North Africa and the European Union:

An option for technically controllable and politically reliable solar electricity supply?

By Dr. Jutta Lauf and Dr. Reiner Zimmermann

Content

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I. Climate change and energy production

Climate change, conflicts, and the production of electricity

Man-made and accelerated climatic changes are the most fundamental challenges the world is facing. Global warming, rising sea-levels, more frequent and intensive extreme weather conditions threaten entire natural ecosystems, agricultural production, infrastructure and human well being[1]. The political, social and economic consequences of these changes increasingly affect the global security agenda e.g. through "water-wars", conflicts over resources or land grabbing - often leading to famines, increasing numbers of climate refugees, social unrest and even military conflicts and open wars[2; 3]. There is general agreement that the major cause of current climate change is the increasing atmospheric concentration of greenhouse gases (GHG) due to fossil carbon burning. Apart from electricity generation, industry, mobility and buildings, agriculture and forestry do contribute significantly to the emission of greenhouse gases. The most important greenhouse gas with respect to the electricity generation is carbon dioxide (CO_2)[4; 5]. Thus most nations agreed to the urgent need for drastically reducing GHG emissions in order to mitigate the current process of global warming.

Human impact onto the "Blue Planet"
The Intergovernmental panel on Climate change (IPCC) is a United Nations body for assessing the science related to climate change. In its most recent report (published in autumn 2021) it concluded that climate change is already affecting every inhabited region across the globe, with humans contributing too many of the observed changes. Most obvious to humanity is the rise in hot weather events as shown below.[1]

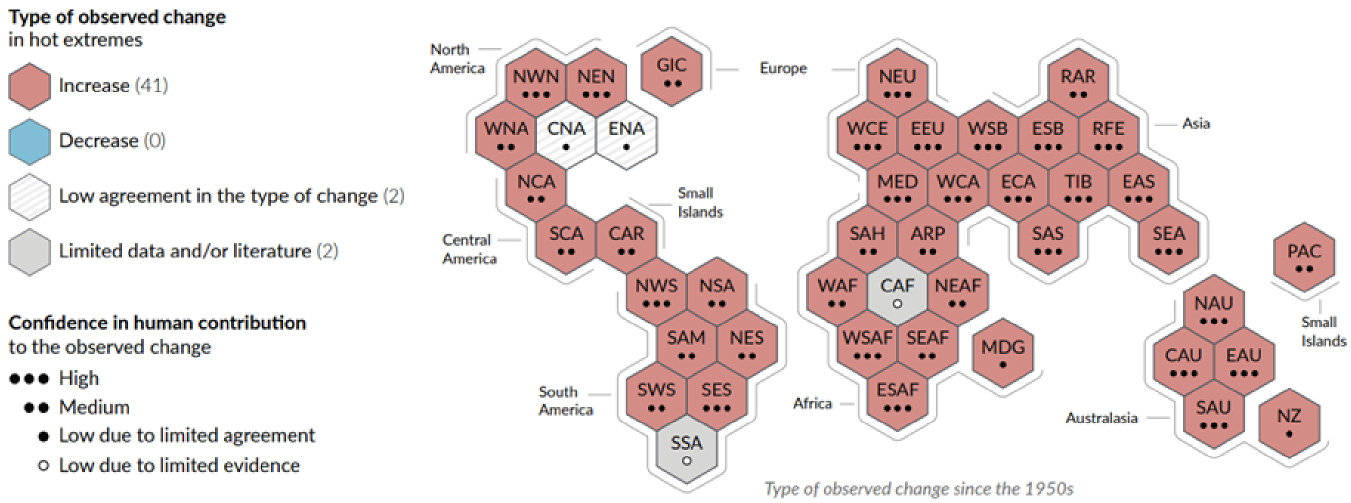


Figure 1: Synthesis of assessment of observed change in hot extremes and confidence in human contribution to the observed changes in the world's regions[1].

Each hexagon corresponds to one of the IPCC AR6 WGI reference regions: North America: NWN (North-Western North America, NEN (North-Eastern North America), WNA (Western North America), CNA (Central North America), ENA (Eastern North America), Central America: NCA (Northern Central America), SCA (Southern Central America), CAR (Caribbean), South America: NWS (North-Western South America), NSA (Northern South America), NES (North-Eastern South America), SAM (South American Monsoon), SWS (South-Western South America), SES (South-Eastern South America), SSA (Southern South America), Europe: GIC (Greenland/Iceland), NEU (Northern Europe), WCE (Western and Central Europe), EEU (Eastern Europe), MED (Mediterranean), Africa: MED (Mediterranean), SAH (Sahara), WAF (Western Africa), CAF (Central Africa), NEAF (North Eastern Africa), SEAF (South Eastern Africa), WSAF (West Southern Africa), ESAF (East Southern Africa), MDG (Madagascar), Asia: RAR (Russian Arctic), WSB (West Siberia), ESB (East Siberia), RFE (Russian Far East), WCA (West Central Asia), ECA (East Central Asia), TIB (Tibetan Plateau), EAS (East Asia), ARP (Arabian Peninsula), SAS (South Asia), SEA (South East Asia), Australasia: NAU (Northern Australia), CAU (Central Australia), EAU (Eastern Australia), SAU (Southern Australia), NZ (New Zealand), Small Islands: CAR (Caribbean), PAC (Pacific Small Islands)

The European Union (EU) aims to be climate-neutral by 2050, which means an economy with net-zero GHG emissions. This objective is at the heart of the "European Green Deal" and in line with the EU's commitment to global climate action under the Paris Agreement. With nearly 80% of the EU's GHG emissions being related to the energy sector, it is evident that a renewable energy transformation which causes much less GHG emissions is key to mitigate global warming by achieving climate neutrality. The need to shift from a fossil energy supply to renewable energy sources became even more pressing by the open military conflict between Russia and the Ukraine in 2022 which led to a massive increase in fossil energy prices and a bottleneck in the energy supply of gas and oil, though it may boost the deployment of renewable energy production[6]. So, both the GHG reduction for climate change mitigation and the de-coupling from the strategic dependence on fossil energy are strong motives for European nations to increase and diversify their renewable energy portfolio. Large amounts of the renewable energy will have to be produced abroad, transported or transmitted over large distances to Europe and distributed within the EU and partner countries.

In general, the amount of electricity production from renewable energy sources like solar and wind is not controllable because it depends on the locality and the weather conditions. Electric energy can currently only be stored in very limited amounts. Also, transmission losses during long distance transport are unavoidable[7]. Within the framework of uncontrollable power generation from renewable sources and a high and continuous electricity demand, load management of the electrical grids becomes increasingly challenging[8]. Enlarging storage capacities and the interconnectivity of power grids are generally deemed as key elements for solving this problem.[9] The terrestrial solar and wind generation potential in Europe is limited and will soon reach its limits with respect to available spaces and social acceptance, while offshore installations still have considerable potential - however incurring large infrastructure investments and maintenance costs. The remaining gap between supply and demand could be closed by importing renewable energy from regions in the global Sun Belt (e.g., in North Africa and the Arabian Peninsula) where solar and wind energy are available at an ample scale. The geothermal potential for electric power generation from geothermal sources in Iceland is an interesting alternative to solar and wind power but is not within the geographic scope of this article. For Europe, the closest neighbours within the global Sun Belt are Morocco, Algeria, Tunisia and Libya. These nations have a high potential for producing renewable energy while the transport (transmission) distance to Europe would be manageable. Of these four nations, only Morocco enjoys a relatively high political stability.

