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Article

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Research paper

Renewable electricity targets in selected MENA countries – Assessment of available resources, generation costs and GHG emissions



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ABSTRACT

MENA countries published national policy targets for the implementation of electricity from renewable energy (RE). These targets are important as they serve as framework for stakeholders in the energy sector like businesses and administration, while also showing governmental ambitions to the public. This paper investigates the impact on resources, generation cost and GHG emissions if the targets are met. It also examines whether the current development is achieving the targets and how the targets perform in the light of the Paris Agreement. 13 to 52 % of electricity from RE is targeted for 2030. The necessary RE expansion exceeds the current expansion in most countries. Only in Morocco and Jordan are projects indicating that the targets might be reached. From a resource perspective, a much stronger expansion is possible. Beneficial locations exist allowing to cover the domestic demand or even an export of electrical energy or derived energy carrier. Furthermore, especially PV, but also wind systems, can generate electricity in many areas for lower cost than fossil fuel fired power plants. Specific GHG emissions of national electricity production in 2017 are estimated to 396–682 g_{CO_2e}/kWh and decrease to 341–514 g_{CO_2e}/kWh if the 2030 RE targets are met. The type of fossil fuel has a strong impact on the GHG emissions. Although Morocco has highest RE deployment today and targets highest RE share in 2030, it shows today and in 2030 specific GHG emissions that are among the highest of considered MENA countries because electricity production from coal dominates whereas other countries use mainly natural gas. Existing policy targets decrease specific GHG emissions until 2030. However, stronger GHG mitigation efforts will be necessary afterwards in order to reach targets of the Paris Agreement. More ambitious 2030 policy target would distribute the load more evenly over time and should be reconsidered.

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1. Introduction

Targets for increasing the implementation of renewable sources of energy (RE) into the power sector have been established by all governments in the MENA region (Middle East & North Africa). The targets are important because they are (or rather should be) the framework of governmental action and show governmental ambitions to the public. Thus, they serve as strategic frameworks for different stakeholders in the energy sector. E. g. businesses use them as frame conditions for strategic decisions and administrations to align their activities accordingly. Some countries set targets for installed capacities of certain technologies (REN21, 2018). These RE targets – if implemented – will result in a substantial expansion of RE capacities. Additionally,

this electricity from RE will be integrated into a power sector that has been dominated by power plants burning natural gas, fuel oil, and/or coal to generate electricity.

Irrespective of these targets, an expansion of the power generation capacity is necessary as the electricity demand is expected to increase significantly in the years to come. This is due to an ongoing strong population growth and an increasing prosperity, coupled with increasing industrial production activities, which are typically energy-intensive (Kost, 2015; Arab Union of Electricity, 2018).

Power generation from RE – although clearly increasing – is low today and plants burning conventional energy carriers – mostly natural gas and oil – still dominate the electricity generation sector. The fact that huge resources and reserves of crude oil and natural gas are available in selected MENA countries can partially explain this. The region owns 45% and 49% of the total proven global natural gas respectively crude oil reserves (British Petroleum, 2018). However, there are huge areas for harnessing

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RE available. In the MENA region each person has statistically 23,000 m² available for electricity production. This corresponds to a population density of 44 people/km². For comparison, only 17,000 m² are available for an average world citizen. For a citizen of a populated country like Germany, there are only 4000 m² available (The world bank, 2019a). Furthermore, areas with beneficial RE resources exist. In certain locations PV systems and wind turbines can provide electricity with up to 2200 h/a and above 4000 h/a at full load, respectively (Huld et al., 2012; Staffell and Pfenninger, 2016). Thus, a large potential for the production of electricity from RE exists, which could be harnessed for covering the local electricity demand in a climate sound manner and which could possibly also be exported as crude oil and natural gas are exported today.

The electricity generation cost based on PV systems and wind turbines declined sharply in recent years. Such generation systems placed in regions with beneficial RE resources can partly produce electricity today at cost lower than fossil fuel fired power plants (IRENA, 2016; Alnaser and Alnaser, 2011; IRENA, 2018). However, this competitiveness depends, among others, on the cost of the electricity generation technology, the available RE resource at a certain spot, and on the cost of the (substituted) fossil fuels. Due to national availability of fossil resources, fuel cost on a national level can be significantly lower than the price on the global energy markets. Thus, implementing RE electricity generation systems, as targeted by all MENA countries, into the existing power sector can lead to increasing, but also to decreasing costs.

One major driver of RE targets is the mitigation of greenhouse gas (GHG) emissions (Alnaser and Alnaser, 2011). The energy sector in the MENA region causes highest GHG emissions of all sectors with 38% of CO₂ emissions (Abbass et al., 2018). So far, increasing energy and especially electricity consumption – as it is also expected in the years to come (Arab Union of Electricity, 2018) – was strongly correlated with increasing CO₂ emissions and no significant impact of RE was detected so far (Al-mulali, 2011; Amri, 2017; Farhani, 2013; Farhani and Shahbaz, 2014; Kahia et al., 2017). If global temperature increase should be kept below the 2 °C target defined under the Paris Agreement, this development must change. However, as most RE targets in the MENA countries are defined as a share of the overall electricity production, the effect on total GHG emissions is not clearly visible, because the absolute amount of GHG emissions depend on the choice of deployed fuel and the total amount of electricity produced.

