5.
Electricity highways across the Mediterranean: a green connection between Northern and Southern Shore

5.1 From a fossil-based to a "green" energy dialogue

The commercial dialogue between the shores of the Mediterranean Sea is characterized by an important role in the basket of traded goods played by energy commodities. Significant energy flows have been converging on Europe from North African and Middle Eastern countries in the last decades, particularly those related to oil (both crude oil and refined petroleum products) and natural gas, as discussed in Chapter 2.

Many Northern African countries qualifies as rentier states (as it is highlighted in detail in Chapter 6) getting a considerable share of their GDP from the rents related to the trade of their energy commodities; this aspect should be therefore carefully considered when discussing energy strategies of the countries on the southern Mediterranean shore and on the possible long-term evolutionary perspectives of their energy systems. In particular, for what concerns crude oil, the revenues deriving from oil and gas (in terms of difference between the value of crude oil and natural gas production at regional prices and the overall production costs) in 2021 were equal to 14.5% for Algeria, 56.4% for Libya and 3.0% for Egypt, while with reference to natural gas they amounted to 8.0% for Algeria, 4.6% for Libya and 2.1% for Egypt, allowing for classifying these countries as rentier (Algeria and Libya) or semi-rentier (Egypt) states. [1]

As mentioned before, the share of fossil energy commodities coming from the Southern shore in the supply mix of the countries belonging to the Northern shore of the Mediterranean region is particularly significant. In 2021, 18% of the total crude oil imports, 9% of the total refined petroleum products imports and 27% of natural gas imports of the Northern shore were from the Southern one. [2]

In particular, fossil commodities from Southern Mediterranean countries are particularly important for some highly energy dependent countries located in the Northern part of the Mediterranean basin, like Italy (whose import dependency in 2020 was equal to 74.7%) and Spain (showing an import dependency of 68.5%). [3] Among them, for example, a key role is played by Algeria in the supply of natural gas to Italy: in 2022, the gas supply through the Transmed Pipeline covered 34.3% of the Italian gas import [4], allowing Algeria for replacing Russia as major Italian gas supplier, as a consequence of the Russia-Ukraine conflict started in February 2022, thus further strengthening the fossil-based dialogue across the Mediterranean Sea, as discussed in Chapter 1, where the related geopolitical implications are highlighted.

If the contingency determined by the ongoing conflict has imposed to consider energy security as a priority in the political agenda of several countries, in the long run the need for an energy transition towards decarbonization and a consequent paradigm shift towards renewable energy sources (RES) is undeferrable, since both the health of the Earth and people are seriously threatened by climate change and pollution, respectively.

The role of electricity in this transition is absolutely fundamental, and the so-called "Electricity Triangle" acquires a strategic importance: 1) Increase in electricity production directly from RES; 2) Privileged use of electricity as an energy carrier, 3) Massive electrification of end-uses of energy.

In this framework, the Mediterranean region is requested to face a double challenge: to decarbonize a traditional energy system that is intensely fossil-based and to build a new "green" energy dialogue across its shores.

The current situation shows significant differences in the starting point among these shores in terms of penetration of renewables in their energy systems. In fact, while the countries located on the Northern shore – in particular those belonging to the European Union – despite the high total energy supply per capita (e.g. 105.9 GJ/person in Italy, 144.4 GJ/person in France and 102.2 GJ/person in Spain [3]), are characterized by a slow but continuous decreasing trend in the share of fossil fuels in the primary energy mix, the countries of the Southern shore, even if characterized by lower per capita energy needs (e.g. 60.7 GJ/person in Algeria, 37.3 GJ/person in Egypt and 25.7 GJ/person in Morocco in 2021 [3]) are still almost completely reliant on fossil commodities. For example, in 2020 the share of fossil fuels in the total primary energy supply (TPES) was equal to 77.6% in Italy, 68.7% in Spain and only 46.9% in France (due to the relevance of nuclear energy), while it was equal to 99.9% in Algeria, 93.9% in Egypt, 95.6% in Libya, 90.2%in Morocco and 88.3% in Tunisia [3]. Moreover, while the European countries already have in place well established (and ambitious) decarbonization strategies and plans, the other Mediterranean countries are quite far in defining effective policies and legislation clearly oriented to an energy transition.

However, the Southern Mediterranean shore shows not only considerable fossil energy resources, but also a great potential of generation from renewables. This shore, in fact, can benefit from the highest average global horizontal solar irradiance in the Mediterranean basin (5.67 kWh/m^2, compared to 5.12 kWh/m^2 on the Eastern shore and only 4.02 kWh/m^2 on the Northern one). Similarly, the Southern shore shows the highest potential of onshore wind electricity generation, with an average wind speed equal to 8.76 m/s, compared to 7.67 m/s of the Northern shore and 7.11 m/s of the Eastern one [5][6]. Despite this potential, the exploitation of renewables in the Southern countries is still limited: the overall installed PV generation capacity in 2021 amounted to just 2.4 GW, in stark contrast with a capacity of 57.1 GW installed on the Northern shore, while the onshore wind installed capacity was equal to 3.3 GW, a value considerably smaller than the 68.4 GW installed on the Northern shore. [7]

These figures highlight the possibility of deploying a large capacity of both photovoltaic plants and onshore wind farms on the Southern shore, allowing, on the one hand, for extensively decarbonizing the domestic energy consumption of these countries and, on the other hand, for effectively building a new energy dialogue with the Northern shore based on the trade of the surplus of electricity from renewables not used locally.

This path leads to the emergence of the need, or opportunity, to have "electricity highways" across the Mediterranean, between the two opposite shores. Obviously, it is extremely important to pay attention to the economic model to be implemented, given that the countries involved in the process on the Southern shore are, as previously highlighted, rentier states and, therefore, the new "green" development should be such as not to create imbalances and rather bring about opportunities of further development and production of local GDP.

Moreover, this is not the only critical aspect of the process, as it raises the need for major infrastructure investments to be made in countries with high geopolitical risk, and the need for identifying and implementing proper protection strategies against malicious attacks against the submarine interconnections crossing the Mediterranean Sea.

The exploitation of the RES (with particular reference to Photovoltaic as the preferred technology at the latitudes of the Southern shore of the Mediterranean) and the consequent creation of new energy interconnectors across the Mediterranean region, could also constitute an opportunity to establish sound geopolitical relationships, and to enable the creation of socio-political "added value" (e.g. in terms of new job positions and economic development) for both the shores.

European and North African countries, can create a win-win condition where a sustainable energy transition meets economic development and climate targets on both sides of the Mediterranean. In this perspective the "electricity highways" will play a crucial role in fostering the Mediterranean energy transition.

5.2 HVDC as the key-enabler for the Mediterranean interconnections

As introduced in the previous section, the electricity transmission infrastructure plays a crucial role in the decarbonization process and it's a key factor to enable the black-to-green dialogue transition. The Mediterranean electricity highways can rely on two technologies: HVAC (High Voltage – Alternate Current) and HVDC (High Voltage – Direct Current). The AC infrastructure is highly developed, but has important technical limitations related to the balance between the "consumed" reactive power and transported active power, with respect to the DC one, which is nowadays the most diffused choice for long distance interconnectors and undersea cables.

There are two primary HVDC technologies: *Line-Commutated Converters* (LCC) and *Voltage-Source Converters* (VSC) that corresponds to different stages in the development of the HVDC converters technology and present different performances and operation possibilities.

- **Line-Commutated Converters (LCC):** *LCC HVDC* systems use thyristor valves to control the conversion from AC to DC and vice versa. LCC technology is well-established, reliable, and cost-effective for long-distance point-to-point connections. However, it has limited controllability and flexibility, making it less suitable for multi-terminal systems and grid integration of renewables.
- **Voltage-Source Converters (VSC):** *VSC HVDC* systems use insulated-gate bipolar transistors (IGBTs) to convert AC to DC and *vice versa*. VSC technology provides superior controllability, adaptability to grid conditions, and compatibility with renewable energy sources. It is well-suited for multi-terminal connections and grid stabilization applications.

