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The transition towards a sustainable energy system in Europe: What role can North Africa's solar resources play?

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ABSTRACT

Securing energy supply and speeding up the transition towards a reliable, sustainable, low-carbon energy system are among the major current and future challenges facing Europe. Importing dispatchable solar electricity from North Africa is considered as a potential and attractive option. Nevertheless, as things currently stand, the European Commission focuses mainly on the exploitation of the existing wind power potential in the North Sea, largely ignoring the solar power potential in the Sahara region of North Africa. After discussing the major challenges and issues facing Europe to achieve the assigned ambitious objectives, the paper emphasises the importance of North Africa's solar resources in helping Europe to successfully address the challenge of decarbonising its electricity system, in particular with regards to the security of supply and sustainability. Within these two major challenges, the paper explores the issues of access, barriers and opportunities. The paper highlights why the EU's energy and climate goals will not be achievable without adequate grid expansion and grid-scale energy storage facilities, as well as other innovative measures to manage demand and ensure a secure energy supply. In this respect, the paper shows how the import of dispatchable electricity from North Africa via specific HVDC links could play a key role in helping the EU achieve its energy targets in a cost-effective way without recourse to significant investments in transmission infrastructure and storage facilities. The paper then attempts to identify and analyze the main barriers that continue to inhibit the export of solar electricity from North Africa to Europe. Finally, to make the project more attractive and achievable in the near future, the paper proposes a systematic approach for setting up energy import scenarios. A promising import scenario is presented where energy import via Italy is shown to be a more viable and effective solution than via Spain.

1. Introduction

Compared to other renewable energy resources, solar energy is abundant and represents one of the most promising source of clean power [1,2]. Most promising regions for solar power plants are certainly located in deserts where the efficiency is higher than other areas and the land is not used for agriculture or urban settlement. Theoretically, about 1% of the earth's total desert surface could provide enough energy to supply the entire population of the world [1,3]. This solar energy can be converted into electricity and transported over long distances via HVDC (High Voltage Direct Current) transmission systems, with minimal energy losses, to the demand centres [4]. Concentrating solar power (CSP) is one of the most promising technologies for generating power in the desert [5,6]. When combined with thermal storage facilities, CSP plants can continue to produce electricity even in times without solar irradiation. CSP plants can also be equipped with backup power from combustible fuels. Due to these characteristics, CSP is suitable for large-scale energy projects providing renewable and dispatchable energy according to demand [7]. In recent years, the idea of large-scale utilization of renewable energy in deserts and transferring it to the demand centers has become the subject of national and international political debates. One of the most prominent projects for CSP is the exploitation of the enormous potential of solar electricity generation available in the South Mediterranean countries [5,6]. Over the past years, several studies have been conducted to quantify the technological and economic dimensions of such a vast project and found it technically feasible and economically attractive [6–8]. For this reason, some initiatives, such as the Mediterranean Solar Plan (MSP) [9], DESERTEC [3] and MEDGRID [10], have been launched to promote the deployment of cross-Mediterranean HVDC links to enable the

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transfer of electricity from renewable energy sources between North-Africa and Europe. But so far, little has been achieved on the ground. However, current scientific studies have shown, that today's tangible, cost-effective and renewable energy technological alternatives to CSP are rare and only CSP can help the European energy system to decrease the energy systemic impact under a high renewable energy share [11,12]. The flexibility of CSP plants to generate electricity in the absence of sunshine provides particular economic benefits in terms of covering demand peaks in the evening and adapting operational strategies to demand curves in European electricity markets [13].

Although the idea of exporting solar electricity from North Africa to Europe is not new, there are still huge gaps in the literature worth investigating. For instance, why solar electricity imports could be beneficial, why concrete deals have not happened in the past, why the various initiatives launched over the past years have failed to attract the required attention of the European decision-makers and how to make the project more attractive and achievable in the near future. In this context, our paper seeks to give some clear-cut answers to these fundamental questions that would provide new insights in this emerging and exciting area of research.

The rest of the paper is organized as follows. Section 2 briefly reviews the present status and future projections for integrating renewable energies into the European system, and then attempts to examine the existing and emerging challenges facing Europe to reach its clean energy objectives, in terms of security of supply and sustainability. Section 3 identifies some of the benefits that might arise from importing dispatchable solar electricity from the South of the Mediterranean and then discusses the main barriers and opportunities. Section 4 provides some criteria and proposals upon which good energy import scenarios can be designed. According to the identified criteria a promising import scenario is given in Section 5. The conclusions of this research study are summarized in Section 6.

2. Integration of renewable energy sources into the European interconnected system

2.1. Present status and future projections

The ENTSO-E (European Network of Transmission System Operators for Electricity) system is a large interconnected system consisting of several regions (Fig. 1) operated by different transmission system operators (TSOs). The increase in economic activities across the EU (European Union) over the last two decades has led to a rapid increase in electricity consumption [14]. Nevertheless, due to the economic crisis in 2008 and its consequences on electricity demand, the majority of ENTSO-E countries observed a decrease of their consumption between 2011 and 2014 (see Fig. 2). However, in 2015, ENTSO-E consumption has increased by 1.37% compared to the previous year, as can be seen in Fig. 2 [14]. Historically, the energy system in the EU is heavily dependent on fossil fuels, especially those countries with no hydro resources or nuclear plants. In recent years, the share of electricity generation from fossil fuels and nuclear has decreased in all ENTSO-E countries, while the share of renewable energy sources has experienced a constant increase (see Table 1).

Currently, renewable generation, mainly solar and wind, represents about 17% of the total ENTSO-E consumption (Fig. 3). Clearly, based on these data, the EU is well on track to achieving its 2020 climate and energy targets namely 20% share in renewable generation, 20% cut in greenhouse gas emissions from 1990 levels and a 20% increase in energy efficiency. Therefore, the share of renewable energy sources (RES) in the generation mix is expected to increase rapidly in the upcoming years to meet medium- and long-term objectives (2030 and 2050). It would be particularly difficult for the European grid to address these major challenges as transmission grids will have to be operated closer to their limits in the future, and this can reduce the system resilience and security of supply [15]. In fact, European power networks are already operating closer to their limits, and this is clearly confirmed by the occurrence of several large blackouts in Europe over the last two decades, such as the 2003 blackout in Italy and the large 2006 blackout in Europe [16,17]. Several cross-border lines are running near their limits in the eastern and south central region. This is mainly due to high north-south power flows (see Fig. 4), which leads to a number of critical bottlenecks in the cross-border transmission systems, especially on the Italian northern border and the Austrian-German border [18,19]. Because numerous market players are using the network at the same time, actual power flows may differ significantly from what has been scheduled ahead. This is known as the effect of loop (or parallel) flows (see Fig. 5), which can be described as follows: while two neighbouring system (A and B) buy and sell contracted power through the tie-lines between them, part of the transacted power may loop around through other systems (C in Fig. 5) in the interconnected power system [20–22]. For example, a transaction between France and Italy may generate severe congestion in the Swiss network and cause an overloading of the tie-lines between Switzerland and Italy (where the Italian blackout of September 2003 started). Usually, when there are large exporters or importers of energy in a meshed network, Power Transfer Distribution Factors (PTDF) are used to evaluate the loop flows problem. This method determines the percentage of a transfer that would appear on each border if a given amount power is sent from a specified source to a specified sink [23]. As an example, Fig. 6 shows PTDFs in base case conditions for a France- Italy transaction. Fig. 6 shows that, only 39% of the contracted power crosses the French–Italian border, while consistent loop flows involve Belgium, Germany, Austria, Slovenia, and especially Switzerland [24]. Due to this problem, the capacities of cross-border tie-lines of the electricity transmission systems are gaining major importance in recent years. To ensure security of supply and improve system stability, it is necessary to increase transmission capacities between the EU member states and within market zones. However, during the past decade, there was no significant increase in cross-border transmission capacity (see Fig. 7), while cross border flow has increased significantly (Fig. 8) [20,25]. Furthermore, the fast deployment of intermittent renewable energies at different corners of the region and far from the load centres creates additional challenges for the European transmission grid. According to the ten-year network development plan (TYNDP), 80% of the bottlenecks in 2020 are associated with RES integration.

