from a more design-oriented and technological point of view. In addition, it brings forward the idea of multi-commodity energy systems as a way to effectively accomplish the energy transition and illustrates some among the most relevant transition-related, technologies, with a detailed focus on electricity-based ones.

2.1 The need for a multi-commodity energy system

Although the Russo-Ukrainian and the Israeli-Palestinian crises brought about a change in the relevance given to the three attributes of the Trilemma (World Energy Council, 2024) – with energy security being prioritized – in the medium- and long-term it will likely be overthrown by environmental sustainability and energy affordability once again.

In fact, the effects of climate change require immediate and effective actions if we want to accomplish the ambitious target that most countries agreed with when they signed the Paris Agreement, of not overcoming the threshold of 1.5°C of global average temperature increase with respect to the pre-industrial era (United Nations, 2015).

In this context, RES and nuclear fission have received further and renovated attention, due to the possibility of generating electricity without any carbon emissions and at costs[10] lower than fossil-fuels', while being less subject to volatility effects (Gasparella et al., 2023). Consequently, several countries have been investing on less carbon-intensive technologies and wish to accelerate the decarbonisation of their electricity generation mix, although with different levels of commitment: China, currently the global largest GHG emitter, strives to achieve climate neutrality by 2060, but coal still largely represents the predominant source it generates electricity from – 62%[11] (Climate Analytic & NewClimate Institute, 2025; IEA, 2024a). During the Biden administration, the USA submitted their latest Nationally Determined Contribution to the UN (UNFCC, 2024), in which they claimed to achieve a 61%-66% GHG emissions reduction with respect to 2005 by 2035, and targeted year 2050 for carbon neutrality. However, with President Trump signing out from the Paris Agreement, the accomplishment of the decarbonization targets seems more uncertain (Climate Analytic & NewClimate Institute, 2025). India, the third largest country in terms of global emissions, is trying to reach carbon neutrality by 2070, while coal still accounts for even 72% of its total electricity generation[9] (Climate Analytic & NewClimate Institute, 2025; IEA, 2024a).

On the contrary, the European Union, despite representing only about 6% of the total worldwide GHG emissions (ClimateWatch, 2021), aims to reach carbon neutrality by 2050, a demanding target that requires a strenuous effort to achieve at least a 55% reduction in GHG emissions already by 2030, as claimed in the *Fit for 55* package of actions published in July 2021 (European Commission Secretariat-General, 2021). Within *Fit for 55*, the electrification of the final consumption plays a key role (40% of the final consumption must be electrified by 2030); the target was further updated to 45% in the 2022 *REPowerEU* plan (European Commission Secretariat-General, 2022), requiring an increase of the overall installed renewable capacity from 511.6 GW in 2021, to 1067 GW within *Fit for 55*, and to 1236 GW within *REPowerEU*.

Electricity will likely play a fundamental role in the energy transition towards decarbonization, mainly thanks to the possibility of exploiting RES and generate electricity with no GHG emissions. Furthermore, the path towards electrification of some final energy consuming sectors (i.e., light-duty transports and domestic heating/cooling) has already reached both technological maturity and satisfactory affordability levels. However, the rate of electrification of other sectors is much clumsier and phasing-out fossil-fuels from them looks significantly more challenging. These so-called *hard-to-abate sectors* include, for instance, road freight transport, shipping, aviation, iron and steel, and chemicals and petrochemicals. In 2022, they jointly accounted for 100 EJ/y out of 411 EJ/y of the world's total final energy consumption, and for 20% of the global CO_2 emissions (7.6 $GtCO_2$ out 37.0 $GtCO_2$) (IRENA, 2024a).

[10] Intended here as marginal costs.
[11] 2022 data.

Additionally, the vast penetration of intermittent, unpredictable, and non-dispatchable sources of electricity such as RES necessarily requires to both adequately strengthen the current power transmission and distribution networks, as well as to substantially increase its overall storage capacity (Q. Li et al., 2022). For these reasons, the total electrification of the future energy system is unlikely, if not even unfeasible.

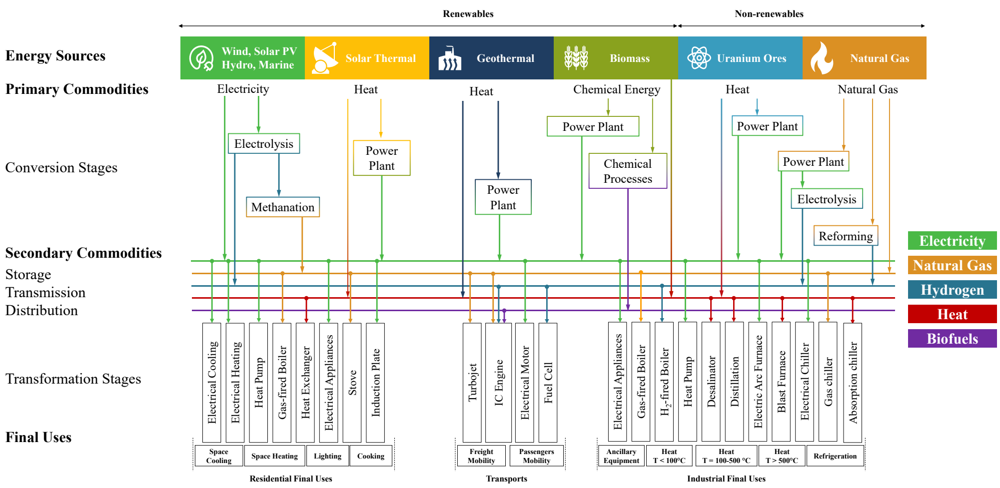
All the above hint at how effective the development of a multi-commodity energy system would be, as a potential driver to match the different energy needs of the full range of final uses and accomplish their decarbonisation in parallel (Plazas-Niño et al., 2022). The 2022 IEA's World Energy Outlook (IEA, 2022) embraces the problem of multi-commodity systems from an even broader perspective, stating that not only the supply of commodities and commodities themselves must be as diversified as possible, but a complete overhaul of the current energy system and of its interacting domains is envisaged. Evidence about the EU27's increasingly growing interest into multi-commodity energy systems and cross-sectoral integration can be found in the bi-yearly joint publication of the *Ten Year Network Development Plan* (TYNDP) Scenario Reports by ENTSO-E and ENTSO-G, the associations of the European electricity and natural gas transmission operators, respectively. In the latest report, the authors claimed that the decarbonisation of both electricity and gas supply before 2050 can be achieved by effectively implementing cross-cutting measures, such as the integration of the electricity, gas and hydrogen grids and infrastructures, and the deployment of a large electrolysis capacity not only to synthetise green hydrogen, but also to produce synthetic, carbon-neutral fuels (ENTSOE & ENTSOG, 2025). Besides, particular attention is devoted to the role of hydrogen, for its potential of gradually abating the use of natural gas and stimulate the deployment of more and more renewable generation capacity. *REPowerEU* also suggested several actions targeting the development of a multi-commodity European energy system, to both accelerate the decarbonisation process and increase the energy independence of the EU27 (e.g., growth in the production of biomethane, the deployment of 17.5 GW of electrolyser capacity by 2025, in-house production of around 10 Mt of green hydrogen in 2030, and investments aimed at adequately strengthening the natural gas and electricity grids and favour their reciprocal integration).

Despite the intrinsic potential of multi-commodity energy systems, finding an effective energy transition commodity mix is extremely challenging, as the choice of specific energy commodities can lead to substantially different results in terms of, for example, the energy efficiency, carbon intensity or economic intensity of the final energy mix. For this reason, being able to compare energy commodities with respect to the several cross-domain aspects of the energy system is crucial to find the commodity mix that would best fit a specific context. To this purpose, the next section presents the concept of Commodity Energy Chain (CEC), a numerical tool that allows to quantitatively assess energy commodities and rank them according to various user-chosen indicators.

2.2 The concept of Commodity Energy Chains

This section provides a definition of CECs and illustrates their basic principles. The starting point for their unambiguous definition consists in distinguishing between primary commodities and energy sources. Primary commodities correspond to energy carriers that can be directly harvested from natural resources: for this reason, they may or may not overlap with the energy sources they are extracted from. For example, crude oil and natural gas can, in principle, be both energy sources and primary commodities. Instead, solar radiation and/or wind are two energy sources from which the primary commodity electricity can be produced. Energy commodities obtained by feeding primary commodities to purposely designed conversion devices and/or facilities are instead called secondary commodities: hydrogen obtained by electrolysis, electricity generated in thermal power plants, as well as synthetic or biomass-based hydrocarbons can all be regarded as secondary commodities. A CEC is defined as the representation of the energy flow, from primary sources to final uses, by also including its use and/or manipulation in intermediate stages, such as conversion, transmission, storage, distribution, and transformation into appliances and devices providing the final energy service. Figure 13 displays a sample overview of what CECs are, together with the conceptual representation of a multi-commodity energy system.

Figure 13 Conceptual overview of CEC in a sample energy system



CECs generally consist of six stages but may either include all of them or only a subset; moreover, their reciprocal order might be different in the actual implementation.

- *Energy Sources*: renewables (solar, wind, and hydropower, marine and ocean energy, and biomass) or non-renewables[12] (natural gas and uranium ores, that we include in the analysis as they may accompany the transition process alongside renewables, as also stated by the European Commission in 2022 (Ferrie & Apostola, 2022)).
- *Conversion*: the process of transforming an energy source into a primary energy commodity, or a primary into a secondary commodity.
- *Storage*: the act of statically preserving a commodity for its future use (time decoupling between the generation/production and the use).
- *Transmission/Transport*: the movement of substantial amounts of energy across long distances (e.g. high-voltage electric transmission lines or transnational gas pipelines); hence, it guarantees space decoupling between generation and use.
- *Distribution*: the infrastructure that moves the energy commodities in a limited geographical area and lying between the transmission infrastructure and the final uses.
- *Transformation*: the process of exploiting ad-hoc devices (boilers, heat pumps, fuel cells, internal combustion engines, reforming furnaces, etc.) to produce a useful energy service exploiting the energy content of the inlet commodities at the consumer level.

In the picture, final uses were classified into three main sectors, according to the energy service they provide to final users:

- *Residential*, including space heating and cooling, domestic hot water production, lighting, and cooking.
- *Transport*, consisting of freight and passengers' mobility.
- *Industrial*, including auxiliary equipment, low-, medium-, and high-temperature processes, and refrigeration.

12 Among non-renewable sources we should also enumerate coal, crude oil and petroleum products. However, since the core of this work is assessing the performances of energy commodities in the process of the transition towards the decarbonization of the current energy system, they are not taken into consideration.

2.3 Quantitative analysis of CECs

In this section, a quantitative and comparative analysis of CECs is presented. Among the possible comparison metrics to choose from, thermodynamics (directly linked to energy efficiency and reduced energy waste) and environmental sustainability were chosen for this work.

The thermodynamic analysis of CECs was carried out basing it on the First Law of Thermodynamics (FLT) and the Second Law of Thermodynamics (SLT), to evaluate the performances of energy commodity chains in terms of their overall energy and exergy efficiencies.

The FLT (or energy) efficiency (η_I) is defined as the ratio between the useful energy (E_P) produced in a process, to the amount of energy (E_S) it was supplied by.

$$\eta_I = \frac{E_P}{E_S} \tag{1}$$

The SLT deepens the thermodynamic analysis of a system, introducing the concepts of *entropy* and its balance, and that of *irreversibilities*.

The importance of the SLT is particularly linked to the definition and distinction between reversible and irreversible processes. More specifically, irreversibilities can be external or internal: the first ones consist in heat transfers across finite temperature differences between a thermodynamic Control Volume (CV)[13] and its surroundings. In contrast, internal irreversibilities include all those phenomena happening within the boundaries of a CV such as friction, hysteresis, spontaneous chemical reactions, fluid mixing, or inelastic deformation, which limit the theoretical amount of energy exploitable from a process. Differently from energy, subject to the Total Energy Conservation Law, the conservation of entropy holds only for internally reversible processes, therefore those characterized by external irreversibilities only (Moran et al., 2003).

The tangible effect of internal irreversibilities occurring within a thermodynamic process is the reduction of the potential maximum quantity of work exploitable from the process itself. Consequently, since internally reversible processes are not affected by any source of dissipation, they represent the benchmark processes to which every non-ideal one should aim. In thermodynamics, the maximum theoretical amount of work obtainable from an internally reversible process is also called *exergy* (Bejan, 2016). The concept of exergy was first introduced in thermodynamics to provide a more user-friendly tool to deal with

[13] In thermodynamics, a region of space through which mass may flow.

entropy analysis and the quantification of irreversibilities. Its introduction followed the basic postulates of the SLT, according to which mechanical work can be entirely converted to heat, but the reverse process cannot happen, not even in an ideal device; therefore, mechanical work stands out as a more valuable source of energy. In this context, exergy is defined as the maximum amount of mechanical work that could be obtained from a given amount of energy, and for this reason it can be also called *available work*. On the contrary, irreversibilities (as purely dissipative phenomena) represent the amount of potentially available work lost in a process, thus they are also referred to as exergy destruction. For this reason, the SLT or exergy efficiency is defined as the ratio between the exergy produced from a process and the exergy supplied to the process.

$$\eta_{II} = \frac{Ex_P}{Ex_S} \tag{2}$$

Another interpretation of exergy states that exergy is the potential of producing mechanical work from any couple of thermodynamic systems whose temperature, pressure, and chemical composition (or even only one among them) are different: in other words, work could be in principle be exploited until two systems do not reach a reciprocal equilibrium state. This led to the definition of a reference equilibirum state whenever carrying out exergy analyses (Bejan et al., 1996), usually corresponding to the conditions of pressure, temperature, and chemical composition of the external environment. Typically, if the thermochemical properties of a system and of the reference environment coincide, its exergy generation potential is null.

If energy efficiency basically gives an estimation of the quantity of energy that is produced from a process, exergy efficiency is linked to the intrinsic quality of the energy fluxes. Recalling the previous statements, higher exergy efficiencies mean that the available work potential of outlet exergy flows that characterize a thermodynamic process is higher.

The importance of carrying out an exergy analyses is double-sided: on the one hand, exergy efficiency is a more meaningful and objective metric with respect to typical FLT-based ones: for example, assessing the performances of a combined heat and power plant computing only its energy efficiency might lead to incorrect conclusions, as the FLT efficiency assigns an equal value to both work and heat.

On the other hand, thanks to the introduction of the concepts of exergy destruction and lost available work, it enables designers not only to immediately spot the largest sources of irreversibility within a complex system, but to quantify them too.

The environmental assessment of CECs was carried out quantifying the GHG emissions per unit of supplied energy along each chain step. Therefore, the environmental indicator associated to a specific chain and, consequently to an energy commodity, will be the sum of the emissions computed along the steps of extraction from energy sources, conversion, transmission and distribution, and utilization in the final transformation appliances. Emissions are expressed in gCO_{2eq}/kWh and can be expressed by the following simple formula:

$$GHG = \sum_{i=1}^{S} GHG_i \qquad (3)$$

Where every GHG_i term indicates emissions of the *i-th* step of the CEC and *S* the overall number of steps.

The following sections will present the numerical results and will compare the several CECs against each other, according to the proposed indicators. operatively, three main commodities were considered and associated to different final energy uses: electricity produced from RES; natural gas; hydrogen produced by electrolysis feeding electrolysers with renewable electricity (generally known as green hydrogen (Bompard et al., 2021)). Italy was assumed as the reference country of the analyses. More specifically, natural gas CECs consider it to be imported via pipeline from the Caucasian-Middle Eastern area; green hydrogen is also supposed to be transported and stored in gaseous form.

Thermodynamic comparison of CECs

Table 4 displays the energy and exergy efficiencies of the considered conversion, storage, transmission and distribution technologies and infrastructures. Regarding hydrogen, it was considered storage in gasified form and assumed the same transmission and distribution losses of natural gas ducts. Computational assumptions are available in the Appendix section.

Table 4 Synoptic view of the energy and exergy efficiencies of considered technologies and devices[14].

CEC Step	Technology	Commodity	η_I	η_{II}
Conversion	Alkaline Electrolyser	Hydrogen	0.60 (IRENA, 2020a)	0.60
Storage	Li-ion Battery	Electricity	0.94 (IRENA, 2017)	0.94
Storage	Pressure Vessel	Hydrogen	0.85 (Gautam et al., 2017)	0.85
Transmission	Power Line	Electricity	0.98 (Chilelli et al., 2021)	0.98
Transmission	Gas Duct	Natural Gas	0.95 (Arco et al., 2020)	0.95
Transmission	Gas Duct	Natural Gas	0.95 (Arco et al., 2020)	0.95
Distribution	Power Line	Electricity	0.93 (ARERA, 2020)	0.93
Distribution	Gas Duct	Natural Gas	0.99 (Albatayneh et al., 2020)	0.99
Distribution	Gas Duct	Natural Gas	0.99 (Albatayneh et al., 2020)	0.99

[14] Numbers shown in this work should be regarded as reference values and may differ from those characterizing real specific applications.

The analytical expression of the exergy efficiencies of chain steps and transformation devices in which no heat transfer is involved are the same as their corresponding energy efficiencies. Generally, all the intermediate steps of the CECs have got fairly high energy and exergy efficiencies, with a single exception represented by 0.60 of alkaline electrolysers, about one third smaller than all the other technologies.

Table 5 lists the energy and exergy efficiencies of the final energy transformation devices considered in the analysis of the CECs. For electrical heat pumps the Coefficient of Performance (COP) was adopted in place of their energy efficiency.

In the space heating sector, heat pumps represent the most energy and exergy efficient alternative: in fact, their COP is more than three times larger than the efficiencies of the other assessed space heating appliances. In the field of transports, electric motors are the most preferable choice: their efficiency, equal to 0.85, is more than twice as larger that of Internal Combustion Engines (ICEs), and more than one and a half times that of fuel cells. In general, combustion-based devices are less desirable choices, when looking only at their values of efficiency.

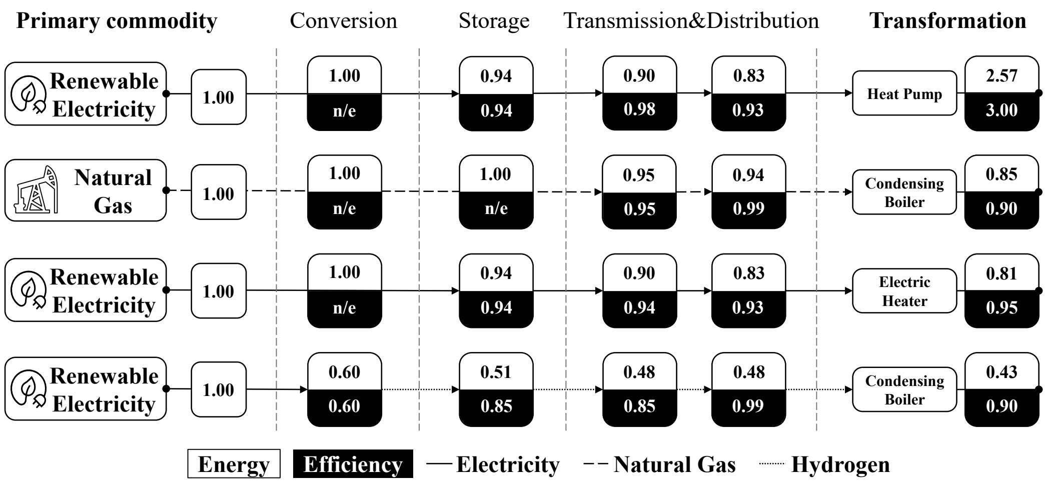
Table 5 Energy and Exergy efficiencies of final transformation devices.

Device	Final Use	Commodity	η_I	η_{II}
Heat Pump	SH	Electricity	3.00 (Abid et al., 2021)	0.20
Condensing Boiler	SH	Natural Gas	0.90 (Arena, 2010)	0.06
Electric Heater	SH	Electricity	0.95 (Bassily & Colver, 2004)	0.06
Condensing Boiler	SH	Hydrogen	0.90 (Gudmundsson & Thorsen, 2022)	0.06
Electric Motor	PT	Electricity	0.85 (Mazali et al., 2022)	0.85
ICE	PT	Natural Gas	0.35 (Khan et al., 2015)	0.35
Alkaline Fuel Cell	PT	Hydrogen	0.55 (Deloitte & Ballard, 2020)	0.55
ICE	PT	Hydrogen	0.37 (Onorati et al., 2022)	0.37

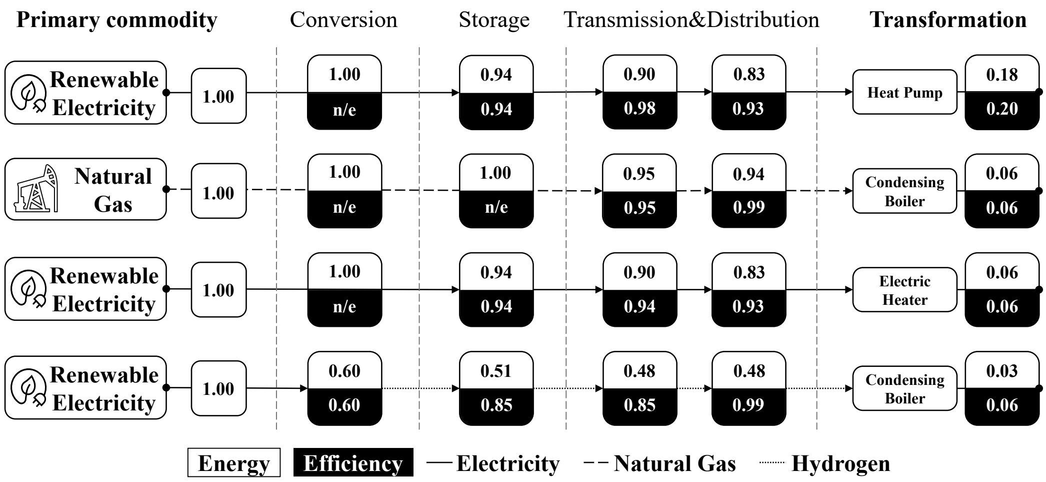
SH: Space Heating. PT: Passenger Transport

Figure 14 and Figure 15 illustrate the graphical formalization of energy and exergy chains, for the space heating and passenger transport sectors. Each CEC shows the primary energy commodity it starts from on the left, while the final energy transforming device on the right. The upper half of the squares contains the amount of energy/exergy available after every step of the chain, while the lower half its energy or exergy efficiency (values marked as n/e indicate that the step is not included in that specific CEC).