The technical prospects to produce and export electricity generated in renewable power plants from North Africa to Europe are given. North Africa has some of the highest solar power potential in the world[10] as well as a good potential for wind energy[11]. Harnessing only a fraction of the Sahara Desert's renewable energy potential with solar and wind farms could supply enough electricity to meet both, the current and the future global electricity demand[12; 13]. Investing in and supporting North African countries to deploy renewable energy for export and domestic use could be attractive to the European nations and the EU for several reasons. Importing renewable energy from resource rich neighbouring countries could be a means of achieving European climate targets more cost efficiently. Electricity could be obtained with up to 60 % lower support costs in comparison to domestic production in Europe[14]. This rationale has for instance been addressed in the EU's "Directive on Renewable Energies", which allows renewable energy cooperation with "third states" and for member states to include it into their national accounting[15]. Within the norms and regulations of the EU, a third state or a third country refers to states, which neither belong to the EU nor to the European Free Trade Agreement (EFTA)[16]. Utility-scale renewable power plants in the Middle East and North African countries (MENA) could thus enhance energy security through a diversification of suppliers and energy sources while securing the affordability and sustainability aspects. Yet several attempts of realizing this vision in the previous decades have failed primarily due to political difficulties, e.g., the Desertec Industrial Initiative (DII)[17; 12].

The conundrum of nuclear power

The "Directive on Renewable Energies" lists nuclear power as "green energy", alongside other power generating technologies[18; 15]. This classification has caused controversy, as nuclear power plants do not emit CO_2 during power production, but the used uranium fuel is not renewable, and the waste disposal problem is not solved. The assumed advantage of nuclear power plants – their ready to go and controllable power production capabilities – have turned into a liability in the era of global warming, as the dependency of water for cooling purposes became obvious. During the 2022 summer drought in central Europe environmental laws to protect valuable river and lake ecosystems from overheating forced the operating companies to reduce production or even to shut down the plants completely. Especially hard hit was France, which on average produced about 60 % of its total power demand via nuclear plants. During the heat wave, with its increasing electricity demand for air condition cooling, France imported power, mostly generated by hydro, wind and solar.[19]

In this paper we will first discuss whether the power demand of the highly industrialized European Union, can be met by an electric grid, which is mainly supplied by renewable energy sources. Then we present a selection process for such an electricity producing country by physical, political, social, and economic criteria in North Africa. This resulted in Morocco as a potential candidate. Finally, we present a roadmap for a possible cooperation between Morocco and the EU for successful electricity exporting/importing projects. We focus on electric power generation and transmission since the production of hydrogen and carbon-based synthetic fuels, their transport and final energy conversion processes result in very large energy losses.

II. Electrical grids and power production costs

Covering electricity demand with "clean energy"

Grids dominated by renewable power plants

Electricity generation is moving away from fossil and nuclear power plants to renewable sources. While the Ukraine-Russian conflict increased the short term use of coal and lignite as well as imports of liquefied natural gas (LNG) from non-Russian suppliers[20] the long term trend of de-fossilization in the energy sector will persists. Because Western countries try to substitute Russian gas[21; 22], it is assumed, that in the long run this conflict will actually speed up the production and use of renewable energy. It is generally assumed that this will increase the production of electricity and of hydrogen via electrolysis of water. The high demand of energy in the EU inevitably leads to two key questions: Where all the "clean" energy can be produced and how it can be transported and distributed to the EU nations[23].

Controllable and storable renewable energy-forms are needed for this transition to be a success. Photovoltaic (PV) and wind generated energy is non-controllable and, in the magnitudes needed, non-storable. Concentration solar power (CSP) plants without thermal energy storage (TES) are also non-controllable. New CSP plants are regularly equipped with TES of up to 12 h of full generator capacity. CSP plants with TES are a game changer as they store the first form of energy harvested which is heat. Heat can economically and on a large scale be stored (e.g., in salt solutions). TES on a KWh basis is 80 - 90 % cheaper compared to battery storage[24]. The stored thermal energy can be - on demand - transformed into electrical energy by conventional steam turbines. Since CSP-TES plants can be classified as controllable and storable energy providers, it can be expected that the most likely technological solution for energy generation for European customers will be provided by CSP plants with TES and conventional steam turbines for electric power generation. Sufficient amounts of solar energy for e.g., the power demand of the EU can only be obtained in the global Sun Belt region. The closest Sun Belt region to Europe is the MENA area and CSP plants with TES would provide a controllable energy input to the electric transmission lines to Europe and the electric grids of the EU consumer nations. Currently, the global CSP power production is small compared to the total global power production. Countries with the highest production – Spain and the USA – are not even located in the global Sun Belt. The technology of CSP plants is described by the authors in an earlier Volume of *Energy Highlights*[8].

Magnitude of the EU energy demand

The EU (27) countries – without the UK, which left the Union in on 31st of Jan 2020 – consumed 16.7 TWh of primary energy in 2021. The primary energy consumption from 1990 – the year of the fall of the Berlin Wall – to 2021 varied approx. ± 9 % due to economic booms and crisis (Figure 2). Electricity contribute with 13 % in 1990 and 17 % in 2021 to the total primary energy consumption of the respective year.[25]

Models do predict that for 100 KW PV capacity 2 – 3 KW CSP-TES capacity is needed to secure the energy supply in an increasingly fossil free power production. CSP-TES plants must be built as huge instalments in the global Sun Belt region because they require direct and high solar irradiance and the economy of scale for being profitable.

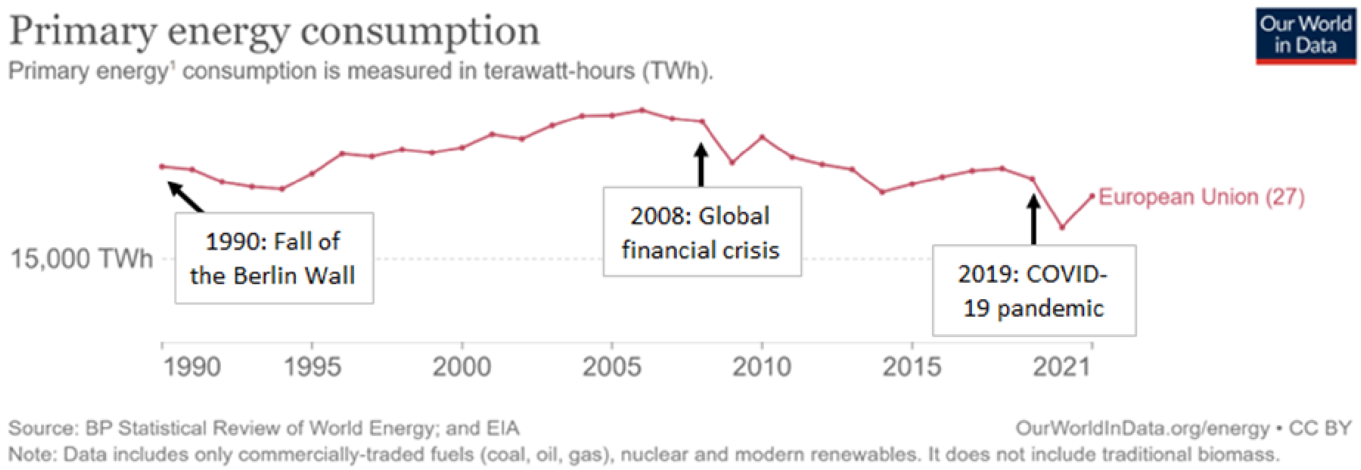


Figure 2: Primary energy consumption in the EU (27) from 1990 to 2021. Altered after Ritchie and Roser[25].

EU (27) refers to the EU without the UK. In 1990 the Berlin Wall fell and in the subsequent years the economy of the former German Democratic Republic (e.g., Eastern Germany) was collapsing. 2008 marks the start of the global financial crisis with several EU economies in severe downturn. 2019 marks the start of the COVID-19 pandemic with shutdowns in all EU countries following in 2020 and 2021.

It appears possible, that future energy demands can be completely covered using renewable sources. This has been demonstrated by modelling the combined renewable power production during a fictitious week in May 2030 in Spain (Figure 3). In this scenario non-controllable and/or non-storable electricity sources will provide as much power as possible e.g., wind and solar PV. CSP-TES plants will supply power when PV production is not possible (e.g., at night). Biomass/biogas power plants will cover peak demands while wind, hydro and combined heat and power plants (district heating systems) serve the base load[24; 26]. For this scenario to become possible, supply and demand sites must be connected via trans-national and trans-continental high-capacity electricity grids.