Power systems have not been designed for wide-area power trading with unpredictable conditions. Several initiatives have been launched to handle these challenges and to define the way forward to support the energy transition in Europe. One of the most famous solutions that can allow large-scale integration of renewable energy sources into the grid is the supergrid concept. A supergrid is an electricity transmission system that will connect national grids with offshore wind farms from the Baltic Sea to the Mediterranean, via the North Sea and the Atlantic, enabling a secure transmission of electricity between European countries (Fig. 9(a)). In some scenarios, undersea grid connections are proposed to link to CSP plants in desert areas of North Africa (see Fig. 9(b)). However, in order to construct such a supergrid, there are several outstanding issues that need to be resolved. The main challenges and difficulties are briefly discussed in the next section.

2.2. Main challenges

In Europe, good wind resources are often found in remote locations, often offshore or near the sea, where the current transmission network will not suffice to satisfy future electricity needs. As mentioned above, several cross-border lines are currently running near their limits and therefore electricity cannot sufficiently flow across borders. In the short term, wind power penetration will increase congestion on the grid, and consequently the vulnerability of cross-border flows in the North-to-South direction will tend to increase. Therefore, to build a supergrid, the existing system needs further extension and significant

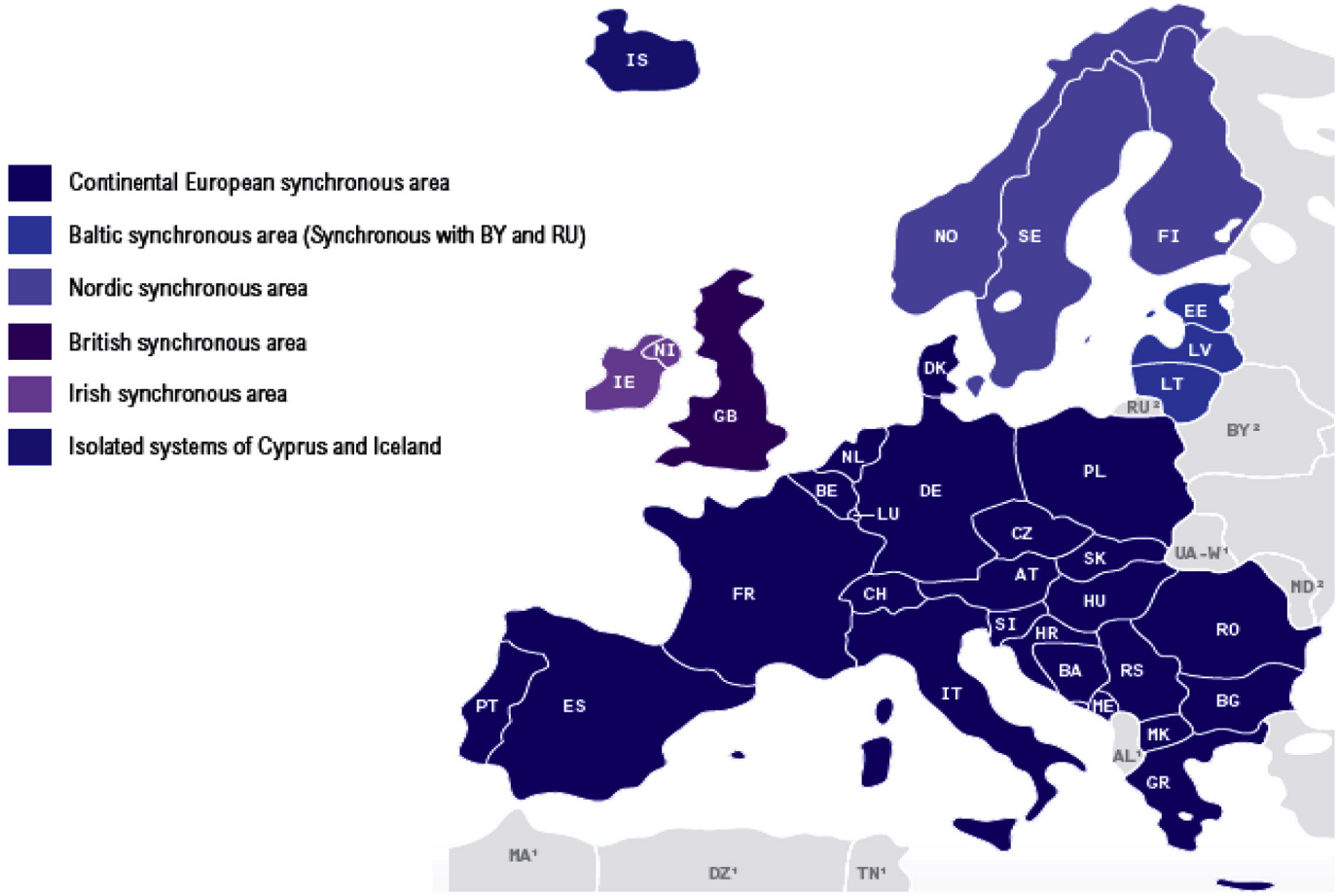


Fig. 1. ENTSO-E member states (source: ENTSO-E).

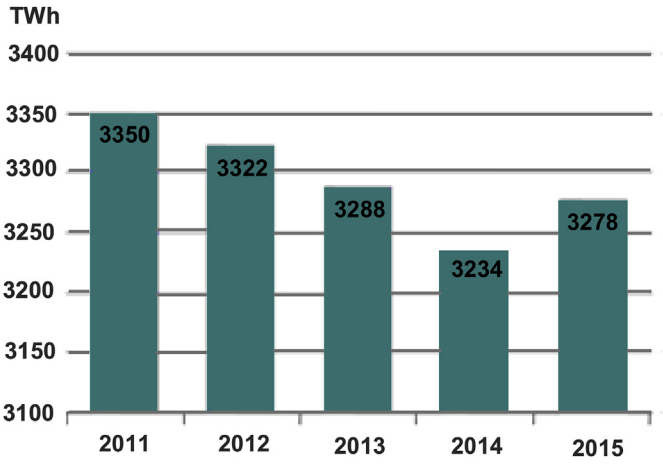


Fig. 2. Yearly energy consumption in the ENTSO-E area (data source: ENTSO-E).

Table 1
Electric net generation (TWh) from 2011 to 2016 in the ENTSO-E area (data source: ENTSO-E).

Source	2011	2012	2013	2014	2015	2016
Fossil fuels	1641	1562	1420	1344	1345	1354
Renewable	323	382	438	495	572	573
Hydro	517	567	590	613	578	583
Nuclear	887	862	857	859	836	817

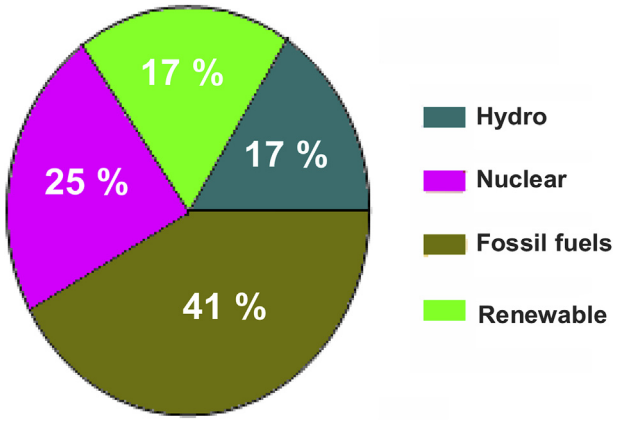


Fig. 3. Energy net generation (2015) in the ENTSO-E area (data source: ENTSO-E).

reinforcements [27–29]. However, the construction of new transmission facilities in Europe can be almost impossible, mainly because of opposition against overhead lines for environmental and political reasons. There are also concerns about the difficulty of obtaining rights of way to build long-distance transmission lines across the EU (some permission processes have taken more than 10 years [27]). For this reason, the significant increase in cross-border flow has not brought about higher investments in transmission capacity. Furthermore, the European high-voltage grid is quite old, which needs to be extensively refurbished and upgraded in the coming years [27,30]. A full-scale age-based refurbishment program is a very significant undertaking in terms