Figure 14 CECs for the space heating sector

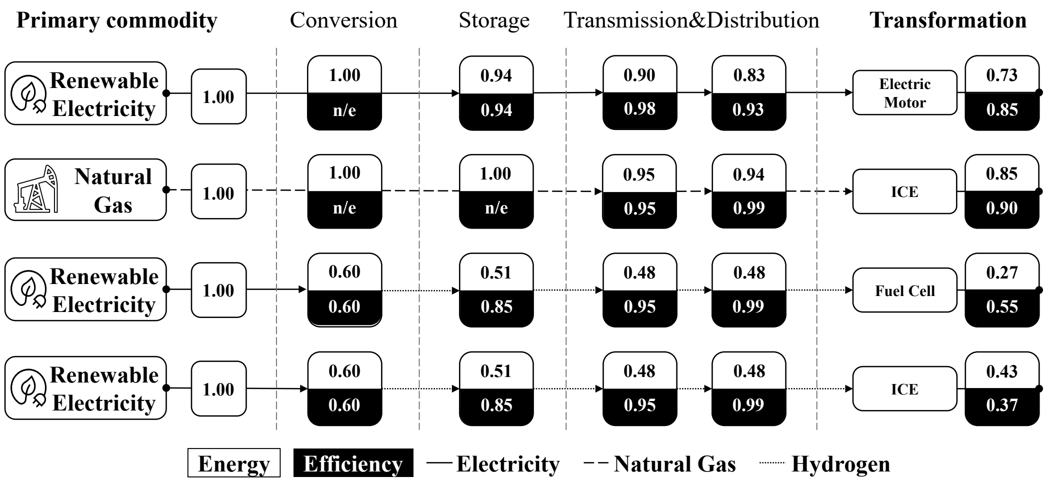


(a) Energy Chains

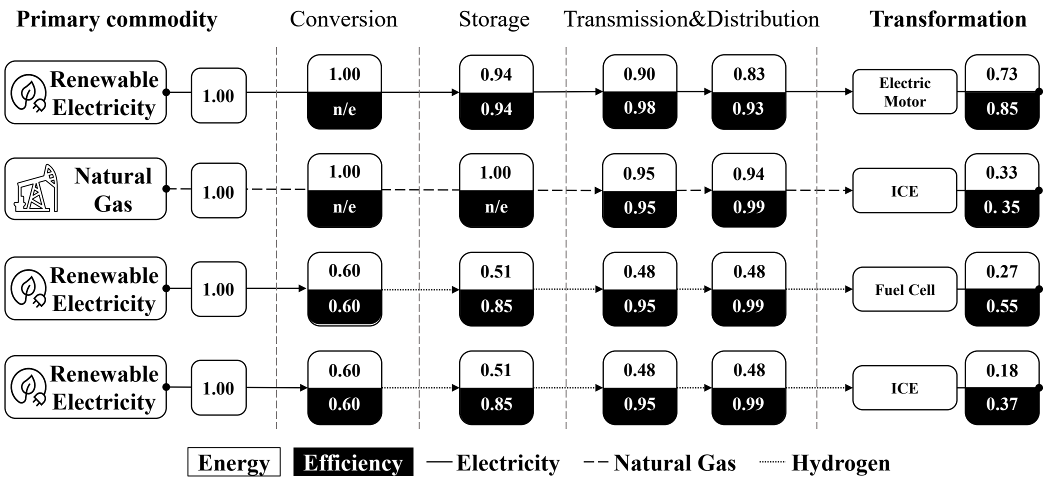


(b) Exergy Chains

Figure 15 CECs for the passenger transport sector.



(a) Energy Chains



(b) Exergy Chains

Environmental comparison of CECs

Table 6 displays the GHG emissions, per kWh of energy produced, for the three chosen energy commodities, downstream each step of CECs (Prussi et al., 2020).

Table 6 GHG emissions (in gCO_{2eq}/kWh) of the chosen energy commodities in the steps of the CEC

	Generation	Conversion	Storage	Transmission	Distribution	Total
Renewable Electricity	0.00	0.00	0.00	0.00	0.00	*0.00*
Natural Gas	14.92	0.00	0.00	28.98	10.55	*54.45*
Green Hydrogen	0.00	0.00	0.00	0.00	34.23	*34.23*

Renewable electricity naturally outperforms both hydrogen and natural gas as the most environmentally sustainable commodity, with null GHG emissions along the entire chain[15]. On the contrary, both green hydrogen and natural gas are characterized by non-null emissions (Prussi et al., 2020). Particularly, the supply of green hydrogen to final uses produces total emissions equal to 34.23 $gCO2_{eq}$/kWh, due to the necessity of powering the compressors[16] installed along the transmission network that raise its pressure from the outlet pressure of the electrolyser (typically 3 MPa) to around 88 MPa, which is adequate for dispensing it to final users. Naturally, if also electricity feeding the compressors came from renewable sources, green hydrogen CECs would be zero-carbon as well (whereas here we adopted the same assumptions of (Prussi et al., 2020)).

[15] The impacts of life-cycle emissions (such as raw materials production and transportation, end-of-life & recycling, etc.) are not accounted for here.

[16] Electricity feeding ancillary equipment could be other than RES.

The overall GHG emissions of natural gas CECs are more than one time and a half larger than green hydrogen's and equal to 54.45 $gCO2_{eq}$/kWh: not only drilling and extracting activities at the well site have a non-negligible environmental impact, but before injecting it into gas ducts, extracted natural gas should be adequately processed, in order to separate heavier hydrocarbons and other undesired substances, such as hydrogen sulphide (H_2S) and inert gases from the starting blend. The GHG emissions affecting the transport stage, amounting to roughly 28.98 $gCO2_{eq}$/kWh are the consequence of the several recompression stations located along the network, which are typically fuelled by the same natural gas that flowing through the pipe. GHG emissions related to piping natural gas into the distribution network, equal to 10.55 $gCO2_{eq}$/kWh, are due to both the presence of recompression stations, but also and especially to losses occurring within local distribution networks.

Table 7 illustrates the specific GHG emissions of the final transformation devices included in the analysis.

Table 7 GHG Emissions of the final transformation devices.

Device	Final Use	Commodity	Emissions [gCO_{2eq}/kWh]
Heat Pump	SH	Electricity	0.00
Condensing Boiler	SH	Natural Gas	225.18
Electric Heater	SH	Electricity	0.00
Condensing Boiler	SH	Hydrogen	0.00
Electric Motor	PT	Electricity	0.00
ICE	PT	Natural Gas	206.14
Alkaline Fuel Cell	PT	Hydrogen	0.00
ICE	PT	Hydrogen	0.00

SH: Space Heating. PT: Passenger Transport

Naturally, all the final devices fed by both electricity and green hydrogen do not emit any GHGs. On the contrary, the combustion of natural gas is responsible for the emission of 206.14 $gCO2_{eq}$/kWh in internal combustion engines (Huss & Weingerl, 2020) and of 253.73 $gCO2_{eq}$/kWh in condensing boilers.

Table 8 illustrates the total emissions of the assessed CECs, showing the two sub-aggregates of emissions from extraction until final transformation (excluded), and the emissions occurring only in the final energy consuming device.

Direct GHG emissions from combustion represent the true downside of natural gas: when respectively considering condensing boilers and ICEs, they respectively account for 81% and 84% of total emissions along the CEC.

Table 8 GHG Emissions of the assessed energy commodity chains

Device	Final Use	Commodity	Emissions [gCO_{2eq}/kWh]		
			Extraction to Distribution	Final device	Total
Heat Pump	SH	Electricity	0.00	0.00	*0.00*
Condensing Boiler	SH	Natural Gas	54.45	225.18	*279.63*
Electric Heater	SH	Electricity	0.00	0.00	*0.00*
Condensing Boiler	SH	Hydrogen	34.23	0.00	*34.23*
Electric Motor	PT	Electricity	0.00	0.00	*0.00*
ICE	PT	Natural Gas	54.45	206.14	*245.67*
Alkaline Fuel Cell	PT	Hydrogen	34.23	0.00	*34.23*
ICE	PT	Hydrogen	34.23	0.00	*34.23*

SH: Space Heating. PT: Passenger Transport

Synoptic comparison of CECs

Table 9 wraps up the analysis and illustrates the energy and exergy efficiencies of the commodity chains, together with the figures of their overall GHG emissions.

Table 9 Synoptic view of chain energy efficiency, exergy efficiency and GHG emissions

Device	Final Use	Commodity	η_I	η_{II}	Emissions [gCO_{2eq}/kWh]
Heat Pump	SH	Electricity	2.57	0.18	0.00
Condensing Boiler	SH	Natural Gas	0.85	0.06	225.18
Electric Heater	SH	Electricity	0.81	0.05	0.00
Condensing Boiler	SH	Hydrogen	0.43	0.03	34.23
Electric Motor	PT	Electricity	0.73	0.73	0.00
ICE	PT	Natural Gas	0.33	0.33	206.14
Alkaline Fuel Cell	PT	Hydrogen	0.26	0.26	34.23
ICE	PT	Hydrogen	0.18	0.18	34.23

SH: Space Heating. PT: Passenger Transport

Regarding space heating, heat pumps are the most energy efficient devices among the considered technologies. In fact, both gas-fired condensing boilers and electric heaters require a three times larger primary energy supply to feed final uses with an equal amount of energy. Hydrogen-fired boilers instead need almost a six-times higher quantity of energy.

Results from exergy analysis show that the overall efficiencies of the chains are considerably lower than their energy counterparts: remembering that exergy is the potential amount of work exploitable by a system whose pressure and temperature are different from those of a reference state, heat transfer processes always show very low efficiencies because the exergy contained into either electricity, natural gas or hydrogen is invested to simply keep the temperature of a room as close to its setpoint as possible. Assuming the temperature of the reference state is 0 C and the setpoint's 20 C, we may say that the available work potential of the commodities is severely underexploited, because only a tiny portion is employed and its largest exergy content lost to the environment. Nonetheless, heat pumps still stand out as the most exergy-efficient devices as they do not involve any combustion, which is amongst the most exergy-destroying processes (Bejan et al., 1996).

In the passenger transports sector, the electric motor is the best performing technology in terms of energy efficiencies, as it needs less than half the amount of energy required by fuel cell vehicles, and around one quarter that of a hydrogen-fired ICE. A lower, but still considerable gap exists between electric motors and gas-fired ICEs, with the second ones needing around twice the amount of primary energy to match the performances of an electric motor.

Although the overall exergy chain efficiencies in the transport sector are numerically equal to their correspondent energy efficiencies, it is possible to draw some insightful considerations concerning exergy too. Electric motors are a preferable choice, because they convert electricity into shaft work: therefore, the quality of the incoming energy flux is not downgraded to less valuable forms of energy, such as heat. Considering the whole chain, gas-fired ICEs are the second-best performing devices. Regardless of the heavily penalizing effect exerted by combustion reactions, fuel cells lag natural gas CECs, because of the substantial inefficiency of electrolysis.

From the environmental point of view, electricity naturally outscores the other two commodities, being harvestable from renewable sources, and therefore providing the only carbon-free[13] alternative to link primary sources and their relative final uses.

The quantitative analysis and comparison of CECs shown in the previous sections is to be meant as a first, simple presentation of a methodology that can be widely applied to energy commodities, technologies and final energy users different from those illustrated here, as well as implemented choosing several other indicators. For example, CECs could also be analyzed and compared in terms of their financial and/or economic aspects choosing, for example, indicators such as the installation costs – per unit power – of the technologies deployed along the several steps of a chain, or the final energy price sustained by final consumers. However, such information is tightly related to the boundaries of the system chosen for the analysis (geographic location, time, time granularity, publicly available information) and a robust study would require a level of detail that lies beyond the purpose of this section, where the aim was to present CECs as an effective tool to compare different energy pathways for the energy transition.

2.4 Relevant technologies for electrification

The previous section briefly introduced some of the technologies potentially employable in the energy transition towards the decarbonization. More in general, the deployment of the energy transition at scale will require a proportionate growth of the pace at which both existing/consolidated and new technologies will penetrate in the future energy system.

Given the preponderant role that will be played by electricity, a more detailed and complete description of the most market-relevant, electricity-based technologies for the transition is provided in this section. Hereafter, market-relevant is meant as having been assigned a Technology Readiness Level (TRL)[17] of 8 or higher by the IEA's *ETP Clean Energy Technology Guide* (IEA, 2024b) (8: First-Of-A-Kind commercial, 9: Commercial operation in relevant environment, 10: Integration needed at scale, 11: Proof of stability reached).

Table 10 summarizes market-relevant electricity-based technologies, adding further information concerning their costs and efficiency (Corgnati et al., 2023; IEA, 2024b).

The technologies are organized in the table with respect to the step of the CEC they belong to and can both be extremely consolidated and represent the benchmark of their respective markets, as well as in a pre-market phase where the competition for the most cost-effective design is still open.

In the case of solar PV technologies, for example, the market is instead in an in-between situation. In fact, it has been dominated for years by crystalline-silicon technologies, and they still represent about 95% of the current global production.

Specifically, Passivated Emitter and Rear Cell/Contact (PERC) is the most employed PV cell architecture, capable of reaching average solar-to-power conversion efficiency of around 21.4%. However, new silicon-based architectures progressively gain relevance, especially due to PERC cells not being capable of reaching conversion efficiencies higher than 24.2%. These include, among the others, Hetero-Junction Technology (HJT) and Interdigitated Back Contact (IBC) cells, whose expected conversion efficiency could be as high as 26.7% (Bompard et al., 2025).

On the contrary, the market of wind turbines is well consolidated and dominated by one specific design, i.e., three-bladed horizontal axis turbines with blades positioned upwind, both for onshore and offshore applications.

Among energy conversion technologies, for instance, fuel cells (FCs) are indeed among those whose multiple functional designs have not yet led the market to select a single sub-technology. In fact, they can substantially differ in terms of the materials they employ, their hydrogen-to-power conversion method, and the reference pressures and temperatures they operate at. Some can only be fed by a direct hydrogen input stream, while some others have an integrated design that foresees a built-in reformer that can synthetize hydrogen from hydrocarbons. Traditionally, functional technologies of FCs available on the market are grouped based on their operating temperature: Proton Exchange Membrane (PEM) and

[17] A numerical indicator that quantifies the technological maturity of a device/process, with respect to a specific market.

alkaline (AFC) FCs work at around 100 °C-120 °C and are thus regarded as low-temperature FCs. On the contrary, high-temperature FCs include Molten carbonates fuel cell (MCFC), whose working temperature is about 600 °C-700 °C, and solid oxide fuel cells (SOFC), which have operational temperatures in the range 500 °C-1000 °C.

Table 10 Overview of the market-ready, electricity-based technologies for the energy transition

Generation

Input	*Technology*	*TRL*	*Cost [$/kW]*	*Efficiency*
Solar irradiance	PV: crystalline-Silicon	10	810-1120	0.174-0.227
	PV: multi-junction	9	4850-8240	0.392-0.471
	Floating PV	8	~ 860	0.174-0.227[18]
Water	Hydropower	11	2650-3900	0.4-0.5
	Tidal stream & tidal range	9	150-800	~0.8
Wind	Onshore wind turbine	10	1590-1950	0.29-0.35
	Seabed fixed offshore wind turbine	9	2600-3721	0.45-0.51
	Floating offshore wind turbine	8	2936-3289	0.45-0.51
Nuclear fuel	Nuclear Thermal PP – Light Water Reactor	11	2157-6920	~0.33
	Nuclear Thermal PP – Sodium Fast Reactor	10	2467	0.4-0.435
Fossil fuels	Natural gas Thermal PP with CCUS	8	2412-2826	~0.6
	Coal Thermal PP with CCUS	9	4490-5991	0.3-0.33
	Natural Gas-H_2 blend Thermal PP	9	2412-2826[19]	~0.608
Geothermal heat	Thermal PP	11	3851-10959	0.12-0.18

Storage

Type	*Technology*	*TRL*	*Cost [$/kWh][20]*	*Efficiency*
Mechanical	Pumped Hydro Storage	11	10-100	0.7-0.84
	Flywheel Energy Storage	9	1500-6000	0.70-0.95
	Compressed Air Energy Storage	8	50-80	0.7-0.8
Electro-chemical	Li-ion batteries	10	245-620	0.92-0.96
	Redox-Flow Batteries	9	315-1680	~ 0.75

Conversion

Input commodity	*Technology*	*TRL*	*Cost [$/kW]*	*Efficiency*
Hydrogen	Solid-Oxide Fuel Cell (SOFC)	9	3000-4000	0.45-0.5
	Molten Carbonates Fuel Cell (MCFC)	9	4000-6000	0.45-0.52

Transmission & Distribution

Type	*Technology*	*TRL*	*Cost [M€/km][21]*	*Efficiency*
Transmission	HVDC	11	~3.5	~0.97
	UHVAC	11	~3.1	0.93-0.94

[18] Assumed equal to c-Si.
[19] Assumed equal to conventional natural gas-fired plants.
[20] Energy installation costs
[21] Exploratory cost for a 765 kV UHVAC line and a 640 kV HVDC line.

As mentioned several times, the electrification of the future energy system will certainly see the wide diffusion of electricity generation, conversion and storage technologies, to especially cope with the expected large penetration of unpredictable and intermittent RES such as solar and wind. However, electrifying not only means replacing the existing technologies with electricity-based ones, but also to electrify the current energy corridors, as well as to build and plan new ones. In other words, electricity interconnectors will play a role of equivalent importance as generators, converters and accumulators.

For these reasons, due attention is paid to the description of the technologies devoted to power transmission in the near-future, with respect to the others presented in Table 10.

As anticipated in Table 10, the electrification process will presumably rely on the following two technologies: UHVAC (Ultra High Voltage-Alternate Current) and HVDC (High Voltage-Direct Current). Although AC infrastructures are extremely robust and widely employed at scale, their performance is bound by technical limitations, lying mainly in dealing with active-reactive power balance. On the contrary, being independent from frequency-related issues, HVDC has emerged as a preferable option for both long-distance and submarine interconnections.

Currently, HVDC systems can be classified into two main families, according to the type of DC/AC converter they adopt: *Line-Commutated Converters* (LCC) and *Voltage-Source Converters* (VSC).

Line-Commutated Converters (LCC): *LCC HVDC* systems convert DC to AC (and vice versa) adopting thyristor valves. LCC has historically represented the market benchmark for long-distance, point-to-point (P2P) power transmission, offering a reliable and cost-effective solution. Nevertheless, their applicability is severely limited in more complex power grids because they cannot be easily controllable and do not offer enough operating flexibility, thus making them less suitable in both multi-terminal systems and grids where a large penetration of renewables is expected.

Voltage-Source Converters (VSC): *VSC HVDC* employs insulated-gate bipolar transistors (IGBTs) to carry out DC/AC and AC/DC conversions. VSC systems basically fill all the technological gaps left by their LCC counterparts: in fact, thanks to their more advanced control over power flows, black start capabilities[22], and lower harmonic distortion they represent a preferable option for multiterminal configurations and the integration of non-dispatchable and unpredictable RES.

For these reasons, despite LCC being the reference DC/AC conversion technology for years, it is being replaced by VSC to better cope with the needs of

[22] The process of restoring the operation of a power system after it blacks out, without any external power supply.

newer power grids and to especially provide the necessary stability in the large presence of RES systems. More in general, regardless of the type of adopted converter, DC interconnections offer several advantages with respect to AC ones.

DC transport requires fewer cables to carry the same amount of power, resulting in a more compact and cost-effective infrastructure. In fact, although DC/AC converter stations are indeed more expensive than AC transformation stations, overall system costs tend to be lower thanks to less demanding insulation requirements that, in turn, also enable to install cheaper and shorter power lines; a reduced number of conductors; simpler right-of-way management (Shaheer Khursid et al., 2015). Moreover, DC technology enables seamless power exchanges between asynchronous networks, a particularly valuable feature whenever interconnecting regions operating at different frequencies like the Japanese grid (Shah Ayobe & Gupta, 2022). DC transmission can even yield lower transmission losses with respect to AC, if the distance from the sending to the receiving terminal is larger than the so-called *critical distance,* namely the intersection point beyond which DC losses become lower than AC losses, thus making the first more preferable for long-distance power transmission. Thanks to their more simplified and compact infrastructure, also with shorter overhead line towers, DC interconnectors have a reduced visual impact and affect the landscape less, hence potentially resulting also more socially acceptable than their AC counterparts.

From the more technical side, DC transmission has very little or negligible weight over short-circuit levels in power systems, compared to AC. Naturally, this significantly simplifies the design of short-circuit protection systems and consequently results in leaner management during the operation of the grid. In grids where more and more capacity of non-dispatchable sources is being installed, DC systems provide quicker and more precise control and regulation capability over load flows, promptly reacting to changes on both the demand and generation sides, thus strengthening the overall stability of the grid (Van Hertem & Delimar, 2013). Furthermore, DC does not propagate electromagnetic disturbances as much as AC does, once again improving the stability and reliability of the network (Mousavi et al., 2013). Lastly, VSC-HVDC offer enhanced black-start capability, greatly improving the reliability and stability of grids and being particularly important for, e.g., insular and/or less interconnected power systems (Sanchez Garciarivas et al., 2021).

HVDC interconnections are generally implemented for P2P interconnections, although there are a few examples of multi-terminal transmission lines, such as the SACOI interconnector linking mainland Italy to Sardinia with an intermediate station on French Corsica, and the Hydro-Québec – New England power line that joins the Canadian with the American grid including five converter stations (Buigues et al., 2017; Terna, 2016). So far, the highest voltage level reached for an HVDC line is that of the Chinese Changji-Guquan link: a 12,000 MW, 3,000 km long bipolar interconnector with a direct voltage of

± 1,100 kV (ABB, 2016; Stan et al., 2022). China also has the only HVDC meshed grid currently operating on a global scale, the Zhangbei VSC-HVDC, consisting in four reciprocally connected terminals shaped into a single mesh (Hitachi Energy, 2020; X. Li et al., 2021).

The cost of VSC converters and the complexity lying within the realization of meshed interconnection represent the two main current bottlenecks for the large diffusion of VSC-HVDC power lines. However, several among under construction and/or planned future HVDC interconnections are expected to employ VSC regardless of their upfront costs, as they represent a considerably more valuable alternative to build a power transmission infrastructure that can consistently cope with the expected large penetration of renewables.

2.5 Renewable Energy Sources and Critical Raw Materials

The large diffusion of renewable generators, in combination with their related technologies employable along the various steps of CECs, is a necessary condition to accelerate the process of the energy transition and of the decarbonization of the current energy system. At the same time, the wide deployment of renewables would be crucial to also relieve both producing and importing countries from their long-standing dependency on fossil fuels, as well as to ensure a more affordable access to energy to more and more citizens.