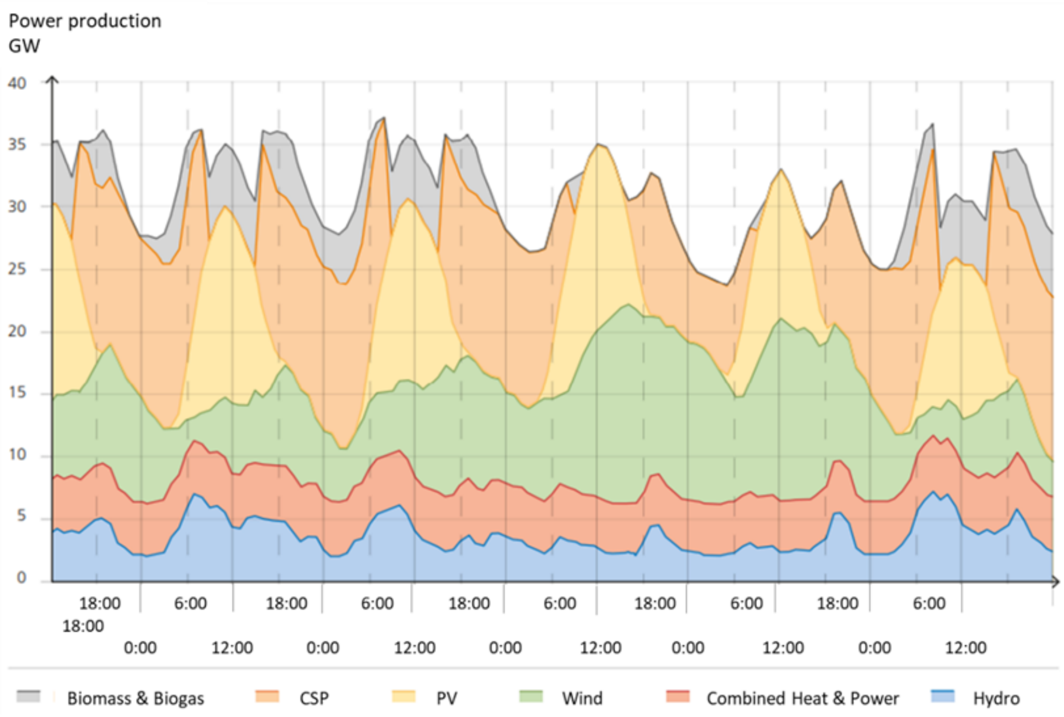


Figure 3: Modelling of a future energy mix, generated from renewable sources only, in Spain for 5 days in Mai 2030. The model starts on Sunday 25th and ends on Wednesday 29th.

Hydropower and combined heat and power plants do serve the base load in addition with wind generated power. PV power will be injected into the grid at full capacity when available while CSP-TES will be used as power supply when the sun is not shining. Peak demand will be met with biomass or biogas power plants. Modified after Daniel Benitez et al..[26]

Trans-national and trans-continental electricity grids

Suppling the grid with the necessary capacity is a demanding task, because most renewable energy sources which are currently used (wind and PV) are neither controllable nor storable[8]. Trans-national and trans-continental power grids would theoretically reduce the volatility of energy production because renewable power production is always possible somewhere on the earth. However, such an approach would require the installation and maintenance of a multiple of electric power generation capacity compared with the actual energy needed and thus is economically inefficient and therefore expensive.

Currently electric grid networks are shaped by political and geographical criteria. For example, the Continental European synchronous area consists of most countries in Central Europe as well as Morocco, Algeria, and Tunisia in North Africa (Figure 4A). However, only a few cables connect North-West Africa with Spain (Figure 4B).[27] A new deep-sea cable is currently build to connect Egypt with Crete. Commissioning should be in 2023.[28; 29] Connections between non-synchronous grid areas are made by high voltage direct current (HVDC) cables. Examples are the NordLink connection between Germany and Norway which was commissioned in 2021[30; 31] and the connection between the British and the Irish synchronous areas.

Synchronous areas

Synchronous areas are groups of countries that are connected via a compatible power grid system. The benefits of synchronous areas include: (A) pooling of power generation resulting in lower power production costs; (B) common provisioning of reserves resulting in cheaper reserve power costs for instance in cases of disturbances or outages and (C) mutual assistance in the event of disturbances. Within a synchronous area, the electric frequency is coupled and disturbances at one single point in the area will be registered across the entire zone. Different synchronous areas can be linked using direct current (DC) interconnectors[32].

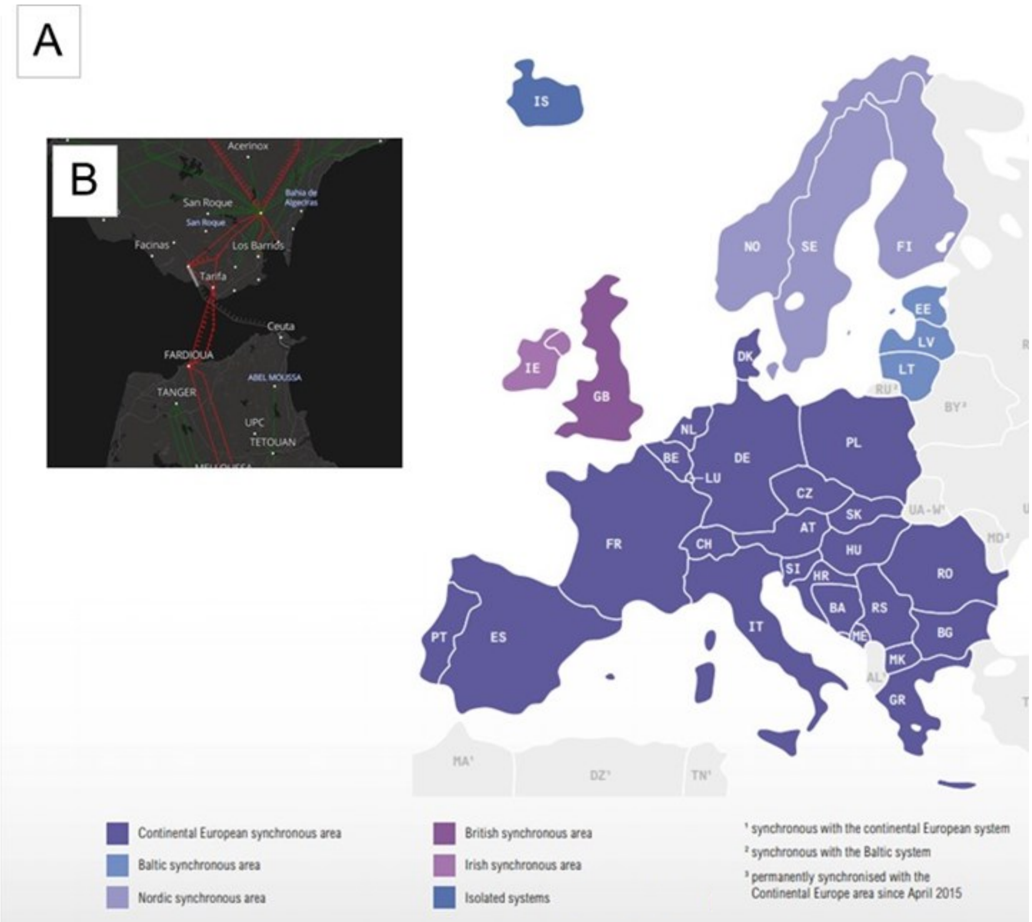


Figure 4: Synchronized power grids in Europe and grid connections between North Africa and Europe.