LCC has been the reference technology for decades, but it has gradually been replaced by VSC, thanks to a better control of reactive power flows, a black start capability, a reduced harmonic distortion and, more in general, a better flexibility in terms the capabilities of power and voltage control. Thanks to these advantages, almost all the new hypothesized interconnectors will be realized by using VSC technology.

DC transmission have several advantages over AC transmission:

- **Less number of cables required for transmission of the same power amount:** DC transmission requires fewer cables than AC transmission for the same power to be transported. This advantage stems from the nature of direct current, which allows for efficient power transmission with a reduced need for multiple cables, simplifying the overall system design and installation.
- **Cost:** In many cases, the overall cost of DC transmission systems can be lower than that of AC systems. While DC converter stations are more expensive than AC transformation stations, the potential cost savings come from factors such as a lower required insulation level (which, in turn, also means shorter and cheaper line towers), fewer conductors, and a more straightforward right-of-way, contributing to a favorable ratio between cost and benefits [8].
- **Power exchange between asynchronous networks:** DC transmission excels in facilitating power exchange between asynchronous AC networks, as demonstrated by the interconnections like the ones in Japan. This capability is crucial for connecting power systems with differing frequencies or phase angles, enhancing the flexibility and efficiency of grid interconnections [9].
- **Efficiency in terms of lower long-distance power losses:** DC transmission exhibits higher efficiency over long distances compared to AC transmission. The critical distance, beyond which DC transmission losses become lower than AC losses makes it particularly advantageous for power transmission covering long distances, while minimizing losses along the lines from their sending-end to the receiving-end.
- **Environmental impact mitigation: more compact and shorter overhead line towers, reduced visual impact: the** DC transmission infrastructure often requires more compact overhead line towers, leading to improve the visual impact on the landscape. This advantage contributes to a more environmentally friendly and aesthetically pleasing power transmission infrastructure, especially in areas where a pleasant view is essential.
- **Lack of impact on the short circuit levels:** unlike AC transmission, DC transmission does not significantly influence the short-circuit levels in power systems. This characteristic simplifies the design and operation of interconnected grids, providing stability and reliability without the need for an extended intervention on the short-circuit protection devices and schemes.
- **Fast and precise load flows control:** DC transmission systems enable fast and precise control of load flows. The ability to regulate power flow allows for an efficient management of the grid, ensuring optimal utilization of resources and responsiveness to dynamic changes in demand and supply, enhancing the overall grid stability [10].
- **No propagation of electromagnetic disturbances:** DC transmission systems do not propagate disturbances in the same way AC systems do. This characteristic minimizes the impact of local disturbances, ensuring a more stable and reliable power transmission network, especially in interconnected grids where disturbances can have widespread consequences [11].
- **Black start capability (VSC):** Voltage-Sourced Converter (VSC) HVDC systems provide black start capability, allowing for the restoration of power in the event of a system-wide blackout. This feature is crucial for grid resilience and reliability, ensuring the ability to restart and re-energize the grid independently, contributing to overall grid stability and recovery capabilities [12].

The first HVDC connection in the Mediterranean area, the SACOI 1, based on mercury vapor valves technology, became operational in 1968, connecting Italian peninsula with the island of Sardinia [13]. In 1988 an intermediate converter station was added, realizing for the first time a multi-terminal connection.

In the 1970s, thanks to the development of power electronics, especially in the field of semiconductors, power conversion bridges built with thyristor valves began to be used for commercial applications. These made HVDC transmission systems a competitive technology for both long-distance power transmission and the interconnection of different electrical systems. The first application of thyristor bridges as a replacement for mercury valves was in 1972, in the Canadian interconnection between the provinces of Quebec and New Brunswick, with a power transport capacity of 3100 MW [14].

To date, the highest voltage level reached for an HVDC line has been achieved in the Chinese ChangjiGuquan UHVDC link, which is a 12,000 MW, 3,000 km bipolar interconnector with a direct voltage of ± 1,100 kV [15], [16].

HVDC solutions are typically used for point-to-point connections: although multi-point architecture is technologically possible, in 2023 there are only two active interconnectors of this type (SACOI, from continental Italy to Sardinia, with an intermediate spilling station in Corse, and from Quebec to New England Transmission in North America) [17]. HVDC meshed grids have been proposed in scientific literature, but currently only the Zhangbei VSC-HVDC infrastructure has four terminals connected together to form a single mesh [18],[19].

The "state of the art" for meshed grids is represented by overhead HVAC lines with voltage levels between 300 kV and 1 MV.

5.3 Interconnectors across the Mediterranean Sea

5.3.1 Operational interconnectors

The Mediterranean Sea has been widely exploited to create many interconnections between the bordering countries. Subsequently, tables and maps representing, respectively, interconnections "in operation" (OP), "planned" (PL or PE, under permitting) and "under consideration" (UC) among the aforementioned countries are reported.

The main goal is to decarbonize as many areas as possible, linking them together by creating an infrastructure in the Mediterranean to exchange the maximum possible power produced by renewable sources. This goal is set both to comply with what was established by the Paris Agreement, signed in 2015, and to find new energy sources for the countries on the northern shore, especially after the recent dramatic events in Ukraine, which was invaded by Russia in February 2022. The war, in fact, has resulted in an unprecedented energy crisis that has forced the European countries to deal with the scarcity of alternatives, but it has pushed in the direction of a more rapid change of course toward an energy transition that involves as many countries as possible, seeking to reach acceptable compromises to all the involved actors.

Nowadays, the overall capacity of the interconnections through the Mediterranean Sea amounts to 6.6 GW, i.e. 60% higher than it was in 2020 and still following an increasing trend. The HVDC technology is widely spread right now in most of the interconnections in operation (Table 1), but HVAC technology is still also present and preferred to cover shorter distances.

SACOI was realized in 1966 to connect the Italian Peninsula to Sardinia passing through Corsica to exchange 300 MW. In 1992 it was modernized (**SACOI2**) to increase the withdrawal of power at the Lucciana terminal, by adding a third terminal to the two already existing ones, still keeping a 200 kV voltage. In this way, it became the first multi-terminal HVDC in the world.

REMO1 (Refuerzo Eléctrico Mediterràneo Occidental – Western Mediterranean Electricity Reinforcement) is the electricity interconnection between Spain and Morocco, commissioned in 1997 to guarantee an optimal exchange of excess of power by keeping a high level of security and frequency control. It provided a 700 MW exchange of power at 400 kV through an AC submarine link. Subsequently, in 2006, a reinforcement of the interconnection was commissioned to double the power capacity and to increase the total length of the link (**REMO2**).

GRITA is a submarine link in LCC-HVDC technology connecting Italy to Greece at a maximum power of 500 MW and a voltage of 400 kV. It started operating in 2002 and it was the first electrical interconnection realized between Italy and abroad at high depth, representing the first step for Italy to be defined as the "Mediterranean Energy Hub".

The **SARCO** link between Sardinia and Corsica is essentially used to help cover Corsica's own cargo according to a transmitted power profile that varies little throughout the year and almost exclusively imported to Corsica. It has a 100 MW power at 150 kV and exploits the HVAC technology.

The electricity interconnection between the Iberian Peninsula and the Balearic Islands (**Romulo**) is crucial to ensure both quality and reliability of electricity supply in the Balearic Islands' system and to promote competitiveness in electricity generation. It was commissioned in 2011, being the first submarine HVDC transmission link in Spain at 250 kV with a power of 400 MW.

The **SAPEI** submarine link is the deepest in the world (1,640 meters under the sea level). It is 435 km long and allows to transfer 1,000 MW. Since it started operating, it has brought several benefits in terms of a higher security of the Sardinian electrical system. Moreover, it reduced the CO_2 released into the atmosphere as a result of increased use of renewable energy sources.