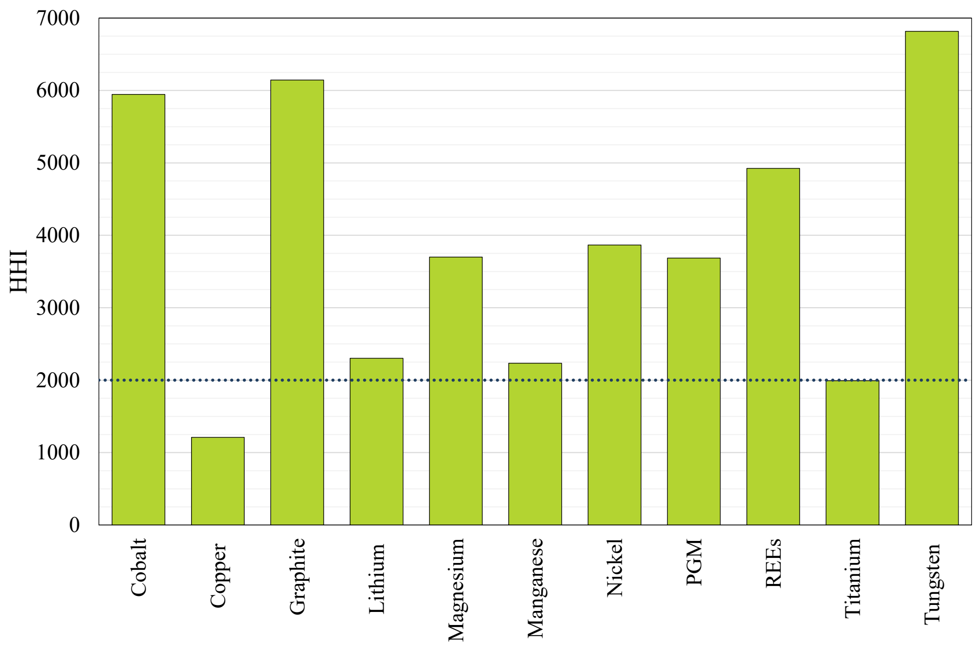
Nonetheless, the significant penetration of renewable energy systems at scale must also pay due attention to a parallel, security-related aspect. In fact, a lot of raw materials widely employed in the manufacturing of some among the most relevant technologies for the transition are scarcely allocated around the globe, thus posing potential issues with their security of supply; for this reason, they are generally called Critical Raw Materials (CRMs). For example, 76% of the 2024 global proved reserves of cobalt were located in the Democratic Republic of Congo only; 82% of the tungsten's, 78% of the Rare Earth Elements'(REEs) and 69% of the graphite's in China; 54% of the Platinum-Group Metals' (PGM: platinum, osmium, ruthenium, rhodium, iridium and palladium) in South Africa (U.S. Geological Survey, 2025).

The topic is crucial for the context of the EU27, whose industrial and manufacturing sectors need a continuous supply of CRMs, but have neither the mining, nor the refining capacity necessary to self-sufficiently match its demand. In 2011, the EU27 released a first list of 14 CRMs, which grew to 34 in 2023 (JRC, 2025). In 2024, it also issued the first edition of its *Critical Raw Materials Act*, a document underpinning the importance of strengthening the domestic production of CRMs and ensuring a sustainable and secure supply chain, while providing the main guidelines to achieve both in the near-future (European Parliament & Council of the European Union, 2024). The main targets envisage that, by 2030: 10% of the

EU27's annual needs for extraction; 40% for processing and 25% for recycling CRMs should be matched domestically. Contextually, alongside CRMs, a second list of 16 Strategic Raw Materials (SRMs) was published too, namely materials characterized by a potentially significant gap between global supply and projected demand. Specifically regarding SRMs, the Act established that no more than 65% of the EU27's supply of any SRM must be supplied by one single third country, whatever the stage of processing of the material itself.

Figure 16 provides further insights into the topic showing the values of the Herfindal-Hirshman Index (HHI) with respect to the production of some SRMs.

Figure 16 HHI values related to the production of selected SRMs (reference year: 2024)



Source: Elaboration on the USGS (U.S. Geological Survey, 2025)

The index ranges from 0 to 10,000 and is commonly used to estimate the market concentration of an industry, i.e., the size of firms with respect to the industry sector they operate in. It is analytically defined as the sum of the squared market shares of each firm, hence lower and higher values of HHI suggest that the market is more competitive or concentrated, respectively (Eurostat, 2025d).

Here, the traditional concept of HHI was borrowed to assess the geographical concentration of the production of several SRMs and spot potential bottlenecks in their supply chains knowing that, according to the EU27's guidelines, a market is concentrated if its HHI is larger than 2000 (European Commission, 2004).

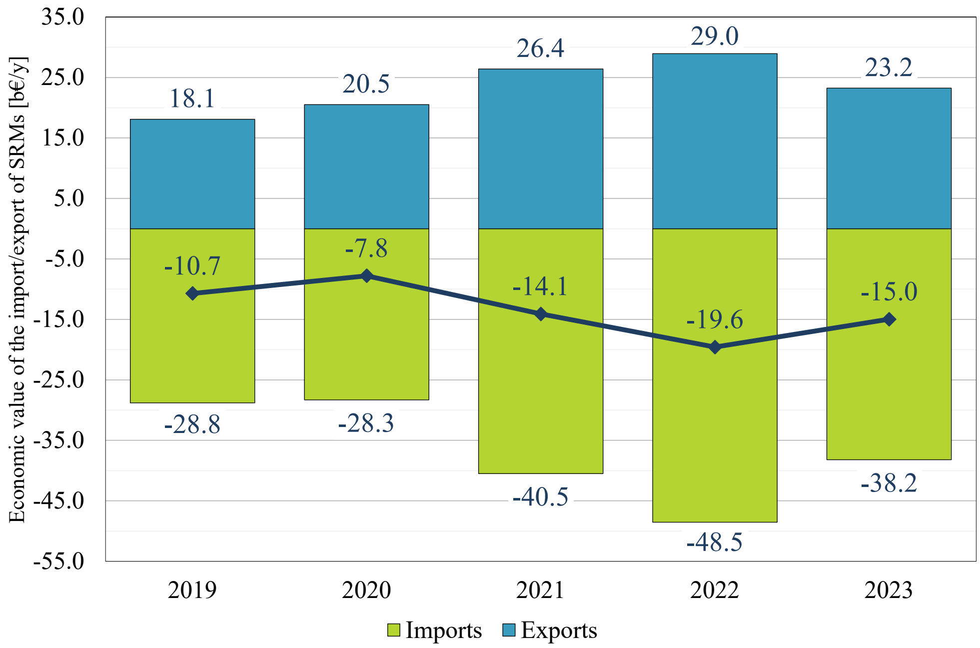
To this purpose, the figure also shows the horizontal line in correspondence of the 2000 threshold value of HHI. With the only exceptions of copper and titanium, the production of the other SRMs is more or less heavily concentrated, with peaks of around 6000 for cobalt and graphite and an even larger concentration for tungsten – almost 7000. More modest, yet not negligible HHI values characterize REEs (approximately 5000) and magnesium, nickel and PGMs, whose HHIs range from

4000 to 4500. Lithium and manganese are the only two slightly above the threshold, once more underscoring how difficult diversifying the supply chain of these materials is expected to be.

Complementing this brief analysis, Figure 16 presents the overall economic value of the imports and exports of SRMs to and from the EU27 in the years 2019-2023, at any relevant stage of processing[23].

Imports are meant as those coming from extra-EU27 countries, while exports are from EU272 countries instead. The figure also displays, in dark blue, the year-specific 'import – export' trade balance[24], which intuitively heavily leaned towards the export side every year, with a gap that significantly widened in 2022 when imports of SRMs costed the EU27 around 48.5 b€, in comparison to only 29.0 b€ gained from their exports, implying a monetary gap of 19.6 b€/y.

Figure 17 Economic value of the imports and exports of SRMs to and from the EU27 in the years 2019-2023



Source: Elaboration on Eurostat (Eurostat, 2025c)

More in general, the economic value of EU27 exports approximately matched only two thirds of the corresponding value of extra-EU27 imports every year, highlighting a systematic and structural problem in the supply chain of SRMs for the EU27. In fact, not only it is clearly unprofitable, but it severely binds the EU272 to be dependent on producing and/or processing countries for a considerable part of its overall supply.

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[23] Extraction and mining, refining and processing, manufacturing, recycling
[24] For some SRMs, values were not available for all five years.

Targets set by the *Critical Raw Materials Act* appear extremely ambitious given the current status of the EU27's CRMs and SRMs supply chains. Considerable efforts need to be put in place, if the EU27 wants to make sure its future energy system not only is sustainable environmentally, but also and more importantly from the point of view of energy security and affordability.

2.6 Conclusions

Competition and cooperation among energy commodities might be promising drivers to accomplish the transition towards a decarbonized energy system. The choice of a specific commodity depends on how it ranks in terms of one or more among the several attributes of an energy system: in fact, giving importance to a specific one usually leads to decisions that deprioritize the others. In this chapter, the multidimensional impacts of several CECs were quantified and reciprocally compared considering their energy and exergy efficiencies and their GHG emissions along the path from generation to final consumption.

Among renewable electricity, green hydrogen, and natural gas, the first generally emerges as a preferable option because electrical appliances provide better energy and exergy efficiencies and have a null carbon-footprint. When looking at environmental sustainability, hydrogen could also be a competitive alternative, considering the modest amount of emissions that characterize electrolysis-based chains, occurring only at the very last stage of hydrogen distribution to final consumers. Not to mention, hydrogen CECs could also be completely carbon-free if green hydrogen itself were employed to feed the ancillary systems. However, electrolysis-based hydrogen is hardly chosen over electricity and natural gas because of the current low conversion efficiencies of electrolyzers which reduce the available amount of energy by around 40%. Nonetheless, technological inefficiency may be offset considering that green hydrogen offers a carbon-free alternative to both store energy (and achieve effective time-decoupling between generation and demand) and decarbonize some hard-to-abate sectors.

In the framework of the transition to decarbonization, the shift towards greener technologies would significantly improve the sustainability of the energy system, but at the same time raise relevant issues related to the security of supply of some raw materials necessary to manufacture the devices commonly employed in both electricity and green hydrogen CECs. In fact, since both their resources and their refining and processing capacities are scarcely allocated, they expose import-dependent countries to the impacts of speculation and monopolistic trade policies.

Such considerations further underline the unbreakable link among the three attributes of the Trilemma and the complexity behind their effective balance, having proved how committing to only one of them could lead to put the integrity of the other two at stake.

Chapter 3

The role of the Mediterranean Basin in the energy transition

This chapter investigates the role of the Mediterranean Basin and its countries in the framework of the energy transition towards decarbonization. The area is worth investigating in light of the diversity and heterogeneity that characterize its different locations and the relevance of the Basin in terms of global socioeconomics, energy and environmental impact. In fact, within the context of the energy transition, the simultaneous presence of energy-dependent and oil&gas exporting countries makes it the perfect candidate for the application of the concepts of Energy Trilemma and CECs.

The next sections provide a detailed portrait of the Mediterranean energy system, illustrating how the long-standing trade of fossil fuels among its countries has shaped its current energy system, and how efforts that are being put in place could hopefully drive the Basin away from its historical "black" energy dialogue, shifting towards a new framework based on the production and trade of renewable electricity and its derived commodities.

3.1 The Mediterranean Basin: a multifaceted area

The Mediterranean Basin occupies only 6% of the total global surface. Nonetheless, its population in 2023 – approximately 553 million persons – represented 6.9% of the world total and its GDP (9.4 trillion USD) even more than 10%, pulled by two among the largest global economies, namely France and Italy. For what GHG emissions are concerned, in 2022 they were 3.2 $GtCO_{2eq}$, accounting for about 5.9% of the world total (JRC, 2023; The World Bank, 2024).

In the following sections, Mediterranean countries are grouped into three so-called 'shores', displayed in Figure 18.

- *Northern Shore*: Albania, Bosnia-Herzegovina, Croatia, France, Greece, Italy, Malta, Montenegro, Portugal, Slovenia, Spain
- *Southern Shore*: Algeria, Egypt, Libya, Morocco, Tunisia
- *Eastern Shore*: Cyprus, Israel, Lebanon, Syria, Türkiye

The grouping was made according not only to the geographic position of each country but also considering their reciprocal affinities and differences.

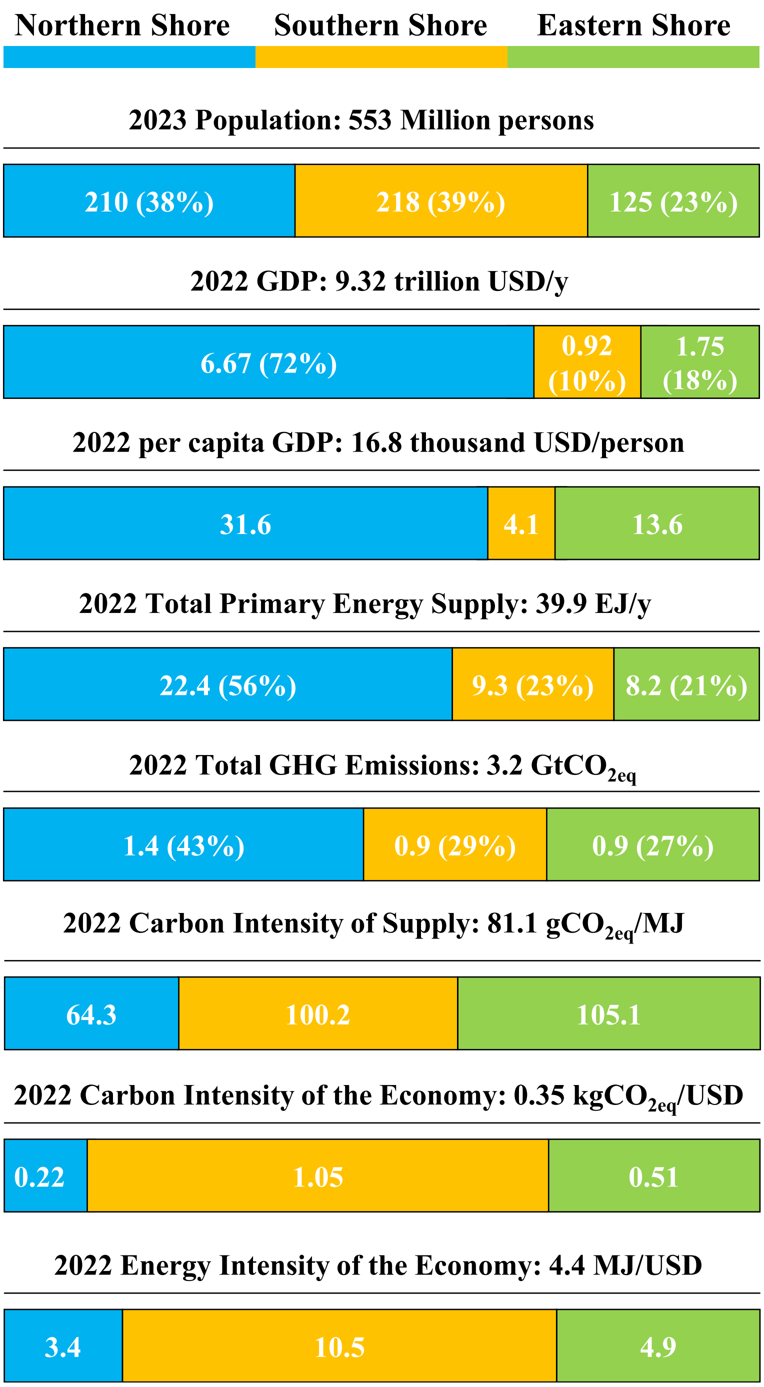
Figure 18 The three Mediterranean Shores

Figure 14 illustrates some among the most relevant socioeconomic, energy, and environmental indicators and indexes for the Mediterranean Basin and its shores.

80% of the Mediterranean population is about equally split between the Northern Shore (210 million persons, 38% of the total) and the Southern Shore (218 million persons, 39% of the total), which is also home to the most populous country of the Mediterranean Basin, i.e., Egypt, with 115 million persons that account for 21% of the Mediterranean population. The remaining 125 million persons in the Eastern Shore predominantly live in Türkiye, whose population of more than 85 million persons weights for 68% of the entire shore's population (The World Bank, 2024).

When looking at shore-specific values of GPD instead, the situation is largely unbalanced towards the Northern Shore with its GDP of 6.67 trillion USD, corresponding to 72% of the Mediterranean's, pulled by some of the largest world economies, namely France (GDP: 2.65 trillion USD, 29% of Mediterranean and 7th globally), Italy (GDP: 2.00 trillion USD, 22% of Mediterranean and 8th globally) and Spain (GDP: 1.35 trillion USD, 15% of Mediterranean and 14th globally).

Figure 14 Main socioeconomic, energy, and environmental indicators and indexes for the three Mediterranean shores



Source: Elaboration on the WorldBank and IEA (IEA, 2024a; The World Bank, 2024)

On the contrary, the GDP of the Eastern Shore (1.75 trillion USD) is just 18% of the Mediterranean's, once again led by Türkiye that accounts for 71% of its shore alone. Southern Shore's GDP, 0.92 trillion US$, is the smallest among the three and only represents 10% of the Mediterranean Basin. An analogous subdivision characterizes per capita GDP, with the Northern Shore leading with 31.6 thousand USD/person, followed by the Eastern Shore with 13.6 thousand USD/person and the Southern Shore with 4.1 thousand USD/person. Country-specific values highlight substantial differences not only among the shores, but also within the shores themselves: for example, in the Eastern Shore there are both the richest and poorest countries of the entire Mediterranean Basin, in terms of per capita GDP: Israel and Syria, showing values of 42.7 thousand USD/person and 0.7 thousand USD/person, respectively (The World Bank, 2024).

The Mediterranean Total Primary Energy Supply (TPES)[25] is mainly allocated to the Northern Shore with 22.4 EJ/y out of 39.9 EJ/y, although 88% relates to France, Italy and Spain only. The remaining 17.5 EJ/y is almost evenly divided between the Eastern Shore and the Southern Shore. 80% of the Eastern Shore's TPES (6.6 EJ/y out of 8.2 EJ/y) is absorbed by Türkiye alone, while 76% of the Southern Shore's by Algeria and Egypt (7.1 EJ/y out of 9.3 EJ/y) (IEA, 2024a).

The distribution of the total GHG[26] emissions in the Mediterranean is more even among the three shores: the Northern Shore is the largest emitter with 1.4 $GtCO_{2eq}$/y, the Southern and Eastern respectively following with around 0.9 $GtCO_{2eq}$/y each. The country with the largest total GHG emissions is Türkiye (688 $MtCO_{2eq}$/y), with 21.2% of the Mediterranean total GHG emissions. Türkiye itself and other four countries only – France, Italy, Spain and Algeria – overall account for 69% of the total GHG emissions in the entire Basin (JRC, 2023).

So far, the situation of the Mediterranean Basin was portraited considering only simple indicators. However, a more exhaustive analysis could be traced if composite indicators were taken into consideration too. In fact, values of the carbon intensity of supply (the ratio between the total GHG emissions and the TPES) show that the least carbon intensive shore is the Northern with 64.3 gCO_{2eq}/MJ, compared against a Mediterranean average of 81.1 gCO2eq/MJ. In contrast, both the Southern Shore and the Eastern Shore show higher-than-average values, respectively 100.2 gCO_{2eq}/MJ and 105.1 gCO2eq/MJ. Similarly, when looking at the carbon intensity of the shores' economies (defined as the ratio between the total GHG emissions and the GDP), the Northern Shore is the one with the lowest value of 0.22 $kgCO_{2eq}$/US$, starkly contrasting with that of the Eastern Shore (0.51 0.22 $kgCO_{2eq}$/US$) and even more with the Southern's, whose carbon intensity of the economy – 1.05 0.22 $kgCO_{2eq}$/US$ – is about five times larger. These two indexes hint at how both the smaller TPES and total GHG emissions of the Southern Shore and Eastern Shore are simply the consequence of them being smaller energy consumers than the Northern Shore. However, their respective carbon intensities show how less environmentally sustainable their energy mixes are. In addition, looking also at the values of energy intensity – the ratio between TPES and GDP, hence providing an estimate of how efficient an energy mix is –

[25] The sum of the total endogenous energy production, net imports, stock changes and international aviation and marine bunkers of a country/area (IEA, 2023b)

[26] Includes emissions from electricity and heat generation in power plants, industrial combustion and processes, stationary combustion in buildings, transport, agriculture, waste disposal, fuel extraction and refining. Does not include emissions from Land Use, Land-Use Change and Forestry (LULUCF) (JRC, 2023).

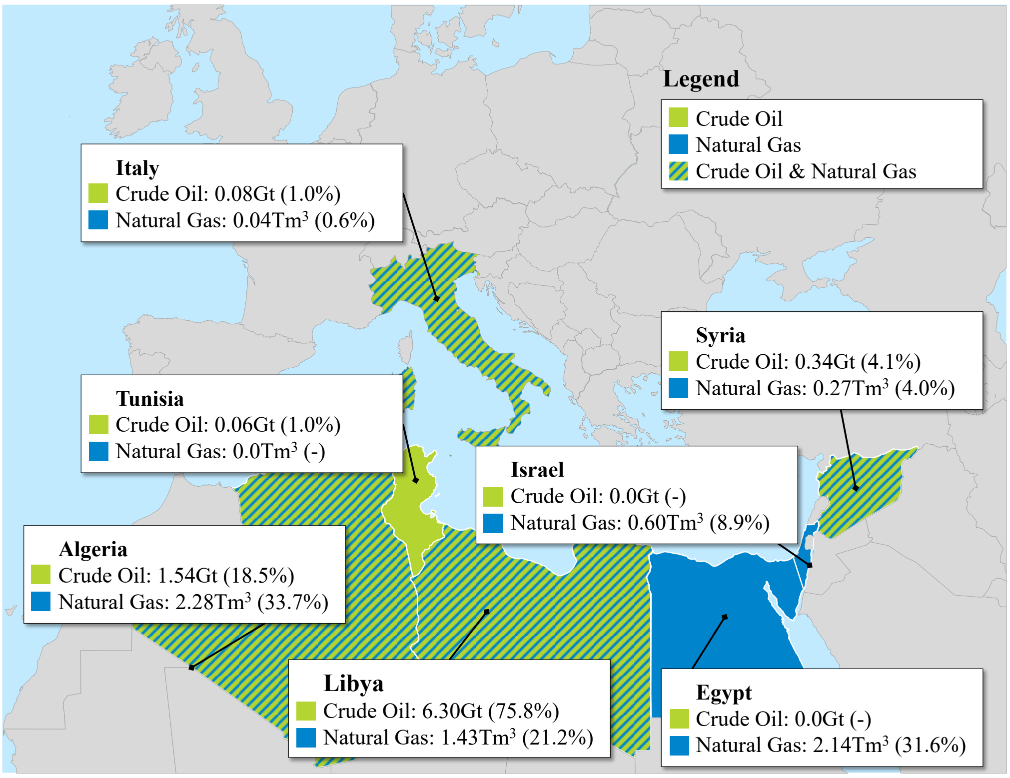
the Northern Shore emerges as the most energy-efficient with an energy intensity of just 3.4 MJ/US$, compared to 4.9 MJ/US$ of the Eastern Shore and 10.5 MJ/US$ of the Southern Shore.

Although introductory, these figures already help to understand how complex and multifaceted the process of energy transition in the Mediterranean would be, given how heterogeneous the frameworks of the three shores are.

3.2 The role of fossil fuels and the historical black energy dialogue

The Mediterranean Basin has been historically crossed by flows of crude oil, refined petroleum products (RPP) and natural gas, predominantly leaving from the Southern Shore and exported to the Northern and Eastern shores. This historical trend is mainly the natural consequence of the geographical distribution of these resources in the Mediterranean area, as illustrated in Figure 15 (Energy Institute, 2024).