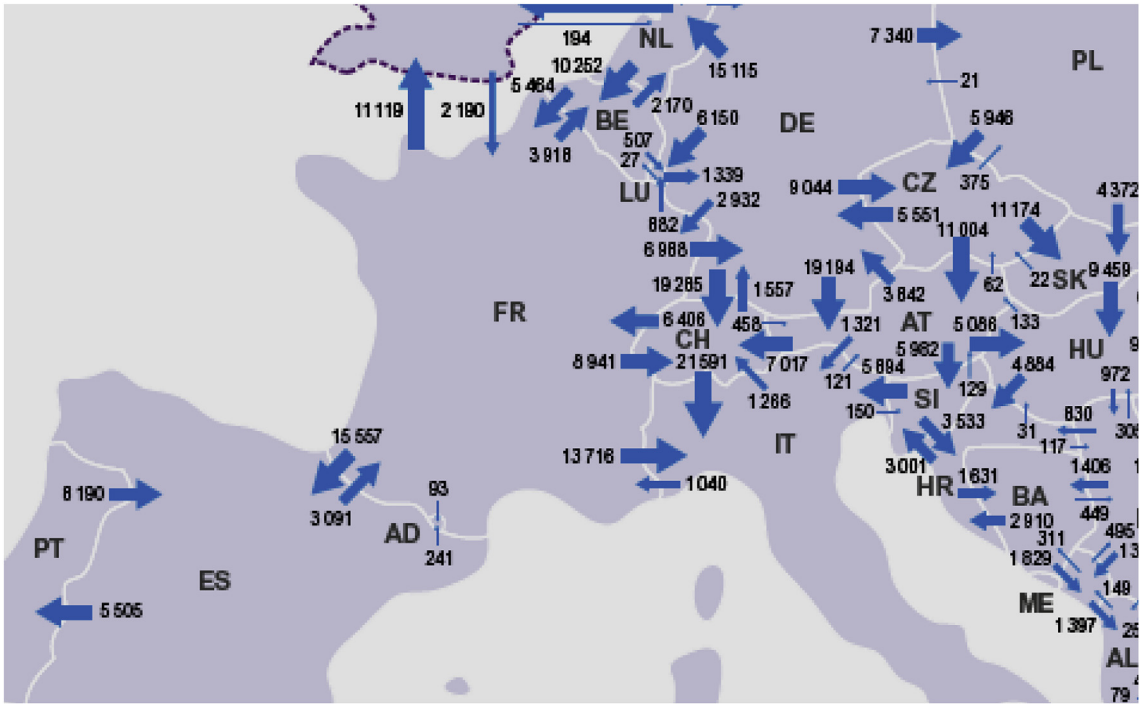


Fig. 4. Cross-border physical energy flows [GWh] (ENTSO-E: statistical factsheet 2017).

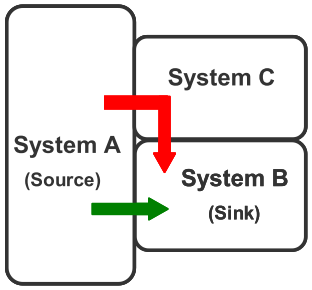


Fig. 5. Loop flow effect.

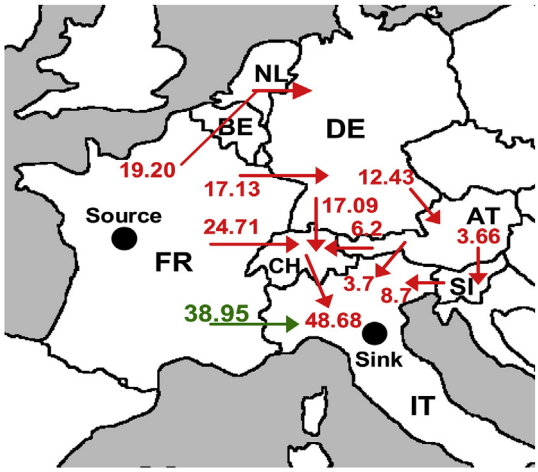
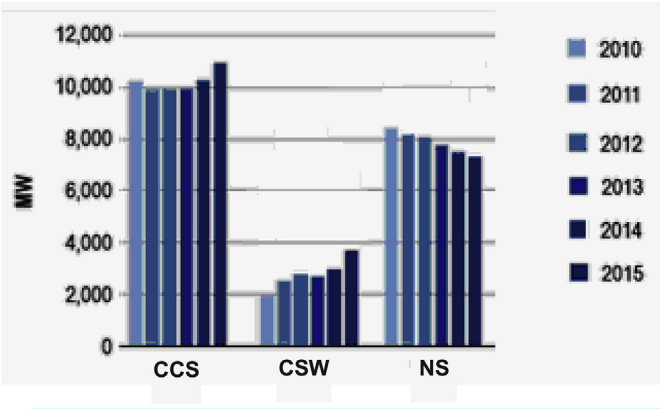


Fig. 6. PTDF values for a France–Italy transaction (data source: [22]).

of cost and outages, and may take up to 30 or 40 years. Moreover, the intermittent nature of wind and solar energies puts extra pressure on the transmission system, in which more transmission lines are required to distribute the same amount of electricity [28]. As a result, Europe is facing an ever growing gap between the dynamics of the development



The Continental Central South (CCS) region: (CH-DE, CH-IT, CH-FR, FR-IT, AT-CH, GR-IT, IT-SI, AT-IT).
The Continental South West (CSW) region: (ES-PT, ES-FR).
The North Sea (NS) region: (DE-NL, DE-FR, BE-FR, BE-NL).

Fig. 7. Average net cross-border transfer capacity (in both directions), values aggregated per region from 2010 to 2015 [20].

of renewable generation and the attainment of the needed transmission infrastructures. This is because the time required to reinforce or build a transmission line can be very long compared with the time needed to build a new wind farm or solar power plant [31]. The increasing penetration of intermittent renewable-energy power plants into the electricity systems not only puts extra pressure on the transmission system, but also raises various stability problems due to the displacement of traditional power plants (the traditional providers of frequency control service). The resulting forecasting errors represent significant challenges for TSOs, where the process of balancing supply and demand becomes a complex task. In addition to these challenges, there are other issues, such as a lack of political support and adequate regulatory framework. Furthermore, the supergrid concept may be unattractive to some large utilities as this could undermine the control of their regional market [29].

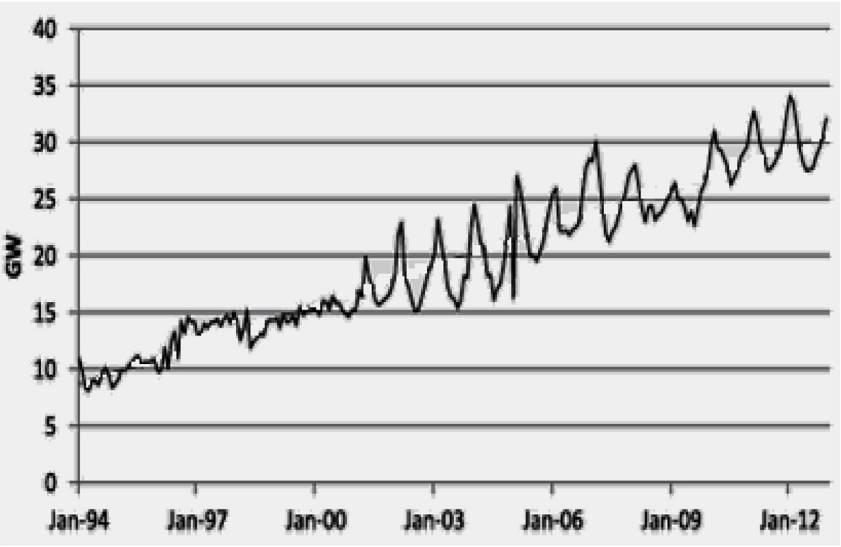


Fig. 8. Cross-border trade in the ENTSO-E area [25].