The **ITMT1** power line is a submarine interconnection cable, commissioned in 2015, that connects the Italian and Maltese power grids through the Malta Channel. This submarine cable has a maximum power transmission of 200 MW at 220 kV. The project to build the cable was partly funded by the European Union and it costs 182 M€. This link is fundamental to ensuring a stable and reliable supply of energy between the two countries, contributing to the diversification of energy sources and environmental sustainability.

The 400 kV **Sorgente-Rizziconi** power line is an important electrical connection between the two Italian regions of Sicily and Calabria, with a power of 1,100 MW. This connection contributes to reducing CO_2 emissions into the atmosphere by about 670,000 tons per year, since its commissioning in 2016. In addition, thanks to the rationalization of the power grid in the provinces of Messina and Reggio Calabria, about 170 km of obsolete power lines (87 in Sicily and 85 in Calabria) will be removed, significantly reducing the environmental impact on the territories crossed by these lines.

The **MON.ITA** electrical interconnection connects Italy to Montenegro via a submarine cable and a section of underground cable at 500 kV with a power of 1200 MW.

The electrical interconnection between Crete and mainland Greece (**GRCR**) is a major project connecting the island of Crete, the largest and most populated island in the Greek archipelago, to the mainland. The project consists of a HVDC submarine cable connecting Crete to the Attica region on the mainland. The maximum transmission capacity of the cable is 1,000 MW, enabling efficient power exchange between the island and the mainland. The interconnection helps improve the reliability of electricity supply and will facilitate the integration of renewable energy sources.

5.3.2 In construction, permitting and planned interconnectors

Considering the 2030 time-horizon over the long term, there will be a total transferable power of 21 GW over the interconnectors. To be more precise, the focus on the energy sector is aimed at developing technologies for RES and improving safety and reliability of the Mediterranean infrastructure. In order to achieve these goals, much work has been going on for years now to implement new interconnections and modernize the existing ones. Several power connections are already under construction, others have been properly designed and their implementation permitted by the governments of the involved countries, and others are still at the planning stage. The above-mentioned infrastructures are listed below.

SPCE is a significant project that will bridge the gap between the Iberian Peninsula and Ceuta, integrating the autonomous city into the peninsular electricity system, aligning with the 2021-2026 Electricity Planning, recently approved by the Spanish Government. An exchange of power of 50 MW is provided at 132 kV, covering a distance of 60 km, exploiting HVAC technology.

ITMT2 was planned and commissioned to double the power capacity of the existing and aforementioned interconnection between Italy and Malta by using HVAC technology.

The **EuroAsia interconnector** is a 2000 MW capacity HVDC multiterminal interconnector between Israel, Cyprus and Crete (Greece) at 500 kV, whose investment cost reached 2,500 M€. It aims to be the longest of its type in the world, with a length of 1,208 km, and to put an end to the energy isolation of Cyprus, which is connected with Greece only (Attica, **GRCR**). Currently, Greece is strongly interconnected with Italy, Türkiye and its Balkan neighboring countries. This ambitious project will lead to the integration of high percentage of RES in the island of Cyprus and, eventually, to a reduction of CO_2 emissions. Moreover, from an economical viewpoint, it will provide mutual benefits to the involved countries in terms of energy prices . It is already in early phase of construction and it is expected to be considered operational in the Mediterranean grid by 2030.

Serving as a "electricity highway", the **EuroAfrica Interconnector** is an impressive project that aims to connect the national electricity grids of Egypt, Cyprus, and Greece through a 1,396 km submarine HVDC cable, providing initially 1 GW of power capacity, that will be later increased at 2 GW in subsequent stages, at 500 kV. Egypt is already planning to expand its grid not only in Europe, but also in Asia, by connecting its network to those of the neighboring countries and, in particular, it will be heavily interconnected to Saudi Arabia by 2030.

The **SACOI2** interconnector is already planned to be modernized and renewed, since it has almost come to the end of its life, it , making it become **SACOI3**. Taking advantage of the work on the entire line, maintaining a voltage of 200 kV, and allowing to achieve a withdrawal power of 100 MW (it is currently 50 MW in Corsica), the power capacity will be increased to 400 MW. The project will make the whole electrical system more efficient and reliable and it will encourage the development of RES as a consequence.

The governmental TSOs of both Tunisia (Steg) and Italy (Terna) have already authorized **TUNITA,** approved as Project of Common Interest (PCI) by the European Commission. It will be an electricity bridge 233 km long between Europe and Africa, connecting the Partanna electrical station (Trapani, Italy) with a corresponding station of Menzel Tenim (Tunisia) at 500 kV (HVDC) with a power capacity of 600 MW. It will allow a bidirectional energy exchange, leading to an efficient use of the excess of energy in both countries.

Terna (Italian's public TSO) has presented Hypergrid in its Development plan this year. It consists of planning several new projects commissioned for the next decade, aiming at making Italy as the Mediterranean Energetic Hub. Through Hypergrid, it will be possible to double the trading capacity between different market zones from the current 16 GW to more than 30 GW.

The **Adriatic link** will connect Abruzzo (Italy) to Marche (Italy), exploiting VSC-DC technology, making available, hypothetically, two new "points" on the shores of the Adriatic Sea (Villanova and Fano, respectively). There will be a capacity power of 1000 MW at 500 kV. It is expected to be commissioned within 2028.

The **Tyrrhenian Link** project is a major initiative to connect the power grids of the Italian peninsula, Sicily and Sardinia through a double high-voltage undersea cable, 950 km long, with a 1,000 MW power capacity at 500 kV (VSC-DC). Four conversion stations will be built at the connection points of the two sections of the link: eastern section, connecting Campania to Sicily, and western section, connecting Sicily to Sardinia. **Dorsale Sarda** will connect Sardinia to both the Italian Peninsula and Sardinia itself from the north to the south, reaching an overall length of about 550 km, and a power of 2,000 MW. The first connection will be done by **SAPEI2**, a new power line that will work in synergy with the existing SAPEI at 500 kV (VSC-DC) providing a power of 1,000 MW. The second connection will be an AC type, between Codrongianos and Sulcis (both in Sardinia), providing a power of 1,000 MW at 220 kV. Finally, **Dorsale Ionico-Tirrenica** will connect Sicily to Lazio (Italy) through a double undersea cable at HVDC (500 kV). It will consist of two main routes: an HVDC Ionian Link, between Priolo (Sicily, Italy) and Rossano (Calabria, Italy), and an HVDC link between Rossano and Montecorvino (Campania, Italy) and Latina (Lazio, Italy).

ITGR2 is a reinforcement of the existing interconnection between Italy and Greece, whose realization will lead to double the power capacity among the two involved countries.

The **ESMA** project consists of the construction of the third interconnection HVAC 400 kV cable between the two countries (Spain and Morocco, already connected through REMO1 and REMO2). It is included in the Spanish National development plan for the year 2026 (planned in Spain only). The interconnection capacity between the two countries will be increased from the current 900 MW Net Transfer Capacity (NTC) to 1,550 MW in the direction from Spain to Morocco and from 600 MW to 1,200 MW in the direction from Morocco to Spain.

The Egypt-Greece (**EGGR**) interconnection is intended to be the first vertical interconnector in the Eastern Mediterranean Sea, consisting of a bipolar HVDC interconnector with a NTC of 2,000 MW. The submarine cable connecting the two countries is 843 km long. The project is promoted by the TSOs of both countries and it is expected to be realized within 2028.

Finally, the **MAPT** project involves the realization of the first DC interconnection cable between Morocco and Portugal (500 kV), namely between Bni Harchen (Morocco) and Tavira (Portugal), with an NTC of ±1000 MW. The project is still at a planning stage and there is no commissioning date defined.