(A) Synchronized power grids in Europe until 15th of March[32]. On 16th of March Ukraine and Moldova were integrated into the Central European synchronous area[33]. Morocco, Algeria, and Tunisia belong to the Continental European synchronous area.
(B) Three electricity cables crossing the Street of Gibraltar are the only power connections between North Africa and Europe. Two 380 - 400 KV alternate currency cables (shown in red) with several circuits each do connect Morocco and Spain. A third 132 – 150 kV cable with several circuits (shown in grey) is connecting the Spanish EU-territory of Ceuta in North Africa with mainland Spain. (Modified after[27])

Maintaining a constant grid frequency of 50 Hz within the European synchronous areas is of upmost importance. Normal grid operation is maintained within a deviation of ± 10 MHz (0.01 Hz). In the case of larger deviations of ± 10 MHz to ± 200 MHz normal operation is regained by activating or deactivating additional power plants. Long-term maximum deviations of ±180 MHz, and for short periods even ± 200 MHz, are allowed. The frequency range in normal operation is thus kept between 49.8 Hz to 50.2 Hz. In case of the breakdown of some supplying or consuming capacity, short-term deviations until 800 MHz are allowed (49.2 Hz to 50.8 Hz). Such large frequency fluctuations may lead to self-induced shutdowns or even damages in high-end technical appliances. With even higher deviations, a massive grid failure is very likely. In this case, load shedding – disconnecting producers or consumers – is used to stabilize the grid. If even load shedding fails, the entire network will cease operation, leading to a full blackout. After such a breakdown, the entire network has to be restarted gradually. As a consequence of their technical importance, net frequency controlling units are considered as critical infrastructure and are highly protected units globally. [34; 35]

Power grids, which are fed by great shares of volatile renewable energy, are inherently less stable and need to be re-thought. Decentralized power production e.g., by wind or PV dependent on uncontrollable weather conditions. Therefore, the currently unsolved obstacle of a missing large-scale electricity storage option demands for a stable grid operation the creation of very large grids which connect several time and climate zones. The situation and options for Europe were studied by the Desertec Foundation in 2009 (Figure 5)[12]. The planned grid for the (never realised) Desertec project should span facilities from Iceland to the Sahel region (approx. 4 000 km) and from the Arab peninsula to the Atlantic Ocean (approx. 5 700 km).

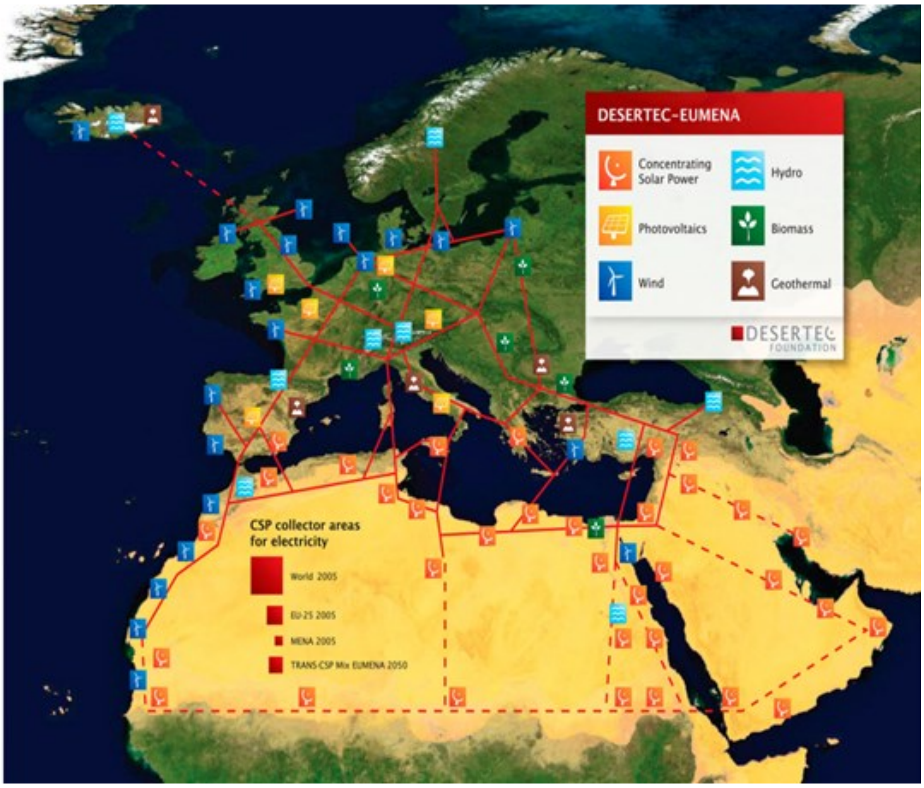


Figure 5: Concept of a transcontinental power grid supplied by renewable energy proposed by the Desertec Foundation in 2009[12].

NATO's Mediterranean Dialogue and the Desertec Industrial Initiative (DII)
NATO started in 2007 the Science for Peace and Security project "Sahara Trade Winds to Hydrogen: Applied Research for Sustainable Energy Systems" with Morocco and Mauretania. Both countries are Mediterranean Dialogue partners. The aim was to create an independent network of industrial and academic expertise, to exploit the regional wind energy resources and to adapt state of the art technology to real world application.[39]

The Desertec Industrial Initiative (DII) was founded in 2009 by several, predominant German enterprises e.g., Munich Re (reinsurance company), Deutsche Bank, Siemens and the two German energy providers RWE and EON. The objective was to supply Europe with electricity produced in North Africa and the Arabic peninsula and to contribute to the self-supply of the Middle East North Africa region (MENA). DII predominantly relied on the concepts of the Desertec Foundation, a non-profit organisation mainly driven by scientists. By 2015 most of the shareholders had backed out of DII. Since 2015 only three shareholders and several cooperation partners remained. DII is relocated from Munich to Dubai and has continued operations in a renewed framework.[12]

Schmitt (2018)[12] tried to analysed the causes of the failure of DII. Dominant explanations are the global financial crisis from 2008/2009, which led to a sharp drop in electricity demand, the Arab spring from 2010 onward with the resulting social unrest and the dramatic reduction und production costs of PV modules (Figure 6), which were installed in large quantities on rooftops especially in Germany. Other cited causes were the focus on technological feasibility and the omission of social aspects and cultural imperialism from industrialised to developing countries.[12]

Investments in electricity lines

End customers of electric power are usually served with alternate current (AC) lines. High voltage lines (convention: > 1 kV AC or > 1.5 kV DC) are currently operated as direct current (DC) lines. Energy losses in AC transmission due to the need for three phase cables (high capital expenditures) and the skin effect in large conductors (high operational expenditures) severely restrict AC technology application for very long-distance power transmission. While conversion of high voltage DC to low voltage AC for the end consumer is more expensive than using AC-AC transformers, the overall costs for operating DC high voltage connections (HVDC) for long distance transport of electricity are substantially lower.

The intercontinental connection in the European Synchronous Area between Europe and North Africa is currently served by several 380 – 400 kV power lines between Morocco and Spain (Figure 4B). An additional 132 – 150 kV line in the strait of Gibraltar connects Spain and the Spanish autonomous city of Ceuta located in Africa[32]. Ceuta belongs to the European Union. In a future scenario of large-scale power transfers from Morocco to Europe, additional power lines must be built.

Investment costs (CAPEX) for the building of electricity lines do vary by a factor of five with respect to length, environment (land, sea), implementation (above ground, underground or deep sea) and the population density (rural or urban) of the respective line. The costs range from $0.9 * 10^6$ €/km for overhead cables to $11.5 * 10^6$ €/km for underground cables (Table 1)[40]. The transmission lines and the electricity producing plants and typically owned and operated by separate companies.

Table 1: Real, projected and calculated capital expenditures for the construction of power lines. CAPEX = capital expenditures. Sources are referenced in numbers as follows: (1) = Leighty et.al. (2012)[41]. (2) = Netzentwicklungsplan Strom (2020)[42]. (3) = RWE (2019)[43]. (4) = TenneT (2020)[30].