Against this background, this paper assesses the national renewable power targets and compares them with the status of the current power sector. Therefore, the national renewable power targets will be presented. Then, the power sector including its historic demand and how this demand is covered today is discussed in detail. This includes the deployed power plants and energy carrier as well as associated energy resources – fossil and renewable. Special focus is put upon renewable energies and recent development. Afterwards the assessment methodology and further input data necessary to answer the following question are presented.

1. What expansion of RE technology is required to reach the RE targets?
2. What is the current potential of electricity production from PV systems and wind turbines and which share will be implemented under the currently valid RE targets?
3. What electricity cost result from implementing these RE targets compared to current electricity production?
4. What GHG emissions result from implementing RE targets compared to current electricity production and how are the RE targets to be assessed in the light of the Paris Agreement?

Table 1

Import vs. consumption of oil and natural gas in MENA countries in 2016. Source: Major data source (British Petroleum, 2018).

	Production of oil ^a [Mt]	Consumption of oil [Mt]	Production of natural gas [bcm]	Consumption of natural gas [bcm]
Algeria	68.4	18.9	91.4	38.6
Egypt	33.8	40.7	40.3	56.0
Jordan	0.0 ^b	3.8 ^b	0.1 ^b	4.2 ^b
Libya	91.4	8.0 ^b	11.5	6.6 ^b
Morocco	0.0	12.6	0.1	1.4
Saudi Arabia	586.6	167.2	105.3	105.3
Tunisia	2.8	4.3 ^b	2.8 ^b	6.2 ^b

^aIncludes crude oil, shale oil, oil sands and natural gas liquids.

^bData taken from International Energy Agency (2018).

In this research paper the MENA countries Egypt, Algeria, Jordan, Libya, Morocco, Saudi Arabia and Tunisia (Fig. 1) are considered. Different categories can be used to group these MENA countries such as the status of economic development, availability of labour and balance in energy trade (Griffiths, 2017). Here, the countries are categorized according to their trade balance for fossil energy (Table 1) into

- net-fossil energy exporting countries (Algeria, Libya, Saudi Arabia) producing more oil and also natural gas than they consume,
- net-fossil energy importing countries (Egypt, Jordan, Morocco, Tunisia) consuming more oil and natural gas than they produce.

In recent years, Egypt turned into a net-fossil energy importing country due to decreasing depletion of domestic oil and gas resources while strongly increasing domestic energy demand (International Renewable Energy Agency, 2018).

2. RE targets

RE electricity production is gaining increasing attention in MENA countries, as they contribute to several policy objectives such as energy independence, lower cost, and GHG emission mitigation (REN21, 2018). Based on RE, net-fossil energy importing countries can increase their energy independence and thus their energy supply security which is one “key national priority for all countries in the region” (Ansari and Ghassan, 2018). Furthermore RE technology is associated with national prestige and attracts institutional investors (Brand, 2015). Increasing supply of energy through domestic sources is also associated with increasing national added value (value creation) and can go along with building up of new industries and with the creation of jobs (e.g. production, installation or maintenance of PV systems) (IRENA, 2016; Brand, 2015). Electricity generation from RE can also reduce local air pollution, which can be especially important in metropolitan areas.

Thus, it is not surprising that all considered countries have set targets for the use of renewable energies. Targets related to primary energy, to transport or to heating and cooling are scattered; for example, four out of seven countries published targets of RE for primary energy. For transport as well as for heating and cooling even fewer countries have announced clear goals. However, all the countries set political targets for the power sector (Table 2).

The implemented RE targets for electricity generation are mostly defined as a share of electricity produced from renewable energies; here these goals are named RE share targets. Depending on the country, these targets are given for different points in time (e.g. 2022, 2025, 2030, 2050). Medium-term targets until

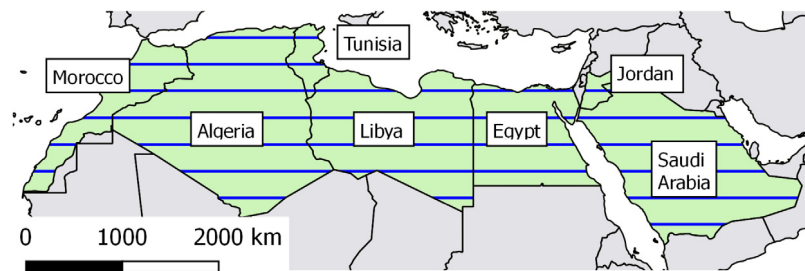


Fig. 1. Considered MENA countries for the investigation (marked with horizontal lines).

Table 2
Types of targets for renewable energies in MENA countries (REN21, 2018).

	Primary energy	Transport	Heating- and cooling	Electricity
Algeria	x			x
Egypt	x			x
Jordan	x	x	x	x
Libya	x	x	x	x
Morocco			x	x
Saudi Arabia				x
Tunisia				x

Table 3
Targeted share of electricity produced from REs related to total national electricity production (RE share targets).