3. Import of dispatchable solar energy from North Africa

From the previous sections, it is clear that a quick and sweeping transition to renewable energy in Europe will not occur overnight, and it is not yet possible to build a supergrid. There are several outstanding issues and open questions that need to be accurately investigated. Despite the publication of several documents outlining some improvements in the congestion management and capacity allocation procedures, the progress on the ground has been far too slow and the discussed problems have not been resolved. The most dramatic question that arises about the implementation of the supergrid is: which sources would be more reliable? Currently, the EU focuses mainly on the exploitation of the existing wind power potential, especially in the North Sea, ignoring the large solar potential in the desert areas of North Africa. This is because the European countries want to produce electricity domestically to decrease the EU energy import dependency and create new jobs opportunities. However, to achieve a sustainable future, Europe must look beyond the short-term challenges to ensure that decisions are consistent with long-term goals.

Returning to the question formulated above, the answer was given by one of the world's leading scientists, Professor Jack Steinberger, a Nobel Prize winner in physic (1988). He said that wind is not the energy of the future; it represents an illusory technology that will lead Europe to a cul-de-sac. This is harmful to the European economy, as it is a waste of time, money and resources in the battle against the environmental issues facing humanity [32]. He added that CSP technology represents a more promising way to replace fossil fuels as the dominant source of electrical power. He then called for European governments to start a huge CSP project in North Africa.

3.1. Possible benefits of importing dispatchable solar energy from North Africa

For MENA (Middle East and North Africa) countries, renewable energy exports are expected to have a significant contribution to the socio-economic development of the region. Renewable energy exports will generate additional revenues, create more job opportunities and accelerate the economic growth in the MENA region. Human resource-development, technology transfer, research and development are other possible benefits which will promote a more sustainable development and rise the leaving standard of the population in the exporting countries [33–35]. Moreover, if the indirect export scenario is adopted, some of the generated renewable electricity will be available for domestic consumption.

For Europe, renewable dispatchable power imports from North Africa will enable the EU to manage its energy demand and ensure a

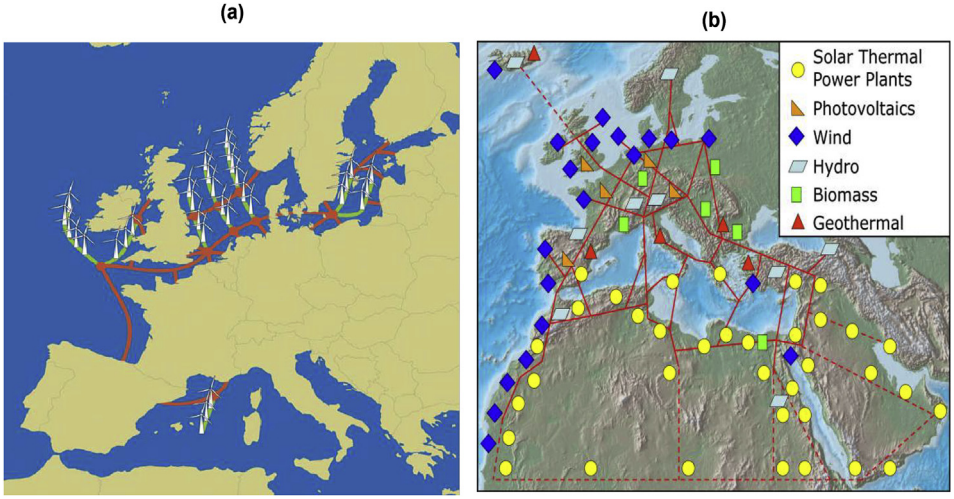


Fig. 9. (a). European offshore supergrid [26]. (b). The Desertec concept [3].

secure electricity supply across its system with higher fluctuating energy shares of wind and PV. CSP electricity from North Africa will play a key role in the long term if ambitious CO_2 reductions are to be achieved in Europe. An import of CSP electricity from North Africa via specific HVDC links will have several technical and economic benefits for the European energy system. The mains benefits are discussed below:

3.1.1. Provide flexible power

CSP plants combined with thermal energy storage can provide dispatchable energy according to demand. This is the most important advantage of CSP technology and it is the main incentive that could prompt European countries to import renewable electricity from North Africa. The electricity imports from North Africa will enable the European electricity system to gain access to more dispatchable and reliable power, and this will reduce the needs for flexibility options such as spinning reserves and storage facilities, thereby reducing the costs of balancing power due to increased penetration of intermittent renewables [36–39]. This benefit is highly motivated by the fast controllability of the HVDC links [24,40]. A CSP plant with an HVDC link can be considered as a remote power plant, with just a longer line from the generator to the feed-in point into the grid and can therefore be used for grid balancing purposes as an alternative solution to conventional technologies. It has been shown in Refs. [11,13] that as electricity imports from North Africa increases, the need for conventional power plants (e.g. gas-fired power plants) and electrical storage capacity decreases. The flexibility of the CSP power plants and the controllability of the HVDC links would make the European system more flexible (i.e. would offer greater flexibility to electricity operators in the European countries), which would make it possible to integrate more wind power into the system. Therefore, electricity imports from North Africa will not eliminate the idea of exploiting the existing wind power potential but, on the contrary, it will reinforce it, and will enable a future supergrid to operate reliably and securely. In other words, imports of dispatchable electricity from North Africa could become the backbone of the future success of the European supergrid, in which wind energy from the North can be balanced with solar energy from North-African desert, (see Fig. 10(a)). However, in the short and medium term, CSP power plants with point-to-point HVDC might be easier to implement than a European supergrid. Such a topology allows bringing dispatchable energy directly to the centres of demand (see Fig. 10(b)). This enables specific off-takers handle with dispatchable energy like today local nuclear and fuel fired power plants. Another benefit of this topology is a possible financing of a combined CSP and HVDC power plant like a traditional pipeline project but with the adoption of renewable dispatchable electricity rather than gas or oil.

3.1.2. Reduce system congestion

A glance at Fig. 4 shows that there are significant power transfers in the North-South direction. These high power transfers mainly result in several critical bottlenecks in internal and cross-border grids [19]. This problem has recently drawn special attention because of the difficulty in constructing new transmission lines. With the rapid development of wind parks in the North, transmission systems will be operated closer to their limits and, as a result, the congestion of internal and cross-border lines will tend to increase in the near future. The more frequently this capacity limit is reached, the more stress the grid will experience, and consequently more interventions are likely to be required from the TSOs. The electricity imports from North Africa would reduce congestion in the existing system by reducing the massive power imports from the Northern countries and the security of supply can increase, especially for Italy, where energy can be imported from North Africa, thus avoiding the heavy congestion across the northern borders corridors. Several studies have shown that the electricity imports from North Africa will have a significant positive impact on the Italian system [41,42]. It has been shown in Ref. [11] that the North African electricity will considerably reduce peak demands in the grid and therefore grid stress. Reducing peaks decreases the number of possible bottlenecks in the grid [11].

