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The renewable energy targets of the Maghreb countries: Impact on electricity supply and conventional power markets

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ABSTRACT

Morocco, Algeria and Tunisia, the three countries of the North African Maghreb region, are showing increased efforts to integrate renewable electricity into their power markets. Like many other countries, they have pronounced renewable energy targets, defining future shares of "green" electricity in their national generation mixes. The individual national targets are relatively varied, reflecting the different availability of renewable resources in each country, but also the different political ambitions for renewable electricity in the Maghreb states. Open questions remain regarding the targets' economic impact on the power markets. Our article addresses this issue by applying a linear electricity market optimization model to the North African countries. Assuming a competitive, regional electricity market in the Maghreb, the model minimizes dispatch and investment costs and simulates the impact of the renewable energy targets on the conventional generation system until 2025. Special emphasis is put on investment decisions and overall system costs.

1. Introduction

The North African electricity markets are in a phase of rapid transformation. Soaring electricity demand, caused by economic growth, demographic changes and progressing urbanization, urges the countries in the region to massively increase their power generation capacity and upgrade their electric grids. However, electric infrastructure projects still face strong barriers due to inflexible electricity market structures prevailing in most of the North African countries. Mainly unliberalized, non-competitive and dominated by cumbersome state monopolies, they often encounter difficulties when seeking project financing at the needed scale. Over the past years a consensus has emerged among the countries that more competitive market rules need to be applied. Moreover, integration and harmonization of the different national electricity markets has been placed on the agenda. Particularly progressive signs show the Maghreb states Morocco, Algeria and Tunisia.[1] In 2003 they signed a protocol for the stepwise integration of their power markets with the long-term objective of a common electricity market with the European Union. Already today, the three Maghreb countries are electrically interconnected with each other and are likewise synchronized with the European electricity network via an undersea interlink between Morocco and Spain. Further projects for transmediterranean interconnections, as well as ongoing construction of new interconnectors between the Maghreb countries indicates that an integrated electricity market might become a realistic scenario in the future.

As an additional aspect, renewable energies have entered the discussions. The high natural potential for wind and solar energy has recently fueled a massive interest for RES-E (Electricity from Renewable Energy Sources) technologies in North Africa (DLR, 2006). Renewable electricity export scenarios, promoted by the industrial initiative Desertec (2010) or the Mediterranean Solar Plan (MSP, 2010) have become prominent in Europe, but it is less known that the North African countries themselves have set up their own goals to integrate RES-E technologies into their national electricity supply schemes. In particular, Morocco, Algeria and Tunisia, seem to give RES-E technologies a very active role in electricity supply, as announcements of relatively well-defined national renewable electricity goals show.

The aim of the present study is to analyze the potential impacts of these goals on a regional electricity market formed by the three Maghreb countries and adjacent EU countries. The time horizon of the analysis is 2025. It should be stressed that this short-term analysis only covers the actual planning perspective of the North African countries—large-scale renewable export projects via High-voltage direct current (HVDC) lines from North Africa to Europe are not considered. The work addresses the following main questions: (1) How do the current national RES-E goals influence the electricity mix and the conventional power plant structure in the Maghreb countries? (2) How large are the financial advantages of

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[1] In the literature, the term Maghreb is in some cases viewed in a wider sense and also includes Libya and Mauritania. In this article we use the narrow definition of Maghreb, meaning the countries Morocco, Algeria and Tunisia.

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Maghreb RES-E goals with regard to lower fuel costs or avoided investments in conventional power plants?

The article is structured in three parts. We start with an overview of the currently ongoing transformations in the Maghreb electricity markets and describe each country's renewable electricity goals. From these findings we derive two scenarios for 2025. The subsequent part provides a description of the model, the assumptions and the input parameters used. In the third part, the model results are outlined, analyzed and discussed.

2. Background and scenarios

We limit our study to Morocco, Algeria and Tunisia for three main reasons (1) Contrary to their neighbors Libya and Mauritania, these three states show relatively advanced policies with regard to liberalization of their electricity markets. (2) The three countries have expressed intentions to form a Maghreb-integrated electricity market, which is intended to be harmonized with the European electricity system in the future. (3) Additionally, as mentioned above, all three countries strive for integrating RES-E capacity to their current fossil-dominated electricity generation systems. In this section we will describe these observations in more detail and draft two scenarios for our subsequent model analysis.

2.1. Electricity market reforms in the Maghreb countries

Algeria's reform objectives of bringing its market closer in line with international standards are built around an electricity law enacted in 2002 (Algerian Electricity Law, 2002). As a direct consequence of the law, the state electricity and gas monopolist Sonelgaz was forced to unbundle its activities, and an independent regulatory body was established. In the years following Algeria's electricity reform, several projects of independent power producers (IPP) – some even with international equity participation – emerged in the country. Tunisia's electricity sector also underwent a liberalization process concerning the market segment of electricity generation. In 1996 the monopoly of power production was withdrawn from the state-owned gas and power utility Société Tunisienne de l'Electricité et du Gaz (STEG), which subsequently resulted in private IPP companies competing in tenders for generation licenses issued by the Tunisian state (CAIMED, 2006). In Morocco, the opening of the electricity market started even earlier, in 1994, when a decree opened up the possibility for private IPPs to act as concessionaires for the national electricity utility Office National d'Electricité (ONE). A further liberalization step came in 2008 when IPPs were given a more general right to access the Moroccan electricity generation market, particularly if they operate smaller power plants with capacities of up to 50 MW. Another step towards more liberalization is a planned split of the Moroccan electricity market into one regulated segment and one open market segment, where certain industrial customers are allowed to freely choose their electricity suppliers (MEMEE, 2008; GTZ, 2009).

Despite these examples of reform efforts, it should be stated that the Maghreb states still have far to go in order to achieve a fully liberalized electricity markets. As of now, the 'market' operations are still almost exclusively performed by the aforementioned, omnipresent state utilities that hold monopsonies on electricity purchase while acting as (quasi-) monopolists in terms of electricity transmission and distribution. Formal trading platforms, where competing generation companies offer their electricity to independent retailers, are in the planning stages, but do not yet exist in any of the three Maghreb states. There is nevertheless evidence that the countries are on a clear pathway towards a competitive electricity market and that this trend will continue and even accelerate in the coming years.