Table 1 - Electricity highways (Interconnectors) in the Mediterranean area

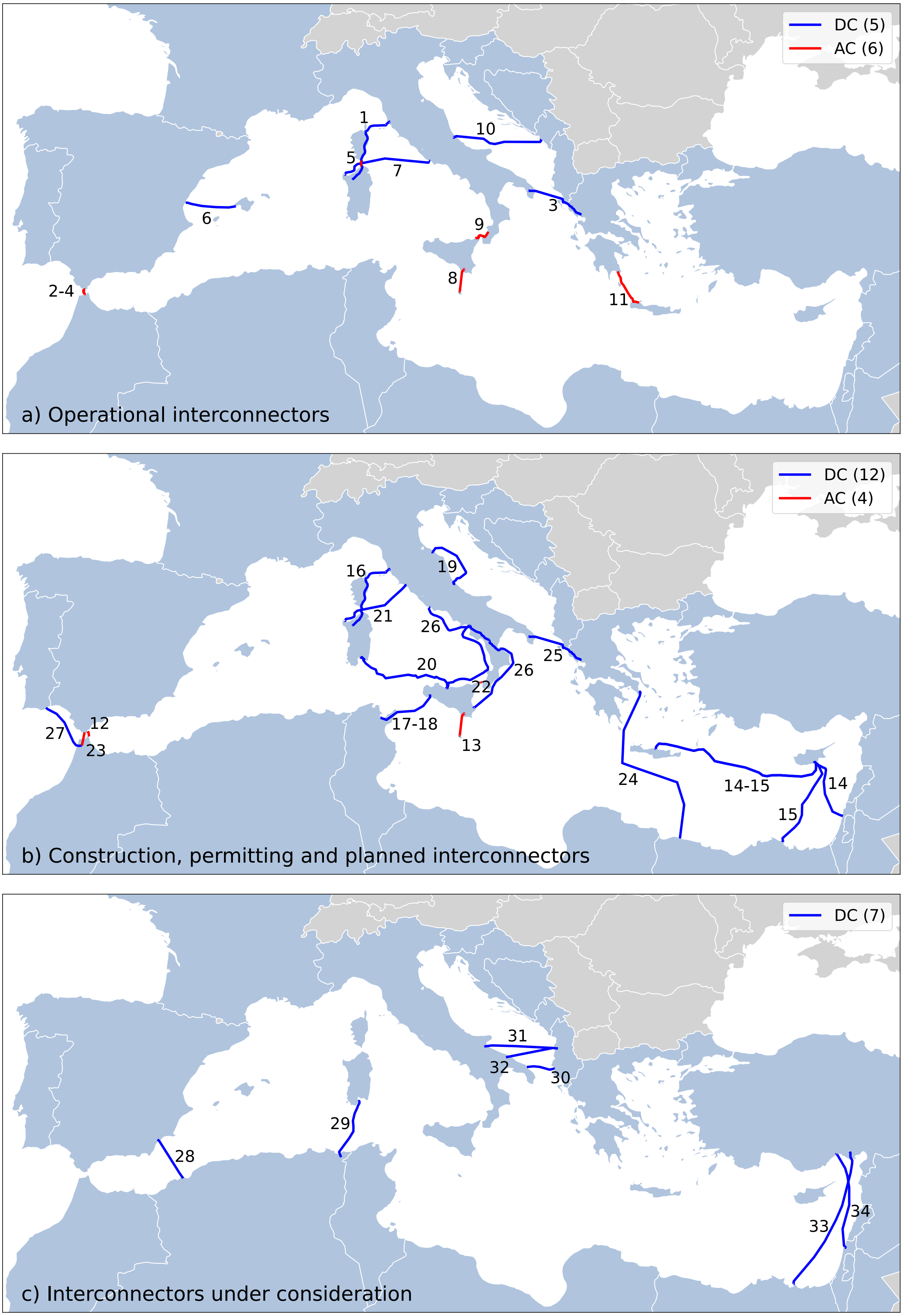
#	Name	Description	Terminal 1[1]	Terminal 2	Type	Status[2]	Comm date[3]	Pub/ Pri	U[4] [kV]	P_{nom} [MW]	Len[5] [km]	Cost [M€]
1	SACOI2	Italy-Corsica	Suvereto, Tuscany (ITA)	Lucciana, Corse (FRA)	LCC-DC	OP	1968	PUB	200	300	413	670
		Corsica-Sardinia	Lucciana, Corse (FRA)	Codrongianos, Sardinia (ITA)								
2	REMO1	Morocco-Spain	Tarifa (ESP)	Fardioua (MAR)	AC	OP	1997	PUB	380	700	26	95
3	GRITA	Italy-Greece	Galatina, Puglia (ITA)	Arachthos (GRC)	LCC-DC	OP	2002	PUB	400	500	153	339
4	REMO2	Morocco-Spain	Tarifa (ESP)	Fardioua (MAR)	AC	OP	2006	PUB	380	700	31	115
5	SARCO	Sardinia-Corsica	Santa Teresa, Sardinia (ITA)	Bonifacio, Corse (FRA)	AC	OP	2006	PUB	150	100	15	40
6	Romulo	Spain-Balearic Islands	Morvedre (ESP)	Santa Ponsa, Maiorca (ESP)	LCC-DC	OP	2011	PUB	250	400	244	420
7	SAPEI	Italy-Sardinia	Fiumesanto, Sardinia (ITA)	Latina, Lazio (ITA)	LCC-DC	OP	2011	PUB	500	1,000	435	750
8	ITMT1	Italy-Malta	Ragusa, Sicily (ITA)	Maghtab (MLT)	AC	OP	2015	PRI	220	200	120	182
9	Sorgente-Rizziconi	Italy-Sicily	Sorgente, Sicily (ITA)	Rizziconi, Calabria (ITA)	AC	OP	2016	PUB	400	1,100	105	700
10	MONITA	Italy-Montenegro	Villanova, Abruzzo (ITA)	Lastva (MNE)	LCC-DC	OP	2020	PUB/ PRI	500	1,200	445	1,100
11	GRCR	Greece-Crete	Molai (GRC)	Chania, Crete (GRC)	AC	OP	2021	PUB	150	400	173	356
12	SPCE	Spain-Ceuta	Puerto de la Cruz (ESP)	Ceuta (ESP)	AC	CO	2025	PUB	132	50	60	221
13	ITMT2	Italy-Malta	Ragusa, Sicily (ITA)	Maghtab (MLT)	AC	CO	> 2025	PRI	220	200	120	200
14	EuroAsia Interconnector	Cyprus-Crete	Kofinou (CYP)	Korakia, Crete (GRC)	VSC-DC	CO	2026	PUB	500	2,000	898	2,500
		Israel-Cyprus	Hadera (ISR)	Kofinou (CYP)		CO	2026				310	
15	EuroAfrica Interconnector	Cyprus-Crete	Kofinou (CYP)	Korakia, Crete (GRC)	VSC-DC	CO	2026	PUB	500	2,000	898	2,500
		Egypt-Cyprus	Damietta (EGY)	Kofinou (CYP)		PE	2029				498	
16	SACOI3	Italy-Corse	Suvereto, Tuscany (ITA)	Lucciana, Corse (FRA)	LCC-DC	PE	2025	PUB	200	400	413	950
		Corse-Sardinia	Lucciana, Corse (FRA)	Codrongianos, Sardinia (ITA)								
17	TUNITA1	Tunisia-Italia	Partanna, Sicily (ITA)	Menzel Temim (TUN)	VSC-DC	PE	2027	PUB	500	600	233	850
18	TUNITA2	Tunisia-Italia	Partanna, Sicily (ITA)	Menzel Temim (TUN)	VSC-DC	PE	> 2030	PUB	500	600	233	
19	Adriatic link	Abruzzo-Marche	Villanova, Abruzzo (ITA)	Fano, Marche (ITA)	VSC-DC	PE	2028	PUB	500	1,000	250	1,300
20	Tyrrhenian Link	Italy-Sicily	Montecorvino, Campania (ITA)	Caracoli, Sicily (ITA)	VSC-DC	PE	2028	PUB	500	1,000	970	3,700
		Sicily-Sardinia	Caracoli, Sicily (ITA)	Selargius, Sardinia (ITA)								

[1] Country codes in both terminals refer to ISO 3166-1 alpha-3 standard. [20]
[2] Interconnectors can be in the following states: OP (Operational), CO (in COnstruction), PE (PErmitting), PL (PLanned), UC (Under Consideration).
[3] Commissioning Date, the date at which the project is energized and permitted to operate by the utility.
[4] Voltage level of the interconnector in kV.
[5] Length of the interconnector in km, including connection sections and underground or undersea cables.