Reference year	2015	2020	2030	2050
Algeria	–	–	37% ^d	–
Egypt	–	20% ^a	35% ^c	–
Jordan	15% ^a	–	22.5% ^e	–
Libya	–	7% ^a	13% ^f	–
Morocco	–	–	52% ^a	100% ^a
Saudi Arabia	–	–	–	–
Tunisia	–	–	30% ^{a,g}	100% ^a

^aData source (REN21, 2018).

^cRecent strategy “Visions 2020” stated for 2030 a target of electricity production: solar 16%, wind 14%, hydro 5% summing up to 35% (The Arab Republic of Egypt, 2016). This value is in line with the value of 42% of electricity from renewable energies in 2035 as stated in Integrated Sustainable Energy Strategy (International Renewable Energy Agency, 2018).

^dData source (République, 2015). REN21 (2018) shows a different value of 27%.

^eExtrapolated value: Jordan’s energy ministry published a value of 20% until 2025 (Ministry of Energy and Mineral Resources, 2018). The extrapolation assumes a similar yearly increase as between 2015–2025.

^fExtrapolated value. Published target are 10% by 2025^d. The extrapolation assumes a similar yearly increase as between 2020–2025.

^gAmbassade (2008).

2025/2030 are given by six out of seven countries and range from 10% for Libya in 2025 to 52% for Morocco in 2030. Egypt, Algeria and Tunisia are in between these goals intending 25 to 30% RE electricity generation. Table 3 shows RE share targets in a structured manner; here all targets are brought to uniform time perspectives (2015, 2020, 2030 and 2050). For countries that defined targets for deviating points in time, linear inter- or extrapolation is applied.

Saudi Arabia has not set RE share targets, but published targets for individual technologies given in installed capacity. All other countries set similar targets called here RE capacity targets. Table 4 shows these RE capacity targets in a structured manner related to the time perspective 2020 and 2030. For Algeria and Egypt, percentage shares are also planned for individual technologies to generate electricity. Algeria is the only country with a target for geothermal electricity generation (15 MW (REN21, 2018)).

3. Status power sector

The assessment of the RE targets is based on the current status of the power generation sector. Thus, basic information on the organizational structure, the generation and demand as well as the power plant park is given below. The major source of information is the statistical bulletin 2018 from the Arab Union of Electricity supplemented by data e. g. from the Statistical Review of World Energy by British Petroleum (BP) and publications of the International Energy Agency. Information is related to the year 2017 if not stated differently.

The power sector in most MENA countries is characterized by a high degree of governmental control and regulation. Today the existing power markets show a narrow openness; i.e., participation of the private sector is strongly restricted in most cases (Hall, 2018). Additionally, the electricity generation sector comes from a tradition of vertically integrated, state-owned utilities operating within a monopoly covering generation, transmission and distribution (Saudi Arabia, 2019). However, several countries started a process of reforming the power sector in order to increase private sector participation. One of the important measures in this respect is the unbundling of generation, transmission, and distribution (Hall, 2018). Today, private participation comes mainly through auctioning tenders which hire independent power producer that own facilities to generate electric power (Saudi Arabia, 2019).

3.1. Generation and demand

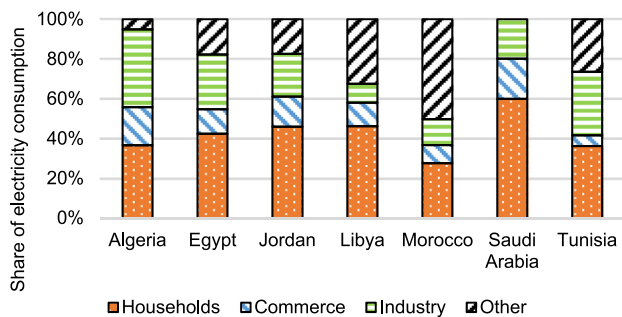
MENA countries are characterized by a steadily rising generation of electricity (Table 16 shows some values). The electricity production of considered countries increased from 157 TWh in to 696 TWh in 2015. This corresponds to an average growth of 5.8%/a. In comparison: Germany showed in the same period very little growth with 0.7%/a and China a significant higher increase by 9.4%/a. The growth differs only slightly between the individual MENA countries from 4.8%/a in Morocco to 6.8%/a in Jordan. There are also minor differences over time. The increase slowed down in recent years, which can partly be explained by the political uncertainties in the region (Griffiths, 2017). The overall growth is mainly based on population growth, rising electrification rate, increasing consumption in the private sector (e.g. cooling, heating, cooking, communication), and economic growth (Kost, 2015).

Fig. 2 shows the share of the various sectors related to the overall electricity consumption in 2017. Apparently, most electricity is consumed in households – on average 49%. Only in Algeria, Morocco and Tunisia this figure is below 40%. In Saudi Arabia, on the other hand, the figure is 60%. For comparison, in an industrialized country like Germany, households consume ca. 25% (AG Energiebilanzen, 2018) of the overall provided electricity. Within the considered MENA countries, electricity consumption from industry has the highest share in Algeria and Tunisia with over 30%. For Morocco the displayed data from the Arab Union of

Table 4

Technology specific targets for RE in the power sector in MENA countries adjusted to the years 2020 and 2030 (RE capacity targets).