Based on the results given in the regional investment plan of 2017 for the Continental Central South (CCS) region [43], the benefit of North African electricity to reduce grid congestion in this region is clear and relevant. In this study [43], the current and future situation of the region's grid has been given considering different scenarios in a 2040-time horizon to determine where an extension of the grid will be necessary. The map in Fig. 11 shows overloads on cross-border lines as a summary of the analyzed scenarios. Based on these analysed scenarios, the interconnections will be challenged in 2040 by larger and more volatile flows due to higher distances flows crossing the CCS region resulting from the large deployment of intermittent renewable energy sources [43]. The analysis shows that significant amount of reinforcements are needed for both cross-border and internal power lines. Most of the internal grids of all CCS countries must be greatly improved by year 2040, mainly France, Germany, Italy and Switzerland. The

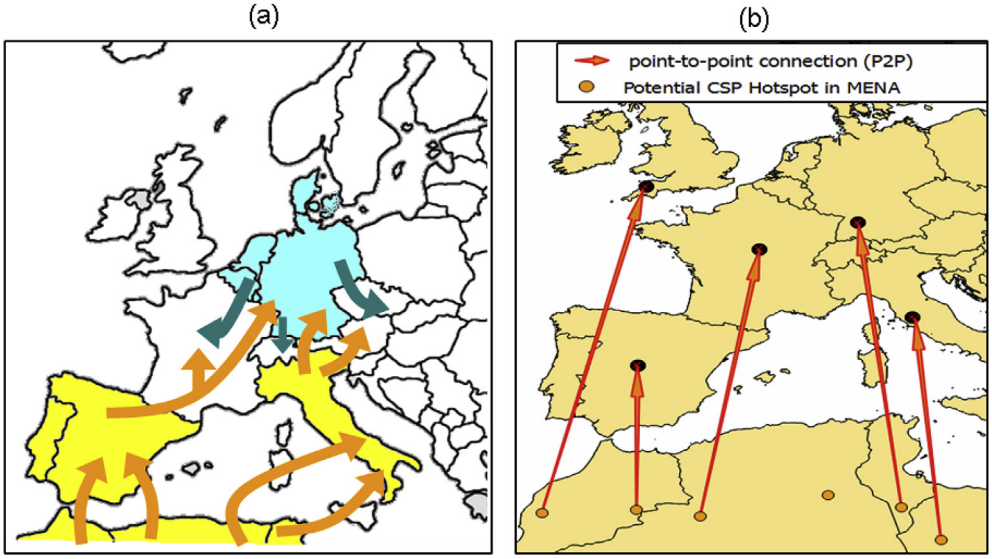


Fig. 10. (a) Wind energy from the North will be balanced with solar energy from North-African. (b) Schema of a combined CSP-HVDC point-to-point power plant bringing dispatchable renewable energy from CSP plants in North Africa to European centres of demand.

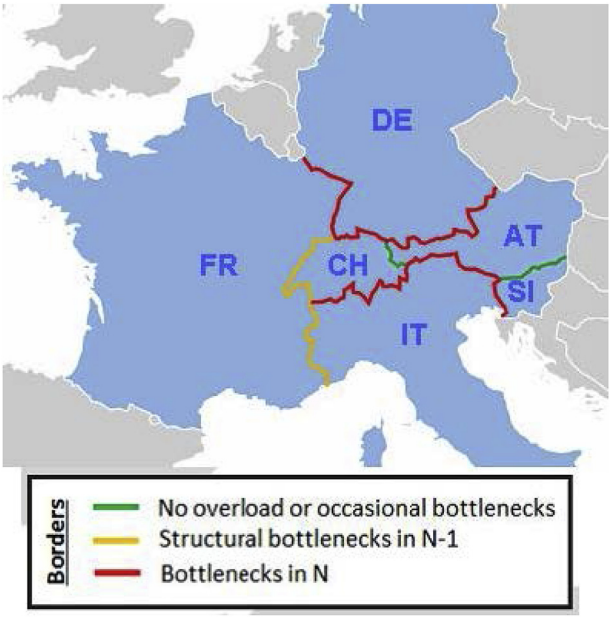


Fig. 11. Future challenges on AC borders for CCS region (source: ENTSO-E).

overloaded and bottlenecks detected in Switzerland are due to the higher and more volatile power flows across Europe (i.e. the effect of loop flows). This confirms what was said above that the fast development of wind parks in the North will increase congestion on the internal and cross-border lines. Regarding cross-border lines, the Northern Italian border and the Southern German border are in dire need of grid development (see Fig. 11). It is clear from this study that, to deal with future situations based on the expected scenarios (without electricity imports from North Africa), it is necessary to significantly strengthen internal and cross-border electricity lines, especially on the North-South axis. A good design of interconnections with North Africa will significantly reduce bottlenecks in Europe without the need to significantly strengthen the grid. The decrease in power flows towards the Southern border resulting from electricity imports from North Africa would not only reduces the congestion in the existing system but will also provide a valuable solution to the problem of loop flows that take place in different parts of the CCS region. Consequently, this would alleviate the cost associated with the so-called inter-TSO compensation [44]. Furthermore, as indicated in Ref. [24] the decrease in North-South power flows can improve the damping of the North-South inter-area oscillation mode which will have a positive impact on the stability of the entire European system.

3.1.3. Stability improvement

The increasing penetration of renewable energy sources has posed several challenges to the entire European electrical system, regarding its dynamic behaviour (i.e. its stability and security). With a large amount of renewable energy sources, frequency stability presents a significant challenge for the secure operation of the ENTSO-E system. It is well known that the frequency excursion does not only depend on the difference between generation and demand, but also on the inertia of the system, usually provided by rotating machines (conventional generators units). Following contingencies, systems with low inertia could be exposed to larger frequency excursions or even blackouts. With the expected massive shut-down of conventional power plants, studies of long-term scenarios have shown that in most European countries, the level of inertia will be low throughout the year, especially in scenarios with a higher share of renewable energy [43,45]. Even with a good inertia level, the ENTSO-E system has experienced in the past several major blackouts related to frequency stability phenomena, such as the 2003 and 2006 blackouts. Thus, mitigation measures are required to cope with the low inertia level of the future ENTSO-E system. Due to its high controllability, the HVDC link is a very effective measure which provides faster frequency response after disturbances by adjusting the transmitted power in proportion to the frequency deviation [24,46]. By including frequency control in DC/AC terminals close to load centres in Europe, HVDC links between North Africa and Europe can effectively help maintain a stable frequency in the ENTSO-E system following disturbances associated with unbalance between demand and generation. This will reduce the risk of load shedding and can even prevent blackouts. In addition to frequency stability improvement, HVDC links can improve other types of power system stability such as transient stability, dynamic stability and voltage stability [24,47]. All these benefits of HVDC links could greatly help Europe ensure a secure energy supply in a system with higher shares of intermittent renewable energy.

3.1.4. Decrease electricity prices

Another advantage of dispatchable electricity imports from North Africa is the expected positive influence on the European power markets. Various studies have indicated that renewable electricity imports from North Africa would be cheaper than electricity production in Europe [5–7]. Indeed, the production of renewable dispatchable electricity in North Africa plus its transport to the EU will require considerable efforts in terms of investment, technological and international cooperation to realise such a huge infrastructure, but this dispatchable electricity is more beneficial and sustainable for the EU power system as it can provide firm power capacity to maintain grid stability and control at very low cost as compared to other technologies like wind, PV and even nuclear power, which may be cheaper under certain conditions, but are also less worth [11,48]. It has been shown in several studies that electricity imports from North Africa would lead to lower electricity prices in Europe [11,13,41].

Considering possible benefits in terms of cost, it is today a pure speculation how the future system cost or LCOE (Levelized Cost Of Electricity) in Europe can develop. Based on international expert assumption, the technological cost still varies in a huge bandwidth [49]. In the case of the German System, for instance, a high renewable energy share (with and without CSP from MENA) can lead to a system cost deviation of about ± 50% [12]. LCOE has been identified as inadequate for intermittent renewables including solar, as it does not consider intermittency of the source [50]. Thus, integration costs such as balancing-related costs and location-specificity grid-related costs must be added to the traditional LCOE to give the total system LCOE [51]. However, several uncertainties emerge during these computations [51]. CSP including thermal energy storage can be considered as a dispatchable technology in the calculation of LCOE [52,53]. However, even in the case of dispatchable generating technologies like nuclear, gas combined cycle, and coal, the LCOE approach does not reflect the true social costs of electricity generation [53]. Due to the balancing measures such as backup transmission capacity, backup power generation and storage, high share of fluctuating renewables (PV and wind) will lead to higher LCOE [52,54]. It has been shown that the lack of energy flexibility options results in an increased demand for long term storage and consequently this will lead to a significant increase in LCOE [52,54]. Importing dispatchable solar electricity from North Africa can reduce the need for balancing capacity and energy. Such a reduction can therefore lead to a decrease in the total power system LCOE.

3.2. Barriers and opportunities

A transfer of dispatchable CSP electricity from North Africa to Europe can be justified by a number of economic, environmental and technical benefits. The project has no technical barrier with regard to CSP and HVDC technologies. There is even a legal right in the EU Renewable Energy Directive (Article 9) formally approves the import of renewable electricity from third countries to reach the assigned targets.