#	Name	Description	Terminal 1[6]	Terminal 2	Type	Status[7]	Comm date[8]	Pub/ Pri	U[9] [kV]	P_{nom} [MW]	Len[10] [km]	Cost [M€]
21	Dorsale Sarda	SAPEI2	Fiumesanto, Sardinia (ITA)	Viterbo, Lazio (ITA)	VSC-DC	PE	2040	PUB	500	1,000	550	1,400
		Sardinian link	Codrongianos, Sardinia (ITA)	Suulcis, Sardinia (ITA)	AC				220	1,000		
22	Bolano-Annunziata	Italy-Sicily	Bolano, Calabria (ITA)	Annunziata, Sicily (ITA)	AC	PE	t.b.d.	PUB	380	2,000	7.5	105
23	ESMA	Spain-Morocco	Puerto de la Cruz (ESP)	Bni Harchen (MAR)	AC	PL	2026	PUB	400	650	100	188
24	EGGR	Egypt-Greece	Tarffehiah (EGY)	Aharnes (GRC)	LCC-DC	PL	2028	PUB	600	2,000	863	1,880
25	ITGR2	Italy-Greece	Galatina, Puglia (ITA)	Arachthos (GRC)	VSC-DC	PL	2031	PUB	400	500	316	750
26	Dorsale Ionico-Tirrenica	Lazio-Campania	Latina, Lazio (ITA)	Montecorvino, Campania (ITA)	VSC-DC	PL	2035	PUB	500	2,000	830	4,100
		Calabria-Campania	Montecorvino, Campania (ITA)	Rossano, Campania (ITA)						2,000		
		Italy-Sicily	Rossano, Campania (ITA)	Priolo, Sicily (ITA)						1,000		
27	MAPT	Morocco-Portugal	Bni Harchen (MAR)	Tavira (PRT)	VSC-DC	PL	t.b.d.	PUB	500	1,000	325	650
28	DZES	Algeria-Spain	Ain Fatah (DZA)	Carril (ESP)	VSC-DC	UC	t.b.d.	PUB	500	1,000	240	1,185
29	DZIT	Algeria-Italy	Cagliari, Sardinia (ITA)	Cheffia(DZA)	VSC-DC	UC	t.b.d.	PUB	400	1,000	350	850
30	ITAL1	Italy-Albania	Brindisi, Puglia (ITA)	Babica (ALB)	DC	UC	t.b.d.	PRI	400	500	145	437
31	ITAL2	Italy-Albania	Manfredonia, Puglia (ITA)	Kallmet (ALB)	DC	UC	t.b.d.	PRI	500	1,000	345	944
32	ITAL3	Italy-Albania	Casamassima, Puglia (ITA)	Porto Romano (ALB)	DC	UC	t.b.d.	PRI	500	500	238	556
33	TREY	Türkiye-Egypt	Adana (TUR)	Port Said (EGY)	VSC-DC	UC	t.b.d.	PUB	600	3,000	800	1,185
34	TRIS	Türkiye-Israel	Mersin (TUR)	Haifa (ISR)	VSC-DC	UC	t.b.d.	PUB	600	2,000	500	1,425
35	EGJO	Egypt-Jordan	Taba (EGY)	Hasseimya (JOR)	AC	PL	2025	PUB	400	550	43	67
36	JOSY	Jordan-Syria	Amman North (JOR)	Der Ali (SYR)	AC	UC	> 2030	PUB	400	1,000	154	54
37	BGTRGR	Greece-Türkiye	Nea Santa (GRC)	Babaeski (TUR)	AC	UC	2035	PUB	400	1,500	130	152
		Bulgaria-Türkiye	Maritsa East 2 (BGR)	Vize Havza (TUR)		UC	2036			1,500	150	
38	DZLY	Algeria-Libya	t.b.d.	t.b.d.	AC	UC	t.b.d.	t.b.d.	400	1,000	520	N/A
39	DZTN	Algeria-Tunisia	Oglet Ouled Mahboub (DZA)	Kondar (TUN)	AC	UC	t.b.d.	t.b.d.	400	1,000	220	95
40	EGLY	Egypt-Libya	Al Saloum (EGY)	Tobruk (LBY)	AC	UC	t.b.d.	t.b.d.	500	1,000	170	128
41	JOPS	Jordan-Palestine	Amman West (JOR)	Jericho (PSE)	AC	UC	t.b.d.	PUB	132	200	40	10
42	SYTR	Syria-Türkiye	t.b.d.	Birecik HPP (TUR)	AC	UC	t.b.d.	t.b.d.	400	600	150	220

Source: Elaboration EST@energycenter – Politecnico di Torino (2023)

Figure 1 - Interconnectors in the Mediterranean area: OP (a), CO+PE+PL (b), UC (c) [(6)]



Source: Elaboration by EST@energycenter – Politecnico di Torino (2023).

[6] Numbers in the Figure correspond to the interconnector unique identifiers of Table 1 (first column).

5.4 Role of the electricity interconnectors in the Mediterranean scenarios

The effective implementation of the energy transition in the Mediterranean region, as mentioned in the previous sections, will imply a pivotal role played by electricity produced from RES. Reaching the decarbonization goals, will, in practice, require significant investments in the electrification of the final energy uses, in the installation of a considerable amount of additional generation capacity from renewables to exploit the huge available potential, and in the construction of a robust system of trans-Mediterranean power interconnectors (the so-called Mediterranean "electricity Highways") that can represent the new key energy interconnectors and the backbone of the "green" energy dialogue across the Mediterranean shores.

Of course, several possible trajectories could be hypothesized, based on how strongly the different national/communitarian policies are expected to be oriented towards environmental sustainability.

With reference to this, in particular, in Chapter 3 we proposed three possible alternative evolutionary trajectories by 2030 related to the penetration of PV and wind power plants on the three Mediterranean shores:

- Trajectory "T1 - historical evolution":

  we considered the historical data series of renewable installed capacity in the Mediterranean region at a country level. Starting from the historical values, we estimated the evolution of the renewable energy mix in 2030 by means of a proper interpolating function fitting them. This trajectory, therefore, given a quantitative assessment of the penetration of solar and wind energy in a business as usual perspective, assuming that current trends will continue in the future.

- Trajectory "T2 - bridging the gap with the targets":

  we considered the renewable targets set by 2030 in the national energy action plans of the different Mediterranean countries, also assessing the effort (in terms of annual capacity to be installed) that the Mediterranean countries should undertake to comply with them.

- Trajectory "T3 - 100% renewables":

  we computed the PV and wind capacity needed for fulfilling the electricity demand completely in 2030, in turn evaluated on the basis of the projections proposed by the 2022 edition of the Mediterranean Masterplan of Mediterranean interconnections (MMP), issued by Med-TSO.

With respect to these trajectories, we introduce an additional one based on the assessment of the large renewables potential of the countries belonging to Southern Mediterranean shore, thanks to their geo-morphologic and climate conditions. As discussed in the 2020 issue of the ENEMED Report, considering the scenarios of medium RES penetration [21] in these countries, a surplus of electricity from of PV and wind generation is available for trade with the Northern shore, after fulfilling the domestic demand, and it can be foreseen. Starting from these considerations, we introduce therefore the fourth trajectory:

- Trajectory "T4 – Renewables surplus":

  We hypothesize to have by 2030 an additional (with respect to trajectory T3) installed capacity of PV and wind power production, coherent with the capacity increase between the two scenarios developed in the 2020 ENEMED Report, i.e. the "Medium RES" (fulfillment of the domestic demand of the Southern shore and surplus available for trade) and the "Low RES" (only fulfillment of the domestic demand of the Southern shore).