Reference year	General renewable energies		Hydropower		Biomass	PV		CSP		Wind power		
	2020	2030	2020	2030	2030	2020	2030	2020	2030	2020	2030	
Share of electrical energy respectively installed capacity												
Algeria ^l	2.6 GW ^d	22 GW ^{a,k}	–	–	1 GW ^{a,e}	–	–	13.5 GW ^a	–	2 GW ^a	–	5 GW ^a 3% ^d
Egypt	–	–	2.8 GW ^a	5% ^b	–	–	16% ^{b,c}	1.1 GW ^a	2.8 GW ^a	12% ^a	7.2 GW ^a	14% ^b
Jordan	1.8 GW ^a	–	–	–	–	–	1 GW ^{a,c}	–	–	–	1.2 GW ^a	–
Libya	–	–	–	–	–	–	0.3 GW ^{a,j}	1.3 GW ^{a,f,j}	0.1 GW ^{a,j}	0.4 GW ^{a,j}	0.6 GW ^a	1.4 GW ^{a,f}
Morocco	6 GW ^a	–	2 GW ^a	–	–	–	2 GW ^a	–	–	–	2 GW ^a	–
Saudi Arabia	1.6 GW ^{a,g}	27.8 GW ^{a,h}	–	–	–	–	8.2 GW ^{a,h}	–	12.9 GW ^{a,h}	–	–	6.7 GW ^{a,h}
Tunisia	–	4.6 GW ^{a,m}	–	–	0.3 GW ^{a,i}	–	–	–	–	–	–	–

^aREN21 (2018).^bThe Arab Republic of Egypt (2016).^cIncluding CSP.^dRépublique (2015).^eBiomass based on waste.^fExtrapolated value: Libya published a target of 0.8 GW of solar PV capacity and 1 GW of wind power in the year 2025. The extrapolation assumes a similar yearly increase as between 2020–2025.^gAdjusted value: Saudi Arabia announced to install 9.5 GW of general RE capacity until 2023 and 54 GW until 2040. A linear capacity expansion is assumed between 2023 and 2040 and the 2020 value is extrapolated accordingly.^hAdjusted value: Saudi Arabia announced 54 GW of general RE capacity in 2040 split into 16 GW of solar PV, 25 GW of CSP and 13 GW of wind power (REN21, 2018). Share of RE technologies as for 2040 are applied to adjusted 2030 general RE capacity target.ⁱSolid biomass.^jRounded value.^kRépublique (2015) shows a value of 12 GW.^lIn 2030 also 15 MW geothermal power generation to be installed.^mAmbassade (2008).ⁿREN21 (2018) shows for 2030 10 GW^a solar PV and CSP capacity and another 16 GW for wind power. This high values exceed the target for total 4.6 GW installed renewable energies by far and could not be verified. Therefore, they are not further considered.**Fig. 2.** Electricity consumption by sector in MENA countries in 2017.

Source: Data from Arab Union of Electricity (2018).

Electricity allocates up to 50% to “other” and no clear picture of sector-wise consumption is possible. Data from the International Energy Agency shows that in 2016 households consumed ca. 35% and industry ca. 17% of the electricity which is in the same range as other MENA countries (International Energy Agency, 2018).

3.2. Power plant park and fuels

The electricity used within the various MENA countries is mostly produced by the national power plant park as no extensive international grid exists between the different MENA countries so far (Kost, 2015). Fig. 3 shows the capacity share of different types of power plants in 2017. Power plants running on natural gas or fuel oil as energy source clearly dominate the power plant fleet throughout the considered countries. Steam power plants burning natural gas or fuel oil, turbines, and combined cycle power plants (CCGTs) account for 29%, 35% and 26%, respectively, of the installed total capacity. These power plants sum up to more than 91% throughout the countries. Jordan shows the peculiarity that 18% of the overall installed capacity is provided by motor

power plants. In 2015, the world’s largest engine power plant with 573 MW was commissioned near Amman, operating on heavy oil, heating oil, or natural gas (Wärtsilä Corporation, 2018). Morocco is an exception since it is the only MENA country with coal-fired power plants accounting for 33% or 2895 MW of the country’s installed capacity.

Across these countries, fuel oil and natural gas dominate electricity generation and more than 93% of the overall electricity was produced in related power plants (Fig. 4). Electricity generation from gas clearly dominated oil and the share of natural gas was above 70% in most countries. Only in Saudi Arabia 68% of electricity came from power plants using fuel oil and Morocco used 45% coal for electricity production (Arab Union of Electricity, 2018). Renewable energies contributed in 2017 16% in Morocco, 8% in Egypt and 7% in Jordan — all countries are net-importer of fossil fuel energy. Net-exporter of fossil energy (Algeria, Libya, Saudi Arabia, Tunisia) show negligible shares of RE with 3% in Tunisia and 1% and in the other countries.

Power plants using renewable energies accounted for 5% of the installed capacity in 2017 across the countries in question, with hydropower having the largest share of 3%. By far the largest hydropower capacities are installed in Morocco (1770 MW) and Egypt (2800 MW) (the Egyptian Aswan dam shows a capacity of 2100 MW alone). These two net-fossil energy importing countries are also characterized by the highest installed wind power capacity in 2017: Morocco with 1018 MW and Egypt with 747 MW. Jordan and Algeria showed with 396 MW and 344 MW, respectively, the largest capacities for solar power plants (Arab Union of Electricity, 2018). If solar and wind power plants are counted together Morocco and Jordan were and still are clearly the forerunner with 14% and 13% (respectively) of electricity produced from RE.