2.2. Goals for transnational market integration

The aforementioned belief in a future common electricity market is also sustained by the Maghreb states' efforts to merge their different national electricity systems into a larger, regional market. The political will for this target was expressed by the governments of the Arab Maghreb Union,[2] which in 1989 created the Maghreb electricity committee Comité Maghrebin de l'Electricité (COMELEC). Besides the realization of a common internal electricity market, COMELEC envisages, as a long-term goal, a gradual integration and regulatory harmonization with the European electricity market (Chouireb, 2008). Particularly COMELEC members Morocco, Algeria and Tunisia have subscribed to this idea already technically interconnected with the European Network of Transmission System Operators for Electricity (ENTSO-E) since 1997, they signed in 2003 an official declaration with the European Commission to further support the integration of their electricity markets into those of the European Union (Athens Declaration, 2003; Eurelectric, 2003). There is strong evidence that this kind of market integration is actually desired by the Maghreb states—since 2001, for instance, the public electric utilities ONE (Morocco) and Sonelgaz (Algeria) have acted as licensed traders on the Spanish electricity exchange platform Operador del Mercado Ibérico de Energía (OMEL).

2.3. Renewable energy targets

Over the past years, as in other regions of the world, wind and solar energy has received significant attention in North Africa. As hydropower faces stagnating expansion potential in the region due to geographical limitations, the governments are increasingly considering wind and solar technologies as the future RES-E technologies for their countries. However, a look at the currently-installed RES-E capacities in Morocco, Algeria and Tunisia, reveals that the actual contribution of these sources of energy is still very low: compared with the overall installed electricity capacity of 16 GW, wind power, with a mere 304 MW cumulated in the Maghreb states by the end of 2009, is at the moment is the only noteworthy new RES-E source (GWEC, 2010). The only solar electricity facilities worth mentioning are two concentrating solar thermal plants are currently under construction in Morocco and Algeria. Once finalized, they will contribute to approximately 50 MW of the Maghreb states' generation capacity. Grid-connected photovoltaic (PV) electricity is at the moment negligible in all countries in the region. Against the background of these relatively moderate achievements, the recent, hereafter listed national renewable development goals of Morocco, Algeria and Tunisia sound relatively ambitious.

2.3.1. Morocco's renewable electricity goals

Morocco's goals target a strong increase in the number of both wind and solar power plants. In a detailed wind electricity development program (ONE, 2008a), the national electricity utility, ONE, intends to increase the installed capacity from the current 253 MW up to 2 GW until 2016. Most of the projects will be located alongside the country's Southern Atlantic coastline, which features excellent wind conditions comparable with off-shore sites in Europe (CDER, 2007). Concentrating solar power (CSP) is the second axis of the Moroccan government's RES-E development plans. In 2009, a multi-billion Euro investment program was announced, likewise targeting 2 GW CSP plants, for which

[2] Besides Algeria, Morocco and Tunisia, the Arab Maghreb Union (and thus COMELEC) also encompasses Libya and Mauritania. As of now, only Morocco, Algeria and Tunisia are electrically interconnected and exchange electricity.

precisely defined project sites already exist. The project, called the 'Moroccan Solar Plan,' will be carried out until 2020, and is promoted by a government agency being exclusively established for that purpose (Masen, 2010). For grid-connected photovoltaic (PV) electricity, a smaller program was set out by ONE in 2007 targeting 150 MW of distributed PV capacity by 2015. This program, however, has suffered from delays, making realization of the goals by 2015 seem unlikely (Hirshman, 2009).

2.3.2. Algeria's renewable electricity goals

Algeria's renewable electricity goals are set out as percentage values of overall power generation. As a short-term goal, for 2017, the Algerian electricity regulatory commission (CREG, 2008) published a 5% renewable electricity target. In the long run, by 2030, Algeria expects to reach 20% overall renewable coverage, of which 70% is generated by CSP, 20% by wind and 10% by PV (CIF, 2009).

2.3.3. Tunisia's renewable electricity goals

In 2009, the Tunisian government released a "Tunisian Solar Plan" containing several detailed renewable RES-E projects. Moreover the plan includes energy efficiency measures, solar water heating technologies and to a minor extent biomass development projects. Compared with the Moroccan and Algerian solar plans, the Tunisian Solar Plan remains relatively modest with regard to solar capacity additions—until 2016, projects in CSP and PV plants will only add up to a total capacity of 120 MW. In terms of wind capacity, around 330 MW of installed capacity are foreseen by 2016, while 1200 MW shall be reached in 2020 and 1800 MW by 2030 (ANME, 2009; Ounalli et al., 2007).

2.4. Scenarios

It is clear that the above mentioned RES-E deployment plans face strong barriers, especially if looking at the political and financial realities in most of the Maghreb countries. Resistance against the renewable energy goals can for instance be expected by those parts of the political elite, which have vested interests with the power sector or the national oil and gas industry. It should be mentioned that in the past, many publicly-announced renewable energy projects in the region have been postponed or were never realized. Therefore, doubts are justified as to whether the recent renewable energy goals will actually stand the test of time. On the other hand, the climate for funding renewable power projects in the region has noticeably improved in recent years (Masen, 2010; CIF, 2009). In addition, there is a certain competition for prestige between the North African governments with regard to renewable energies. This might accelerate the pace of RES-E penetrating the Maghreb's electricity markets. Against this background, we decided to draft two scenarios. Both consider the situation of an integrated, competitive electricity market as given—while they differentiate between two contrasting situations regarding renewable energies.

A) RES-E scenario: the Maghreb countries fulfill their renewable targets and build renewable power plants according to the published RES-E development plans.
B) Business as usual (BAU) scenario: here, the assumption is that the countries do not build any new RES-E at all and continue a conventional pathway until 2025.

It should be stressed that, apart from the different RES-E integration, all other remaining technical input parameters, e.g. the conventional power plant data, investment costs or fuel prices and assumptions, e.g. on the countries' demand growth and political strategies for the use of fossil fuels, stay unchanged for both scenarios.