Figure 19 Proved reserves of crude oil and natural gas in the Mediterranean Basin



Source: Elaboration on BP (Energy Institute, 2024)

Overall, the Mediterranean Basin hosts 3.4% and 3.6% of the global crude oil and natural gas proved reserves, as of 2021. However, their distribution is extremely uneven. In fact, 94.2% of the Mediterranean crude oil reserves – meaning 7.84 Gt out of 8.32 Gt is in Algeria and Libya, the second accounting for 76% alone and the first among all the African countries in terms of oil reserves. Smaller reserves in the Eastern Shore are in Syria (0.34 Gt, approximately 4.1%), while the only Northern Shore country possessing oil reserves is Italy, although to a negligible extent – not even 1%. Similarly, the quasi-totality of the Mediterranean natural gas reserves is in Algeria, Egypt and Libya only, which together account for 86.5% of the total, translating to 5.85 Tm^3 out of 6.76 Tm^3. More abundant (than crude oil) reserves are in the Eastern Shore (0.87 Tm^3, equal to 12.9%), split between Syria and Israel, therefore only 0.6% of the Mediterranean natural gas reserves belong to the Northern Shore.

The unbalanced allocation of fossil resources in the Mediterranean Basin consolidated an energy dialogue based on the trade of oil and gas leaving from the Southern Shore and exported to the other two. To this purpose, Table 11 illustrates the yearly imports of crude oil, RPP and natural gas of the Northern Shore and Eastern Shore together in the decade 2013-2023, detailing the portion exported from the Southern Shore and its weight over the total imports (Eurostat, 2025b).

On average, crude oil imports from the Southern Shore always weighed more than 12% and fluctuated above and below 30 Mt/y, with peaks of 16.51% (35.02 Mt/y) in 2019 and 15.20% (34.84 Mt/y) in 2023. On the contrary, the import dependency on the RPP exported from the Southern Shore oscillated between about 7% and 8%, except increases of 8.77% (9.39 Mt/y) and 8.88% (9.80 Mt/y) registered in 2020 and 2021, respectively.

When looking at natural gas imports, the Southern Shore has always been a major trading partner for the Northern and Eastern ones. In fact, on average it matched 23.55% of their total imports.

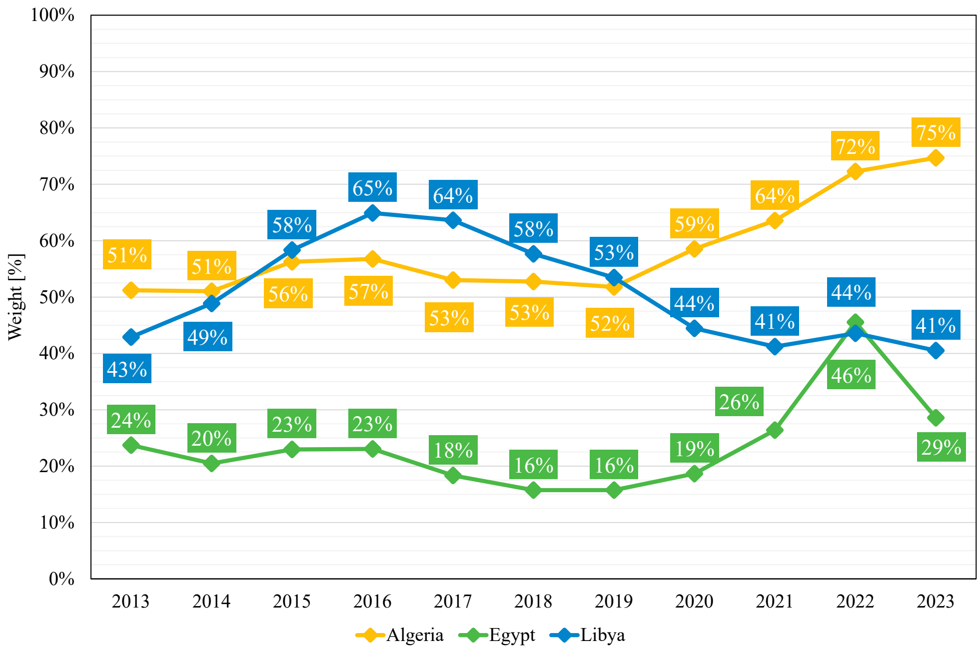
Table 11 Crude oil, RPP and natural gas export flows from the Southern Shore (SS) to the Northern and Eastern Shores in the decade 2013-2023

	Imports	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Crude Oil	Total [Mt/y]	221.95	215.57	246.04	243.76	255.70	242.81	244.13	201.85	212.16	231.70	229.21
	From SS [Mt/y]	30.96	22.71	23.01	20.79	27.02	31.38	34.26	17.74	35.02	32.78	34.84
	SS weight [%]	*13.95*	*10.54*	*9.35*	*8.53*	*10.57*	*12.92*	*14.03*	*8.79*	*16.51*	*14.15*	*15.20*
RPP	Total [Mt/y]	100.86	104.89	107.82	115.48	120.53	123.58	121.64	107.14	110.41	110.64	111.61
	From SS [Mt/y]	7.22	7.69	8.25	8.01	8.68	9.38	8.56	9.39	9.80	8.87	8.50
	SS weight [%]	*7.16*	*7.33*	*7.65*	*6.94*	*7.20*	*7.59*	*7.04*	*8.77*	*8.88*	*8.02*	*7.61*
Natural Gas	Total [Gm^3/y]	196.91	190.97	191.77	196.95	218.44	212.14	220.39	204.27	227.60	234.45	206.97
	From SS [Gm^3/y]	49.62	45.61	44.64	54.80	52.83	51.03	43.41	39.21	54.01	53.88	51.82
	SS weight [%]	*25.20*	*23.89*	*23.28*	*27.83*	*24.19*	*24.05*	*19.70*	*19.20*	*23.73*	*22.98*	*25.04*

The yearly historical trend registered a peak of 54.80 Gm^3/y out of 196.95 Gm^3/y in 2016, then steadily decreased to a minimum of 39.21 Gm^3/y (accounting for 19.20%), before ramping up again the following year and topping at 51.82 Gm^3/y in 2023, when it weighed 25.04%.

Among Southern Shore countries, Algeria, Egypt and Libya are the three major exporting countries of the shore and can be regarded as *rentier states*, meaning they source a considerable part of their income from selling a limited number of goods – in their specific cases, naturally, oil and gas. This implies that, if Northern and Eastern Shore countries depend on these three countries to match a considerable part of their oil and gas demand, Algeria, Egypt and Libya conversely rely on the export of fossil fuels to the other two shores in terms of total revenues: indeed, **Errore. L'origine riferimento non è stata trovata.** illustrates, for the 2013-2023 period, the percentage weight of their economic value of the exports of crude oil and natural gas[27] to the Northern Shore and Eastern Shore over the total value of exports.

Figure 20 Weight of the economic value of exports of crude oil and natural gas to the Northern and Eastern shores over total economic value of exports



Source: Elaboration on CEPII (CEPII, 2025)

Algeria sourced more than half its fossil fuels-derived income from sales of crude oil and natural gas to the Northern Shore and the Eastern Shore, registering a substantial growth from 2019 onwards, when the share grew from 52% to 75%. Libya's economic dependency on the other two Mediterranean shores peaked at 65% in 2016 before steadily decreasing in the following years, despite never dropping below 40%. The Egyptian weight of crude oil and gas exports has been instead lower and oscillating above and below 20%, except for year 2022 when it peaked at 46%, following the increased need of the countries of the Northern Shore

[27] Includes both natural gas sent via pipeline and maritime supplies of LNG

to diversify the oil and gas supplies after the beginning of the Russo-Ukrainian conflict.

This two-folded, energy-economy dependency on the trade of oil and gas underscores how difficult a homogeneous energy transition towards decarbonization in the Mediterranean Basin would be.

In fact, the Northern Shore and the Eastern Shore need the Southern Shore to match their internal oil and gas supplies. Conversely, the rentier states of the Southern Shore need the other Mediterranean countries to not lose a considerable portion of the income coming from exporting crude oil and natural gas abroad.

3.3 An underexploited renewable generation potential

The Mediterranean Basin could be a fertile ground for the deployment of the energy transition at scale, as it possesses promising solar and wind intensities that could be effectively harnessed to generate electricity. The distribution of solar irradiances and wind speeds varies across the three shores and within their countries. Table 12 shows the average, shore-specific values of Global Tilted Irradiance (GTI) and wind speed (at a height of 100 m) for the three shores and the entire Mediterranean Basin (DTU & World Bank Group, 2024; World Bank Group et al., 2024).

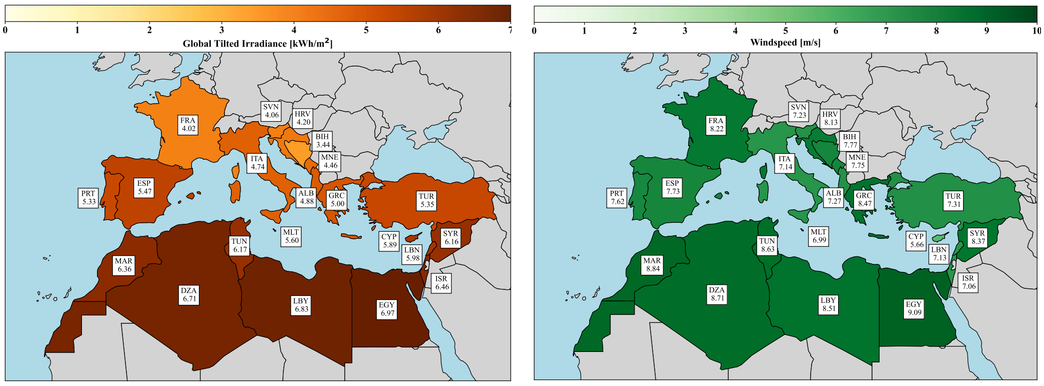
Table 12 Average GTI (per day) and wind speed in the Mediterranean Basin

Area	**GTI**		**Wind speed at 100 m**	
	Value [kWh/m²]	*p.u.*	*Value [m/s]*	*p.u.*
Southern Shore	6.62	1.00	8.76	1.00
Eastern Shore	5.97	0.90	7.11	0.81
Northern Shore	4.65	0.70	7.67	0.88
Mediterranean Basin	***5.49***	***0.83***	***7.79***	***0.89***

The Southern Shore has the most promising solar and wind intensities in the entire Mediterranean Basin. In fact, its average GTI and wind speed are 6.62 kWh/m^2 and 8.76 m/s, respectively. In comparison, the GTI of the Eastern and Northern shores is 0.90 and 0.70 times – and their wind speeds 0.81 and 0.88 – smaller. Figure 21 shows also the country-specific values for both GTI and wind speed at 100 m.

When looking at the values of GTI, Egypt is the country benefitting from the highest solar intensity of 6.97 kWh/m^2, followed by Libya with 6.83 kWh/m^2 and Algeria with 6.71 kWh/m^2. In the Eastern Shore, promising GTIs are found in Israel (6.46 kWh/m^2) and Syria (6.16 kWh/m^2), while in the Northern Shore the average GTI is below 5.50 kWh/m^2 anywhere, with the only exception of Malta (World Bank Group et al., 2024).

Figure 21 Solar and wind intensities of Mediterranean countries



Source: Elaboration on Solar Atlas and Wind Atlas (DTU & World Bank Group, 2024; World Bank Group et al., 2024)

In terms of wind speed, Egypt ranks in the first place again with an average of 9.09 m/s, followed by Morocco (8.84 m/s) and Algeria (8.71 m/s). Promising wind speeds are more evenly distributed across Mediterranean countries: for example, Greece and France can respectively harness promising average wind speeds of 8.47 m/s and 8.22 m/s while, in the Eastern Shore, Syria can exploit wind intensities of 8.37 m/s (DTU & World Bank Group, 2024).

The Southern Shore could be the main player in the Mediterranean energy transition. In fact, its extremely favorable solar and wind intensities would enable it to harvest them and generate large amounts of renewable electricity exploiting solar (both photovoltaic and thermal) and wind (onshore and offshore) generators.

However, very little of both the currently installed PV and wind generation capacity in the Mediterranean Basin is presently located in the Southern Shore, as shown in Table 13**Errore. L'origine riferimento non è stata trovata.**. Out of 112.50 GW of PV installed capacity, 81.9% is in the Northern Shore only (92.09 GW), while additional 17.24 GW in the Eastern Shore, meaning that only 3.17 GW is installed in the Southern Shore, corresponding to just 2.8% of the total Mediterranean installed capacity. The same subdivision characterizes the allocation of the installed capacity of onshore wind generators, 82.7% of which is in the Northern Shore (77.29 GW) and 13.2% in the Eastern Shore (12.18 GW, although heavily biased by 11.70 GW installed in Türkiye only) When looking more closely at country-specific data, France, Italy, Spain and Türkiye alone account for 80.3% (90.33 GW) and 82.1% (76.72 GW) of the total Mediterranean PV and onshore wind installed capacity, reasonably due to being the main energy consumers in the Mediterranean Basin (IEA, 2024a).

Figure 22 provides additional insights and also shows the division between the total RES and non-RES installed in the Mediterranean countries.

In Albania, Croatia and Montenegro the share of RES is above 60% (with Albania almost reaching 100%) thanks to the large exploitation of hydropower. In Italy, Spain, Greece and Portugal, the more favorable latitudes enable a more effective exploitation of PV and wind generators bringing, for example, the Spanish

RES share above 62% and the Portuguese one to even more than 77%. In the Eastern Shore, Türkiye is the only country whose share of RES (55.0%) accounts for more than half the total electricity installed capacity, yet modest shares of RES can be found in Cyprus (34.3%) and Lebanon (31.8%).

Table 13 2023 PV and wind installed capacity in Mediterranean countries

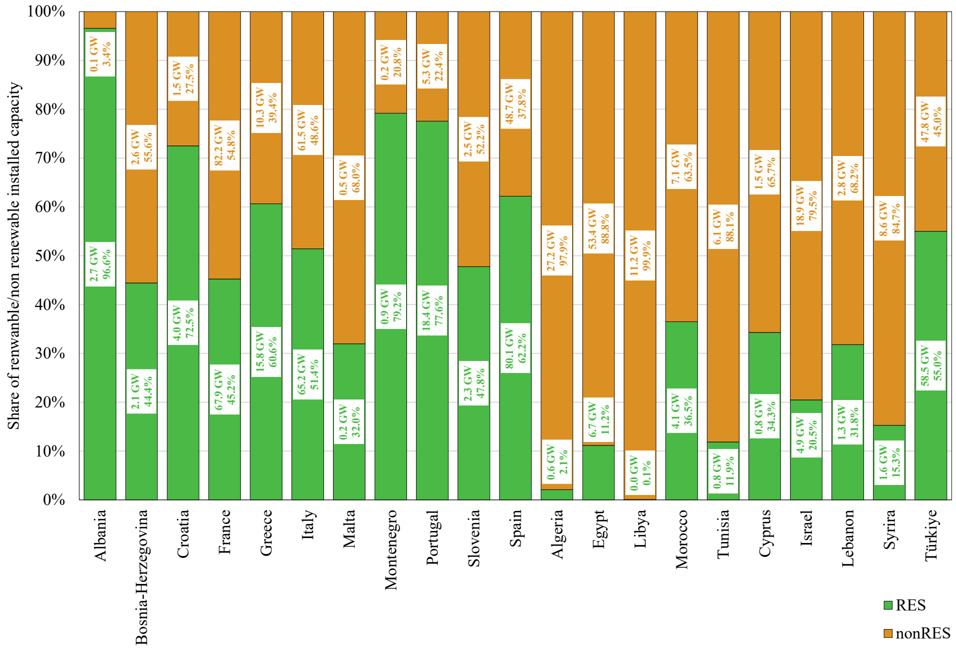
	Solar PV		**Wind**	
Country/Area	*Value [GW]*	*Share [%]*	*Value [GW]*	*Share [%]*
Albania	0.24	0.2	0.00	0.0
Bosnia-Herzegovina	0.13	0.1	0.14	0.1
Croatia	0.46	0.4	1.14	1.2
France	20.54	18.3	21.65	23.2
Greece	7.03	6.2	5.22	5.6
Italy	29.79	26.5	12.34	13.2
Malta	0.23	0.2	0.00	0.0
Montenegro	0.04	0.0	0.12	0.1
Portugal	3.88	3.4	5.64	6.0
Slovenia	1.03	0.9	0.00	0.0
Spain	28.71	25.5	31.03	33.2
Northern Shore	*92.09*	*81.9*	*77.29*	*82.7*
Algeria	0.43	0.4	0.01	0.0
Egypt	1.84	1.6	1.89	2.0
Libya	0.01	0.0	0.00	0.0
Morocco	0.39	0.4	1.86	2.0
Tunisia	0.51	0.4	0.25	0.3
Southern Shore	*3.17*	*2.8*	*4.00*	*4.3*
Cyprus	0.61	0.5	0.16	0.2
Israel	4.28	3.8	0.32	0.3
Lebanon	1.00	0.9	0.00	0.0
Syria	0.06	0.1	0.00	0.0
Türkiye	11.29	10.0	11.70	12.5
Eastern Shore	*17.24*	*15.3*	*12.18*	*13.0*
Mediterranean	***112.50***	***100.0***	***93.46***	***100.0***

Source: Elaboration on IRENA (IRENA, 2024b)

In the Southern Shore, the only country with a non-negligible share of RES is Morocco, where renewables account for 36.5% of the total electricity installed capacity. On the contrary, in all the other four countries the relevance of RES is extremely limited if not almost inexistent, such as in the cases of Algeria (2.1%) and Libya (0.1%) (IRENA, 2024b).

The distribution of the PV and wind, and more in general of the RES installed capacity in the Mediterranean Basin is in stark contrast with where the most promising solar and wind generation intensities are. In fact, despite benefitting from the most favorable values of both GTI and wind speed, the Southern Shore is the area – in the Mediterranean Basin – where both PV and wind generation are the least exploited.

Figure 22 2023 Total RES and non-RES installed capacity in Mediterranean countries



Source: Elaboration on IRENA (IRENA, 2024b)

Such a paradoxical situation is directly linked with the vast availability of fossil fuels in the Southern Shore and, more precisely, in its three rentier states – Algeria, Egypt, and Libya. The decarbonization of the energy system of the Southern Shore struggles to be as effective and consistent as in other areas of the Mediterranean Basin because – although not the only reason – the economic system of its three largest countries is too tightly bound to the exploitation of fossil fuels.

3.4 Mediterranean policy frameworks for the energy transition

The energy transition in the Mediterranean Basin is happening at different rates of deployment on the three shores and among its countries. The Northern Shore and other countries such as Cyprus, Türkiye and Morocco, also pulled by the need of reducing their energy import dependency, are steadily driving away from fossil fuels and targeting more sustainable sources of energy, with RES naturally in the first place. In parallel, this enables them to also increase their endogenous electricity generation and consequently strengthen their energy security. On the contrary, the shift towards a decarbonized energy system in oil and gas producing/exporting countries of the Mediterranean is heavily hindered by – among several reasons –

the large availability of fossil fuels themselves, which constitute a firm pillar of their economies.

The pace at which the transition happens in the different Mediterranean countries is also strictly linked to the commitment of both national governments and supranational bodies to the topics of sustainability and decarbonization.

In the Northern Shore, the EU27 MS have been encouraged to widely introduce RES in their energy mixes since 2009, when the first version of the *Renewable Energy Directive* (REDI) was issued (European Parliament & Council of the European Union, 2009): here, countries were bound to ensure at least 20% of the total energy consumption and 10% of the energy consumption in transports had to come from renewables; contextually, it also set country-specific targets. More importantly, it required MS to submit a report every two years detailing the trajectories and the measures undertaken (or planned to be) to achieve their decarbonization targets and track their progress. In 2018, REDI was overwritten by its first revision, commonly known as REDII (European Parliament & Council of the European Union, 2018): the second version of the directive imposed a new, binding target of at least 32% and 14% renewables in final gross energy consumption and transports respectively, to be achieved by 2030. In addition, member countries had to integrate it as a national law by June 2021 and deliver to the European Commission their first 10-year National Energy and Climate Plans (NECPs) by 2023, to be updated once every two years.

In 2019, the European Commission issued the *European Green Deal*, a set of policies and measures devoted to achieving the ambitious target of net carbon neutrality by 2050 and accomplish economic growth detached from the extensive use of resources (The European Green Deal, 2019). The Green Deal set the baseline for the *Fit for 55* package that came into force in 2021 and corroborated the proposals and guidelines published two years before, with the ultimate goal of reaching an overall reduction of 55% in GHG emissions, with respect to the 1990 value (European Commission Secretariat-General, 2021).

In 2022, following the beginning of the Russo-Ukrainian crisis, the *Fit for 55* package was updated by the *REPowerEU* set of measures, which aimed at accelerating the path towards carbon neutrality, while phasing-out the supplies of Russian oil and gas (European Commission Secretariat-General, 2022). Lastly, in 2023 the third revision of the RED, known as REDIII, came into action and further increased the target share of RES in EU27's final energy consumption to 42.5%, while trying to make the administrative procedures for the approval of new renewable power plants leaner (European Parliament & Council of the European Union, 2023).

In the Southern Shore, the absence of a supranational entity capable of coordinating and guiding the initiatives and the policy-making process of its countries – especially when looking at the topics of sustainability and decarbonization – is among the reasons why the energy transition in this area is still significantly hobbling. Moreover, because of the frequent tensions and geopolitical instabilities ongoing both within and between countries, the theme of sustainability is hardly prioritized. Indeed, frictions between states can even threaten the security of their supplies. For example, at the end of 2021, Algeria halted gas supplies to Morocco through the Maghreb-Europe-Gas Pipeline (Bilde, 2021).

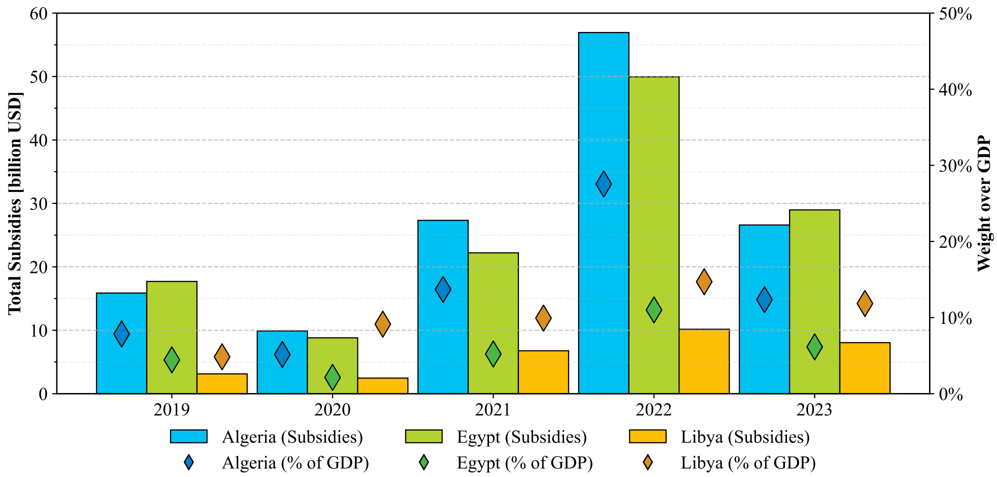
As mentioned, the tight bond between national economies and fossil fuels in the rentier states of the Southern Shore is among the reasons that dramatically prevent the process of the energy transition to take place. Another direct consequence of the large availability of fossil fuels in such countries, in turn responsible for the slow pace of the energy transition, is the diffuse deployment of fossil fuels subsidies in oil and gas producing countries. Subsidies consist in financial and fiscal relief measures provided by national governments to their citizens (here, to be intended as final energy consumers) when purchasing fossil fuels and electricity, which can be bought at prices lower than their market reference price. Figure 23 shows the total value of the oil, natural gas and electricity[28] subsidies in the three rentier states of the Southern Shore in the period 2019-2023, also highlighting how much they weighed with respect to their national GDP.