However, this data is partly outdated as the development of RE gained pace in 2018 and 2019.

- In Morocco, after the first stage of the Ouarzazate Concentrated Solar Power (CSP) plant “Noor I” with 160 MW started

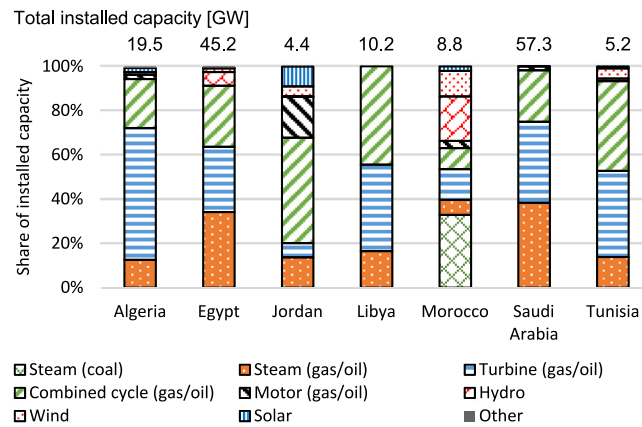


Fig. 3. Total installed capacities and share of power plants in fleet of MENA countries in 2017.

Source: Data from Arab Union of Electricity (2018).

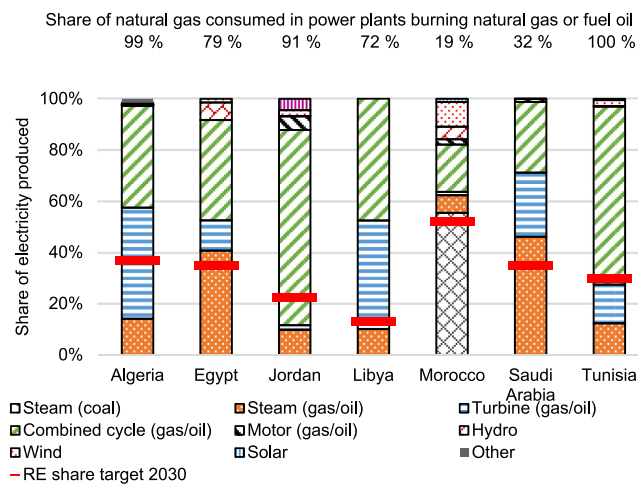


Fig. 4. Electricity produced by type of power plants in MENA countries in 2017 (data from Arab Union of Electricity, 2018) and 2030 RE share targets (for Saudi Arabia 35% are assumed, see Section 6.1).

operation in 2016, another 200 MW were added in Noor II in 2018. Noor III with 150 MW was close to commissioning in 2018 (helioscp, 2019; Parke and Giles, 2019). Including Noor III, Ouarzazate is the largest CSP power plant in the world (Ansari and Ghassan, 2018). Morocco also set up further PV projects including innovative concepts such as the project Noor Midelt consisting of two hybrid PV–CSP power plants with a capacity between 150 and 190 MW each (NewEnergyUpdate, 2019). Due to this development, Morocco has 887 MW solar power under operation by the end of 2018 (Petrova, 2019a); this capacity represents ca. 8% of the totally installed capacity in this country. Regarding wind, Morocco inaugurated for example the Khalladi wind park with 120 MW in 2018 (Climate Home News, 2019) and further projects are on the way (Table 5). With such projects Morocco is targeting to produce electricity from wind parks with 2 GW in total and another 2 GW of solar power plants in 2020.

- In Jordan, after the first wind park “Tafila” with 38 turbines and a total capacity of 117 MW started operation in 2015, the Maan wind park with 80 MW and the Al-Rajef wind park with 86 MW were commissioned in 2016 and 2018, respectively (Jordan Times, 2019). The Fueiji wind project with 89 MW add up to this. Furthermore, in 2020 another wind park in Tafila with 52 MW is expected to start operation (Shumkov, 2018). Regarding solar power production,

Jordan’s largest PV plant Quweira with 103 MW was inaugurated in the south of Jordan close to the Red Sea in 2018 (Jordan inaugurated, 2018; Enviromena, 2018). Additionally, a 23 MW PV plant came into operation in the north of Jordan close to Mafraq, which is installed to increase grid stability through peak shaving (Bellini, 2019). In total, 250 MW were commissioned through 13 PV projects in the second round of a national commissioning process, which ended in 2018. In the first round 230 MW were commissioned (Hall, 2018). Besides utility-scale PV production to the national grid, systems with less than 5 MW providing distributed power generation is increasingly interesting and more than 200 MW are installed so far (The weekend read, 2019). In 2018 a total of ca. 800 MW PV capacity were installed (Kenning, 2018), which is in reach of the goal of 1 GW of PV capacity and 1.2 GW of wind capacity targeted by 2020.

Morocco and Jordan remain the forerunners in RE project developments. In comparison, the other two net-fossil energy importing countries – Tunisia and Egypt – show significantly less ambitions in recent years.