Kind of transmission line	Unit	Value
Overhead cable (AC, DC, 500 KV), (1)	[10^6 US$/km]	3.0
Overhead cable (AC, DC 380 kV), (2)	[10^6 €/km]	2.0 – 2.2
Underground cable (AC, DC 380 kV), (2)	[10^6 €/km]	6.0 – 11.5
Deep sea cable, (3,4)	[10^6 €/km]	3.2

Cost of electricity production with emphasis on CSP-TES

The costs of electricity production are typically expressed as Levelized Cost of Electricity (LCOE). They reflect a measure of the live time (production) costs of the plant and the produced amount of electricity (KWh). They are used to compare technologies either within a fuel (i.e., energy) category or over different fuel categories. LCOE follow the general economic laws of production, which means that the costs per unit of output decrease with increasing output[44; 45].

Since 2010 the LCOE for PV show the steepest decline compared to CSP, offshore and onshore wind. This development was due to the enormous roll-out of new PV panel production plants (Figure 6)[46]. Economy of scales effects for onshore wind were nearly as huge as for PV and LCOE are in the same order of magnitude. For CSP the effects of economy of scales have not yet reached its full potential due to the small market penetration. Decreasing LCOE for CSP depends on constant high -level output of new plants in the coming years. Up to 2019 approx. 100 CSP plants with a capacity of 6.2 GW were installed[26] compared to approx. 100 GW of PV plants[47].

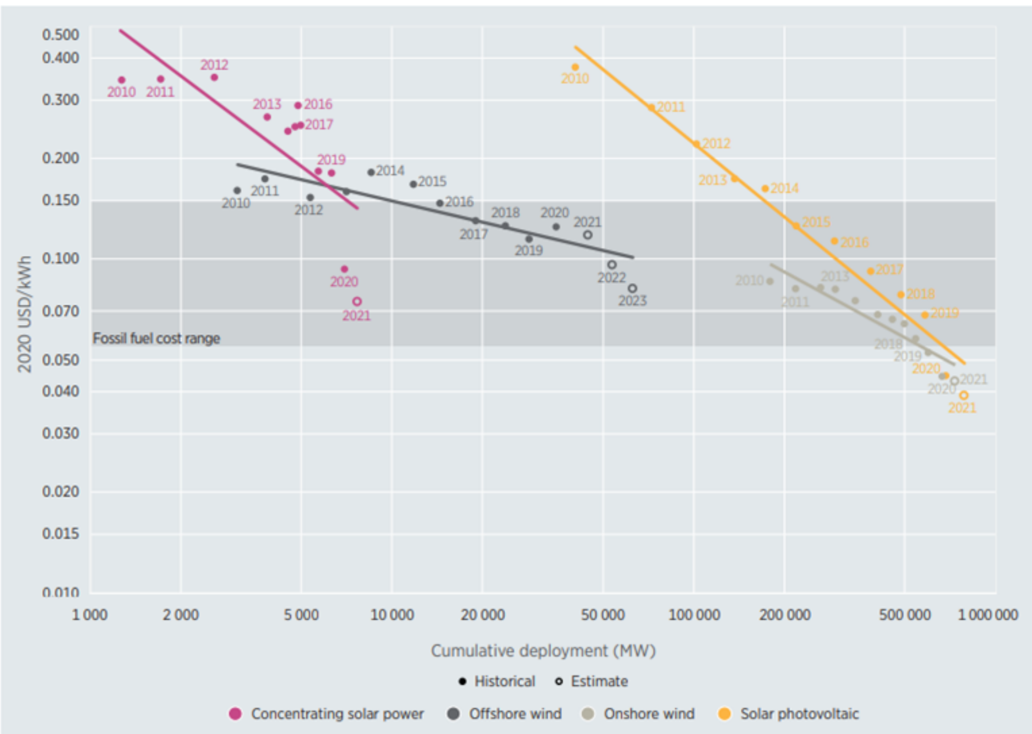


Figure 6: Global weighted average LCOE learning curve trends for solar PV, CSP, onshore and offshore wind from 2010 – 2020 as well as estimated LCOE 2021/23 The grey marked area marks the costs for fossil fuel plants.[46]

LCOE of renewable power plants are now in the same range as conventional fossil fuel plants, or as in case of PV and onshore wind even lower. This trend will probably continue. Mean LCOE for the three commercially used CSP technologies – with and without TES - ranged in 2015 from 13 – 41 €-ct_{2015}/kWh (14 – 45 US$-$ct_{2015}$/kWh)[48] and thus are still the highest of all available renewable power generating technologies and most conventional fossil fuel technologies. Only gas turbines, typically using fossil gas, show LOCE in the same order of magnitude as CSP-TES plants (11.0 – 22.0 €-ct_{2018}/kWh or 13.0 – 25.9 US$-$ct_{2018}$/kWh). Gas turbines are used to cover fast peaking demands and therefore have low working hours and high costs. CSP-TES can also meet this requirement and may in the future compete with gas turbines.[46, 49; 50] In 2011 the US government started the *Sun Shot* initiative in an effort to dramatically reduce the LCOE of CSP-TES plants and project results are implemented in advanced research plants.[51]

The technological challenges for the implementation of new large-scale technological projects are huge but manageable. Most projects in democratic countries are stopped in various phase of their development due to civil society obstacles like property rights to land or water, unequal distribution of the benefits between locals and elites or a general mistrust against the project itself or foreign investors. Therefore, the "soft aspects" of a project must be managed with great care. In the following, we focus on the geographically closest MENA nations of Algeria, Egypt, Morocco, and Tunisia.

III. Business models for cooperation

Political, social, and economic environment in Algeria, Egypt, Morocco and Tunisia

The four MENA countries considered in this article are Morocco, Tunisia, Algeria, and Egypt. They were chosen based on their location within the global Sun Belt, their geographic proximity to Europe and their relative political stability compared with neighbouring MENA countries like Libya. All four countries are not members of the EU or of EFTA and qualify for the European Union as "third countries" where cooperation are allowed to increase the share of renewable energy used within the framework of the "European Green Deal".

Political, social, and political indicators of nations also called key performance indicators (KPIs) are published on a regular basis by several independent international organizations. A selection of ten important indicators for investments are categorized into political/social, technical/environmental and safety/security related topics for Algeria, Egypt, Morocco, and Tunisia (Table 2). The highest and the lowest scoring countries are also given as comparison. The selection was chosen in accordance to Brunström (2021)[17]. More detailed KPI's are available, which may provide a better understanding of the specific situation in a country.

Table 2: Section of political/economic/social, technical/environmental and security/safety key performance indicators (KPI's) for Algeria, Egypt, Morocco, and Tunisia as well as the highest and the lowest ranking countries for comparison.
* A connection is under construction. Commission is planned for 2022.

Criteria	Algeria	Egypt	Morocco	Tunisia	Max and min ranks
Political/economic/social KPI's					
Fragile State index[52] (2020)	74.6	86.0	71.2	68.1	Most stable: Finland 16.6 Most unstable: Yemen 112.4
GDP per capital (US$) (2020)[53]	3 974	3 019	3 204	3 317	Highest: Monaco 173 688 Lowest: Burundi 239
Corruption[54] (2020)	36	33	40	44	Highest: Denmark/New Zealand 88 Lowest: Somalia/South Sudan 12
Population growth (%) (2019)[55]	1.8	1.9	1.2	1.1	Highest: Bahrain 4.5 Lowest: Moldavia -1.6
Mean years of education (2019)[56]	8.7	7.6	4.8	7.1	Highest: Germany 14.1 Lowest: Burkina Faso 1.4
Technical/environmental KPI's					
Operating power connections to Europe	No	No*	Yes	No	---
Renewable energy share of electricity capacity (%) (2020)[57]	2.8	10.1	30.9	6.0	Highest: Lesotho 99.8 Lowest: Turkmenistan 0
Renewable energy usage ambitions (% of total production), (reference year)[17]	27 (2030)	42 (2035)	52 (2030)	30 (2030)	---
Security/safety KPI's					
Global terrorism index (2020)[58]	2.696	6.419	0.565	3.858	Highest: Afghanistan 9.529 Lowest: e.g., Iceland 0.000
International sanctions (2022)[59]	No	No	No	No	Highest: Democratic People's Republic of North Korea

In the political, economic and social sector, the KPI's for the fragility of the state, GDP per capita, corruption and populations growth show no great difference between the four countries investigated. An exception to this is the level of education in which Morocco is significantly lagging behind.