3. Methodology and input parameters

Our analysis uses the linear optimization model DIME (EWI, 2010), a bottom-up power market simulation tool, which was designed by the Institute of Energy Economics at the University of Cologne to provide long-term forecasts for the European power markets. For the purposes of this study, the model was redesigned for the three North African countries of Morocco, Algeria and Tunisia. DIME calculates the optimal dispatch as well as the investment pathway of commissioning and retirements of the conventional power generation system by minimizing the total discounted costs. Simulations are conducted over representative periods, ranging from 2010 to 2025 in 5 year intervals. For every period, the optimization is carried out under the boundary condition that electricity generation meets demand at any time during the sequence of representative days and throughout all simulation periods. There are 12 representative days consisting of four different seasons (winter, spring, summer and autumn) and three days of the week (Wednesday, Saturday and Sunday).

Renewable energies are introduced exogenously in the model: in the RES-E scenario, the installed capacities follow through the pathways given by the countries' renewable electricity goals. RES-E generation has prioritized access to electricity generation. This is realized in the model by deducting the feed-in of solar and wind power from the countries' specific electricity load curves. The remaining, residual load is then covered by the daily dispatch of conventional power plants. For each of the 12 days the dispatch is computed by DIME on an hourly basis in 1 h intervals. The optimization also takes into account physical exchanges between the neighboring regions.

3.1. Model regions and interconnectors

In order to provide a complete picture and optimize the model's accuracy, we include several adjacent European countries that interact with the Maghreb electricity market (see Fig. 1). The Iberian Peninsula (Spain and Portugal) is included because it holds an already operational alternating current (AC) interlink to Morocco via the Strait of Gibraltar (ONE, 2008c). Italy will, with its ELMED line have an HVDC interconnection link from Sicily to Tunisia (ELMED, 2010). This project is already in an advanced planning stage, as are other interconnectors between Morocco and Spain and between Tunisia and Algeria. Furthermore, on a longer time horizon, two Algerian projects are being planned for interconnectors to the Spanish mainland and to Sardinia, Italy (Benabid, 2009).

The gross (thermal) transfer capacities between the Maghreb countries, as well as the trans-mediterranean interconnectors, are shown in Fig. 1. For the net transfer capacities (NTC) required by our model as input parameters, either published data is used (ENTSO-E, 2009), or NTC values are estimated at 60% of the gross transfer capacity. Power losses alongside the transmission lines are likewise taken into account. Within a model region, no power losses occur. While Spain and Italy are (or will be) directly connected to the Maghreb electricity market, France is included as a model region because it bridges the Spanish and Italian power markets. Switzerland, as an important electricity transit country, likewise takes part in the model. For all 5 European model regions, power plant data, interconnection capacity and the individual RES-E development plans have been assessed in former studies (EWI, 2010) and are introduced in our simulations.

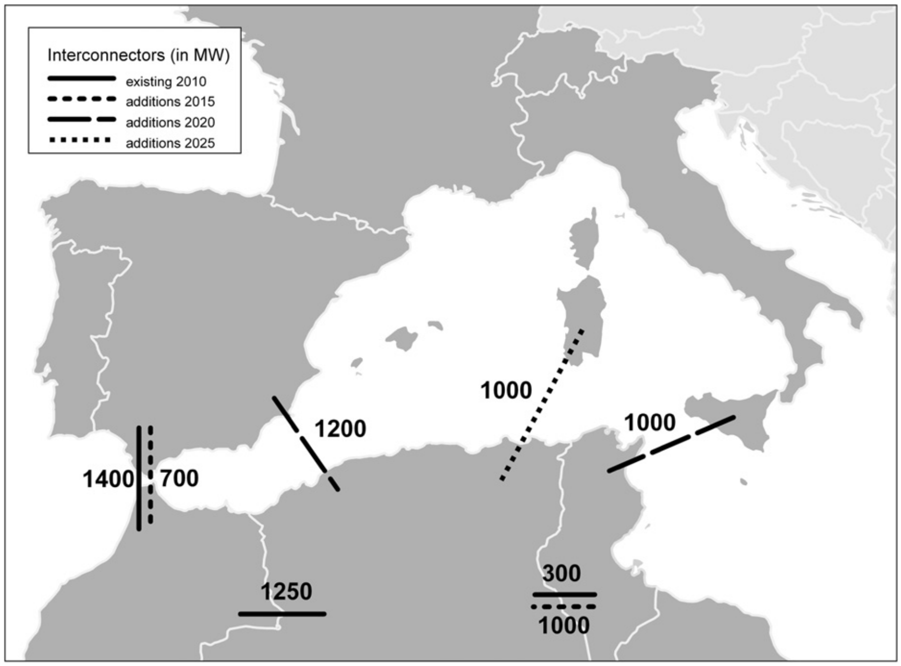

Fig. 1. Model regions and thermal transfer capacities, including expected construction pathways. Transmission lines between the European countries are not shown in this figure.

Table 1
RES-E scenario: cumulated installed generation capacity (MW) according to renewable goals and average and country-specific full load hours (FLH).

	Morocco (MW/FLH)			Algeria (MW/FLH)			Tunisia (MW/FLH)		
Year	**Wind**	**CSP**	**PV**	**Wind**	**CSP**	**PV**	**Wind**	**CSP**	**PV**
2010	250/3400	20/3300	–	50/2000	100/3500	–	19/2100	–	–
2015	1650/3400	800/3300	5/1650	525/2000	700/3500	–	175/2100	25/3300	10/1650
2020	2000/3400	2000/3300	100/1700	1100/2000	2000/3500	400/1700	1200/2100	100/3300	50/1700
2025	3000/3400	3000/3300	200/1800	2200/2000	4400/3500	1200/1800	1600/2100	200/3300	100/1800

3.2. Renewable electricity goals and model parameters

As outlined in Section 2.3, the Maghreb states consider three basic renewable technologies as future contributors for their electricity supply—wind power, CSP and PV. Hydroelectric plants only play a noteworthy role in Morocco, but due to geographically limited expansion potentials, no major capacity additions are expected. The same accounts for other potential RES-S technologies, such as geothermal and biomass electricity, which do not currently appear on the RES-E development agenda of the Maghreb states.