- Egypt deployed a total capacity of 890 MW by the end of 2018 (Siemens Gamesa, 2018), which is less than 2% of installed capacity. However, wind park development projects are on the way aiming to install more than 1400 MW in the

years to come. For example, one project with 262 MW located in the Gulf of Suez in Ras Ghareb will be commissioned in 2019 (Siemens Gamesa, 2018). Additionally, 800 MW are announced but no specific projects are allocated to it so far. Regarding solar energy, Egypt started tendering 600 MW solar PV projects in 2016 and the process is still ongoing (Bellini, 2018a). One major project is the Ben Ban solar complex located in the Aswan region, which is supposed to be the world's largest solar power station (Reda, 2018). It encompasses several projects and in total it is planned to have 1.8 GW of installed capacity of which 1.5 GW are already financed (Reda, 2018; Launch of the construction, 2019).

- As of today, Tunisia does not have a wind park in operation. The first park “Mornag” with 30 MW is expected to be commissioned in 2021 (ABO, 2019). This is one of four wind park projects each having 30 MW capacity that are under development (Petrova, 2019b). Regarding solar projects, the 10 MW PV plant under operation in Tozeur (Bellini, 2017) is planned to be expanded by another 10 MW maybe in 2019 (Bellini, 2017; Tunisia, 2017). Furthermore, the winner solar tender for a total capacity of 64 MW were published in 2018. The capacity consists of six projects with 10 MW and four with 1 MW. Thus, the operational capacity of RE is low, but plans and partially contracts exists to expand it soon.

Additionally, the net-fossil energy exporting countries appear to gain pace in the development of RE projects.

- Saudi Arabia announced to implement large solar projects with a capacity of 41 GW by 2032 (ClearSky Advisors, 2018). However, the installed capacity of 1 MW was negligibly low in 2017 (Arab Union of Electricity, 2018). So far, Saudi Arabia is known for staying with conventional energy. However, in February 2019 Saudi Arabia conducted tenders for seven solar projects with a total capacity of 1.5 GW under the Saudi National Renewable program. Another 1.6 GW are planned for tendering in 2019 (Saudi Arabia, 2019). Already in 2018 a 300 MW solar tender was awarded (Bellini, 2018b). Furthermore, bids for the first utility-scale wind farm in Dumat Al-Jandal were collected in 2018 and contracts were awarded for 400 MW (https, 2019). This followed shortly after the first wind turbines in Saudi Arabia was commissioned in the same year.
- Algeria shows less ambition regarding the development of RE projects. Tenders for a total 150 MW PV capacity were issued at the end of 2018; this is true for ca. 50 MW in Guerara (region of Ghardaïa), 50 MW in Diffel (region of Biskra) as well as five smaller wind parks with each 10 MW in Meggarine, Nezla, Belhirane, Tendala, and Nakhla. Furthermore, another 50 MW of off-grid capacity will be installed (Bellini, 2018c). One wind farm in Kabertene with 10 MW is running since 2014 (The wind power, 2019).
- The political situation in Libya is uncertain and no stable government is in place. This makes the development of RE projects very difficult (Griffiths, 2017). In 2013, a contract was signed by the government to build Libya's first wind park with 37 turbines. Due to civil war, it was never completed. Additionally, the Emsalata wind farm is planned with 27 MW and first wind turbine parts arrived in the country (Wind turbine, 2019). However, no information is available on the status of the project.

Table 5

Upcoming RE projects in MENA countries (helioscsp, 2019; Parke and Giles, 2019; NewEnergyUpdate, 2019; Petrova, 2019a; Climate Home News, 2019; Jordan Times, 2019; Shumkov, 2018; Jordan inaugurated, 2018; Enviromena, 2018; Bellini, 2019; Hall, 2018; The weekend read, 2019; Kenning, 2018; Siemens Gamesa, 2018; Bellini, 2018a; Reda, 2018; Launch of the construction, 2019; ABO, 2019; Petrova, 2019b; Bellini, 2017; Tunisia, 2017; ClearSky Advisors, 2018; Saudi Arabia, 2019; Bellini, 2018b; https, 2019; Bellini, 2018c; The wind power, 2019; Wind turbine, 2019).

Country	Project	RE technology	Capacity [MW]	Expected commissioning
Algeria	Guerara	PV	50	
	Diffel	PV	50	
	Meggarine	PV	10	
	Nezla	PV	10	
	Belhirane	PV	10	
	Tendala	PV	10	
	Nakhla	PV	10	
Sum			150	
Egypt	Ras Ghareb	Wind	262	2019
	Ras Ghareb	Wind	250	
	Gulf El Zeit III	Wind	120	
		Wind	800	
	Ra Solar	PV	32	2019
Sum			1464	
Jordan	Fujeij	Wind	89	2018
	Ma'an	PV	50	2019
	Tafila	Wind	52	2020
	Sum		191	
Morocco	Taza	Wind	100	2019
	Mibladen	Wind	180	2019
	Amerssid	Wind	180	2019
	Koudia El-Baida	Wind	70	2019
	Tiskrad	Wind	300	2020
	Midelt	Wind	150	2020
	Jbel Lahdid	Wind	200	2020
	Boujdour	Wind	100	2020
	Tangie II	Wind	100	2020
	Noor III	CSP	150	2019
	Noor PV 1	PV	170	2019
	Noor Midelt	PV+CSP	150–190	
Sum			ca. 1850	
Saudi Arabia	Faisaliah	PV	600	
	Rabigh	PV	300	
	Jeddah	PV	300	
	Madinah	PV	50	
	Mahd Al Dahab	PV	20	
	Rafha	PV	45	
	Qurayyat I	PV	200	
	Qurayyat II	PV	40	
	Wadi Adwawser	PV	70	
	Mahad	PV	20	
	Dumat al-Jandal	Wind	400	
Sum			2045	
Tunisia	El Bethia	Wind	30	2020
	Mornag	Wind	30	2021
	Sum		60	