The four countries have high ambitions for the further development of their existing renewable energy sector. Algeria wants to increase its share of renewable energy usage tenfold within the next 10 years. Morocco starts with a high base level and plans to double its share during the next decade. Although from a high base level. Since most of the new capacity will be used to satisfy growing national demands, only small surplus production may be used for supplying the European market. This small production for export would match the currently very limited capacities for power transport to Europe.

No international sanctions are imposed against any of the investigated countries. Internal security in Morocco is e.g., considered to be 12 times better than in Egypt. Morocco is within the best 10 % of all investigated countries in this category while Egypt is part of the last 50 %. The discussed countries are members of NATO's Mediterranean Dialogue partners[39]. With respect to all the criteria discussed, Morocco seems to be best suited for a renewable energy cooperation with the EU and is discussed in detail in the following chapters.

Financing - a selection of possible business models

Financing large infrastructure projects is a major task with many obstacles to overcome, especially when different legal systems and cultures have to be considered. The choice of the appropriate business model depends on the partners involved (Table 3). Big infrastructure projects are often laden with prestige and scrutiny and in many cases either do not survive the concept and planning phase like the Desertec Industrial Initiative[12] or were not successfully implemented like the container terminal in Mombasa (Kenia)[60].

The electricity import-export business encompasses at least three parties: the producer/supplier (exporter), the procurer (importer), and the grid operators in several countries. The producing site may consist of two companies, one that owns the facilities and one that runs them. The procurer - with a registered office in the EU - generally is one entity, which, for a sustainable, long-term business model, needs local European customers and purchasing guarantees. These may be industrial customers, public power suppliers, or - in very rare cases - the procurer itself, e.g., a chemical or steel producing company. Without long-term contracts, which cover most of the procured electricity, any business model will fail. The power grid operation is a necessary service, often overlooked. The existence of the power grid connections (i.e., transmission lines) is a precondition for the viability of the enterprise. The grid operating companies will not expand transmission capacities or build new lines without guarantees from the supplier and the procurer.

The contracting parties may be private sector companies, governmental backed companies, or governmental entities. In the case of foreign direct investment, all partners are private sector companies. In the case of private electricity procurement contracts, the procurer is a private sector company while the supplier side may involve governmental or private sector companies. Interstate treaties only involve governmental agencies. In the case of import/export of electricity between Morocco and the EU, interstate treaties are very unlikely, as both countries have private sector economies.

Table 3: Selection of possible contract designs for the electricity delivery contract between the electricity supplier e.g., Morocco and the electricity procurer e.g., an EU member state.

Contracting Partners		
Electricity supplier North Africa		**Electricity procurer EU**
Investment	**Operation**	**Distributer**
Foreign (European) direct investment		
Private sector company	Private sector company	Private sector company
Private electricity procurement contract		
Government	Government	Private sector company
Governmental backed company	Governmental backed company	Private sector company
Private sector company	Private sector company	Private sector company
Interstate treaty		
Government	Government	Government

SWOT-analyses (Strength-Weakness-Opportunity-Threat-Analysis) for the various business models depends on the specific point of view of the involved partners. Once partners advantage may be the others disadvantage and perceived advantages can turn rapidly into disadvantages by changes in the political or economic environment e.g., a global health crisis like COVID-19, conflicts like the Russian invasion of the Ukraine or political and military unrest.

Depending on the bargaining power and the preferences of the contracting parties, the agreed common understanding may shift. Preferences of the involved parties may exclude each other e.g., high selling prices for the north African producer contradict low procuring prices of the EU buyer. A selection of long-term political decision preferences is listed in Table 4.

Table 4: Selection of best interest long-term preference of the contracting partner.

North African state	Producers within North African state	Procurer within the EU	European Union
- New income source (foreign exchange) - Social and economic development - Environmental protection of construction sites - Creation of a skilled workforce	- Selling at high prices - Secure investment - High profits - Long term contracts	- Procuring at low prices - Secure investment - High profits - Long term contracts	- Low electricit prices with the EU - Energy security - Diversified power supply mix - Reaching climate goals

Companies

Control over business affairs: State control is decreasing in the following order: governmental entity > governmental backed company > private sector company.

Distribution of profits in the case of foreign direct investment: Hosting country or EU country.

Financing: Private or public funds, local or international banks e.g., Islamic Banking rules.

Stability of contracting partners: Risk of business (insolvency) or state failure (examples are the financial crisis in 2008/2009 or the Arab Spring 2010/11)

Technology transfer: Training and education or intellectual property theft

Pricing policy: Fixed prices, flexible prices depending on demand or prices fixed to another commodity e.g., oil.

Supplier (state level) – Morocco

Domestic policy: Rivalry with other public projects e.g., building hospitals, increasing GDP etc.

Cultural influence: Western influences to be maximized or minimized.

Distribution of local resources: Development or exploiting of local resources and communities.

Distribution of profits: Local communities or distant elites.

Procurer (state level) – EU member state.

Security issues: Decreasing migration pressure into the EU due to economic opportunities and retaining skilled people in the North African country.

Skilled personnel: Efforts on long-term education of the local population for building and running the plant or importing of skill workers from the EU.

The multiple levels of expectations to be managed requires sophistication and clear goals. The lack of commitment and changing environments can easily lead to failure.

History of CSP - cooperation and competition between Morocco and Spain

In 2016, Spain had the highest operational capacity for producing electricity from CSP on a global scale. The existing 50 plants with a capacity of 2.3 GW were commissioned between 2008 and 2012 with huge subsidies from the Spanish government. TES were included in approximately one third of the plants and can store up to 9 hours of full power generator capacity. In 2012, the governmental subsidy scheme (feed-in renumeration) was stopped due to the high costs for managing the financial crisis of 2008/2009 which nearly resulted in state bankruptcy. Since then, no more CSP plants were commissioned. During the more than 10 years of service time, the power supply has proved very stable due to constant improvements and maintenance. In 2019 CSP and PV plants covered 8 % of the total Spanish power consumption[12; 61]