Table 1 summarizes how the renewable goals are translated into technical input parameters for the DIME model. Trends are extrapolated to provide a match to the type years required by the model. For Algeria, which expresses its renewable goals in percentages of overall electricity supply, we calculate the capacity values with the help of electricity demand projections (DLR, 2005) and the expected full load hours of the technology.

The full load hours in the table are estimations for typical RES-E power plants and reflect the geographical differences of the countries. Wind farms in Morocco feature higher performances than those in Algeria and Tunisia, while CSP plants in Algeria result in higher yields due to better sites with higher irradiation. The increase in PV full load hours over time reflects increases in module efficiency and the expected trend to large-scale PV plants in the future. The daily and seasonal feed-in profiles for PV plants are based on an exemplary 1 MW plant with crystalline cells on the 33° northern latitude. For the CSP feed-in, data from an exemplary 100 MW parabolic trough plant with a solar multiple of 1.5, including a thermal salt storage, is used. The intermittent character of wind is considered by implementing a random component in the feed-in profile.

3.3. Conventional power plants

3.3.1. Power plant data

The following conventional power plant technologies for the North African countries are incorporated into the model: hard coal power stations (only Morocco), liquid fuel (oil) power plants, open cycle gas turbines (OC), combined-cycle gas-fired power stations (CC), hydro-storage plants and pumped storage hydropower plants (only Morocco). Our model uses a 2007 power station inventory by the Arab Union of Producers, Transporters and Distributors of Electricity (AUPTDE, 2007) as a database of existing power plants. This database is updated by more recent power plant projects following information published in the annual reports of the Maghreb utilities. For the three countries, the model's current power plant inventory encompasses 197 power generating units by the end of 2009. According to their construction years, the power plants are classified into different vintage classes, each having its specific parameters for efficiency, fuel consumption, ramp-up behavior and operation and maintenance (O&M) costs (EWI, 2010).

Table 2
Investment costs of conventional power plants (source EWI 2010).

	Investment costs (€/kW)	Lifetime years	Net efficiency (%)
Coal before 2015	1350	40	46
Coal after 2015	1200	40	50
CC gas before 2015	550	30	58
CC gas after 2015	550	30	61
OC gas before 2015	350	25	35
OC gas after 2015	350	25	40
Oil after 2010	450	25	40

3.3.2. Cost assumptions

Fuel costs are derived from market price assumptions for Europe that were carried out in 2009 (EWI, 2010). Coal prices are estimated to be 9.9 €/MWh_{th} in 2010 and are expected to rise to 11.5 €/MWh_{th} by 2025. Gas prices start at a level of 20.1 €/MWh_{th} in 2010, reaching 26.8 €/MWh_{th} in 2025. These price levels are assumed to also be valid for the Maghreb power plants. For the gas-producing countries Algeria and Tunisia this might be bewildering at first glance, because it is well known that both countries supply their economies with cheap gas. In the logic of the model, however, it is necessary to consider the opportunity costs, as the countries could, in principle, sell their gas to Europe instead of using it in their own power plants.[3] CO_2 costs are fixed and set exogenously, and they amount to 15€ in 2010, and increase by 5€ steps every 5 years. For reasons of fair competition on a common electricity market, an equal CO_2 price is assumed over all model regions.

The investment costs input parameters are based on an analysis of recently completed plants, as well as costs of future power plant projects (EWI, 2010). The investment costs of conventional power plants are considered identical for all countries, and held constant until 2015. Afterwards, conventional power plant investment costs are expected to decrease, as Table 2 indicates.

3.3.3. Capacity additions and decommissionings

The model endogenously incorporates investment decisions concerning the commissioning of power plants and their retirement over the different representative periods. To better reflect the actual situation in the North African energy markets, several considerations, primarily political, are implemented in the model. Tunisia and Algeria, for example, have prioritized the use of natural gas as a domestic energy resource, while Morocco pursues a more diversified approach, which includes the use of imported coal in its conventional power mix. A restriction is made with regard to nuclear energy—although the nuclear option for North Africa is an increasingly discussed topic, it is unlikely that first plants will come online before 2030 (Prognos, 2009). Therefore, nuclear capacity additions are not considered in the model setup.

3.4. Demand

For each country, DIME requires long-term electricity demand projections, as well as daily load curves representing the countries' characteristic electricity demand fluctuations throughout representative days. With regard to long-term demand projections, particularly those beyond 2020, unfortunately no data from North African sources are available in the literature or databases. Therefore, our model input reverts to a scenario outlined by the German Aerospace Center (DLR) in its MED-CSP study (DLR, 2005). DLR's demand forecast for Morocco, Algeria and Tunisia is based on historical electricity demand data, as well as on assumptions for population growth and future growth of GDP. With annual rates of 7–8% per year, the DLR scenario leads, as shown in Fig. 2, left, to rather high, but not unrealistic, demand increases. In fact, historic electricity demand data shows that, over the past years, demand increases in all the three Maghreb states has been consistently above 5% per year (ONE, 2008b; STEG, 2009; CREG, 2006).

Daily load profiles (see example of a summer day in Fig. 2, right) are retrieved from online databases and annual reports of the Maghreb national utilities or regulatory authorities. The load curves in North Africa show a relatively similar pattern with two characteristic maxima—one relatively broad-spread maximum at midday and a second, more distinct peak later in the evening hours. Extreme peak events usually occur either on hot summer days at the midday peak, due to extensive use of air conditioning, or at the evening peak in winter, due to electric heating. For simplicity, it is assumed that this typical shape of the load curves is not changing over the time periods covered by our simulation.

4. Results

4.1. Impact on the electricity mix

The first aspect the model examines is the change in the Maghreb's electricity mix over time and between the two scenarios. This is illustrated in Fig. 3. As a general finding, it can be seen that in both scenarios, the total electricity generation of the three Maghreb countries almost triples over the next 15 years—an obvious reaction to the anticipated massive power demand increase that the region faces in the coming years.