The results in terms of solar PV and wind capacity and electricity production for the different countries of the Southern Mediterranean shore are summarized in Table 2.

Table 2 - PV and wind installed capacity and electricity generation in the Southern shore in 2022 and 2030 by country and considered trajectory

	Installed capacity and electricity generation by country										
	Country/Shore	2022		2030							
			T1		T2		T3		T4		
		PV	Wind	PV	Wind	PV	Wind	PV	Wind	PV	Wind
Capacity [GW]	**Southern Shore**	**2.66**	**3.46**	**6.82**	**6.35**	**46.10**	**33.44**	**268.72**	**49.12**	**384.57**	**69.13**
	Algeria	0.44	0.01	0.75	0.01	13.58	5.01	55.58	1.23	80.29	1.77
	Egypt	1.7	1.64	4.57	3.51	22.9	20.6	183.38	33.79	246.61	45.45
	Libya	0.01	0	0.01	0.01	3.35	0.85	24.84	0	49.67	0
	Morocco	0.31	1.56	0.86	2.51	4.76	5.22	1.52	7.44	2.13	10.42
	Tunisia	0.2	0.25	0.65	0.31	1.51	1.76	3.4	6.66	5.87	11.5
Electricity [TWh/y]	**Southern Shore**	**2.4**	**10.9**	**6.1**	**19.6**	**46.3**	**85.9**	**204.1**	**133.0**	**308.9**	**185.8**
	Algeria	0.6	0.0	1.0	0.0	17.5	5.0	71.6	1.2	103.4	1.8
	Egypt	0.8	4.3	2.1	9.3	10.6	54.6	85.2	89.6	114.5	120.5
	Libya	0.0	0.0	0.0	0.0	5.1	2.6	37.9	0.0	75.7	0.0
	Morocco	0.7	6.0	1.9	9.7	10.4	20.1	3.3	28.6	4.6	40.1
	Tunisia	0.4	0.5	1.2	0.6	2.7	3.6	6.1	13.6	10.6	23.5

The implementation of trajectory T4 allows for a surplus with respect to the capacity needed for satisfying the domestic electricity demand evaluated by trajectory T3. In particular, the overall RES capacity surplus can be quantified in 155.4 TWh/y, of which 33.0 TWh/y for Algeria, 58.3 TWh/y for Egypt, 37.0 TWh/y for Libya, 12.8 TWh/y for Morocco and 14.3 TWh/y for Tunisia.

For bench-marking purposes, we consider three additional scenarios by 2030, proposed by the Association of the Mediterranean Transmission System Operators for electricity (MED-TSO) [22], namely:

- **Inertial Scenario**:

  It hypothesizes a moderate growth of GDP and electricity consumption, a moderately but steadily progressive RES development, a slow progress of electrification of final uses and enhancement of energy efficiency in the end-uses sector (with the exception of very few countries implementing strong incentive policies). It represents an evolution of the system based on current policies.

- **Proactive Scenario**:

  It hypothesizes a marked increase of GDP and electricity consumption, an intensified RES development (coherent with the goal of climate neutrality in Europe by 2050), an acceleration in the electrification and implementation of energy efficiency measures with respect to the "Inertial Scenario", and a prevalence, as far as electricity generation is concerned, of distributed generation. Despite these aspects, this scenario still foresees significant differences and a limited cooperation among the various Mediterranean countries.

- **Mediterranean Ambition Scenario**:

  Similarly to the "Proactive Scenario", it hypothesizes a marked increase of GDP and electricity consumption, an intensified RES development (coherent with the goal of climate neutrality in Europe by 2050) and an acceleration in the electrification and implementation of energy efficiency measures. Moreover, it also foresees an increasing cooperation among countries. As far as electricity generation is concerned, it assumes a prevalence of large-scale generation.

Focusing on the obtained results for the Southern shore (summarized in Table 3), it can be noticed that the forecasted trends of installed capacity for the "Mediterranean Ambition" scenario are aligned with the T2 trajectory projections, resulting coherent with the achievement of the different national energy plans by 2030.

Table 3 - Installed PV and wind capacity in the Southern shore by 2030 in the three MED-TSO scenarios

	Inertial 2030 Capacity [GW]		Proactive 2030 Capacity [GW]		Med. Ambition 2030 Capacity [GW]	
Country/Shore	**PV**	**Wind**	**PV**	**Wind**	**PV**	**Wind**
Southern shore	**20,88**	**16,21**	**32,61**	**21,12**	**34,72**	**26,10**
Algeria	4,27	0,00	9,27	0	9,27	0,0
Egypt	10,14	10,00	13,14	14	15,14	17,0
Libya	2,00	0,20	3,5	0,5	3,5	0,5
Morocco	3,04	4,85	4,79	5,33	4,99	7,25
Tunisia	1,43	1,16	1,91	1,29	1,82	1,35

Under a perspective of developing a "green" energy dialogue, it is interesting to assess the capability of Operational (OP), Construction & Permitting & Planned (CO+PE+PL) and Under Consideration (UC) infrastructures to transfer the surplus of energy from renewable sources that can be produced in excess with respect to the domestic consumption of the Southern shore (assumed to be both increased and electrified, as discussed in Chapter 3).

This evaluation does not take into consideration power flow models, neither for the Southern shore, nor for the interconnections between the Southern and the Northern shores of the Mediterranean, since it is simply based on an overall energy balance.

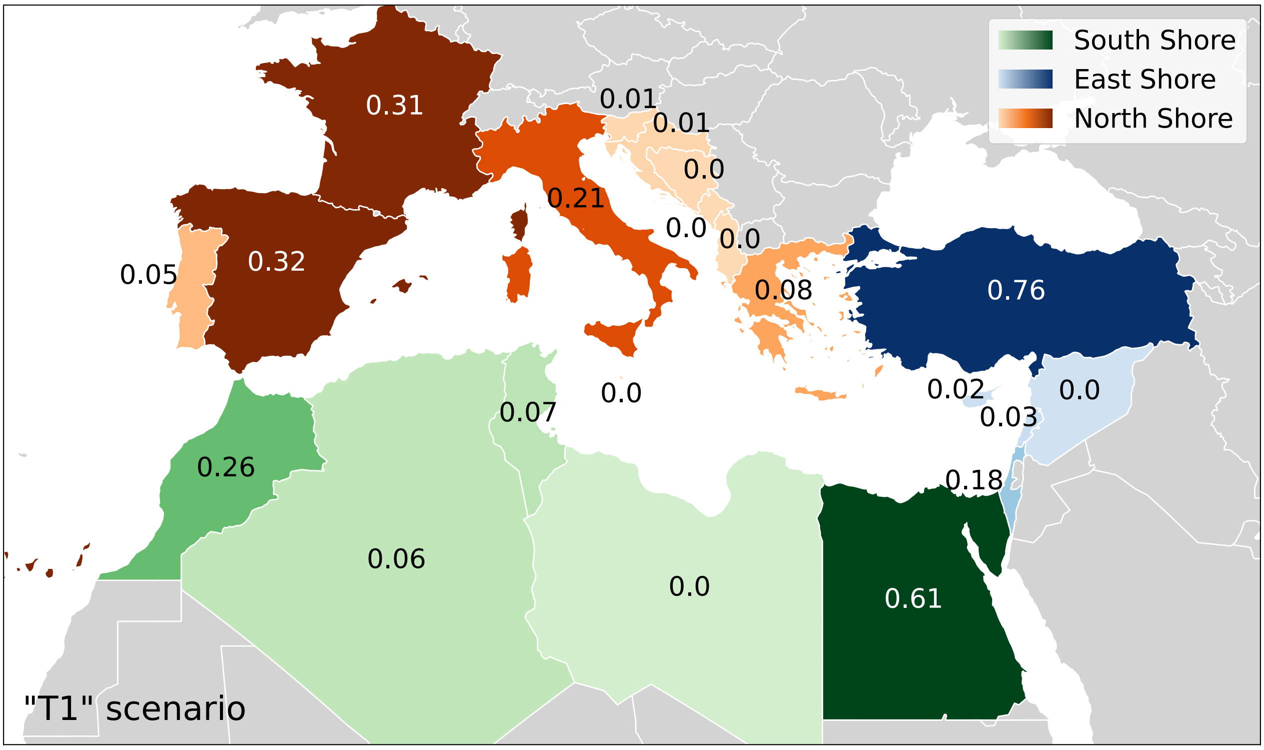
The analysis is performed by considering the previously described trajectory T4 and by assuming a transmission energy factor of the interconnections related to the availably of electricity production from renewables that can be transferred through the interconnectors themselves and that varies during the day. For the calculation of the transmission energy factor it has been assumed that for 8 h/d the infrastructures carry the 100% of the maximum amount of energy that they can transfer, for 8 h/d the 60% of it and for 8 h/d the 40% only. This assumption leads to a value of the transmission energy factor equal to 0.667. By multiplying the maximum amount of energy that the infrastructures can transfer by the transmission energy factor, we obtain the annual energy transferred.