4. Assessment methodology

The focus of this paper is the assessment of renewable energy targets in the context of the current power generation system of the MENA countries discussed above. This includes investigating implications on electricity generation and associated capacity expansion regarding the use of RE resources, the cost of electricity production, and the GHG emissions of electricity production. Below the respective methodological approach is presented and used variables and indices are given in Table 6.

4.1. RE resources

The methodology applied to estimate potential electricity generation by RE is based on Stetter (2012) connecting information

Table 6
Variables and indices.

Variables		Indices	
<i>co</i>	Cost	<i>j</i>	Power generation technology (e.g. pv, wind turbines)
<i>el</i>	Electricity produced per year	<i>i</i>	Grid point
<i>em</i>	GHG emissions	<i>agg</i>	Aggregated values
<i>es</i>	Electricity share	<i>up</i>	Upstream
<i>fs</i>	Fuel share	<i>mid</i>	Midstream
<i>pe</i>	Potential electricity generation	<i>down</i>	Downstream
<i>pd</i>	Power density	<i>spec</i>	Specific values related to electricity production
<i>po</i>	Power output	<i>t</i>	Turnkey
<i>sa</i>	Surface area	<i>f</i>	Fuel
<i>sf</i>	Suitability factor	O&M	Operation and maintenance
η	Energetic efficiency from fuel input to power output		
WACC	Weighted average cost of capital		

Table 7
Global warming potentials for methane and nitrous oxide according to IPCC AR 5 (IPCC, 2014).

	GWP 20 years	GWP 100 years
	[kg CO ₂ e/kg]	
Carbon dioxide (CO ₂)	1	1
Fossil methane (CH ₄)	85	30
Nitrous oxide (N ₂ O)	264	265

on the renewable energy resources in a certain area and the capacities of power generation technologies that can be installed. Thus, a technical potential is investigated here.

The power output *po* is defined as the capacity specific electricity generation from a power generation technology *j* for one year and a grid point *i* (a grid is laid over a considered area). The value on the capacity that can be installed per area is determined by the power density *pd* and a suitability factor *sf* as well as the surface area *sa*.

- The power density *pd* describes the maximum amount of capacity that can be installed per area.
- The suitability factor *sf* determines how much of the available surface area can be used for the installation of capacity and ranges between 0 and 1.
- The surface area *sa* is the available land area.

The potential electricity generation *pe* by renewable energies for a certain region sums up the potential electricity production for all grid points existing in a certain region (Eq. (1)).

$$pe_j = \sum_i po_{i,j} pd_j (sf_i sa_i) \quad (1)$$

Information on power output *po* and suitability factors *sf* are not available in the same grid resolution. Data on power output is available on a coarser grid than data on the suitability of areas. Thus, information on area suitability is aggregated to the coarser grid. Therefore, for each of the power output grid points a new sub-grid is created. The information on suitability of areas are added up for all sub-grid point and then normalized by the number of sub-grid points.

Table 8
Suitability of PV systems and wind turbines per type land (data mainly from Stetter (2012) and own assumption).

Land cover label (Land cover classification system)	Suitability factor PV	Suitability factor wind turbines
Shrubland (120, 121, 122)	1	1
Grassland (Grassland; 130)	1	1
Sparse vegetation (140, 150, 151, 152, 153)	1	1
Bare area (200, 201, 202)	1	1
Agriculture (Rainfed/irrigated cropland; 10, 11, 12, 20)	0	0.2
Agriculture (Mosaic cropland, Mosaic natural vegetation; 30,40)	0.1	0.1

4.2. Cost

The generation costs for electrical energy are calculated as levelized cost of electricity (*LCOE*). The technology specific *LCOE_j* per technology *j* encompass all cost during the lifetime of the electricity production including annualized turnkey cost *co_t*, fuel cost *co_f* and cost for operation, and maintenance *co_{O&M}* (O&M cost). These cost elements are given as annual values and normalized by the yearly provided electricity *el* (Eq. (2)). The turnkey cost of the power producing units are discounted using the weighted average cost of capital *WACC* (Short et al., 1995; Darling et al., 2011). *N* equals the lifetime of considered technologies. The average electricity cost per country are given as aggregated values as *LCOE_{agg}* according to (Eq. (3)). The electricity share *es* denotes the share of electricity that is produced through the power plant technology *j*.

$$LCOE_j = \frac{\frac{c_{t,j}}{\sum_{n=1}^N \frac{1}{(1+WACC)^n}} + c_{f,j} + c_{O\&M,j}}{el_j} \quad (2)$$

$$LCOE_{agg} = \sum_j LCOE_j es_j \quad (3)$$

4.3. GHG emissions

GHG emissions are estimated based on the carbon footprint approach (Finkbeiner, 2009) using global warming potentials (GWP) for a 20 and a 100 year time horizon (Table 7). 100 years is a commonly used time horizon for GWP. However, natural gas respectively methane is a short-lived gas and thus shows a stronger radiative forcing over a shorter time period (IPCC, 2014). The 20 years time horizon lays a stronger focus on methane emissions and short term global warming. It is presented because natural gas is a dominant fuel in the MENA region.