The trend of subsidies immediately shows how the Russo-Ukrainian crisis impacted oil and gas exporting countries too. In fact, a sharp increase was registered from 2021 to 2022, when subsidies doubled (or almost doubled) in each country, passing from 27.3 billion USD/y to 56.9 billion USD/y in Algeria, from 22.2 billion USD/y to 50.0 billion USD/y in Egypt, and from 6.8 billion USD/y to 10.2 billion USD/y in Libya. Consistently, their weight on the national GDPs also increased, reaching 28%, 11% and 15%, respectively.

More in general, subsidization policies in the three countries always consumed a non-negligible portion of their GDP, with the only exception of 2020, although due to the economic recession that characterized the pandemic period (IEA, 2025).

[28] Included in the analysis, considering that it is almost entirely produced in thermal power plants

Figure 23 Total value of subsidies in Algeria, Libya and Egypt in the period 2019-2023 and weight over national GDP



Source: Elaboration on IEA's Fossil Fuel Subsidies Database (IEA, 2025)

Although safeguarding final consumers from the effects of fuel prices volatility, subsidies also encourage the large and inefficient use of fossil fuels instead of more sustainable solutions, therefore hindering the energy transition process. Subsidies also drain public funds that could otherwise be invested to implement climate adaptation and/or mitigation measures. In this regard, they also obstacle the implementation and diffusion of effective social and energy equity measures, as they generally advantage the middle/high-income parts of the population more, which most of times are also the larger consumers of both fossil fuels and electricity (IEA, 2023a; Mahjoubi et al., 2024). Therefore, phasing-out subsidies to fossil fuels would be another among the key enablers of a clean and just energy transition.

Countries of the Eastern Shore are differently positioned along their respective energy transition paths. Cyprus, as a MS of the EU27, is aligned with both the action plans and the guidelines set by the European Commission (*REPowerEU*, *REDIII*, etc.) and can benefit from its continuous support like most countries of the Northern Shore. Indeed, it submitted its latest NECP in July 2023 (Republic of Cyprus, 2024)).

Both Israel, Lebanon and Syria are committed to the improvement of the sustainability of their energy systems: the first is pursuing the phasing-out of all coal-fired power plants (to be replaced by natural gas) by 2025 and a 30% target of RES production by 2030 (Ministry of Environmental Protection, 2023). Lebanon seeks to achieve the same share of RES in final energy consumption by 2030 (IRENA, 2020b), while Syria is planning to add further 2.5 GW of solar PV and 1.5 GW of wind generation capacity – currently only 0.06 GW of PV capacity is installed (Al-Attar, 2025).

However, despite the efforts undertaken – at least on paper – towards more sustainable energy mixes, the regional geopolitical tensions and conflicts inevitably drive the attention of the local governments and policy decision-makers away from these themes.

On the contrary, being both one among the largest energy consumers, as well as the richest economies in the Mediterranean Basin, Türkiye is successfully matching its renewable energy and energy efficiency targets: in fact, as of February 2025, both the solar PV (17.9 GW) and onshore wind (13.1 GW) targets set for 2025 by the Turkish government in its National Energy Strategy have already been met and overcome (Energy Exchange Istanbul (EXIST), 2025; Ministry of Energy & Natural Resources, 2022).

3.5 Perspectives for a Mediterranean green energy dialogue

The previous section highlighted how the energy transition process is happening fragmentedly and at starkly different paces across the Mediterranean Basin: while Türkiye, Morocco, and the countries of the Northern Shore keep pursuing their paths towards sustainability and decarbonization, other Mediterranean countries and – particularly – Algeria, Egypt and Libya, are not able to steer away from fossil fuels. In fact, they still represent a substantial asset of their economic systems, paradoxically implying that the areas where the most promising solar and wind intensities could be harnessed are actually those where they are the most underexploited.

However, in the context of the energy transition, renewable electricity produced by solar and wind generators will likely play a pivotal role, thanks to its opportunity of being continuously harvested from natural resources. Consequently, the overall electricity consumption of Mediterranean countries is expected to increase. Indeed, Table 14 illustrates the projected values of electricity demand in 2030, as forecast by Med-TSO, i.e, the association of all the power Transmission System Operators (TSO) of Mediterranean countries.

Table 14 Comparison between 2023 and 2030 forecast electricity demand in the Mediterranean shores

	2023	**2030**	
Area	*Demand [TWh/y]*	*Demand (range) [TWh/y]*	*Demand growth*
Northern Shore	1217	1633 - 1678	25.5% - 27.5%
Southern Shore	417	619 - 645	32.7% - 35.5%
Eastern Shore	421	590 - 598	28.7% - 29.6%
Mediterranean Basin	***2054***	***2877 - 2887***	***28.6% - 28.9%***

Source: Elaboration from Med-TSO (Med-TSO, 2022a)

The 2030 electricity demand of the Mediterranean Basin is expected to grow from the current 2054 TWh/y to between 2877 TWh/y and 2887 TWh/y, marking an increase of about 28.6%-28.9%. The Southern Shore should experience the largest growth, in the range between 32.7% and 35.5%, starting from the current 417 TWh/y. A more modest increment of 25.5%-27.5% is forecast for the Northern Shore, while the Eastern Shore stands in between with projected increases lying in the range 28.7%-29.6% (Med-TSO, 2022a).

The considerable increment in electricity demand, supposed to happen in the relatively short 2023-2030 period, can unlikely happen unless the current power transmission networks are adequately improved and strengthened, particularly incentivizing the reciprocal transmission of electricity among the three shores. In fact, so far, the only operating power transmission interconnectors in the

Mediterranean Basin are the twin lines REMO1 and REMO2 connecting Morocco and Spain and offering a technical transmission capacity of 700 MW each (Red Eléctrica, 2019).

Further efforts should be made to also strengthen the electricity interconnections between the countries of the Southern Shore. In fact, although all of them are reciprocally interconnected, several segments of the network suffer from frequent technical issues. According to IRENA (IRENA, 2023), the Tunisian-Libyan interconnection is frequently subject to faults and/or malfunctions and can only operate if Libya's Eastern and Western grids are mutually disconnected.

Moreover, the current Mediterranean transmission network would not be able to handle an electricity exchange happening across the three shores simultaneously. In fact, problems arise whenever trying to synchronously interconnect the areas of Tunisia-Algeria-Morocco, Libya-Egypt-Jordan-Syria, and the Northern Shore: the issue is due to insufficient generation in the Southern Shore-Eastern Shore portion of the network, causing a frequency drop that in turn activates protections on the lines that consequently disconnect. To corroborate this statement, a test carried out in 2010 (the last known to date) proved that Tunisia and Libya could mutually transfer power, only if Libya itself and Egypt were not electrically connected.

Additionally, the interconnections among the countries of the Southern Shore are significantly underexploited, considering that out of 4500 MW of technical available capacity, only 1310 MW is presently used.

Nevertheless, the Tunisia-Algeria-Morocco interconnections could offer a large enough reserve margin capable of making the overall transmission system more resilient to unexpected faults and sudden fluctuations on the demand side.

More in general, the transition towards electrification inevitably requires to both improve the reliability of the power grid, as well as to increase the border transmission capacity to encourage electricity exchanges among the Mediterranean countries and shores.

The future power transmission network, coupled with the expected increased renewable generation capacity, could be the first enabler to help the Mediterranean Basin to transition from the current *black energy dialogue* to a new, *green energy dialogue* based on the generation, consumption and trade of renewable electricity, gradually relieving the Basin from the long-standing burden of fossil fuels.

Electricity interconnectors across the Mediterranean Basin

Currently, apart from the few power transmission lines crossing the Mediterranean, a considerable number of projects of new electricity interconnections are either under construction, in their permitting phase, or planned and waiting to be ratified and approved. These were thoroughly mapped in (Bompard et al., 2023) and are recalled and detailed below.

Operational interconnectors

SACOI (Sardinia-Corsica-Italy) connects mainland Italy to Sardinia, stretching through Corsica as well. Built in 1966, it offers a technical transmission capacity of 300 MW at a voltage level of 200 kV. The first version of SACOI allowed to withdraw power from the two Italian terminals and used Corsica as a physical bridge only. In 1992, the line was added a third withdrawal terminal on the French island while keeping the same voltage level and renamed as **SACOI2**. At the time, it was the first and only multi-terminal HVDC interconnector in the world (Terna, 2016).

REMO1 (Refuerzo Eléctrico Mediterràneo Occidental) has linked Spain and Morocco across the Gibraltar Strait since 1997. It is a submarine, 400 kV AC cable, whose construction enabled the effective transport of excess electricity and, consequently, improved frequency control of the Spanish and Moroccan grids. In 2006 the connection was strengthened with a twin line (**REMO2**) that brought the overall transmission capacity to 1400 MW. REMO1 and REMO2 are currently the only operational power lines connecting two Mediterranean countries belonging to different shores.

GRITA (Greece-Italy) is an LCC-HVDC submarine cable that bridges between Greece and Italy with a technical capacity of 500 MW at 400 kV, operating since 2002. It was Italy's first interconnection with a foreign country stretching at a high submarine depth: in its deepest point, cables were placed at around 1000 m below the sea level (Terna, 2025a).

The **SARCO** (Sardinia-Corsica) is a second interconnection that links Sardinia and Corsica, operating at 150 kV with a maximum capacity of 100 MW. Differently from SACOI, its purpose is providing an almost flat-profiled power supply to Corsica, to help it match its own electricity demand, therefore its power flow is basically monodirectional.

ROMULO connects mainland Spain to the Balearic Islands and was built in 2011, the first submarine cable in the Spanish transmission network. Operating at a voltage of 250 kV and granting a technical capacity of 400 MW, its introduction in the power grid improved frequency stability and encouraged competitiveness in electricity generation (Red Eléctrica de Espana, 2013).

The **SAPEI** (SArdegna-PEnisola Italiana) is another Italy-to-Sardinia connection and, together with being the most expensive project ever commissioned in the Italian power grid (750 M€), it also holds the record for the greatest sea depth (1640 m) for a transmission cable of its size (1000 MW) at a voltage level of 500 kV. Its construction and subsequent operational activity (started in 2009) substantially improved the reliability of the Italian power grid. In fact, not only it enhanced the security of both the Sardinian and Central Italian grids, but also contributed to the abatement of CO_2 emissions, thanks to the possibility of transmitting more renewable electricity. In addition, it granted access to the national electricity market to more Italian system operators, and the market itself benefitted in terms of its flexibility (Terna, 2025c).

The **ITMT1** (Italy-Malta) was commissioned in 2015 and now stretches undersea and across the Malta Channel to connect Malta to Sicily. Its rated capacity is 200 MW, it operates at 220 kV and, analogously to other cross-country interconnectors, it helped to improve the Maltese-Italian stability of the respective power grids.

The **Sorgente-Rizziconi** line, operating since 2016, links the power grids of mainland Italy and Sicily, bridging the Messina Strait with a rated capacity of 1100 MW and a voltage of 400 kV. The connection between the two grids enabled overall CO_2 emissions reductions estimated at around 700 ktCO_2/y (Terna, 2021b).

The **MON.ITA** (Montenegro-Italy) is the first power connection between Italy and the Balkans and links the Italian city of Cepagatti (Abruzzo) to Budva (Kotor) in Montenegro. The current technical capacity offered is 600 MW and is expected to double in the near-future; the voltage level is 500 kV (Terna, 2019).

Under construction, permitting and planned interconnections

GRCR (Greece-Crete) The 1000 MW, 500 kV electrical interconnection between Crete and Attica (Greece) (**GRCR**, known as Ariadne) is, alongside SAPEI, the world's largest cable linking an island to the mainland. Like other projects of the same kind, joining the Cretese power grid to Greece's can improve its reliability and flexibility, while enabling a larger exploitation of renewable electricity. The interconnection helps improve the reliability of electricity supply and will facilitate the integration of renewable energy sources (IPTO, 2023).

SPCE (Spain-Ceuta) is a significant project that will bridge the gap between the Iberian Peninsula and Ceuta (one of the two Spanish exclaves on Moroccan land), integrating its grid into the mainland Spanish one. The cable, running undersea, has a rated capacity of 80 MW and works at a rated voltage of 132 kV (Ministerio para la Transición Ecológica y el Reto Demográfico & Red Eléctrica de España, 2021).

ITMT2 was approved at the end of 2024 and will be the second electricity link between Italy and Malta, running alongside ITMT1 with a transfer capacity of 225 MW and a rated voltage of 220 kV (European Investment Bank, 2025).

The **EuroAsia Interconnector** is an ambitious project consisting in a multiterminal interconnection that would simultaneously join the Israeli, Cypriot and Greek power grids, the last of which linked to Cyprus from the island of Crete, in turn expected to be connected to mainland Greece via GRCR. The connection will run at 500 kV will be 314 km long in the Israel-Cyprus portion, and 894 km in the Cyprus-Crete segment. It is going to consist in two 500 MW twin cables but, for operational security reasons, the import/export capacity to and from Cyprus will be bound to 500 MW. The project is massive and expected to cost as much as 2500 M€. More importantly, it will finally link the Cypriot energy system to those of other countries, putting an end to its long-standing isolation (Med-TSO, 2022d).

The **EuroAfrica Interconnector** complements the EuroAsia Interconnector adding a third l000 MW, 400 kV segment that goes from Egypt from Cyprus, thus electrically linking the three Mediterranean shores simultaneously (Med-TSO, 2022e).

SACOI3 (Sardinia-Corsica) will be the modernized version of the existing SACOI2, increasing its overall transport capacity to 400 MW (Terna, 2025b).

TUNITA will link Sicily (Italy) to Tunisia through a 233 km, 600 MW HVDC cable, operating at 500 kV. The project will add another electricity link between the Northern Shore and the Southern Shore, while being a promising opportunity for the second to encourage the wider usage of renewable electricity generators (Med-TSO, 2022c).

Adriatic link is a project of the Italian TSO Terna, aimed at linking the two regions of Marche and Abruzzo to build an electricity bridge between Central and Southern Italy. The interconnector will have a significant capacity of 1000 MW and operate at a rated voltage of 500 kV, improving the manageability of the Italian grid while reducing congestions (Terna, 2021a).

Tyrrhenian Link is a major project from Terna consisting in a multi-terminal interconnector simultaneously joining the electricity networks of mainland Italy, Sicily and Sardinia. It is a two-segments undersea cable of 1000 MW rated capacity and a voltage level of 500 kV. Thyrrenian Link will greatly favour the integration of renewables in the Italian electricity grid (Terna, 2025e).

Dorsale Sarda is the combination of two connections, the first linking Sardinia to mainland Italy and being the upgraded version of SAPEI (SAPEI2); the second – called Sardinian Link – stretching across Sardinia itself from North to South. Both interconnectors will offer a capacity of 1000 MW, SAPEI2 operating at 500 kV while Sardinian Link at 220 kV (Terna, 2025d).

Dorsale Ionico-Tirrenica is another multi-terminal interconnector aimed at linking insular to mainland Italy. In fact, its four terminals will be in Sicily, Calabria (Southern Italy), Campania (Southern Italy) and Lazio (Central-Southern Italy) and will grant an overall additional transmission capacity of 2100 MW at a voltage level of 500 kV (Terna, 2025d).

ITGR2 (Italy-Greece) will be the reinforcement of the existing Italy-Greece interconnection, adding further 1000 MW of transmission capacity at 500 kV. It will be made up of two undersea cables, approximately 250 km long (Terna, 2025a).

The **ESMA** (Spain-Morocco) project consists in incrementing the existing Spanish-Moroccan transmission capacity adding two new 400 kV lines, increasing the transferable capacity by 650 MW towards Morocco and by 600 MW towards Spain. The new connection will enable Spain to drastically increase its electricity exports to the African country (Ministerio para la Transición Ecológica y el Reto Demográfico & Red Eléctrica de España, 2021).

EGGR (Egypt-Greece) would be a large, 2000 MW undersea cable representing a major electricity bridge between the Southern Shore and the Northern Shore, in addition to the EuroAsia Interconnector and EuroAfrica Interconnector power lines (Med-TSO, 2022f).

MAPT (Morocco-Portugal) will be a 1000 MW, 220 kV interconnection between the Moroccan terminal of Beni Harchan (Tanger-Tétouan-Al Hoceima) and the Portuguese one of Tavira (Algarve), representing the first electricity interconnection between the two countries (Med-TSO, 2022b).

Table 15 recaps all the aforementioned electricity interconnectors, detailing their main techno-economical features and including those under consideration but not officially approved and/or licensed.

Table 15 Techno-economical features of existing and future electricity interconnections in the Mediterranean Basin

Name	Terminal 1	Terminal 2	Type	Status	Date	U [kV]	NTC [MW]	L [km]	Cost [M€]
SACOI2	Suvereto (ITA)	Lucciana, Corse (FRA)	LCC-DC	OP	1968	200	300	413	670
	Lucciana, Corse (FRA)	Codrongianos (ITA)							
REMO1	Tarifa (ESP)	Fardioua (MAR)	AC	OP	1997	380	700	26	95
GRITA	Galatina (ITA)	Arachthos (GRC)	LCC-DC	OP	2002	400	500	153	339
REMO2	Tarifa (ESP)	Fardioua (MAR)	AC	OP	2006	380	700	31	115
SARCO	Santa Teresa (ITA)	Bonifacio (FRA)	AC	OP	2006	150	100	15	40
Romulo	Morvedre (ESP)	Santa Ponsa, (ESP)	LCC-DC	OP	2011	250	400	244	420
SAPEI	Fiumesanto (ITA)	Latina (ITA)	LCC-DC	OP	2011	500	1000	435	750
ITMT1	Ragusa (ITA)	Maghtab (MLT)	AC	OP	2015	220	200	120	182
Sorgente-Rizziconi	Sorgente (ITA)	Rizziconi (ITA)	AC	OP	2016	400	1100	105	700
MONITA	Villanova (ITA)	Lastva (MNE)	LCC-DC	OP	2020	500	1200	445	1100
GRCR	Molai (GRC)	Chania, (GRC)	AC	OP	2021	150	400	173	356
SPCE	Puerto de la Cruz (ESP)	Ceuta (ESP)	AC	CO	2025	132	50	60	221
ITMT2	Ragusa (ITA)	Maghtab (MLT)	AC	CO	>2025	220	200	120	200
EuroAsia Interconnector	Kofinou (CYP)	Korakia (GRC)	VSC-DC	CO	2026	500	2000	898	2500
	Hadera (ISR)	Kofinou (CYP)		CO	2026	310		310	
EuroAfrica Interconnector	Kofinou (CYP)	Korakia (GRC)	VSC-DC	CO	2026	500	2000	898	2500
	Damietta (EGY)	Kofinou (CYP)		PE	2029	498		498	
SACOI3	Suvereto (ITA)	Lucciana (FRA)	LCC-DC	PE	2025	200	400	413	950
	Lucciana (FRA)	Codrongianos (ITA)							
TUNITA1	Partanna (ITA)	Menzel Temim (TUN)	VSC-DC	PE	2027	500	600	233	850
TUNITA2	Partanna (ITA)	Menzel Temim (TUN)	VSC-DC	PE	>2030	500	600	233	850
Adriatic link	Villanova (ITA)	Fano (ITA)	VSC-DC	PE	2028	500	1000	250	1300
Tyrrhenian Link	Montecorvino (ITA)	Caracoli (ITA)	VSC-DC	PE	2028	500	1000	970	3700

	Caracoli (ITA)	Selargius (ITA)							
Dorsale Sarda	Fiumesanto (ITA)	Viterbo (ITA)	VSC-DC	PE	2040	500	1000	550	1400
	Codrongianos (ITA)	Suulcis (ITA)				220	1000		
Bolano Annunziata	Bolano (ITA)	Annunziata (ITA)	AC	PE	t.b.d.	380	2000	7.5	105
ESMA	Puerto de la Cruz (ESP)	Bni Harchen (MAR)	AC	PL	2026	400	650	100	188
EGGR	Tarffehiah (EGY)	Aharnes (GRC)	LCC-DC	PL	2028	600	2000	863	1880
ITGR2	Galatina (ITA)	Arachthos (GRC)	VSC-DC	PL	2031	400	500	316	750
Dorsale Ionico-Tirrenica	Latina (ITA)	Montecorvino (ITA)	VSC-DC	PL	2035	500	2000	830	4100
	Montecorvino (ITA)	Rossano (ITA)					2000		
	Rossano (ITA)	Priolo (ITA)					1000		
MAPT	Bni Harchen (MAR)	Tavira (PRT)	VSC-DC	PL	t.b.d.	500	1000	325	650
DZES	Ain Fatah (DZA)	Carril (ESP)	VSC-DC	UC	t.b.d.	500	1000	240	1185
DZIT	Cagliari (ITA)	Cheffia(DZA)	VSC-DC	UC	t.b.d.	400	1000	350	850
ITAL1	Brindisi (ITA)	Babica (ALB)	DC	UC	t.b.d.	400	500	145	437
ITAL2	Manfredonia (ITA)	Kallmet (ALB)	DC	UC	t.b.d.	500	1000	345	944
ITAL3	Casamassima (ITA)	Porto Romano (ALB)	DC	UC	t.b.d.	500	500	238	556
TREY	Adana (TUR)	Port Said (EGY)	VSC-DC	UC	t.b.d.	600	3000	800	1185
TRIS	Mersin (TUR)	Haifa (ISR)	VSC-DC	UC	t.b.d.	600	2000	500	1425
EGJO	Taba (EGY)	Hasseimya (JOR)	AC	PL	2025	400	550	43	67
JOSY	Amman North (JOR)	Der Ali (SYR)	AC	UC	>2030	400	1000	154	54
BGTRGR	Nea Santa (GRC)	Babaeski (TUR)	AC	UC	2035	400	1500	130	152
	Maritsa East 2 (BGR)	Vize Havra (TUR)		UC	2036		1500	150	
DZLY	t.b.d.	t.b.d.	AC	UC	t.b.d.	400	1000	520	N/A
DZTN	Oglet Ouled Mahboub (DZA)	Kondar (TUN)	AC	UC	t.b.d.	400	1000	220	95
EGLY	Al Saloum (EGY)	Tobruk (LBY)	AC	UC	t.b.d.	500	1000	170	128
SYTR	t.b.d.	Birecik HPP (TUR)	AC	UC	t.b.d.	400	600	150	220

If all the interconnections listed in Table 15 started their operational activity, the overall Mediterranean transmission capacity would increase from the current 6.60 GW to 44.75 GW, more than sextuplicating. With a very preliminary, first and rough approximation, the overall amount of electricity transported in one year can be assumed equal to the rated capacity multiplied by the total number of hours in one year, weighted by a utilization factor that accounts for the intermittent output of renewable sources. If this is chosen equal to 2/3, the electricity that can be potentially transported across the Mediterranean shores will amount to 261 TWh/y. This means that, with respect to the electricity demand values depicted in Table 14, interconnections could transport about 9% of the 2030 Mediterranean electricity demand. In combination with the expected increase in renewable electricity installed capacity and generation, this means that Mediterranean countries have the potential of gradually moving away from fossil fuels and transition from a black, to a green energy dialogue based on renewables.