For this analysis we considered: interconnectors number 2 and 4 (see Figure 1) for the OP infrastructures; interconnectors number 12, 14, 15, 17, 18, 23, 24 and 27 for the CO+PE+PL infrastructures; interconnectors number 28, 29 and 33 for the UC infrastructures.

According to trajectory T4, the total energy surplus of the Southern shore, theoretically available for being transferred to the Northern shore, is equal to 155 TWh/y. If we consider the OP infrastructures only, the annual energy transferred corresponds to 8.18 TWh/y, i.e. 5.3% of the total energy surplus. If we considered, instead, both the OP and the CO+PE+PL infrastructures, the amount of annual energy transferred is 60.15 TWh/y, i.e. 38.7% of the total energy surplus. Finally, if we considered all the possible infrastructures (OP, CO+PE+PL and UC), we would obtain an annual energy transfer of 89.35 TWh/y, i.e. 57.5% of the total energy surplus.

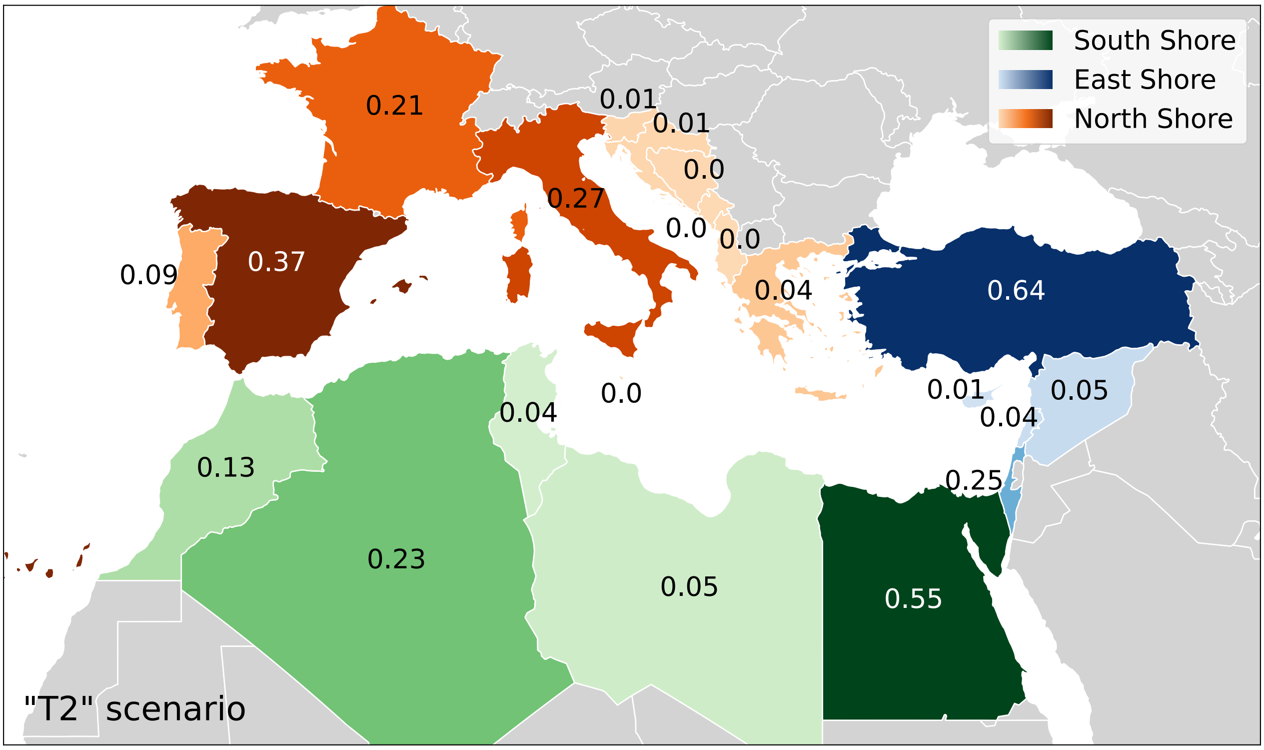
These results highlight that the current development framework for the trans-Mediterranean electricity interconnections (which could be further enhanced in the future), already allows for a significant energy exchange among the North African countries of the Southern European countries, corresponding to 3.6% of the overall final consumption of electricity in the Europe in 2021, and to 8.1% of the final consumption of electricity on the Northern shore in 2021. This clearly highlights the key role that electricity can play in the "green" dialogue across the Mediterranean region.

Figure 2 - Share of RES among the countries of each shore in "T1" scenarios (pu of total electricity generation)



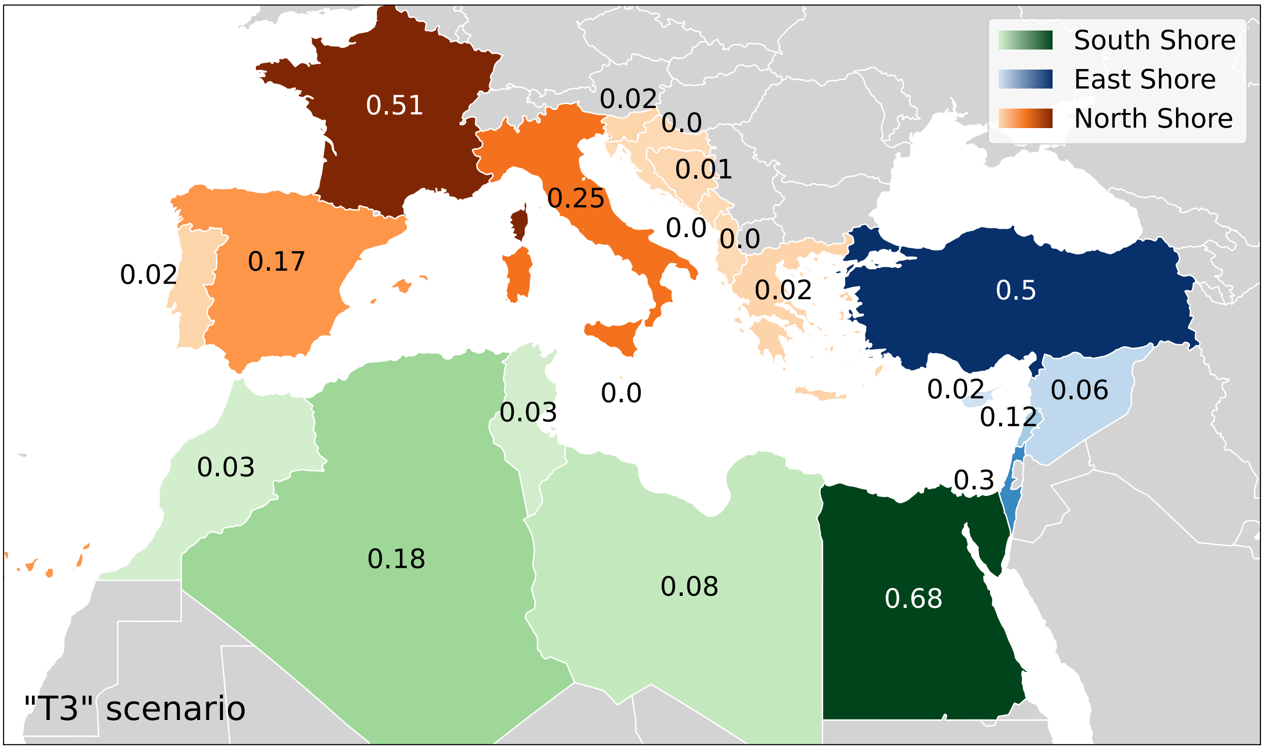
Source: Elaboration EST@energycenter – Politecnico di Torino (2023)