Why then, to date, there is no export of dispatchable solar electricity from North Africa to Europe?

The uncertainty of the political situation in many states of the MENA region is considered as the most important barrier to solar electricity exports to Europe. The uprisings that swept the MENA region referred to as the “Arab Spring”, which started in Tunisia in December 2010 has generated an unprecedented wave of political upheaval across the region. In North Africa alone this has resulted in the overthrow of governments in Tunisia, Egypt and Libya while substantial governmental and political reforms have been conceded in Morocco. These countries faced political turbulence and social unrest which led to a deterioration of the security situation and created uncertainty for local and foreign investors. Due to the unstable political situation in the MENA region following the Arab spring, doubts are raised about the future of industrial initiatives where many stakeholders of the Desertec project have pulled out, and some key governments lost interest [55,56].

In fact, there are several barriers to the deployment of renewable energy in North Africa countries and the export of CSP electricity to Europe, which have been assessed by the researchers engaged by the BETTER project [8]. The main barriers identified are summarized below:

- Inappropriate regulatory framework
- Lack of interconnections
- Lack of political support
- Undefined tariffs
- Low regional cooperation
- High investments required
- Lack of financial support
- High investment risks
- Lack of awareness

All this may seem obvious, but apparently these are not the main barriers. This is because in the past and present an enormous amount of money has been invested in the oil and gas sector in these same countries. For instance, the Maghreb–Europe gas pipeline between Algeria and Spain (through Morocco) was established and completed during that country's large-scale internal conflict of the 1990s. From the statements made by the European officials over the past few years and the documents provided by the European Commission on energy issues in Europe, it is easy to understand why renewable energy partnership with North Africa countries still not happening. The fact of the matter is that the EU wants to reach its targets without importing electricity from foreign sources with a view to reduce the EU's dependence on energy imports and increase its energy security. The last crisis between Russia and Ukraine has clearly emphasized clear how vitally important energy security issues are for the EU [57].

Indeed, it is desirable for EU to achieve its energy agenda using domestic energy resources (so-called low hanging fruits), especially in the beginning of this energy transition, which is a key element for competitiveness, growth, and job creation. But this strategy does not ensure the security of energy supply and does not lead to a long-term goal of a sustainable energy supply in the EU [58]. Renewable sources in Europe are mostly fluctuating in nature, while the domestic sources, which are both renewable and dispatchable (geothermal, biomass, CSP and hydro) have limited potential to provide the necessary balance between supply and demand, which is essential for the security of supply [11,58]. Due to their intermittency, the success of domestic renewable sources to ensure the bulk of low-carbon energy supply in Europe at a low cost and high reliability is not ensured. The reason is a high need of flexibility options [12,58,59]. This major problem is recognized by experts and policy makers from Europe and abroad [57]. For this reason, some political strategies of countries in Europe see nuclear power as part of their future low-carbon electricity system. This trend poses additional challenges, particularly convincing public opinion that it is worth continuing to invest in this type of energy. Although nuclear plants do not emit carbon dioxide at the point of generation, nuclear energy is not clean energy, because carbon dioxide is not the only pollutant that threatens the safety of humanity and the planet. To date, there is still no safe and reliable solution to deal with the radioactive waste produced by nuclear plants. In addition, nuclear disasters like the ones in Chernobyl or Fukushima have increased public awareness of the dangers of nuclear energy and besides, the capital cost of new nuclear power plants is significantly high [60].

As the penetration of intermittent renewable generation increases, power flows become much more volatile and less predictable, resulting in an increased risk of cascading outages and large blackouts. The large 2006 blackout in Europe is a good example of this risk in which failures propagated from Germany to Southern Europe [17]. There are other examples such as the 2016 blackout in South Australia and the Scottish blackout in 2014, indicating that large-scale integration of intermittent generation by renewable energy sources sharply increases the risk of blackouts [61–63]. Given that most all of the major energy supply disruptions across Europe in the past have been caused by domestic events (storms, floods, heat waves, strikes, mishandling of nuclear safety), the EU's vision of energy security by reducing dependency on energy imports is wrong and leads to more open questions and seems like a glorified political dream of autonomous energy supply [58]. Indeed, the diversification of suppliers and import routes is a key to energy security in the EU [57].

The EU must ensure that its energy policies meet the aspirations of the EU citizen who wants an energy which is safe, affordable, compatible with the environment and the society and in sum sustainable. Therefore, access to sustainable and reliable sources of energy at competitive prices is indispensable prerequisites for economic growth and social development. Imports of solar electricity from North Africa would be different from imports of fossil fuels because renewable electricity can be produced in Europe and therefore the exporting countries should provide reliable and economic power, otherwise the demand would decrease, and the non-exported solar electricity will be lost and can not be exported later as with gas and oil [3]. This raises a strong interdependence between supplier and offtkaer in the case of a dispatchable solar energy transfer which allows also a WIN-WIN situation.

In light of the above-mentioned points, the main question that arises is why the various initiatives that have been launched over the past years with the aim of generating and transmitting solar energy from North Africa to Europe have failed to attract the required attention of the European decision-makers. For example, Desertec foundation, the main body dealing with CSP integration in the region, seems to have made some mistakes in designing its concept, which prevented the implementation of the project, especially when it is visible that the former shareholders of the Desertec consortium continue to be interested in the idea of fostering renewable energy in MENA and importing solar electricity from North Africa despite leaving the consortium. For instance, a solar energy export project (the TuNur project) was launched by the British company Nur Energie, which is looking for investment to export solar electricity from the southern part of Tunisia to Italy and then to the rest of Europe including the UK.

The most important part of each initiative is the proposed scenario. Among the main factors in the mentioned Desertec scenario (see Fig. 9(b)) that may have hampered the implementation of the project, one can highlight the following:

1. The Desertec scenario is proposed to cover a large area of the MENA region which makes it very difficult to implement the project. Beyond the extremely high investment required, the MENA region is not organised like the EU which has a common energy policy and speaks with one voice on the international stage. Each country in the MENA region has its own priorities, economic interests, policy strategy, renewable energy program, distinct legislation and a

distinct approach to the concept of renewable energy exports.
2. The Desertec scenario includes intermittent energy sources (wind power), and as mentioned above, the only reason that could push European countries to import renewable electricity from North Africa is the quality and reliability of the provided electricity (i.e. dispatchable power from CSP plants). It makes sense that no country in Europe would be interested in importing electricity that can be produced in Europe, albeit at higher cost [48].
3. The Desertec scenario is based on a supergrid concept, and as discussed above, it is not possible to build a supergrid in the near future due to several challenges and limitations. The main issue delaying the implementation of a supergrid is that it is not yet possible to build a meshed HVDC grid with the current existing of technology [64,65]. Most HVDC schemes under operation and planned for the next years are point-to-point schemes. Around the world there are only five multi-terminal HVDC systems under operation and the maximum converters that are connected to a common DC line are only five.
4. Demand for electricity in the MENA region is increasing dramatically, which is expected to double by 2030 and is likely to be the same as that of Europe by 2050 [6]. As a result, a very large proportion of the produced electricity will remain in the MENA region, especially since many countries in the region have no fossil energy sources and are struggling to meet their own demand.

Following from the discussion above, the direct export scenario is seen as the only possible approach that will make the idea of transferring dispatchable solar electricity from North Africa to Europe possible in the near future. In this scenario, the CSP power plants will be built exclusively to export electricity to Europe via point-to-point HVDC links (i.e. without a need to integrate the CSP plants into the grids of the producer countries).