However, technical potential alone is not enough to accomplish an effective and inclusive transition. In fact, this requires paying attention to the different local socioeconomic, energy and environmental contexts and address the specific needs of final energy consumers.

3.6 Conclusions

The Mediterranean Basin is a complex and multifaceted area characterized by significant energy, socioeconomic and environmental disparities among its three shores. The Northern Shore is both the richest, the largest energy consumer and GHG emitter. However, even very simple composite indicators already portrait a different situation: for example, the Southern Shore is five times more carbon-intensive and three times more energy-intensive than the Northern Shore; the Eastern Shore is both twice as carbon- and energy-intensive than the Northern Shore.

Historically, the Mediterranean has been the landing basin and transit hub of fossil commodities, predominantly exported by countries of the Southern Shore, where respectively more than 95% and 85% of the crude oil and natural gas reserves are located. This led to the consolidation of a strong relation based on the export of crude oil, refined products and natural gas among the shores: the Northern and Eastern shores need the Southern to match their energy demand, while the third depends on the first two ones as one of its main sources of income.

Paradoxically, most countries of the Southern and Eastern shores would be those capable of harnessing the most promising solar and wind intensities in the entire Basin, yet their long-standing dependence on fossil fuels makes them the places where renewable energy sources are the least exploited – only about 7% of the overall Mediterranean PV and wind capacity is installed in the Southern Shore – and where the development of the energy transition is the most cumbersome. The situation can be traced back to several causes, such as the absence of a supranational entity capable of both tracing the guidelines of an effective transition process and encouraging member countries to strive to achieve their decarbonization targets. In addition, frequent internal and international geopolitical instabilities divert the attention of the local governments from the theme of decarbonization.

Despite the current slow pace of deployment of the transition in the Southern and Eastern shores, the planned evolution of the Mediterranean power system, both in terms of renewable generation installed capacity and transmission infrastructure leaves room to hope for a shift from the actual fossil-based energy paradigm to a new one based on the generation, consumption and trade of renewable electricity. In fact, future electricity interconnectors should be able to grant an overall power transmission capacity of almost 45 GW, thus being able to carry a significant portion of the Mediterranean electricity demand across the three shores. In this framework, not only could they significantly contribute to the electrification and decarbonization of the Basin's energy system, but they would considerably relieve it from the long-standing burden of fossil fuels.

Chapter 4

An optimization framework to compare energy commodities for the energy transition

This chapter combines the topics illustrated in the previous sections of this work presenting the simulation results of an Energy System Optimization Model (ESOM) where the concepts of Energy Trilemma and multi-commodity energy systems are brought together and applied to a specific case study in the geographical context of the Mediterranean Basin. Operatively, the model wishes to assess how different energy commodity mixes can be ranked with respect to the three attributes of the Energy Trilemma, namely energy security, environmental sustainability and energy equity/affordability (World Energy Council, 2024). In fact, as discussed in Chapter 1, these are often competing against each other and finding an energy mix capable of achieving satisfactory levels in all of them could be particularly challenging.

As mentioned, in the context of the energy transition towards the decarbonization of the present energy system, electricity will likely be the most exploited energy commodity, thanks to the opportunity of being continuously harnessed from natural energy sources. At the same time, the process of electrification will be supported by other energy commodities as several final energy uses cannot be easily electrified. This premise led to the definition of multi-commodity energy systems and to consequently underscore their importance as key drivers to achieve cross-sectoral integration and accomplish the energy transition. Energy commodities, as well as the Trilemma attributes, can cooperate and/or compete to match the same final energy uses: the problem of finding the preferable commodity energy mix, while simultaneously targeting the three items of the Trilemma is still object of discussion and is directly addressed in this chapter.

4.1 Connecting multi-commodity and the Energy Trilemma

This section presents the main features and the narrative of a proposed ESOM framework where the concepts of Energy Trilemma and Commodity Energy Chains are joined together to quantitatively estimate how different energy commodity mixes compare in terms of their energy security, environmental sustainability and affordability. The proposed approach differs from others commonly found in literature, which more often exploit optimization algorithms to find the least-cost energy mix and assess how it performs in the three Trilemma attributes afterwards. Such is the case, for example, of (Zafeiratou & Spataru, 2018), (Pamulapati et al., 2022), (Yap et al., 2021) and (Gad et al., 2025). Other works include all the three attributes of the Trilemma in the analytical formulation of the objective function, but are different from the one presented here because they either are applied to smaller, local energy networks (Wu & Sansavini, 2021) (Jing et al., 2021) or do not investigate the problem of the future energy system from a multi-commodity perspective (Weiss et al., 2021). In addition, energy security is generally included in the analysis from its technical point of view, i.e, the ability of local and/or national networks to provide uninterrupted energy supplies. In this work, each attribute of the Trilemma is numerically quantified by means of a specific indicator and fed to the optimizer, which means the objective function is itself dependent on the three Trilemma attributes simultaneously. Furthermore, differently from the above-mentioned literature examples, energy security is instead linked to the geopolitical risk of energy suppliers and supply corridors. Moreover, the analysis is carried out adopting a multi-commodity perspective, as it simultaneously considers electricity, natural gas and hydrogen as energy commodities, therefore effectively intersecting the vision of the Energy Trilemma with the application of multi-commodity and CECs.

Whenever developing and implementing an ESOM, the first step of the analysis consists in defining what its Reference Energy System is going to be. Generally, a Reference Energy System can be defined as the formal representation of all the relationships characterizing the components of an energy system and generally consists of three elements: refining/conversion/transport/transformation processes occurring within the system, energy commodities and commodity flows linking two subsequent processes between each other (Loulou et al., 2019).

In this work, Italy and its natural gas, electricity and hydrogen interconnections[29] with bordering countries were chosen as the object of the analysis, together with all the endogenous infrastructures of energy generation.

More specifically, Italy was selected as it represents a relevant player in the energy context of the Mediterranean Basin and, as such, it is worth studying for several reasons. First, it is a heavily energy-dependent country: in the 2013-2023 decade, the Italian total energy import dependency averaged at 76%, with specific values for both crude oil and natural gas being even larger than 92%. In addition, Italy has historically showed a large oil and gas import dependency on countries of the Southern Shore only. In fact, when looking at crude oil imports, the Southern

[29] For sake of simplicity, less relevant commodities such as biofuels or synthetic fuels were not included in the analysis.

Shore weighed 23%, 19% and 22% in 2021, 2022 and 2023, respectively. The natural gas import dependency is stronger (for instance, 36% in 2021), and grew even more in the following years (2022: 41%, 2023: 46%), because of Algeria having replaced Russia as the main Italian natural gas exporting partner (Eurostat, 2025b). Therefore, addressing the topic of the development of a multi-commodity energy system for Italy is crucial to find out how Italy could diversify its total energy supply mix and achieve better levels of energy security.

Furthermore, its geographic position places the country at the crossroads of energy flows coming both from Northern Europe, Northe Africa and the Middle East. Therefore, Italy has the potential to become one of the main Mediterranean and European energy hubs of the future. Such a statement is corroborated by – among others – the presence of three main energy projects within the list of the Projects of Common Interest of the European Union:

- The ELMED HVDC undersea power line that will connect the Tunisian and Italian power systems starting from 2028 and strengthen the electrical interconnection (and cooperation) between the Northern and the Southern shores of the Mediterranean.
- The SoutH2 Corridor, part of the European Hydrogen Backbone, which will bring hydrogen from North Africa to Italy and Central Europe. The estimated total production of 4 Mt_{H2}/y could match 40% of the future European hydrogen demand, as forecast by the *REPowerEU* plan (European Commission Secretariat-General, 2022; Snam, 2024b).
- The CALLISTO (CArbon LIquefaction transportation and STOrage) Mediterranean CO_2, aiming at building, in the Italian city of Ravenna, the largest Carbon Capture and Storage (CCS) hub of the Mediterranean Basin, with even a dedicated CO_2 transport network (Snam, 2024b).

The analysis covers a one-year long time span, from January 1st, 2030, to December 31st, 2030, with daily granularity. Decision variables are represented by the energy flows – expressed in GWh/d – entering or exiting the Italian borders and by the endogenous energy generation (source terms), for each of the three aforementioned energy commodities.

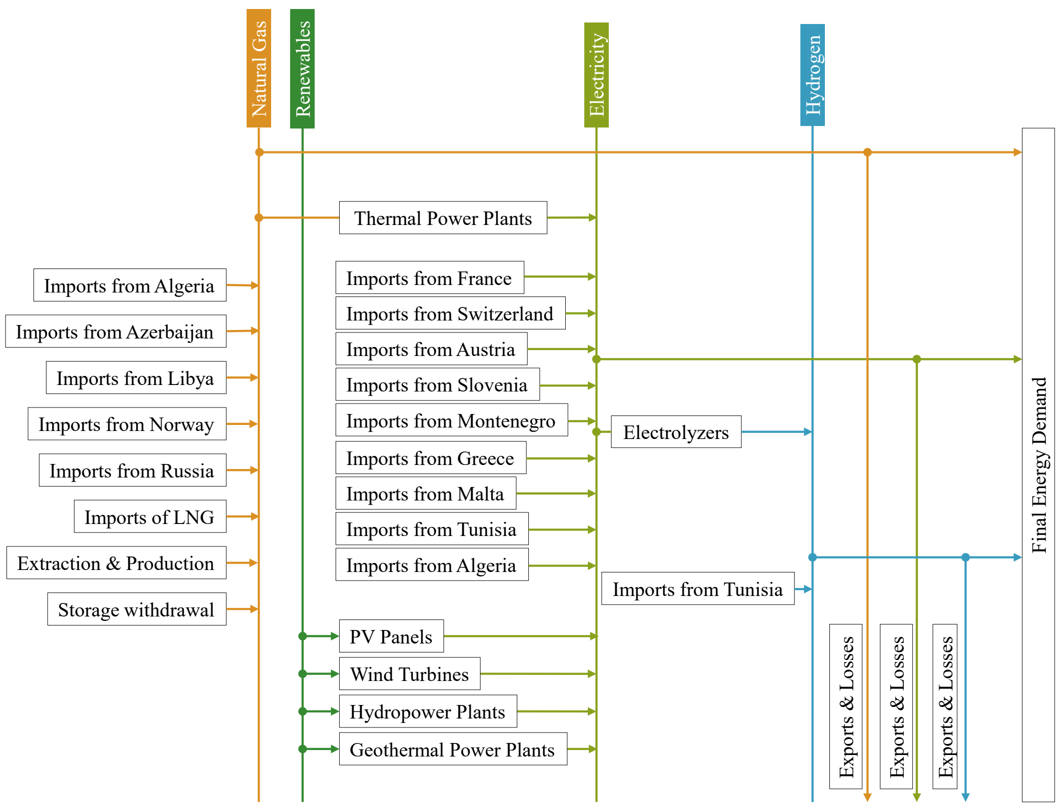
For what concerns natural gas more specifically, Italy is connected to the European and extra-European pipeline transmission networks via five national natural gas entry points: Passo Gries (Piedmont) and Tarvisio (Friuli-Venezia Giulia) in the North; Melendugno (Puglia), Gela (Sicily), and Mazara del Vallo (Sicily) in the South. Italy can also count on five LNG regasification terminals: LNG Panigaglia (Liguria), Adriatic LNG Terminal (Veneto), OLT Offshore LNG (Tuscany), FSRU Piombino (Tuscany), and the new FSRU Ravenna (Emilia-Romagna) that started its commercial operation on April 3rd, 2025 (Staffetta Quotidiana, 2025).

The existing electricity interconnections connect the Italian power grid with France (both French mainland and the Corsica Island), Switzerland, Austria, Slovenia, Montenegro, Greece and Malta. Future power lines include those already listed in Chapter 3: ITMT2 (Malta, 225 MW), SACOI3 (France – Corsica, 200 MW), ITGR2 (Greece, 1000 MW), TNIT (Tunisia, 600 MW) and DZIT (Algeria, 1000 MW). In addition, further 400 MW of transfer capacity will be available at the Italo-Slovenian border, following the infrastructural improvements planned by 2030 (MASE, 2024a).

So far, Italy has no hydrogen transmission infrastructure. Therefore, for the purposes of the analysis, it is assumed that hydrogen could be produced either within national borders by means of electrolysis – as envisaged by the Italian National Hydrogen Strategy (MASE, 2024b) – or imported from Tunisia in an ad-hoc hydrogen duct, whose construction is endorsed by the Tunisian government (giz & Ministére de l'Industrie, 2024).

Figure 24 provides a graphical representation of the Reference Energy System of the model under analysis, where white boxes represent the processes, colored boxes the energy commodities, and arrows the energy commodity flows. Final energy demand is also regarded as a process considering that, depending on the specific final energy consuming sector, it is always converted into useful energy services that, for sake of simplicity, were not detailed in the present analysis.

Figure 24 Reference Energy System of the model under study



The Reference Energy System displays two additional energy supply alternatives coming from the intermediate conversion stages, namely electricity generation from thermal power plants and green hydrogen synthesis from electrolyzers. Since they both represent alternative ways to feed energy to final energy users in the form of electricity and hydrogen, their respective natural gas and renewable electricity input demands are included within the set of decision variables. Given that, being physical fluids, both natural gas and green hydrogen could not be, in principle, compared to electricity and vice versa, they are included in the simulation model considering their energy content, which can be easily obtained multiplying their volume/mass quantity by their respective Lower Heating Value (LHV). In this way, all the energy flows related to the Reference Energy System can be consistent in terms of their units of measure and are expressed in in GWh/d.

4.2 Main components of the optimization model

Decision Variables

Let

$$\mathcal{T} = \{t \mid t = 1 \ldots, 365\} \tag{4}$$

Be the set of the 365 time steps (days) considered in the simulation. Then, the set of all the energy supply corridors is defined as

$$\mathcal{C} = \left\{c_i^j(t) \,\middle|\, i = 1 \ldots, C\right\} \tag{5}$$

where superscript j specifies the energy commodity (g: natural gas; e: electricity, h: green hydrogen) and subscript i its origin, according to the nomenclature proposed in Table 16.

The values of 2030 natural gas, electricity and green hydrogen demand for the chosen year are taken from the report *Documento di Descrizione degli Scenari 2024* (Snam & Terna, 2024), jointly published by Terna and Snam, the Italian electricity and natural gas Transmission System Operators (TSO) and portraying the evolution of the Italian natural gas, electricity and green hydrogen demand in 2030. The document only reports the total yearly values of these quantities; therefore, for the sake of the optimization, 2023 was chosen as a reference baseline year and daily values of 2023 rescaled to be proportionate to the 2030 totals.

Table 16 Decision variables considered in the simulation

Variable name	Description
c_{DZ}^{g}	Natural gas imports from Algeria
c_{LY}^{g}	Natural gas imports from Libya
c_{NO}^{g}	Natural gas imports from Norway
c_{AZ}^{g}	Natural gas imports from Azerbaijan
c_{RU}^{g}	Natural gas imports from Russia
c_{LNG}^{g}	Total LNG imports
c_{Pr}^{g}	Natural gas production
c_{Sw}^{g}	Withdrawals[30] from natural gas storage systems
c_{Th}^{e}	Natural gas input stream for thermal power plants
c_{FR}^{e}	Electricity imports from France
c_{CH}^{e}	Electricity imports from Switzerland
c_{AT}^{e}	Electricity imports from Austria
c_{SI}^{e}	Electricity imports from Slovenia
c_{GR}^{e}	Electricity imports from Greece
c_{ME}^{e}	Electricity imports from Montenegro
c_{MT}^{e}	Electricity imports from Malta
c_{DZ}^{e}	Electricity imports from Algeria
c_{TN}^{e}	Electricity imports from Tunisia
c_{Hp}^{e}	Electricity generation from hydropower
c_{Ge}^{e}	Electricity generation from geothermal power plants
c_{PV}^{e}	Electricity generation from PV
c_{WT}^{e}	Electricity generation from wind
c_{Ey}^{h}	Electricity input stream for electrolyzers
c_{TN}^{h}	Green hydrogen imports from Tunisia

Analogously to how corridors were grouped, the set

$$\mathcal{D} = \left\{ d_i^j(t) \mid i = 1 \dots, D \right\} \qquad (6)$$

Defines all the known, time-dependent demand components of the energy system, detailly listed in Table 17. The table also shows the total yearly values of the demand components, expressed in TWh/y.

Following, Table 18 illustrates the constant, scalar parameters adopted in the computations.

[30] Withdrawal season lasts from Jan 1st to Apr 30st, and from Nov 1st to Dec 31st, 2030.

Table 17 Values of final energy demand given as input to the simulation model

Name	Description	Value [TWh/y]	Source
d_E^g	Natural gas exports	76.0	(Snam, 2024a; Snam & Terna, 2024)
d_I^g	Natural gas demand-industrial sector	237.8	(Snam, 2024a; Snam & Terna, 2024)
d_R^g	Natural gas demand-residential sector	84.9	(Snam, 2024a; Snam & Terna, 2024)
d_{Si}^g	Natural gas injection in storage systems	89.2	(Snam, 2024a)
d^e	Total electricity demand[31]	351.9	(Snam & Terna, 2024; Terna, 2023)
d^h	Total hydrogen demand	8.4	(MASE, 2024a)
d_{tot}	*Total energy demand*	*848.2*	

Table 18 Constant parameters considered in the simulation

Name	Description	Unit	Value	Source
P_{PV}	2030 PV installed capacity in Italy	GW	79.17	(MASE, 2024a)
P_{WT}	2030 wind installed capacity in Italy	GW	28.14	(MASE, 2024a)
P_{Th}	2023 Thermal PP installed capacity	GW	45.93	(Terna, 2023)
α_{Th}	Availability factor of thermal power plants	%	0.60	User-defined
M_{TN}^{H2}	2030 green hydrogen exports from Tunisia	kt_{H2}/y	300	(giz & Ministére de l'Industrie, 2024)
P_{Ey}	2030 electrolyzers installed capacity in Italy	GW	3.00	(MASE, 2024b)
E_{Ey}	2030 total electricity feed to electrolyzers	TWh/y	10	(MASE, 2024a)
η_{Ey}	Conversion efficiency of electrolyzers	kWh_{H2}/kWh_e	60	(IRENA, 2020a)
LHV_g	LHV of natural gas	kWh/Sm^3	10.57	(Snam, 2024a)
LHV_h	LHV of hydrogen	kWh/kg_{H2}	33.33	(Eurostat et al., 2023)
η_{Th}	Natural gas consumption of thermal PP	kWh_g/kWh_e	1.74	(Terna, 2023)

The 2030 Italian installed capacities of PV, wind and electrolyzers are equal to those included in the latest version of the Italian *National Energy and Climate Plan* (MASE, 2024a), while the yearly exports of green hydrogen from Tunisia correspond to the value hypothesized by the Tunisian government in its green hydrogen strategy (giz & Ministére de l'Industrie, 2024). The installed capacity of thermal power plants is instead assumed equal to the value of 2023, as the natural gas demand devoted to electricity generation is expected to decrease in 2030 (Snam & Terna, 2024)

The simulation model also assumes the following: considering that the expected electricity installed capacity increases for both hydropower and geothermal electricity generation will be almost negligible (MASE, 2024a), to ensure the behavior of the simulated power system is as close as possible to a real one, daily electricity generation from these two sources is bound by their respective daily values of 2023.

[31] Includes exports and losses. Does not include electricity demand of electrolyzers.

The same hypothesis holds for daily natural gas withdrawals from storage systems, while a similar one for internal natural gas production; the only difference being that values of 2023 were rescaled to match the (larger) yearly total forecast value of 2030 (Snam & Terna, 2024).

Electricity production from PV and wind generators should be consistent with local weather conditions. Therefore, a reference daily generation behavior was derived from hourly production profiles expressed in energy per unit of installed power (kWh/kW) (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016), multiplied by the 2030 value of PV and wind installed capacities of Table 19.

Table 19 presents the nomenclature of the time-dependent, known variables included as upper bound constraints in the optimization model.

Table 19 Nomenclature of time-dependent known variables included as upper bound constraints in the optimization model

Name	Description
b^{g}_{Pr}	Internal natural gas production
b^{g}_{Sw}	Storage withdrawals
b^{e}_{PV}	Electricity production from PV generators
b^{e}_{WT}	Electricity production from wind generators
b^{e}_{Hy}	Electricity production from hydropower
b^{e}_{Ge}	Electricity production from geothermal PP

Constraints

Maximum Natural gas transport capacity from South to North

Because of infrastructural bottlenecks in the current Italian natural gas transport network, the daily natural gas volume able to be jointly by the Transmed, Greenstream and TAP pipelines towards Northern Italy is currently limited to 122 MSm^3/d but will increase to 150 MSmc/g within 2030, thanks to several strengthening interventions planned by Snam for the Italian natural gas transport network (Snam, 2023). The right-hand side of the constraint is adequately adjusted to ensure consistency of units.

$$\left(c^{g}_{DZ}(t) + c^{g}_{LY}(t) + c^{g}_{AZ}(t)\right) \leq \left(150 \cdot LHV_{g}\right), \forall\, t \in \mathcal{T} \quad (7)$$

Natural gas injection in storage systems

To ensure a high enough filling level of natural gas storage systems at the beginning of the withdrawal season (ranging from November 1st to April 30th of the following year), the total daily natural gas supplies must at least match the injection values, as defined by d^{g}_{Si}.

$$\sum_{g=1}^{G} c_i^g(t) \geq d_{Si}^g(t), \forall\, t \in \mathcal{T} \quad (8)$$

Maximum daily natural gas production and withdrawal from storage

Both endogenous natural gas production and storage withdrawal are bound by their daily values, defined as explained in Table 17. The analytical expressions of the two constraints are easily derived as follows.

$$c_{Pr}^g(t) \leq\; b_{Pr}^g(t), \forall\, t \in \mathcal{T} \quad (9)$$

$$c_{Sw}^g(t) \leq\; b_{Sw}^g(t), \forall\, t \in \mathcal{T} \quad (10)$$

Maximum daily electricity generation from thermal power plants

Daily electricity generation from thermal power plants cannot exceed the total installed capacity, weighted by its availability factor. Given that the simulation runs with a daily granularity, daily generation was assumed equal for each of the 24 hours.

$$\frac{1}{\eta_{Th}} \cdot c_{Th}^g(t) \leq 24 \cdot \alpha_{Th} \cdot P_{Th}\,, \forall\, t \in \mathcal{T} \quad (11)$$

Maximum daily electricity production from renewable energy sources

Daily values of electricity generation from PV, wind, hydropower and geothermal power plants are bound by the daily profiles shown in Table 18.

$$c_{PV}^e(t) \leq b_{PV}^e(t), \forall\, t \in \mathcal{T} \quad (12)$$

$$c_{WT}^e(t) \leq b_{WT}^e(t), \forall\, t \in \mathcal{T} \quad (13)$$

$$c_{Hp}^e(t) \leq b_{Hp}^e(t), \forall\, t \in \mathcal{T} \quad (14)$$

$$c_{Ge}^e(t) \leq b_{Ge}^e(t), \forall\, t \in \mathcal{T} \quad (15)$$

Maximum electricity feed for electrolysis and green hydrogen

In absence, to the author's knowledge, of more precise and detailed information about daily green hydrogen internal generation profiles, the electricity feeding electrolyzers is bound by an average daily value, simply computed from the total yearly electricity-for-electrolysis demand forecast in the Italian NECP (MASE, 2024a). The model also ensures internal hydrogen production only comes from renewable sources.

$$c_{Ey}^{e}(t) \cdot \eta_{Ey} \leq \frac{1}{365} \cdot E_{Ey} \text{ ,} \forall\, t \in \mathcal{T} \tag{16}$$

$$c_{Ey}^{e}(t) \leq c_{PV}^{e}(t) + c_{WT}^{e}(t) + c_{Hy}^{e}(t) + c_{Ge}^{e}(t) \text{ ,} \forall\, t \in \mathcal{T} \tag{17}$$

Total final energy balance

Every day, the total energy supply and demand must match. The constraint can be expressed exploiting the definitions of the sets of supply corridors and demand components as follows.

$$\sum_{c=1}^{C} c_i^j(t) = \sum_{d=1}^{D} d^j(t) \text{ ,} \forall\, t \in \mathcal{T} \tag{18}$$

Other infrastructural constraints

To make sure simulation results can be consistent with the ordinary behavior of the Italian natural gas and power supply systems, the daily supply capacity of most of the supply corridors is bound by lower and/or upper values. These are displayed in Table 20.