Rising demand for electricity is also responsible for the observation that the RES-E goals, although ambitious from today's perspective, will in the future be superposed by the still much higher need for fossil fuel generation from gas and coal plants. Nevertheless, if comparing the generation shares in the RES-E scenario with the BAU scenario, it can be seen that fossil generation cedes noticeable parts of its production to solar and wind electricity generation—if all three countries reach their respective renewable electricity targets, wind and solar electricity will replace approximately 20% of fossil fuel generation by 2025.

Table 3, which shows the detailed generation percentage differences between the two scenarios, allows a more thorough analysis of how RES-E generation replaces conventional generation in the RES-E scenario: (1) in Morocco, coal generation gives shares to wind and, to a minor extent, solar generation; (2) in Algeria, gas-generated electricity is partially replaced by solar and, to a minor extent, wind generation; (3) in Tunisia, gas-generated electricity cedes generation shares to wind and, to a minor extent, solar electricity.

As shown in Fig. 3, the model also computes power exchanges between the North African countries and Europe. It can be seen that the Maghreb region remains in both scenarios a net importer of electricity. This result can be explained by exports from Spain, which incorporates nuclear power plants in its generation portfolio and is, according to our market model, able to provide a cheaper generation cost structure than the North African countries. Major differences between the RES-E and BAU scenarios with regard to the total exchanged amounts of electricity were not observed.

4.2. Impact on the power plant system

The interesting parameters for an analysis of the generation system are the installed capacities (see Fig. 4), as well as the full load hours. The latter reflect the intensity of utilization of the technology. As in the previous section, we compare the modeled

[3] Avoided transport costs for gas are nevertheless taken into account, as they reduce the opportunity cost of gas in the North African countries.

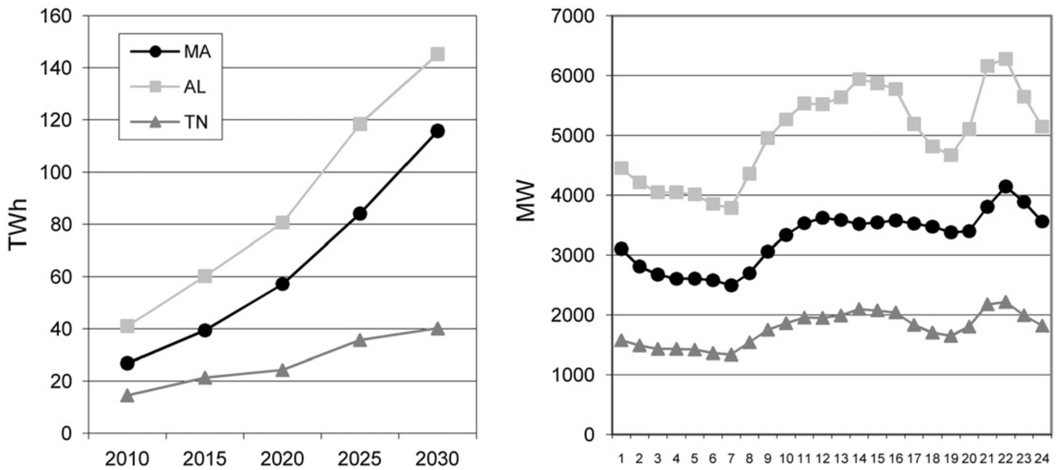

Fig. 2. Annual electricity demand growth of the Maghreb countries (left) and their daily electricity demand pattern (right) for a Wednesday in summer 2010.

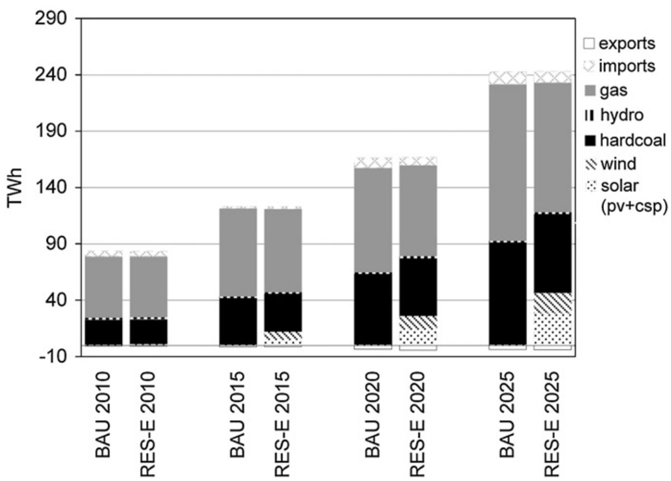

Fig. 3. Cumulated electricity generation of all three Maghreb countries (Algeria, Morocco and Tunisia) by technology in the BAU and the RES-E scenario.

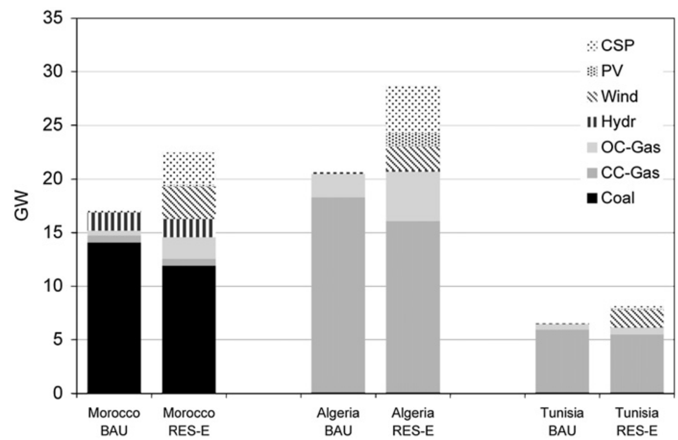

Fig. 4. Installed capacities (in GW) for the RES-E scenario and the business as usual (BAU) scenario for the year 2025.

Table 3
Renewable and fossil generation shares for Algeria, Morocco and Tunisia and for the three countries (NA-3) in the RES-E and the BAU scenario.