4. Selection of promising sites in Europe for the import of CSP electricity

To design a scenario for CSP electricity imports, there are generally three steps involved [7,66]:

- Selection of promising sites to build CSP plants
- Selection of potential sites for electricity imports in Europe
- Selection of suitable corridors for HVDC lines

While the criteria used to define the locations of CSP plants and HVDC corridors are clear and well defined in the literature [7,66,67], the criteria used to define the import sites are not well defined in terms of justifying the need to import dispatchable solar electricity. Beyond the compulsive criteria, such as the availability of land for placing the HVDC stations and the capability of the AC grid for the absorption of imported electricity, total demand for electricity is the only criterion used in Refs. [7,66] to choose the import sites, where the major centres of demand in Europe are identified based on some indicators such as population density and nightly light emission. This single criterion is not enough to justify the need for importing dispatchable solar electricity and may therefore render the project ineligible for funding. For instance, sites where dispatchable renewable energy sources or energy storage facilities are available in Europe may not attract the required attention of decision makers and stakeholders of those regions to invest in dispatchable solar electricity imports. Moreover, the major European demand centres are generally located in the centre of the continent, which means that extensive rights of way are required. Thus, the selection criteria should be well defined to make the project attractive and enable it to move forward. Based on the above discussion on the challenges facing Europe in achieving its clean energy objectives and the benefits of dispatchable solar electricity imports from North Africa, the following criteria are defined:

4.1. Lack of dispatchable energy sources

As discussed above, the penetration of intermittent renewables has increased considerably during the last years in European countries. Given that base-load generation is needed to maintain a high degree of quality and security of supply, countries with high penetration of intermittent renewables and with too few dispatchable energy sources would be good candidates for choosing import sites. Because of their controllability, HVDC links between North Africa and Europe will play an important role in ensuring supply security and improving system stability in the southern regions, while allowing additional intermittent renewables capacities to be integrated. Dispatchable CSP electricity from North Africa can balance fluctuations in PV and wind power turbines and hence reduce the need for storage facilities [11]. Therefore, the following countries are chosen as good candidates: Germany (high penetration of intermittent renewables with low share of biomass, geothermal energy and hydropower in electricity production and there is a plan to shut down the existing nuclear power plants), Italy and Portugal (high penetration of intermittent renewables with low renewable dispatchable energy share and absence of nuclear power plants), Spain (high penetration of intermittent renewables with low share of hydropower in electricity production), however Spain has also the economic solar potential to use CSP seasonally [5].

4.2. Impact on the internal energy market

Electricity prices in EU countries are extremely high compared to other non-EU developed countries (2.3 times higher than in the US and 1.2 compared to China). Electricity prices paid by European industry have increased by 4% between 2008 and 2012 [57]. Therefore, EU countries and operators cannot import solar electricity without considering the value of the benefit that will accrue to their energy markets. The production of renewable dispatchable electricity in North Africa and its transport to the EU is not only more efficient but also more beneficial and sustainable for both the energy system in EU and MENA as compared to an isolated European energy system [11,68]. It is therefore expected that dispatchable renewable imports have a positive influence on the European power markets [11,13,41], which would help reduce the prices that consumers currently pay for their energy consumption. According to Eurostat statistics for 2017 [69], electricity prices for both industrial and household consumers in the EU are very high in Germany, Italy and Belgium. Therefore, these countries can be considered as potential candidates to choose the best import sites. The expected positive impact of solar electricity imports on the Italian market was confirmed in Refs. [41,42,70].

4.3. Level of accomplishment in achieving legally binding 2020 targets

In order to decarbonize its energy supply, the EU has set itself ambitious targets by decreasing the share of fossil fuels and increasing the share of renewables, ranging from short to medium and long term (2020, 2030 and 2050). Although the EU is well on the road to meet the 2020 targets, with the current policies, it will be difficult or even impossible for the EU to achieve the 2030 and 2050 targets [71]. Achieving the 2030 targets will require drastic actions and a review of the current policies and strategies, especially for those countries still far away from meeting their legally binding 2020 targets. As can be seen in Fig. 12, France, the Netherlands, the United Kingdom, Spain, and to a lesser extent Belgium are the furthest away from their targets and it is expected that these countries will not achieve their targets by 2020. As a means to meet the legal binding national targets, Article 9 of the European Directive (DIRECTIVE 2009/28/EC of 23 April 2009) provides the possibility of importing renewable electricity from third countries. Therefore, the mentioned countries are good candidate for choosing best import sites.

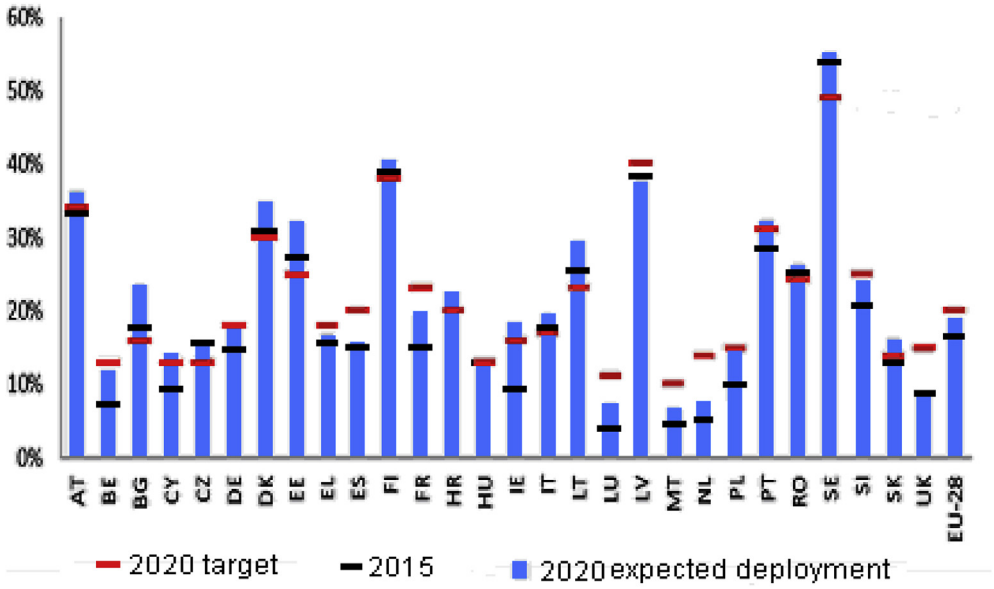


Fig. 12. Share of energy from renewable sources in the EU Member States, 2015 (data source: Eurostat and [71]).

5. A promising import scenario

According to the identified criteria, the countries that would be the right candidates for choosing import sites are western European countries such as Germany, Italy, France, Spain, Belgium, Netherlands and the UK. The import sites can be chosen from these countries based on the criteria given in Refs. [7,66]. However, the situation of the European transmission grid and the geographical location of each country are additional criteria that will play a vital role in the selection process. For example, Germany is a very relevant region for selecting import sites, especially after the decision of phase-out all the nuclear power plants by 2022, but transferring the imported electricity to the heart of Europe is a concern, because it makes the project progress more difficult and time consuming. Given that the closest routes from North Africa to Europe are only towards Spain and towards Italy, both countries would have a key role in ensuring the success of any solar energy export project.

Spain is very low connected to Europe (relatively isolated), as the interconnection with France represents only 3% of power installed capacity [72]. In 2002, EU member states agreed that every Member State should achieve interconnection across its borders of at least 10% of its installed generation capacity by 2005. Although the deadline has long passed, Spain is still substantially far from the recommended target (see Fig. 13). Even when current interconnection projects are realized, Spain will not meet the target in the foreseeable future [73]. This can be explained by the difficulty of getting rights of way to build transmission lines in the region. The new interconnection between Spain and France across the eastern Pyrenees is a good example of this problem, where parts of this interconnection were built underground at a very high extra cost [29].

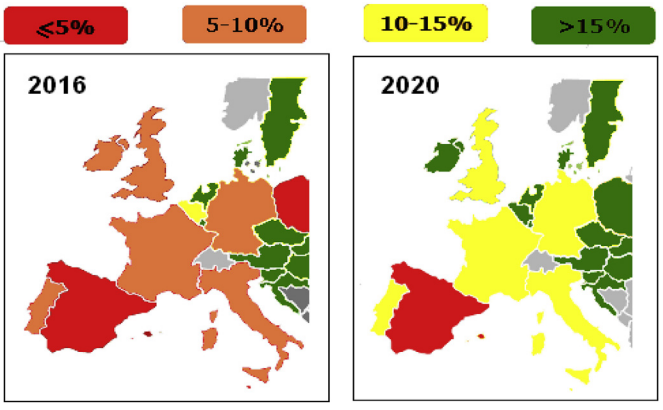


Fig. 13. Interconnection levels in 2016 and expected levels in 2020.