Table 20 Lower and upper bound constraints to capacities of supply corridors

Variable name	Rated capacity [GWh/d]	Constrained capacity	
		Lower [GWh/d]	Upper [GWh/d]
c_{DZ}^{g}	1096.4	274.1	1096.4
c_{LY}^{g}	475.8	0.0	71.4
c_{NO}^{g}	623.8	0.0	218.3
c_{AZ}^{g}	470.5	164.7	470.5
c_{RU}^{g}	1154.5	0.0	150.1
c_{LNG}^{g}	936.7	0.0	655.7
c_{FR}^{e}	112.4	0.0	67.5
c_{CH}^{e}	109.7	0.0	64.7
c_{AT}^{e}	7.8	0.0	4.0
c_{SI}^{e}	27.7	0.0	27.7
c_{GR}^{e}	36.0	0.0	36.0
c_{ME}^{e}	14.4	0.0	14.4
c_{MT}^{e}	10.2	0.0	10.2
c_{DZ}^{e}	24.0	0.0	24.0
c_{TN}^{e}	14.4	0.0	14.4

For sake of improved readability, the constraints displayed in the table were grouped into set

$$\mathcal{L} = \{l = 1, \dots, L \mid l = l(c), \forall c \; in \; \mathcal{C}\} \tag{19}$$

with l being the generic constraint imposed on the daily supply capacity of every $c\text{-}th$ corridor.

Objective Function

The objective function inherits the main ideas and concepts of the Energy Trilemma, as it tries to simultaneously balance together energy security, environmental sustainability and energy affordability. To this purpose, each supply corridor of set $\mathcal{C}$ was assigned an indicator for three attributes of the trilemma.

Energy security was measured by means of a risk indicator, i.e., a number ranging from 0 (minimum risk) to 100 (maximum risk), corresponding to the complementary value of the Worldwide Governance Indicator (WGI)[32] related to the country of origin of the supplies (Worldbank, 2024). In the case of LNG, the risk indicator is equal to the average of the WGIs of the exporting countries (with reference to 2023), weighted by their respective exported quantities. The risk indicator of internal supply corridors is assumed equal to 0. Natural gas demand for thermal power plants was assigned a risk indicator equal to the average of the WGIs of every natural gas supply corridor, weighted by its respective exported quantities (with reference to 2023).

Environmental sustainability was quantified assigning a carbon emission factor (expressed in gCO_{2eq}/kWh) to all the supply corridors considered in the simulation, depending on the energy commodity (Bastos et al., 2024). In the case of natural gas, the emission factor corresponds to that of natural gas itself. For electricity import corridors, the emission factor was computed as the average of the energy source-specific factors, weighted by their respective electricity installed capacity (with reference to 2023) of exporting countries (IRENA, 2024b). The emission factor of hydrogen is null, following the assumption made in (17).

The quantification of affordability indicators followed different methods. In the case of existing and operating energy supply corridors, the Italian monthly natural gas and electricity import prices by export country were adopted and divided by the respective monthly imports of natural gas or electricity, to obtain an average

[32] Since WGI is a measure of the geopolitical stability of a country, its complementary value can be regarded as an indicator of its geopolitical risk.

monthly import price (expressed in €/MWh). Table 21 shows the 2023 average monthly import price values of existing natural gas and electricity corridors (Eurostat, 2025b).

Table 21 Average 2023 monthly natural gas and electricity import prices by export country

Variable name	Monthly average import price [€/MWh]											
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
c_{DZ}^{g}	66.8	61.6	49.3	45.5	43.5	40.7	38.2	38.1	40.7	43.9	46.9	44.1
c_{LY}^{g}	66.4	54.3	44.3	42.1	34.3	31.0	28.5	29.5	34.7	40.6	40.2	34.7
c_{NO}^{g}	83.6	59.8	51.4	47.9	40.2	34.7	32.9	37.9	44.0	41.9	41.3	40.3
c_{AZ}^{g}	100.3	65.1	53.5	43.4	43.1	31.9	30.5	29.0	35.0	37.2	66.6	42.3
c_{RU}^{g}	68.7	58.9	58.4	46.0	38.4	41.7	32.9	40.6	39.0	48.1	57.7	36.0
c_{LNG}^{g}	54.80	46.74	41.96	36.28	34.93	33.79	41.27	37.33	38.21	32.42	39.58	54.80
c_{Th}^{g}	75.02	57.06	48.79	44.25	40.24	36.64	34.49	36.88	38.49	40.61	44.08	39.43
c_{FR}^{e}	79.8	54.8	46.7	42.0	36.3	34.9	33.8	41.3	37.3	38.2	32.4	39.6
c_{CH}^{e}	176.9	193.1	139.1	129.8	86.8	87.2	111.0	120.5	109.0	107.4	113.1	108.5
c_{AT}^{e}	184.1	147.1	135.1	139.3	121.8	138.6	106.1	121.6	124.9	141.8	127.4	106.1
c_{SI}^{e}	178.6	216.9	168.8	164.9	125.2	107.7	108.8	102.3	108.5	214.5	128.8	103.5
c_{GR}^{e}	103.6	115.0	97.7	88.3	55.3	66.4	59.3	51.8	67.0	86.6	67.5	50.3
c_{ME}^{e}	161.0	149.6	124.0	117.9	94.0	108.9	122.2	115.1	116.3	123.7	114.1	103.6
c_{MT}^{e}	169.0	160.7	142.2	130.0	102.6	110.1	107.6	117.8	116.0	122.9	119.1	107.6

Source: Elaboration on Eurostat, Snam and Terna (Eurostat, 2025c; Snam, 2024a; Terna, 2023)

Price per unit energy of natural gas demand for thermal power plants was computed as the average of corridor-specific values, weighted by their respective supplied quantities.

The affordability indicator of future foreign electricity import corridors (the Italy-Algeria and Italy-Tunisia power lines), as well as of the additional PV and wind national installed capacities in 2030 is included in the model as Levelized Cost of Electricity (LCOE), following the methodology described by the IEA's report *Projected Costs of Generating Electricity* (IEA, 2020). The affordability indicator of internal natural gas production and storage withdrawals, as well as of electricity generation from hydropower and geothermal power plants is assumed null. The estimates of the Levelized Cost of Hydrogen (LCOH), both for electrolysis and imports from Tunisia, were directly sourced from the Italian National Hydrogen Strategy (MASE, 2024b).

Table 22 displays a synoptic view of all the indicators, for each of the corridors included in the simulation.

Considering that both the emissions factors and the prices of energy supplies are expressed in their original units of measure, their values were normalized with respect to their column-specific maximum, before being included in the optimization model.

Table 22 Chosen values of security, sustainability and affordability indicators for the simulation

Variable name	Security Indicator [%]	Sustainability Indicator [gCO2eq/kWh]	Affordability Indicator [€/MWh]
c_{DZ}^{g}	76.88	0.202	Variable (See Table 21)
c_{LY}^{g}	95..87	0.202	
c_{NO}^{g}	6.21	0.202	
c_{AZ}^{g}	72.13	0.202	
c_{RU}^{g}	83.12	0.202	
c_{LNG}^{g}	37.01	0.202	
c_{Pr}^{g}	0.00	0.202	0.00
c_{Sw}^{g}	0.00	0.202	0.00
c_{Th}^{e}	49.99	0.202	Variable (See Table 21)
c_{FR}^{e}	19.79	0.048	
c_{CH}^{e}	3.31	0.012	
c_{AT}^{e}	12.92	0.064	
c_{SI}^{e}	22.73	0.127	
c_{GR}^{e}	37.28	0.134	
c_{ME}^{e}	46.48	0.074	
c_{MT}^{e}	24.59	0.163	
c_{DZ}^{e}	76.88	0.000	34.24
c_{TN}^{e}	59.67	0.000	35.68
c_{Hp}^{e}	0.00	0.000	0.00
c_{Ge}^{e}	0.00	0.000	0.00
c_{PV}^{e}	0.00	0.000	48.76
c_{WT}^{e}	0.00	0.000	66.12
c_{Ey}^{e}	0.00	0.000	283.31
c_{TN}^{h}	59.67	0.000	93.66

The objective function is a linear combination of the energy flows supplied by each supply corridor and the three indicators they are associated with. To account for the possibility of giving both equal and more/less relevance to the attributes of the energy trilemma, the indicators are in turn weighted by as many weighting factors that can be arbitrarily tuned by the user. Since the preferable mix is the one that can simultaneously yield both the most secure (lowest risk), most environmentally sustainable (lowest GHG emissions) and cheapest (lowest total costs) supply mix, the objective function computes the minimum of all the contributions given by the various corridors.

Let

$$\mathbf{C} = \begin{bmatrix} c_i^j(1) & \cdots & c_C^j(1) \\ \vdots & \vdots & \vdots \\ c_i^j\,(T) & \cdots & c_C^j(T) \end{bmatrix} \in \mathbb{R}^{(\mathcal{T},\mathcal{C})}, \forall t \in \mathcal{T}, \forall i \in \mathcal{C} \qquad (20)$$

Be the matrix of the column vectors of daily energy flows of every $c\text{-}th$ supply corridor. Let

$$\mathbf{I^k} = \begin{bmatrix} i_i^k(1) & \cdots & i_i^k(T) \\ \vdots & \vdots & \vdots \\ i_C^k(1) & \cdots & i_C^k(T) \end{bmatrix} \in \mathbb{R}^{(C,T)}, \forall i \in \mathcal{C}, \forall t \in \mathcal{T} \tag{21}$$

be the matrix of the daily values of trilemma indicators related to the $c\text{-}th$ corridor, where superscript k can take values s, e and a respectively relating to security, environmental sustainability and affordability. Let

$$\boldsymbol{w} = \{[w^s, w^e, w^a] | \, (w^s + w^e + w^a) = 1\} \in \mathbb{R}^{(1,3)} \tag{22}$$

be a row vector of weights, each of which linked to one among the three attributes of the trilemma. The objective function is the linear combination of the contributions represented by the column-row product between the energy supplied by every $c\text{-}th$ corridor and its corresponding indicators, in turn weighted by the elements of $\boldsymbol{w}$. Consequently, its analytical expression can be written as follows:

$$\begin{aligned} f &= \min_{c \cdot i} \sum_{k=1}^{3} \sum_{t=1}^{T} \left[\boldsymbol{c}_i^j(t) \cdot \boldsymbol{i}_c^k(t) \cdot w^k \right] \\ f &= \min_{c \cdot i} \left[\sum_{k=1}^{3} w^k \cdot \sum_{t=1}^{T} \left[\boldsymbol{c}_i^j(t) \cdot \boldsymbol{i}_c^k(t) \right] \right] \\ f &= \min_{c \cdot i} \left[\sum_{k=1}^{3} w^k \cdot \sum_{t=1}^{T} \left[\boldsymbol{c}_i^j \cdot \boldsymbol{i}_c^k \right](t) \right] \end{aligned} \tag{23}$$

The next section will present the numerical results of the optimization[33]. In this work, four different cases were compared, according to different values assigned to the elements of $\boldsymbol{w}$:

- Case S: minimum risk, with $w^s = 1,\ w^e = 0,\ w^a = 0$
- Case E: minimum emissions, with $w^s = 0,\ w^e = 1,\ w^a = 0$
- Case A: minimum cost, with $w^s = 0,\ w^e = 0,\ w^a = 1$
- Case T: trilemma balance, with $w^s = 1/3\,,\ w^e = 1/3\,,\ w^a = 1/3$

[33] Used solver: GLPK Simlpex Optimizer, v4.65. CPU: 11th Gen Core™ i7-1165G7@2.80GHz; memory used: 8.8 MB

The four cases shown in this work represent a preliminary and simple approach (which could also be inferred by observing the optimization function is linear) to a multi-objective problem whose nature is more complex and where, most of all, pursuing one among the three attributes of the trilemma usually deprioritizes the other two. For these reasons, a more robust approach could present all the feasible solutions along a front, rather than as scattered points. However, the results presented in the following section are valuable regardless of the adopted simplifying assumptions, as they enable to carry out a quantitative estimation and comparison of the impacts of several energy supply mixes that purposedly target one among the three trilemma attributes.

Below follows the overall formulation of the optimization problem.

$$f = \min_{c \cdot i} \left[\sum_{k=1}^{3} w^k \cdot \sum_{t=1}^{T} \left[\boldsymbol{c}_i^j \cdot \boldsymbol{i}_c^k \right](t) \right], s.t.$$

$$\begin{cases} \left(c_{DZ}^g(t) + c_{LY}^g(t) + c_{AZ}^g(t) \right) \leq \left(150 \cdot LHV_g \right), \forall\, t \in \mathcal{T} \\ \sum_{g=1}^{G} c_i^g(t) \geq d_{Si}^g(t), \forall\, t \in \mathcal{T} \\ c_{Pr}^g(t) \leq\ b_{Pr}^g(t), \forall\, t \in \mathcal{T} \\ c_{Sw}^g(t) \leq\ b_{Sw}^g(t), \forall\, t \in \mathcal{T} \\ \frac{1}{\eta_{Th}} \cdot c_{Th}^g(t) \leq 24 \cdot \alpha_{Th} \cdot P_{Th}, \forall\, t \in \mathcal{T} \\ c_{PV}^e(t) \leq b_{PV}^e(t), \forall\, t \in \mathcal{T} \\ c_{WT}^e(t) \leq b_{WT}^e(t), \forall\, t \in \mathcal{T} \\ c_{Hp}^e(t) \leq b_{Hp}^e(t), \forall\, t \in \mathcal{T} \\ c_{Hp}^e(t) \leq b_{Hp}^e(t), \forall\, t \in \mathcal{T} \\ c_{Pr}^g(t) \leq b_{Pr}^g(t), \forall\, t \in \mathcal{T} \\ c_{Sw}^g(t) \leq b_{Sw}^g(t), \forall\, t \in \mathcal{T} \\ c_{Ey}^e(t) \cdot \eta_{Ey} \leq \frac{1}{365} \cdot E_{Ey}, \forall\, t \in \mathcal{T} \\ c_{Ey}^e(t) \leq c_{PV}^e(t) + c_{WT}^e(t) + c_{Hy}^e(t) + c_{Ge}^e(t), \forall\, t \in \mathcal{T} \\ \sum_{c=1}^{C} c_i^j(t) \geq \sum_{d=1}^{D} d^j(t), \forall\, t \in \mathcal{T} \\ \mathcal{L} \end{cases}$$

4.3 Numerical Results

Table 23 displays the synoptic view of the energy flows delivered by each supply corridor in the four simulated cases. For sake of completeness and easier interpretation, the table also shows the minimum and maximum yearly values of energy that could be supplied by each corridor, in compliance with the constraints illustrated in **Errore. L'origine riferimento non è stata trovata.**.

Table 23 Synoptic view of yearly energy fluxes (in TWh/y) delivered by each supply corridor, for the four simulated cases

Variable name	Range		Case			
	Min	*Max*	*S*	*E*	*A*	*T*
c^g_{Pr}	0.00	38.00	38.00	5.63	38.00	37.96
c^g_{Sw}	0.00	85.64	85.64	0.07	85.64	85.58
c^g_{RU}	0.00	54.78	0.00	35.59	26.25	0.00
c^g_{NO}	0.00	79.69	79.20	2.27	41.65	77.15
c^g_{LY}	0.00	26.05	0.00	8.66	25.60	0.00
c^g_{AZ}	60.10	171.73	62.36	112.69	124.68	61.90
c^g_{LNG}	0.00	239.34	143.61	158.41	193.65	114.94
c^g_{DZ}	100.05	400.18	100.05	146.10	170.44	100.05
c^e_{FR}	0.00	24.62	23.81	24.62	0.00	24.62
c^e_{CH}	0.00	23.63	23.63	23.63	0.00	23.63
c^e_{AT}	0.00	1.45	1.42	1.45	0.00	1.45
c^e_{SI}	0.00	10.10	9.67	10.10	0.00	10.02
c^e_{GR}	0.00	13.14	1.20	13.11	0.00	12.03
c^e_{ME}	0.00	5.26	0.38	5.26	0.00	4.88
c^e_{MT}	0.00	3.72	3.52	3.71	0.00	2.26
c^e_{DZ}	0.00	8.76	0.00	8.76	8.05	8.76
c^e_{TN}	0.00	5.26	0.35	5.26	4.63	5.26
c^e_{Hp}	0.00	46.20	46.20	46.20	46.20	46.20
c^e_{Ge}	0.00	5.35	5.35	5.35	5.35	5.35
c^e_{PV}	0.00	105.00	105.00	105.00	22.92	105.00
c^e_{WT}	0.00	64.00	64.00	64.00	6.81	64.00
c^e_{Th}	48.29	241.43	48.29	48.29	48.29	48.29
c^e_{Ey}	0.00	6.00	6.00	6.00	0.00	0.80
c^h_{TN}	0.00	8.00	0.46	8.00	0.00	8.00

For each row, the case(s) where the corridor-specific supplied energy is maximum is highlighted in red. As foreseeable, endogenous and existing energy corridors always supply their respective maximum amount of energy, regardless of the commodity, in cases *S* and *A*. In case *S*, this is the natural consequence of the null risk indicator they were initially assigned. The same happens for c^g_{Pr}, c^g_{Sw}, c^e_{Hy} and c^e_{Ge} in case *A*.

Looking at case *S*, electricity imports from European exporters are generally preferred over natural gas and hydrogen ones, mainly thanks to the lower geopolitical instabilities of countries Italy shares an electricity interconnection with. For the same reason, the new Algerian and Tunisian power lines are little exploited. Among natural gas corridors, LNG imports are the most preferred choice, thus underscoring the importance of a diversified energy supply import mix.

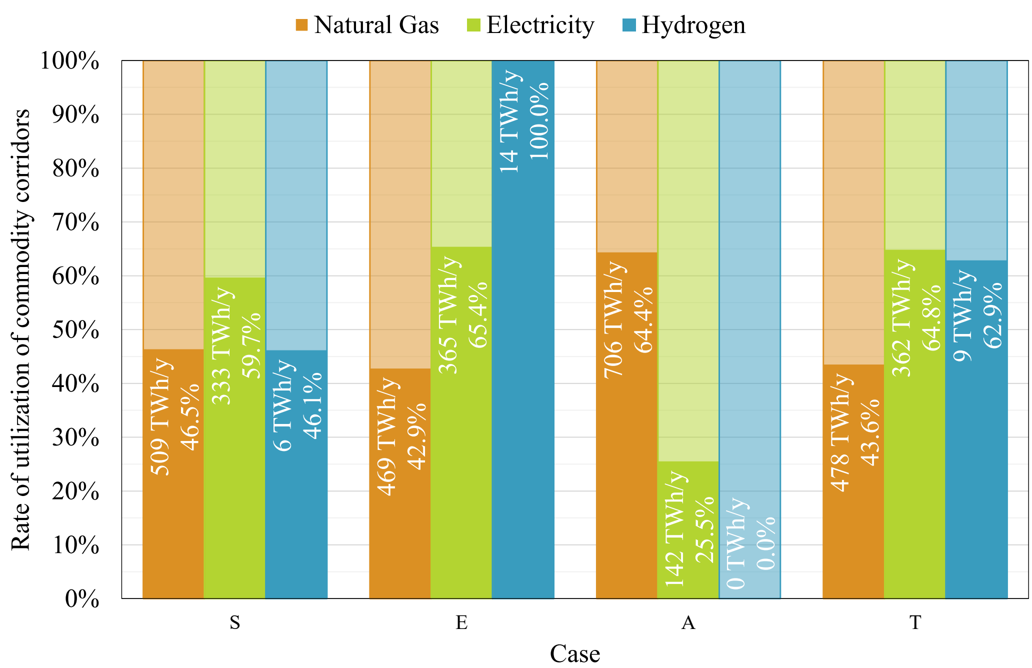
In case *E*, electricity and hydrogen corridors are the most exploited ones, naturally thanks to their null carbon footprint. In this case, both DZIT and TNIT connectors are widely exploited. Natural gas is exploited only consistently with lower bound constraints and to match remaining portions of energy demand.

On the contrary, natural gas is generally chosen over both electricity and hydrogen, when maximum affordability is sought for. The only chosen electricity import corridors are Algeria and Tunisia, both of which are more cost-effective than their European counterparts.

Numerical results of case *T* show that, with the current optimization framework, great relevance is given to corridors whose indicators – regardless of the Trilemma attribute – have a null (or very close to null) value: this is also reasonable, because their contributions are nullified in the computation of the objective function. Therefore, electricity corridors are almost entirely exploited, as well as internal natural gas production and storage withdrawals.

Complementing the analysis, Figure 25 shows the energy delivered by each of the three energy commodities for each simulated case, and the overall percentage rate of utilization of their specific corridors.

Figure 25 Rate of utilization of supply corridors by energy commodity



Case *S* is the most balanced, mainly due to the possibility of sourcing natural gas from zero-risk corridors such as internal production and withdrawal from storage systems, which ensure a 46.5% utilization rate of its corridors. Cases *E* and *A* instead present inverse behaviors, with the first dominated by electricity and green hydrogen (which even completely saturates the capacity of its corridors), and the second with natural gas employing 64.9% of its total capacity, compared to only 25.5% for electricity and no energy supply at all for hydrogen. In case *T*, the selection of commodities by the optimizer is slightly unbalanced towards electricity and hydrogen, which respectively take up 64.8% and 62.9% of their total supply capacities. Natural gas instead stands at levels of utilization comparable to those of case *E*, with a supply corridor utilization rate of 43.6%.

Concluding the discussion, Table 24 shows the values of total costs, total greenhouse gas (GHG) emissions and average energy supply risk, for the four simulated cases. The average supply risk was evaluated as the mean of the risk indicators of all the supply corridors with a non-null energy supply, weighted by their respective values of supplied energy.