	Morocco 2025		Algeria 2025		Tunisia 2025		NA-3 2025	
	BAU	RES-E	BAU	RES-E	BAU	RES-E	BAU	RES-E
PV (%)	0.0	0.4	0.0	2.0	0.0	0.5	0.0	1.2
CSP (%)	0.0	10.7	0.0	14.3	0.0	2.0	0.0	11.1
Wind (%)	0.9	11.0	0.0	4.1	0.0	10.3	0.4	7.7
Hard coal (%)	97.5	75.7	0.0	0.0	0.0	0.0	39.0	30.0
Liquid fuels (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydro (%)	1.2	1.3	0.1	0.1	0.3	0.3	0.6	0.6
Gas (%)	0.4	0.9	99.9	79.5	99.7	86.9	60.0	49.4

capacities of the RES-E scenario with those resulting from the BAU scenario for the year 2025.

For conventional power plants, the realization of renewable goals has the following consequences:

a) In Morocco, the RES-E scenario leads to a significantly reduced need for coal plant capacity. Around 2.2 GW (18%) less coal power stations need to be installed. The utilization of coal plants also decreases—while in the BAU scenario, they run at 6400 full load hours, this number drops to 5900 under RES-E penetration. Alternatively, Morocco's demand for gas-driven electricity plants increases from approximately 1.1 GW in the baseline scenario to 2.7 GW in the RES-E scenario. This is almost entirely due to open cycle (OC) gas turbines. Although they operate only scarcely (our simulations partially show full load hours of below 100 h), their spinning reserve is needed to cover potential peak demand in times of very low renewable feed-in. Combined cycle (CC) gas power plants are not added under the competitive market environment of the model. Existing CC plants, which have been built before 2010 still remain online, but their utilization decreases over the years. In 2025 they only run 800 full load hours in the RES-E scenario and 500 full load hours in the BAU case.
b) Algeria and Tunisia show a different pattern. Here, in the absence of other base-load technologies, CC gas power stations can be considered to be providers of base-load capacity. In both countries, the increased penetration of renewables leads to a reduction in installed CC gas capacity of 14% in Algeria and 8% in Tunisia with its lower RES-E penetration. Likewise, the average utilization of CC gas plants decreases from 5700 to 5300 full load hours in Algeria and from 5600 to 5200 in Tunisia. In both countries, a significant increase in the OC gas power plant population is required to maintain peak reserve capacity; in Tunisia, OC gas capacity must be increased by more than 20%, while in Algeria, the RES-E scenario requires a doubling of the OC gas capacity.

From this it can be concluded that a high penetration of renewable generation capacity entails a significantly reduced need for new base-load coal plants in Morocco. Tunisia and Algeria, which currently have no coal power strategy on their short-term political agenda, show a reduced need for the addition of CC gas power plants. All three countries face a significant increase in OC gas capacity, which is the most cost-efficient solution for peak load coverage.

4.3. *Impact on power plant dispatch*

DIME allows the output of daily dispatching profiles for every reference day for each country. In order to illustrate the behavior of the power plant dispatch, the cases of Algeria and Morocco – exemplarily on summer week-days for the years 2010 and 2025—are compared (see Fig. 5). Besides showing the RES-E penetration, the figures also illustrate the enormous challenges which the Maghreb countries will likely face under the aspect of increasing capacity to meet projected demand within only a 15 year time period.

In the Algerian case, it can be clearly seen how the renewable feed-in, mostly provided by solar power plants, comes into generation during daytime (there is an extension of solar generation into the evening hours, which is related to the use of thermal storage of the CSP plants). Conventional gas power plants (CC and OC are aggregated) react to the RES-E feed-in and cover the largest portion of the residual load. The small, constant band of imported electricity, visible on top of the domestic generation, completes Algeria's dispatch. A closer look reveals that these imports originate from Morocco, which, due to its coal-dominated power generation system, has cost advantages allowing electricity sales to Algeria. Morocco's exports to Algeria can also be identified in Fig. 6 as a 'negative' generation band on the bottom of the dispatch curve.

Morocco's dispatch pattern on a week-day in summer 2025 shows that, besides solar generation, an important amount of wind power also pushes into the daily generation of electricity. The residual load is mainly covered not only by coal power stations, but also by imports from Spain and the dispatch of hydro and gas plants. The example shows that during the evening load peak, especially when it coincides with a low wind feed-in, Morocco must launch gas and hydro plant generation and allow imports, in this case from Spain. A conclusion which can be drawn is that CSP plants with a higher storage capacity might be more advantageous for the Moroccan power system, as they would further extend solar production into the evening hours and consequently reduce the need for electricity imports and the costly dispatch of gas plants. A quantitative analysis of whether the related cost savings justify the investments in CSP plants with a higher storage capacity is currently under way.

4.4. *Impact on system costs*

In this section, we attempt to quantify the extent to which the integration of renewable energies lead to costs savings inside the conventional power generation systems of the Maghreb states. These savings will then be mirrored against the investment and operation costs of the RES-E plants, which the national economies must bear if the renewable electricity goals are to be achieved. In order to provide an accurate comparison, all considered costs are annualized and aggregated to a discounted net value in 2010 ($€^{2010}$).

The first value, the savings of the conventional power system, can be derived from the output results of the DIME simulations. Here, the differences between the BAU and RES-E scenarios regarding investment costs, O&M costs, fuel costs and other variable costs come into calculation. The second value, the aggregated RES-E system costs, is calculated separately on the basis of the renewable capacity installation pathway outlined in Table 1 and under consideration of technology-specific cost assumptions, which are summarized below in Table 4. The calculation of the annualized and aggregated costs is carried out by using a 25-year depreciation period for all renewable technologies at a real discount rate of 5%. It is worth to mention that the cost input parameters do not include risk primes or safety and security expenses related to the risk of political instability and terrorism. In particular, RES-E infrastructure in the desert regions of Algeria can be considered vulnerable with regard to terrorist attacks. A monetary assessment of this issue, however, cannot be given at the moment.