On the other side, Italy, Europe's largest energy importer, is relatively well connected to its neighbours (approximately 10 GW), especially with Switzerland and France [74]. Although Italy is still 3% below the target of 10%, it is expected that the country will reach or even exceed the target level by 2020 (Fig. 13) [73]. Terna (the main transmission system operator in Italy) is actively investing in the development of the transmission grid within the country and at the borders. The new transmission facilities that will be commissioned in the coming years will increase interconnection capacity on the northern borders, particularly with France thanks to the new HVDC link (Piossasco-Grand'Ile HVDC link), which is expected to be commissioned by 2019.

As discussed above, Italy is a huge net importer of electricity, which leads to high north-south power flows in the CCS region. A large-scale import of CSP electricity from North Africa to Italy would allow Italy to stop import electricity from the north. Northern interconnections can then be used to transfer CSP electricity to the Northern countries. Therefore, given the current and expected situation of the European grid, the vision of making Italy an electricity hub in the region is a promising and attainable scenario for transferring solar electricity from North Africa to appropriate sites in Europe in the near future. The scenario is based on a number of HVDC links interconnecting the points of solar power production in North Africa with the main centres of demand in Northern Italy like the cities of Milan and Turin (see Fig. 14). The links can take place along Sardinia and follow the path of the SACOI HVDC link existing in Corsica. CSP electricity can be transferred to Germany with little or no investment required in cross-border interconnections, thanks to the very large transfer capacities available across the borders of Switzerland. Since most nuclear power plants in Germany are located in the south, CSP electricity from North Africa will greatly help Germany to phase out all of its nuclear generation capacity in a perfect manner as it eliminates or minimizes the high investments needed for building new high-voltage transmission lines to transmit wind-generated electricity from the north. Parts of CSP electricity can be transferred from France and Germany to Belgium, the Netherlands and the UK through available interconnections.

However, without direct access to CSP power plants in North Africa,

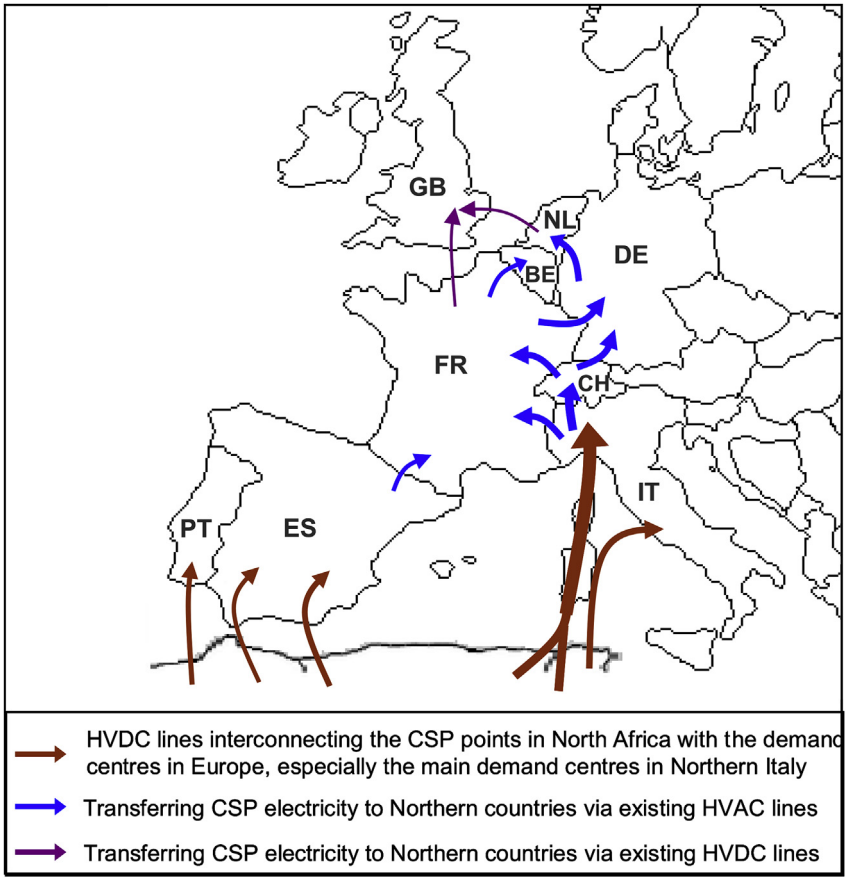


Fig. 14. Import scenario based on the view of creating an electricity hub in Italy.

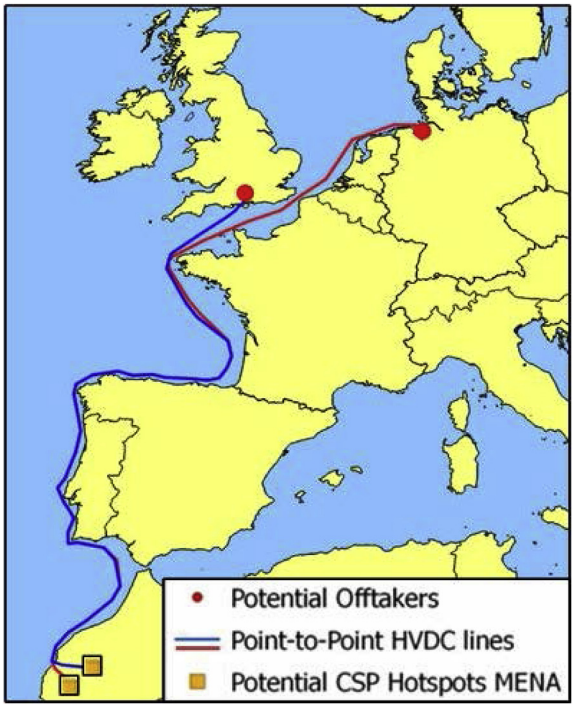


Fig. 15. Examples of connections across the Atlantic for the UK and Germany from Morocco.

the Northern regions may not benefit greatly from the imported dispatchable solar electricity. Giving each European balancing authority area the possibility to integrate dispatchable CSP from North Africa like nuclear and coal fired power plants in their energy system, point-to-point HVDC links are needed to feed such energy into their grid section. In addition to the HVDC links through the Mediterranean Sea (Fig. 14), Sea routes in the Atlantic which could allow a direct access to CSP plants in North Africa for Central and Northern European countries could be possible touching only the exclusive economic zones of southern European countries instead of their land area to avoid the lengthy and time-consuming procedures for obtaining approval for land use. Such sea cable routes may be longer than going over land areas. However, the losses and overall effort in time and investment may be not much higher [66]. Fig. 15 shows some examples for these possible connections. For economic consideration, multi-terminal configurations can be used. HVDC links from North Africa to UK through Italy over land may be longer than HVDC links from Morocco to UK through the Atlantic. The approach to connect resources from long distance between two countries is applied e.g. with the Nord Stream gas pipeline from Russia to Germany [75]. Thus, this example can be used in its best practise to concretise a combined CSP-HVDC power plant. The HVDC links through the Atlantic can greatly help the Northern European countries such as Germany to balance their wind power.

6. Conclusion

A successful transition towards a secure, sustainable, resource-efficient and low-carbon energy system in Europe requires a re-thinking of the planning and operation of the future power grid. Adequate and efficient planning based on a realistic long-term vision is essential. Given the fact that the solar power potential in the Sahara region of

North Africa has a broad range of benefits that can support and facilitate a successful transition towards a low carbon energy system in Europe, the transfer of dispatchable renewable solar power from North Africa to Europe should be considered as major element for a co-operation between these regions and the interconnections between the two regions should be considered to become one of the building blocks for developing a European supergrid. For geographical and logistical reasons, interconnections with Italy will probably be the first to be developed in the short-to medium-term, while in the long term, interconnections with Spain might be put into place. Transmission grid expansions inside Europe are also important to strengthen the spatial flexibility option for the grid leading together with the point-to-point lines to a European supergrid in the long-term.

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