Table 24 Synoptic view of Trilemma indicators, for the four simulated cases

Case	Total costs		Total GHG emissions		Average risk	
	Value [b€/y]	*p.u.*	*Value [$MtCO_{2eq}$/y]*	*p.u.*	*Value*	*p.u.*
S	11.81	1.07	54.38	1.04	28.04	1.00
E	14.72	1.33	52.31	1.00	43.51	1.55
A	11.05	1.00	71.24	1.36	46.08	1.64
T	11.98	1.08	52.98	1.01	28.45	1.01

The minimum total costs, GHG emissions and average supply risk amount to 11.05 b€/y, 52.31 $MtCO_{2eq}$/y and 28.04, respectively. In case *E*, the search for the commodity mix with the lowest carbon footprint generates a considerable imbalance in both the total costs (14.72 b€/y) and the average supply risk (43.51), respectively 1.33 and 1.55 times larger than the corresponding minimum values of cases *A* and *S*. The same happens when optimizing to find the least costly energy mix: in fact, GHG emissions of 71.24 $MtCO_{2eq}$/y and an average risk of 46.08 are 1.36 and 1.64 times larger than the values registered for cases *E* and *S*. Case *S* is the most evenly balanced among the four simulated ones, mainly thanks to the relatively high geopolitical stability (and, consequently, of the low supply risk) of the majority of electricity exporting countries, and the selection of LNG over the other natural gas import corridors. In this case, total costs of 11.81 b€/y are only 7% larger than those of case *A*, while total GHG emissions (54.38 $MtCO_{2eq}$/y) only 4% with respect to case *E*. The results obtained in case *T* are useful to assess the influence of the values of the indicators on the value of the objective function. In fact, several corridors are characterized by both zero GHG emissions and supply risk. With reference to the analytical expression of the objective function written in (23), they immediately emerge as preferable choices because their numerical contribution to the objective function is almost zero. For this reason, one may say that – in cases where the three Trilemma attributes are reciprocally competing, environmental sustainability and energy security have a stronger influence than affordability. Indeed, both total GHG emissions and average supply risk are just 1% larger than their respective minimum of cases *E* and *S*; nonetheless, the total costs obtained in case *T* are still only 1.08 times higher those of case *A*, from which it derives that seeking for the minimum emissions and average supply risk yields satisfactory results also in terms of affordability.

4.4 Conclusions

This chapter presented an optimization framework and its related computational methodology, implementable to define the composition of different energy commodity mixes and reciprocally compare them to assess how they rank with respect to the three attributes of the Energy Trilemma: energy security, environmental sustainability and energy affordability.

The reference energy system chosen for the analysis consisted in Italy and all its present and future energy supply corridors related to three main commodities: natural gas, electricity and green hydrogen. The results compared four different energy mixes obtained running as many simulations, three of which aiming at finding the mix that minimized one among the three Trilemma attributes, while the fourth assigning equal importance to all of them.

Electricity stood out as the most frequently chosen commodity: in fact, endogenous renewable electricity generation is considerably less affected by external events of geopolitical nature than energy import corridors. Furthermore, a large installed renewable capacity also enables to generate considerable amounts of energy with no carbon emissions. In terms of energy security, the Italian electricity trading partners are geopolitically more stable than their natural gas counterparts, thus improving the overall security of the energy import mix. Electricity can also be effectively supported by green hydrogen, especially to decarbonize the hardest-to-abate sectors. Indeed, the uptake of green hydrogen further underscores the role of electricity in the energy transition, considering it is necessary to feed electrolyzers and produce hydrogen. Natural gas stands out as the preferable choice when affordability is accounted for. However, the increasing penetration of renewables could let electricity outscore natural gas also in this field, thanks to the massive production of renewable energy at zero cost. In this framework, natural gas may be progressively phased-out or take part in the future energy mix only to a small extent.

Although the presented computational framework fits well within the ESOM approaches found in scientific literature, it could be improved and refined in several ways. In fact, the results shown in the previous sections effectively demonstrated how looking for the energy mix that minimizes only one of the Trilemma attributes can return unsatisfactory results in the other two. Therefore, presenting the feasible solutions along a frontier instead of comparing discrete points could produce more robust and reliable results. The optimizer could be improved by also simulating more than one year to introduce a more precise modeling of both investments and dynamics of storage systems, integrating electricity and hydrogen ones too.

Adjustments can be made to the objective function as well, because the large gaps between some of the indicators make the selection of the optimal solution straightforward and do not enable enough competition among the decision variables. Furthermore, indicators may be more complex and integrate additional aspects pertaining to the Trilemma attribute they relate to: for example, sustainability could also account for life-cycle emissions – thus including those incurred in the processes of extraction and refining of raw materials, manufacturing of semi-finished and finished products, and end-of-life. Affordability may instead be split into costs incurred by investors and those incurred by final energy consumers, or even account for market-related dynamics. The concept of security could be extended beyond geopolitical stability only and consider, for instance, the infrastructural stability of the different energy networks – particularly power grids, given the large penetration of renewables expected for the near-future – or more precisely model geopolitical risk itself, perhaps accounting for the diversification of the overall supply mix, rather than comparing single supply corridors.

Nonetheless, the presented optimization model can be useful to draw some key and preliminary observations about the potential competition and cooperation of different energy commodities. In this framework, electricity stood out as the leading commodity in the energy transition process, being the one capable of achieving satisfactory results in all the Trilemma attributes.

Conclusions

This thesis discussed energy transition in Euro-Mediterranean countries, investigating how they reacted to the two most recent geopolitical crises that affected the area and its energy system: the Russo-Ukrainian war and the latest phase of the Israeli-Palestinian conflict. Due attention was specifically devoted to observing how the two crises have changed the degree of priority Euro-Mediterranean countries had attributed to environmental sustainability, energy security and energy affordability – together known as the Energy Trilemma – until that moment.

The Russo-Ukrainian conflict unprecedently rewrote the Euro-Mediterranean gas infrastructure systems, making countries that had been significantly dependent on Russian supplies seek for new and alternative import partners, while directing part of their investments towards improving the reliability and flexibility of their transmission networks. In this context, the most tangible impact of the phase-out of Russian natural gas was the remarkable growth of the supplies of Liquefied Natural Gas (LNG), parallelly accompanied by the diffusion of new LNG regasification terminals, as a mean to diversify the origin of supplies, as well as to preventively reinforce the energy security of the European countries' natural gas infrastructures.

In this framework, while EU27 member countries strived to find a new balance between the accomplishment of decarbonization targets and the definition of a new, secure and affordable energy mix, oil and gas producing and exporting countries on the Southern and Eastern shores of the Mediterranean Basin saw the withdrawal of Russia as an opportunity to consolidate their role as exporting partners for the EU27, cementing the link between fossil fuels and their economies.

This twofold situation further enlarged the technological gap between the Mediterranean shores, with the Northern robustly poised to increase the role of renewables in its future electricity generation mix while, on the contrary, the transition happens at dramatically slower paces in the other two shores, too heavily burdened by the weight of fossil fuels. Paradoxically, the Southern Shore would even be the Mediterranean area able to harness the most promising solar and wind intensities in the entire Basin, thus having the potential of leading a transition not only towards decarbonization in general, but also towards a new, trans-Mediterranean energy dialogue based on renewable electricity instead of fossil fuels.

Indeed, the widespread diffusion of renewables could not only substantially reduce the carbon intensity of the Mediterranean energy mix but also grant more affordable access to clean energy to more people, being able to generate more electricity at zero marginal cost.

Although fossil fuels seriously stall the deployment of the transition in the Southern Shore of the Mediterranean, the current plans to build new electricity interconnections among the three shores leave enough room to hope for a future Mediterranean energy system based on the mutual exchange of electricity among its countries. In fact, the forecast power transmission infrastructure could be as capable to match almost 10% of the future Mediterranean electricity demand. Additionally, interconnected power grids would reciprocally improve their overall flexibility and reliability, while being readier to accommodate larger capacities of intermittent renewables.

Simulations carried out to track the evolution of the future Italian energy system further underscored the importance of electricity in the pathway towards decarbonization. In fact, replacing a part of thermal electricity generation with renewables could significantly relieve the Italian oil and gas import dependency, thus intrinsically improving its overall energy security – naturally, this could be generalized and referred to any country with a heavy import dependency on fossil fuels. Additionally, given the unfeasibility of a complete electrification of final energy uses, electricity would still be the main commodity feeding the energy conversion devices that synthetize the alternative energy commodities that will presumably take part in the future energy mix. These include, for instance, green hydrogen, biofuels and synthetic fuels, which will effectively contribute to the decarbonization of the hardest-to-abate sectors.

Electrification would be advantageous from a technological point of view too: in fact, electricity-based technologies are generally more energy- and exergy- efficient than their fossil fuels-based counterparts, mainly thanks to the absence of combustion processes that heavily affect the overall efficiency of any energy process.

In conclusion, regardless of how advantageous a process of massive electrification could be for the Mediterranean countries, it needs to be carefully planned and subsequently deployed, considering their current starkly different energy, environmental and socioeconomic contexts. Promoting cooperation, attracting investments and sharing technological knowledge can be the keys to achieve a fair and just transition while successfully targeting the three attributes of the Trilemma.

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Appendix

A.1 Exergy balance for a generic Control Volume

$$\dot{W} = \dot{W^{el}} + \dot{W^{ch}} - \frac{dE}{d\tau}(E - T_0 \cdot s) + \sum_{j=1}^{n}\left(1 - \frac{T_0}{T_j}\right) \cdot \Phi_j + \sum_{in}[\dot{m} \cdot (h^0 - T_0 \cdot s)] - \sum_{out}[\dot{m} \cdot (h^0 - T_0 \cdot s)] - T_0\Sigma \quad \text{(A.1)}$$

where:

- $\dot{W}$ is the *net mechanical power* (also known as *shaft work*) exchanged at the boundaries of the control volume (positive if done by the system).
- $\dot{W}^{el}$ is the *net electric power* entering the CV.
- $\dot{W}^{ch}$ is the *net chemical power* entering the CV.
- $dE/d\tau = (E - T_0 s)$ is the variation of the *total exergy* within the CV, where E is the total energy and s the specific entropy per unit mass.
- $\left(1 - \frac{T_0}{T_j}\right)$ is called Carnot Factor and is inversely proportional to the ratio between the temperature of the reference environment and the temperature of the system.
- $\left(1 - \frac{T_0}{T_j}\right) \cdot \Phi_j$ is the *exergy flux* associated to the j^{th} thermal flux Φ_j, exchanged across the boundaries of the CV with the j^{th} thermostat (positive if entering).
- $[\dot{m}\,(h_0 - T_0 \cdot s)]$ is the exergy of the mass-flow rates of substances entering or exiting the CV, where $h_0 = h + gz + w^2/2$ is the specific methalpy per unit mass.

A.2 Simplified models for the computation of exergy efficiencies

The exergy efficiencies of the devices considered in the analysis of Commodity Energy Chains (CECs) were computed based on the following assumptions.

- The environmental reference conditions are set at $T_0 = 273K$ for temperature and $p = 1\ atm$ for pressure. For space heating applications, room temperature is assumed equal to $T_r = 293K$.
- Electricity can be integrally converted into mechanical work, which means electricity fluxes can be regarded as pure exergy fluxes.
- For sake of simplicity, the lower heating values of hydrocarbons (hereafter indicated as LHV_i) were adopted in place of their chemical exergies, as it can be demonstrated that their reciprocal difference can be neglected.
- In the following formal schemes of energy consuming devices, the dashed red line identifies the chosen CV; green arrows represent power fluxes, while blue arrows mass-flow rates.

Additionally, the symbol η_I is used to indicate energy efficiency (First Law of Thermodynamics efficiency), while η_{II} exergy efficiency (Second Law of Thermodynamics efficiency).

Power Lines

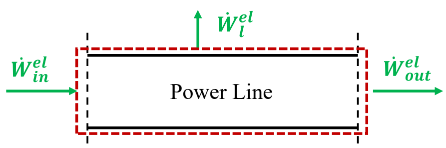

Figure A.1 Thermodynamical model adopted for power lines

In a power line, the downstream electricity flux $\dot{W}_{out}^{el}$ is equal to the difference between the upstream flux $\dot{W}_{in}^{el}$ and losses $\dot{W}_l^{el}$ occurring along the line and due to the Joule effect. The exergy efficiency is expressed as follows.

$$\eta_{II} = \frac{\dot{W}_{out}^{el}}{\dot{W}_{in}^{el}} = \eta_I \tag{A.2}$$

Gas and Hydrogen pipelines

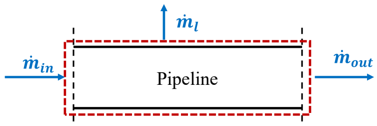

Figure A.2 Thermodynamical model adopted for gas and hydrogen pipelines

The only exergy flows that can be identified in a pipeline are the ones associated with the incoming and exiting mass-flow rates of either natural gas or hydrogen, and their respective fugitive losses $\dot{m}_l$. The exergy efficiency of a natural gas/hydrogen pipeline is then:

$$\eta_{II} = \frac{\dot{W}_{out}^{ch}}{\dot{W}_{in}^{ch}} \approx \frac{\dot{m}_{out} \cdot LHV_i}{\dot{m}_{in} \cdot LHV_i} = \frac{\dot{m}_{out}}{\dot{m}_{in}} = \eta_I \tag{A.3}$$

Electrochemical Storage

In electrochemical storage systems, discharged electricity $\dot{W}_{out}^{el}$ is equal to the difference between the charging flux $\dot{W}_{in}^{el}$ and the losses $\dot{W}_l^{el}$ occurring the charging and discharging phases.

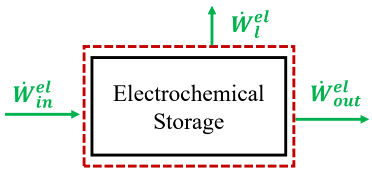

Figure A.3 Thermodynamical model adopted for electrochemical storage systems

The exergy effciency can be computed as

$$\eta_{II} = \frac{\dot{W}_{out}^{el}}{\dot{W}_{in}^{el}} = \eta_I \tag{A.4}$$

Compressed Gas/Hydrogen Storage

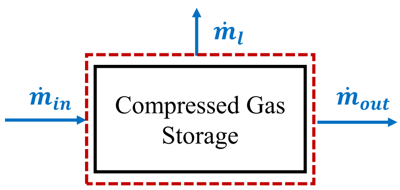

Figure A.4 Thermodynamical model adopted for storage systems of compressed gas/hydrogen

In systems devoted to storing compressed gases, the outlet stream $\dot{m}_{out}$ is equal to the difference between the input mass-flow rate $\dot{m}_{in}$ and fugitive losses $\dot{m}_l$. The exergy efficiency can be expressed in terms of the exergy content of the inlet and outlet mass-flow rate as

$$\eta_{II} = \frac{\dot{W}^{ch}_{out}}{\dot{W}^{ch}_{in}} \approx \frac{\dot{m}_{out} \cdot LHV_i}{\dot{m}_{in} \cdot LHV_i} = \frac{\dot{m}_{out}}{\dot{m}_{in}} = \eta_I \tag{A.5}$$

Electrolyzer

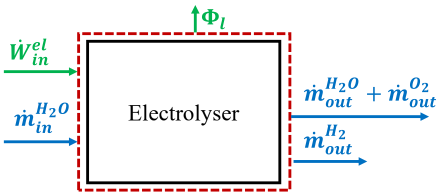

Figure A.5 Thermodynamical model adopted for the electrolyzer

In electrolyzers, the incoming electricity flux $\dot{W}^{el}_{in}$ splits the incoming water mass-flow rate $\dot{m}^{H_2O}_{in}$ into the two mass-flow rates of hydrogen ($\dot{m}^{H_2}_{out}$) and oxygen $\dot{m}^{O_2}_{out}$, leaving as by-products leftover water ($\dot{m}^{H_2O}_{out}$) and the waste heat (Φ_l) released from auxiliary devices. Since the only useful outlet stream is hydrogen, the exergy efficiency of the electrolyzer can be written as

$$\eta_{II} = \frac{\dot{W}^{ch}_{in}}{\dot{W}^{el}_{in}} \approx \frac{\dot{m}^{H_2}_{out} \cdot LHV_i}{\dot{W}^{el}_{in}} = \eta_I \tag{A.6}$$

Heat Pump

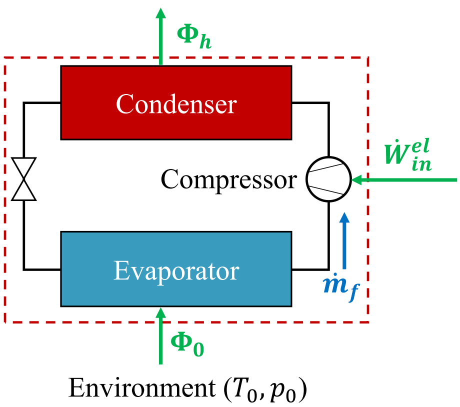

Figure A. 6 Thermodynamical model adopted for the heat pump

In a heat pump, the useful effect is the thermal flux Φ_h supplied to the building. Since spent energy is electricity $\dot{W}^{el}_{in}$ supplied to the pump, the exergy efficiency of the heat pump will be

$$\eta_{II} = \frac{\Phi_h \cdot \left(1 - \frac{T_o}{T_r}\right)}{\dot{W}_{in}^{el}} = COP \cdot \left(1 - \frac{T_o}{T_r}\right) \tag{A.7}$$

Where COP is the conventional Coefficient of Performance of the heat pump.

Natural Gas/Hydrogen Boiler

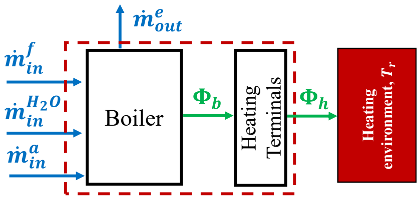

Figure A. 7 Thermodynamical model adopted for gas and hydrogen boilers

A boiler is fed air ($\dot{m}_{in}^{a}$) and a fuel ($\dot{m}_{in}^{f}$). In the case of natural gas condensing boilers, a third mass-flow rate of water ($\dot{m}_{in}^{H_2O}$) enters the device. Upon combustion, the thermal flux Φ_b is released and used to heat the water flowing through the heating terminals placed inside the building and leaving exhaust gases ($\dot{m}_{out}^{e}$) as by-product. The heat released from the combustion can be expressed as

$$\Phi_b = \eta_I \cdot \dot{m}_{in}^{f} \cdot LHV_i \tag{A.8}$$

Useful heat is produced at the expense of the chemical energy contained in the fuel. Here, thermal losses occurring within the heating terminals are assumed negligible, therefore $\Phi_b \approx \Phi_d$. The exergy efficiency of the boiler can be expressed in the following way:

$$\eta_{II} = \frac{\Phi_d \cdot \left(1 - \frac{T_o}{T_r}\right)}{\dot{W}_{in}^{ch}} = \frac{\eta_I \cdot \dot{m}_{in}^{f} \cdot LHV_i \cdot \left(1 - \frac{T_o}{T_r}\right)}{\dot{m}_{in}^{f} \cdot LHV_i} = \eta_I \left(1 - \frac{T_o}{T_r}\right) \tag{A.9}$$

Electrical Heater

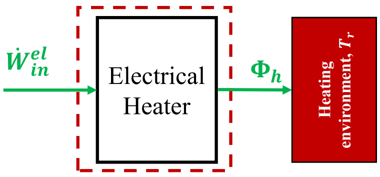

Figure A.8 Thermodynamical model adopted for the electrical heater

Electrical heaters convert electricity into heat by simply heating a resistor and exploiting the Joule effect. The exergy efficiency of an electrical heater is:

$$\eta_{II} = \frac{\Phi_h \cdot \left(1 - \frac{T_o}{T_r}\right)}{\dot{W}_{in}^{el}} = \frac{\eta_I \cdot \dot{W}_{in}^{el} \cdot \left(1 - \frac{T_o}{T_r}\right)}{\dot{W}_{in}^{el}} = \eta_I \left(1 - \frac{T_o}{T_r}\right) \quad \text{(A.10)}$$

Internal Combustion Engine (ICE)

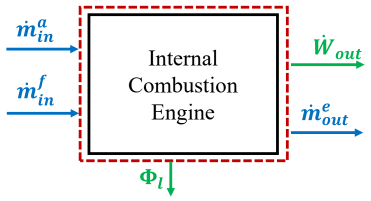

Figure A.9 Thermodynamical model adopted for internal combustion engines

In ICEs, the chemical energy of the fuel is converted into shaft work. $\dot{m}_{in}^{a}$ indicates the air injected into the combustion chamber, $\dot{m}_{out}^{e}$ exhaust gases and Φ_l the heat lost to the environment. The exergy efficiency is:

$$\eta_{II} = \frac{\dot{W}}{\dot{W}_{in}^{ch}} \approx \frac{\dot{W}}{\dot{m}_{in}^{f} \cdot LHV_i} = \eta_I \quad \text{(A.11)}$$

Electrical Motor

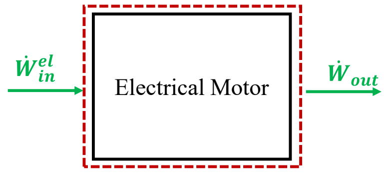

Figure A.10: Thermodynamical model adopted for the electrical motor

Electrical motors convert electricity into mechanical work, therefore their exergy efficiency is simply the ratio of these two quantities, as this already accounts for any losses occurring within the device.

$$\eta_{II} = \frac{\dot{W}}{\dot{W}_{in}^{el}} = \eta_I \quad \text{(A.12)}$$

Fuel Cell

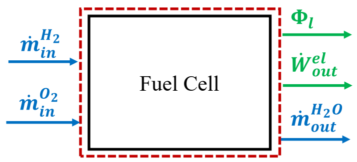

Figure A.11: Thermodynamical model adopted for fuel cells

In a fuel cell, electricity is produced blending hydrogen ($\dot{m}_{in}^{H_2}$) and oxygen ($\dot{m}_{in}^{O_2}$), and the only by-product of the reaction is water vapor ($\dot{m}_{out}^{H_2O}$). During the process, heat (Φ_l) is released and lost to the environment. The exergy efficiency is:

$$\eta_{II} = \frac{\dot{W}_{in}^{el}}{\dot{W}_{in}^{ch}} \approx \frac{\dot{W}_{in}^{el}}{\dot{m}_{in}^{H_2} \cdot LHV_i} = \eta_I \tag{A.13}$$

A.3 ISO Country Codes

Table A. 1 ISO Country codes

Country Code (ISO 3166-1 alpha 3)	Country Name
ALB	Albania
DZA	Algeria
BIH	Bosnia and Herzegovina
HRV	Croatia
CYP	Cyprus
EGY	Egypt
FRA	France
GRC	Greece
ISR	Israel
ITA	Italy
LBN	Lebanon
LBY	Libya
MLT	Malta
MNE	Montenegro
MAR	Morocco
PRT	Portugal
SVN	Slovenia
ESP	Spain
SYR	Syria
TUN	Tunisia
TUR	Türkiye