Figure 3 - Share of RES among the countries of each shore in "T2" scenarios (pu of total electricity generation)



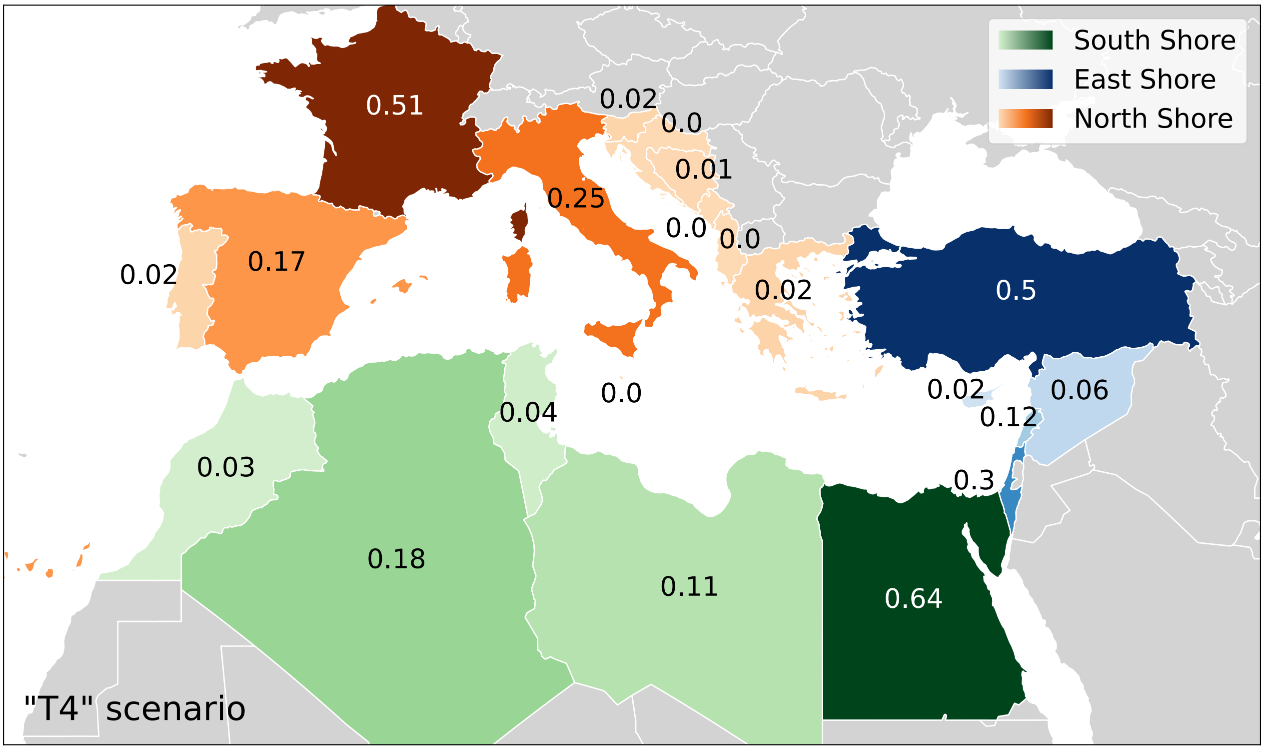
Source: Elaboration EST@energycenter – Politecnico di Torino (2023)

Figure 4 - Share of RES among the countries of each shore in "T3" scenarios (pu of total electricity generation)



Source: Elaboration EST@energycenter – Politecnico di Torino (2023)

Figure 5 - Share of RES among the countries of each shore in "T4" scenarios (pu of total electricity generation)



Source: Elaboration EST@energycenter – Politecnico di Torino (2023)

5.5 Cost evaluation and comparison

The cost estimation of the electrical interconnection infrastructure through the Mediterranean Sea needs to consider three costs: ① Infrastructure construction costs (CAPEX, *CAPital EXpenditure*); ② O&M costs of the infrastructure (OPEX, *OPerational EXpenditure*).

As for the CAPEX, we consider the interconnections corresponding to projects in construction (CO), permitting (PE) and planned (PL) stages only (12-27 in Table 1).

All the building costs are considered as overnight costs, referred to 2023.

As for the OPEX, the cost of the complete AC electrical stations was not considered in this analysis, because it is common to the two technologies families and is highly variable and dependent from local constraints.

With reference to HVDC technology, O&M costs are mainly related to the converter stations. As a preliminary approximation, these may be considered constant regardless of the used conversion technology; moreover, the dependence on voltage level can be neglected, since all proposed interconnectors are characterized by the same voltage magnitude.

With reference to AC connections, the maintenance costs of transformers operating at the very high voltage levels have been considered in addition to the ones of cables.

As far as the interconnectors lifetime is concerned, a minimum lifetime of 25 years (after which the conversion equipment of the HVDC facilities requires extraordinary maintenance and technological upgrading), has been considered as the useful life of the assets, coherently with scientific literature, TSOs experience and regulatory entities evaluations [23], [24].

Table 4 - Total and specific (per GW) costs of the transmission lines

	Tech					CAPEX	OPEX					Cost		
	C[7]	L[8]	#CS[9]	#TR[10]	Y[11]	CC[12]	OMST[13]	OMC[14]	OMy[15]	r[16]	OMd[17]	$\overline{\text{CC}}$[18]	$\overline{\text{OM}}$[19]	$\overline{\text{TC}}$[20]
HVAC	3.9	488	-	10	25[21]	1,336.20	20	15	7.52	9.0	73.9	702.1	38.8	740.9
HVDC	14.1	6,574	31	-	25	18,717.30	2,000	25	226.35		2,223.3	201.9	24.0	225.9

Source: Elaboration by EST@energycenter – Politecnico di Torino (2023)

[7] **C**: total interconnectors capacity, in [GW]
[8] **L**: total interconnectors length, in [km]
[9] **#CS**: total number of converter stations
[10] **#TR**: total number of transformers
[11] **Y**: lifetime of the infrastructure
[12] **CC**: total construction cost, in [M€]
[13] **OMST**: operation and maintenance station yearly costs, in [k€/y/converter] for HVDC and [k€/y/transformer] for HVAC
[14] **OMC**: operation and maintenance cable yearly costs per unit of length, in [k€/y/km]
[15] **OMy**: total annual O&M cost, considering converters, transformers and cables, in [M€/y]
[16] **r**: discount rate for OPEX, in [%] [25]
[17] **OMd**: discounted O&M costs in the expected lifetime, in [M€]
[18] $\overline{\text{CC}}$: average construction cost respect to power and length, in [k€/GW/km]
[19] $\overline{\text{OM}}$: average O&M cost respect to power and length, in [k€/GW/km]
[20] $\overline{\text{TC}}$: average total cost respect to power and length, in [k€/GW/km]
[21] Limited by the lifetime of undersea cables [26]

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