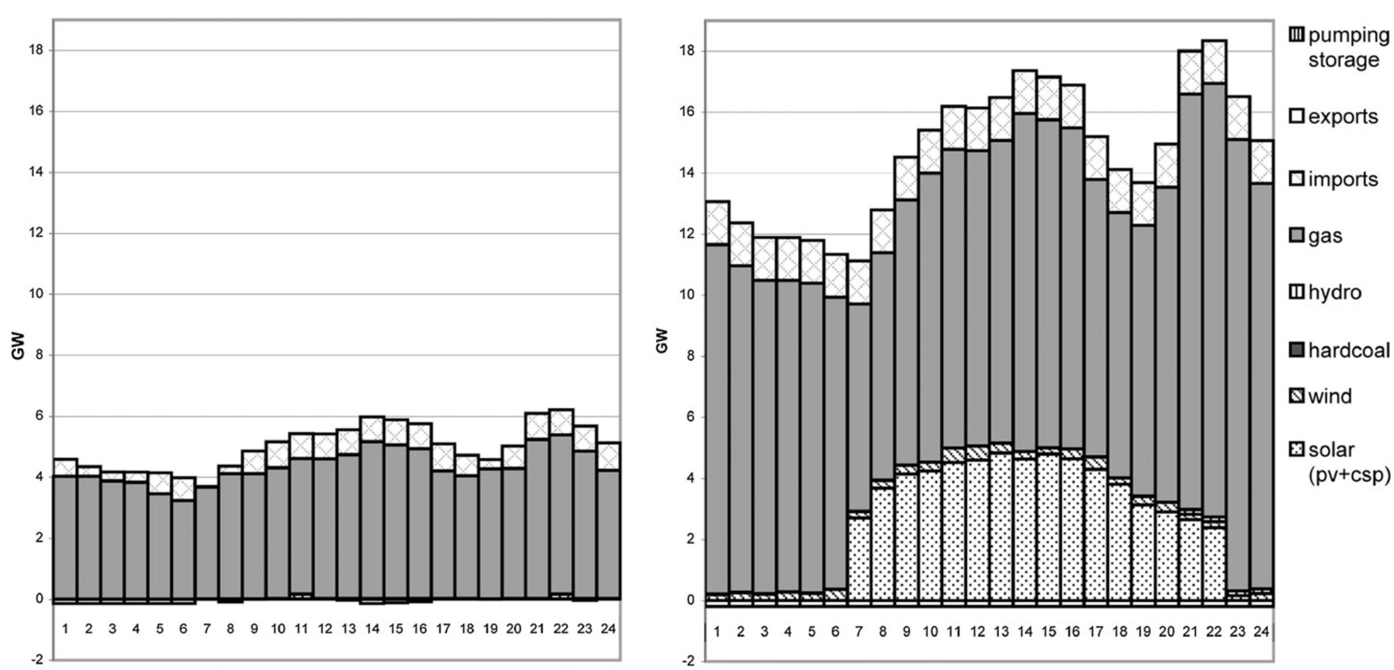

Fig. 5. Dispatch in Algeria 2010 (left) and 2025 (right) on a Wednesday in summer for the RES-E scenario.

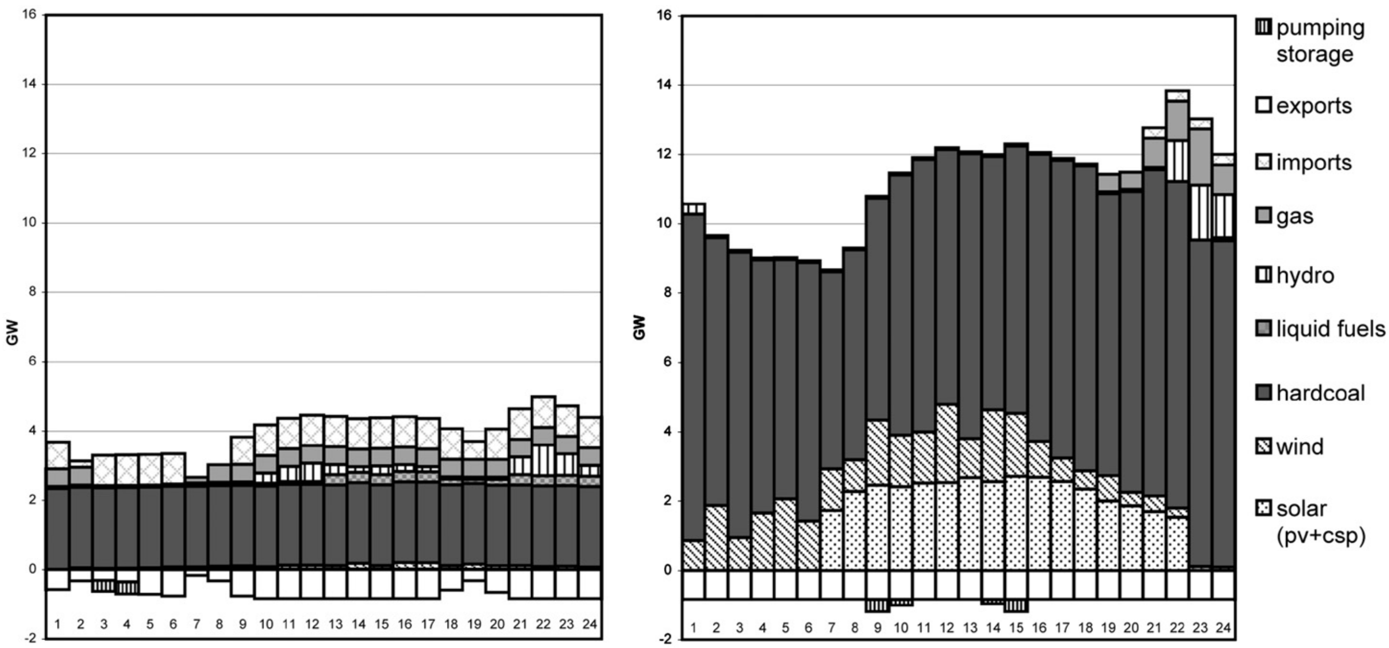

Fig. 6. Dispatch Morocco 2010 (left) and 2025 (right) on a Wednesday in summer for the RES-E scenario.

Table 4
Cost input parameters for RES-E technologies.

	2010	2015	2020	2025	O&M costs (% of inv. cost)
CSP (SM 1.5)	4500	4000	3300	3200	2.3
Wind	1050	900	850	825	5.0
PV	3000	2300	1900	1300	1.0

Table 5
Net present value of the aggregated costs until 2025.