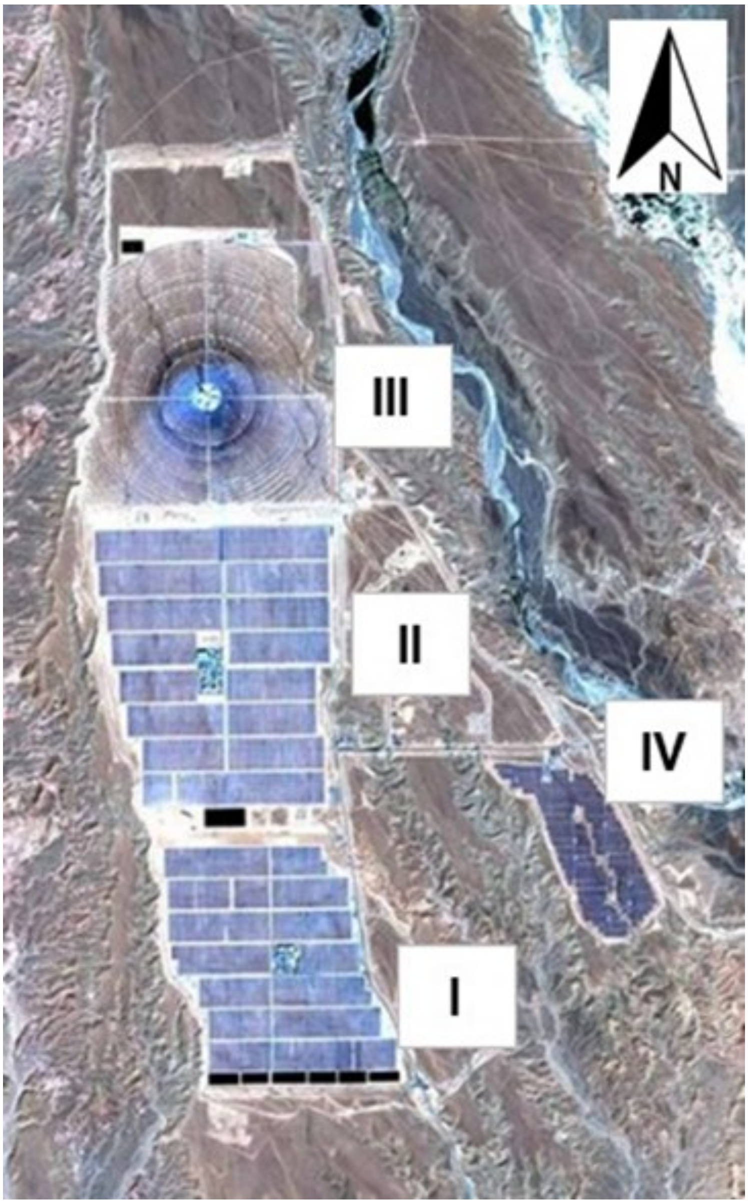
In 2020, Morocco was producing approx. 8 % (20 TWh) of its power production with renewable sources (wind, solar and hydro). Many of the plants where build on sites already identified by Moroccan scientists involved in the Desertec foundation[12]. The share of hydropower was 3 TWh in 2020 but is fluctuating highly on a yearly basis depending on the rainfall in the region. The electricity produced by windfarms was constantly rising since 2010 reaching now 13 TWh due to new installments[62]. The largest wind park in North Africa is located in Tarfaya in the south of the country where 131 turbines with an installed capacity of 301 MW do cover an area of 8 900 ha[63].

By 2016 Morocco was producing more power from CSP than the combined rest of the Middle East and North Africa region (MENA)[64]. Most important for this production is the Noor solar plant complex ("noor" in Arabic means light) near the ancient town of Quarzazate (Figure 7). It contains state-of-the art parabolic through (Noor I and II) and power tower (Noor III) technology with integrated

TES for up to 7 h. Noor IV is a PV plant (Table 5). The plants were established in cooperation with Spanish partners. The complex is situated in proximity of a water reservoir, as the water demand for cooling the power generators and cleaning of the mirrors is considerable. Electricity is sold for 19 US$-ct per kWh, which is more expensive than LCOE from fossil and nuclear plants (Figure 6)[46, 49, 65].

Table 5: Technical details of the Noor Solar complex near Quarzazate (Morocco). See also Figure 7. TES = Thermal energy storage.[65]

Plant	Technology	Commission	Area [ha]	Capacity [MW]	Energy [GWh]	TES [h]
Noor I	Parabolic through	2016	450	160	370	3
Noor II	Parabolic through	2018	680	200	600	7
Noor III	Power Tower	2018	530	150	500	7
Noor IV	PV	Not yet		72		--



Morocco built the Noor complex (Figure 7) with the support of funds for clean energy research and development and renewable energy production[66]. Simultaneously, Morocco achieved in 2015 the complete electrification of all its households, up from 48 % in 1990[67] and thus has reached the UN's Sustainable Development Goal 7 of "Affordable and clean energy" well bevor the target year of 2030[68]. All these efforts were in line with Morocco's own pledges and targets to the *Paris Agreement* from 2019[69]. Morocco therefore is a poster child for sustainable development within the 1.5 °C *Paris Agreement* temperature goal although 73 % of its total power production comes from fossil fuels[61].

Figure 7: Aerial photo of the Noor I – IV CSP-TES and PV complex including the fresh water source near Quarzazate (Morocco). The CSP-TES plants covers approx. 1,660 ha.[65] For details see Table 5.

The Noor solar plants are operated by Masen, the Moroccan Agency for Sustainable Energy, which is a governmental backed company[70]. The Noor plants were financed – among others - by the World Bank, the European Investment Bank, the French Development Bank (Agence Française de Développement), the German Kreditanstalt für Wiederaufbau with a mandate from the government and the Clean Technology Fund of the African Development Bank Group (French: Groupe de la Banque africaine de développement)[65].

In the aftermath of the global financial crisis of 2008/09 the idea of producing power in Morocco for the European market came to a hold and was finally blocked by Spain. Spain's economy shrunk substantially and state revenues as well as electricity demand were reduced. Homegrown renewable power production exceeded the demand and the thought of importing cheap power from Morocco was politically not sustainable. The transfer of the power to France was not possible in the short term because of missing high voltage power lines.[12; 71; 72]

Roadmap for a future energy cooperation between Morocco and the EU

When proposing a roadmap for a future energy cooperation between Morocco and the European Union, the experiences of the past do offer valuable information for future actions. The major lesson should be that technical feasibility does not automatically result in social acceptance[12]. Therefore, political issues on the inter- and supra-state level should be dealt with from the very beginning of a future project. Also, some of the below mentioned tasks should be dealt with in parallel rather than in sequence.

Consensus of the value of controllable electricity production in the EU
Electricity plants with uncontrollable power output like PV and wind plants have been subsidised in many countries. These measures led to an increase in production, a decrease in costs (Figure 6). However, this causes overshoot peaks of electricity in the power grid when the sun is shining, and the wind is blowing (Figure 3). Either when the grid is at full capacity these plants have to shut down or the controllable power plants (e.g., nuclear and fossil fuel power plants) have to reduce their output.

As coal, lignite and in some countries nuclear power plants are decommissioned, controllable renewable power plants like CSP-TES are needed. PV has come out as a niche product during the past 10 years. The process of establishing sufficient controllable power capacity must be pushed by respective subsidies, which renumerates the controllability within the importing country and intense cooperation with Morocco.

Consensus of routes for new power lines within the EU

Large-scale electricity transport from Morocco to the EU requires additional power lines. The implementation of large infrastructure projects in Europe is difficult and agreement of the governments and the public is almost impossible without tangible benefits for the transit countries. In this article, we focus on the transit section from the coast of Morocco to the EU.

The shortest connection between Morocco and an EU member state is to Spain through the strait of Gibraltar in the Mediterranean Sea. The usage of the already existing well established pathways would reduce planning costs but requires new power lines inside Spain and a connector to France (Figure 4B). As an alternative, a deep-sea cable could be established from Morocco to Marseilles in France with a short land connection to one of the nuclear power plants on the valley of the Rhone and the usage of their grid infrastructure further on. Deep-sea cables are cheaper to build as landlines and easier and quicker to plan. On the other hand, they are more difficult to protect, as they may pass through international waters[73]. The inflicted damages on the Nord Stream pipelines in the Baltic Sea in September 2022 highlighted these threats (see below).

A consensus within the EU is of paramount importance in order to avoid any discord between the member states as well as the creation of stranded assets. As a recent negative example serves the Nord Stream 2 project. There, the Baltic states , Poland, the USA and other neighbours strongly objected the project even before the construction of the gas pipeline from Russia to Germany started[74]. The pipeline construction was finished shortly before the Russian invasion into Ukraine and since then never became operational[75]. On the 26th of September 2022 both, the Nord Stream 1 and 2 pipelines were severely damaged by yet unknown causes. The pressure maintenance methane gas leaked into the air and seawater entered the pipeline, which may permanently damage the pipes. Repairs of the pipeline may take several years.[76]

Letter of intent and treaties between Morocco and the EU

The political environment mostly defines the framework of business opportunities and possibilities. As the EU is interested in long-term power purchasing contracts, a letter of intent followed by state treaties should secure the basis of private sector actors. A similar formal agreement was recently reached for the cooperation between Germany and Morocco for the production of hydrogen from renewable electricity[77] as well as between the EU and Morocco[78]. Such legally binding agreements would secure the governmental backing of the project. Topics of interest are the share of local power consumption and power export, the share of local and foreign investment, the share of local and foreign workers, the possible zones for the power plants and lines as well as non-electricity related projects, training programs and the duration of the cooperation, to name only a few. On this, secure basis, private sector actors could start to develop their projects.