Discounted costs (€^{2010} million)	Morocco	Algeria	Tunisia
CSP	5640	6670	290
Wind	1780	950	690
PV	110	540	60
Total costs RES-E system (I)	7530	8160	1040
Total savings conventional system (II)	1260	1230	280
Net costs to fulfill renewable targets (I-II)	6270	6930	750
RES-E system-efficiency (II/I)	0.17	0.15	0.27

The result of the cost calculations is presented in Table 5. As expected, the realization of the renewable targets leads to substantial additional costs for all three countries (I). Until 2025, Morocco and Algeria have encountered total aggregated RES-E system costs of approximately € 7.5 billion and € 8.2 billion, respectively, whereas Tunisia spent only € 1.0 billion for the aggregated RES-E investments and O&M costs. In all countries, the higher costs related to the setup of the RES-E system (I) are partially compensated by savings in the conventional power system (line II in Table 5). For Morocco and Algeria, these savings amount to approximately € 1.3 billion and € 1.2 billion, respectively, Tunisia realizes savings of € 0.3 billion.

A qualitative look at the origins of the RES-E induced savings reveals that the main contributors to the savings are not the avoided investments in conventional power plants, but rather the avoided fossil fuel consumption. In Algeria and Tunisia, avoided fuel costs contribute to around 90% of the total savings; in Morocco they amount to 80%. This difference between the countries can be explained by the fact that renewable plants in Tunisia and Algeria substitute electricity generated by gas, which is a relatively expensive fuel. In Morocco, where coal-fired power stations dominate the generation market, RES-E plants can only reduce the utilization of the less-costly hard coal. Therefore, fuel savings in Morocco are comparatively low.

Alternatively, renewable energies have a stronger impact on avoided investment costs in Morocco's conventional power generation system. By substituting expensive hard coal plants, more investment savings can be achieved in Morocco compared with Algeria or Tunisia, where only the additions of less capital-intensive gas facilities are avoided.

Another important parameter—particularly relevant for political decision-makers in North Africa—is the resulting net costs which must be covered by the countries in the RES-E scenario. As outlined in Table 5, these costs are the difference (I–II) between the aggregated costs for the RES-E system (I) and the resulting savings within the conventional power system (II). Until the 2025 period, these net costs amount to approximately € 6.3 billion for Morocco, € 6.9 billion for Algeria and €0.75 billion for Tunisia.

If the cost reductions of the conventional system (II) are put in comparison with the corresponding costs of the RES-E system (I), a further interesting aspect arises. The ratio between the two values (II/I) gives an indication how efficiently the countries' renewable energy targets match the conventional power system. In the RES-E scenario, the Tunisian RES-E mix substitutes for conventional electricity costs nearly twice as efficiently as the Algerian and the Moroccan RES-E mixes. For each Euro (€) spent for Tunisia's RES-E goals, a cost reduction of € 0.27 in the conventional power system can be achieved, whereas the corresponding savings in Algeria and Morocco are only € 0.15 and € 0.17, respectively. The explanation of these differences goes in line with the above-described cost effects of RES-E integration into the conventional power system: Tunisia, with its strong dominance of gas power plants, profits significantly from RES-E integration, because it substitutes for expensive gas fuel. Additionally, Tunisia takes advantage of a second effect—its high wind share compared to CSP and PV decreases the overall RES-E system costs. Algeria also profits from avoided expenses for gas fuel, but has more extensively invested in CSP and PV capacity. Therefore, the integration of RES-E sources into the Algerian power system is significantly less cost-efficient than in Tunisia. Morocco, alternatively, shows a mixed picture. Its renewable generation system contains relatively expensive solar power plants, as well as very cost-efficient wind farms, which, due to excellent conditions, contribute to more than 70% of the RES-E generation in 2025. On the other hand, the monetary fuel substitution effect in Morocco is low, because only relatively cheap coal-generated electricity is replaced. Both effects lead to a modest RES-E system efficiency in Morocco, which remains at the same level as Algeria.

From a purely economic perspective, setting aside technical aspects related to grid integration and system stability, this poses the question as to why Morocco and Algeria currently put so much emphasis on solar power plants in their renewable goals, instead of focusing on wind power as the cheaper, 'low hanging fruit.' While in Algeria this might be due to a geographically-limited availability of wind sites (Himri et al., 2009), Morocco could very likely enhance the cost efficiency of its RES-E goals by increasing the presence of wind power, as suitable wind sites are considered abundant in the country (CDER, 2007).

5. Summary and discussion

In this study, we used a linear power market optimization model to analyze the impact of renewable energy integration into the power systems of three North African countries—Morocco, Algeria and Tunisia. For this purpose it was assumed that the countries fulfill their self-imposed renewable electricity targets until 2025 and form a competitive regional electricity market that includes adjacent European countries. By comparing a renewable energy scenario (RES-E) to a baseline (BAU) scenario with no renewable electricity generation, we characterized and quantified some principal effects that accompany an increased RES-E penetration in the countries' electricity systems. The model results show that for all countries, renewable energies are able to replace an important part of fossil generation. This leads to noticeable effects in the conventional generation system—the utilization of base-load plants is reduced, while there is a stronger need for investments in flexible OC gas power plants.

Additionally, fluctuating renewable energy generation influences the hourly dispatch of conventional power plants which, under peak load conditions and weak RES-E feed-in, reacts with an increased dispatch of gas power plants. In a subsequent cost analysis, we compared the surplus costs incurred from achieving the RES-E goals with the savings resulting from avoided use of fossil fuels and investments in conventional power plants. For each Euro (€) spent on the RES-E goals, savings in the conventional power system of € 0.15 (Algeria), € 0.16 (Morocco) and € 0.27 (Tunisia) can be achieved. These relatively strong disparities between the countries' specific RES-E savings raise the question of whether there is still room for improvement in the national renewable electricity targets of the Maghreb countries. Further work in this field will be required, for example by providing an analysis of how RES-E power plants could – in conjunction with the conventional generation system – better reflect the specific renewable potentials of the Maghreb states. Another topic to be discussed is whether RES-E integration could be additionally optimized by more trans-national coordination and, perhaps, even a future harmonization of the renewable energy policies of the Maghreb states.

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