Creating business contracts

Businesses are most likely involved in the creation of the letters of intent and state treaties. Parts of the cooperation project may be covered by inviting tenders. Finding suitable business partners can be a pain-stricken process. A wide range of sometimes-contradictory issues must be considered. First and foremost a company's proven expertise should have priority and outcompete any other considerations. Nepotism may be a problem. Official or unofficial boycotts against companies located in - or with ties to – e.g., Israel may exist in Morocco. The same may be the case for Spanish companies, as Spain has irritated Morocco with a new position on the conflict in the West-Sahara[79]. European or North American based businesses partners may face allegations of neo-colonization while Moroccan companies may be involved in business links to countries boycotted by the EU or NATO.

After the "social – soft" criteria are covered, the work on the technical topics can be started. Conflicts with local communities and authorities will occur in these phases, but the general commitment of the governments involved will aid to resolve them.

Building of renewable electricity plants and power lines

After the framework is set, the technical decisions can be made purely on terms of best practice experiences and possible advanced technologies. The selection of the sites, the technologies used and the installed capacity for power plants are among the decisions to be made.

Finding suitable sites for CSP plants is not easy. In theory, already a tiny fraction of the Sahara Desert would cover the global energy demand. However, semi-arid regions and deserts consist of many different landscapes (Figure 8). Ergs (sandy deserts) pose the problem of abrasion and dust storms and Wadis can be episodically flooded. Oases are densely populated and used for agriculture. Mountain regions may be used but show problems of lateral wind obstruction and shading. Only the semi-arid shrub lands (with open vegetation cover) and the regs (regions with rocky or stony underground) are suitable for solar and wind power plants[13]. Additionally, water availability is of importance and the workers of the plant, and their families need an adequate infrastructure. A power plant of the scale of e.g. the Noor complex requires approx. 2 000 workers and their families[12].

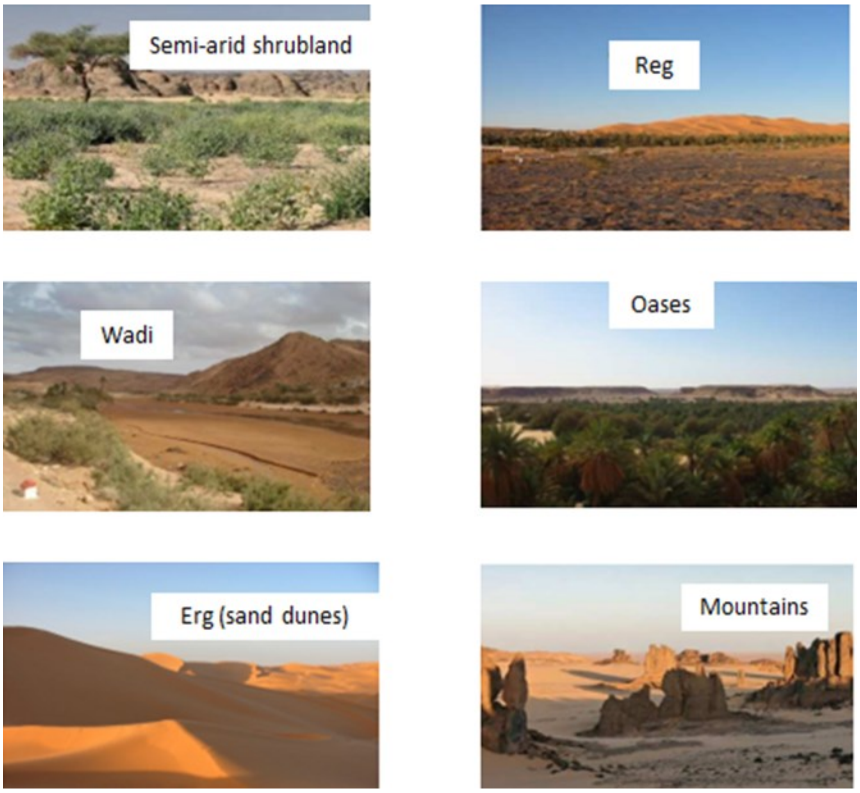


Figure 8: Typical desert landscapes. Only the landscape types of regs and semi – arid shrublands provide possible locations for CSP plants[13].
Semi-arid shrublands and regs (stone deserts) allow the construction of solar and wind plants by avoiding problems caused by potential flooding (Wadis), population and horticulture conflicts (Oases), sand blast (Erg) or solar and wind shading (Mountains).

Inauguration

After the CSP plants and power lines for long distance transmission of electricity are operational, the new network has to be connected and integrated into the European network system. This requires a substantial effort in technical coordination and international contractual agreements with respect to net stability, load distribution, emergency procedures and financial compensation. It is also challenging to show improvements and milestones to the public in order to ensure the social and political acceptance of such a project.

IV. Conclusions

Global economies depend on a steady, reliable, and affordable energy supply. Prolonged disruptions of this supply and its ripple effects lead to increases in energy prices. The immediate negative economic consequences can be seen in the wake of the current invasion of Russia into Ukraine. The reduction of gas delivery to Europe by Russia already caused economic fallouts and political disagreements in Europe. Even third-party countries in other continents are affected: reduced options of fertilizer production and delivery result in increased poverty, hunger crises and even the potential failure of whole states. In the wake of the current on-going military conflict between Russia and the Ukraine, these effects are obvious on a global scale as energy supply is used by Russia as a means of warfare against Ukrainian allies.

A diversified energy supply is of utmost importance as it may soften the shocks of disruptions of any kind[19]. As the global energy demand may rise in the coming decades and the effects of global warming becoming more obvious, GHG-poor or GHG neutral energy sources have to be developed and rolled out. Many countries, federation of states e.g. the EU and supranational entities like, NATO have committed themselves to become GHG emission free and carbon neutral in the future[5; 80]. Cooperation between countries with high untapped renewable energy potential (e.g., in the global Sun Belt for solar power or on the coastlines of higher latitude regions for wind power) and countries with a currently high fossil energy consumption are needed to reach these goals. If managed well, the direct and indirect benefits of such cooperation will reach all parts of society in the contributing countries.

Large international energy infrastructure projects are prone to political, economic, social and security related problems[12; 60]. Technical challenges are normally handled without jeopardizing the entire joint enterprise. However, even for earmarked flag ship projects operations commissioning is not guaranteed[12]. To avoid stranded assets[75] lessons learned from successful and even more important from unsuccessful endeavours should be considered during planning and implementation[75]. For all these reasons existing political, economic, and infrastructural ties as well as cultural similarities should be used to increase the chances of achieving the goals (e.g., in the H_2Altlas Africa initiative[81]). Supply chains should be as short as possible to reduce cost and possible disruptions.

For the EU with its high-energy demand, a closer cooperation in the renewable energy sector with North African countries appears to be inevitable. Especially Morocco seems to be a promising and reliable partner as the basic conditions for renewable energy production and power transmission are present. Power lines between Morocco and Spain already exist, and Morocco is already part of the Central European Synchronized Area[33]. In the future, Egypt may also become a promising partner as new submarine HVDC power lines will be connecting Egypt with mainland Greece via Crete by the end of 2023[28; 29].

Within the EU, major infrastructure projects will be necessary to transport the energy to the consumer. Additional overhead and underground HVDC power lines are needed. In most industrialized western countries such infrastructure projects usually are time consuming because of public opposition. The current war between Russia and the Ukraine and the resulting energy crunch may have changed the public opinion with respect to the urgent need of building a new, diversified, and resilient infrastructure system for electric power.

Ramping up power production and transportation from the western MENA countries to the EU will be a long-term task which requires major development projects in the producing, transporting and consuming countries. However, if successfully implemented, this will not only improve the reliability of European Energy supply but may also strengthen the economic and political ties between Europe and North Africa.

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The photo on page 1 was provided by Unsplash[82].

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