GHG emissions are subdivided into downstream, midstream and upstream emissions and for each step aggregated data is used.

- Upstream emissions primarily encompass all emissions arising from the extraction and processing of natural gas, crude oil or coal.

- Midstream emissions are related to the transportation of the fuel.
- Downstream emissions are caused by the use of fossil fuels (i.e. electricity generation).

Depending on data availability, the emissions are given as country specific values. In order to derive specific GHG emissions for electricity production per country em_{agg} , up-, mid- and downstream emissions em_{up} , em_{mid} , em_{down} are added per fuel type. These GHG emissions are converted to electricity specific values based on the conversion efficiency of the corresponding power plant η (Eq. (4)).

$$em_{agg} = \sum_j \frac{(em_{up} + em_{mid} + em_{down})}{\eta_j} es_j \quad (4)$$

Here all input values for the calculations of GHG emissions are converted to GWP AR5 (IPCC, 2014) through detecting underlying share of methane and nitrous oxide on the GHG emissions.

5. Input data

Below the most important input data is explained.

5.1. RE resource

Information on the power output of PV systems are based on weather data from the year 2014. Data on power generation from PV systems is taken from PVGIS version 5 using the satellite database SARA as input (Huld et al., 2012). Hourly simulation results are aggregated to power production per year. Crystalline silicon photovoltaic (PV) modules with a fixed inclination resulting in a yearly maximum energy generation are assumed for power generation. 10% system losses as well as losses due to temperature changes of the modules are taken into consideration (Huld et al., 2012). A power density of 48 MW/km² is assumed for the calculation of the electricity generation potential (Denholm and Margolis, 2008).

The power output of wind turbines is also based on weather data from the year 2014. Hourly mean wind velocities and the respective power output are taken from “renewables.ninja” (Staffell and Pfenninger, 2016) using the satellite database MERRA2. Again, hourly data is aggregated to yearly values. Two different turbine types are considered depending on the wind conditions at each location. An IEC III class wind turbine is selected for low wind speed locations (i.e., annual average wind speed at hub height below 7.5 m/s) and power curve similar to Vestas V110/2000 for a hub height of 125 m is chosen for such low wind conditions. For higher average wind speeds, an IEC I/II class wind turbine is selected with a power curve similar to Vestas V90/3000 with a hub height of 105 m. A power density of 3 MW/km² is assumed for the calculations of the electricity generation potential (Lopez et al., 2012).

Information on RE based on the MERRA 2 dataset is provided on a raster of 0.625° longitude and 0.5° latitude. Each location covers a surface area of approx. 3900 km². The sub grid for determining the suitability factor per locations uses a raster of 0.020° longitude and 0.017° latitude. This raster is laid upon the global land cover database provided by ESA Climate Change Initiative showing 22 different vegetation classes and each class is associated with a ten values code (ESA, 0000). Suitability factors corresponding to each of the vegetation classes are shown in Table 8.

Table 9

Turnkey cost estimations and efficiencies for fossil fuel fired power plants (Kost, 2015).

Type of power plant	Lifetime [a]	Turnkey cost [€/kW]	Operation and maintenance cost [€/kW/a]	Efficiency [%]
Steam	40	1223	32	47
Combined cycle	30	815	19	59
Turbine/Motor	40	408	19	37

5.2. Cost

Turnkey cost of PV systems and wind turbines decreased significantly in recent years (Fu et al., 2016). Nevertheless, RE technologies in the MENA region show typically higher investment cost than internationally (IRENA, 2016, 2018). In 2017 turnkey cost in PV installations have been in a range from 805 to 4190 €/kW and 1063 to 3407 €/kW with a weighted average of 1922 €/kW and 2201 €/kW in Africa and Middle East, respectively. Turnkey costs of wind turbines show a similarly wide range: 1314 to 2522 €/kW and 810 to 1643 €/kW with a weighted average of 1805 €/kW and 1168 €/kW in Africa and Saudi Arabia, respectively (IRENA, 2018). As Africa is a large continent with very different conditions, turnkey costs of the Middle East are taken as reference.

Although cost for PV and wind systems in MENA countries are higher than in other regions, tenders for electricity production resulted in partially very low bids. In Saudi Arabia even a world-record low bid with 16 €/MWh for electricity production from PV systems was submitted (Bellini, 2018b). Also in Morocco tenders resulted in very low price bids with less than 30 €/MWh for electricity from wind and less than 40 €/MWh for PV projects (Ansari and Ghassan, 2018). Thus, this investigation assumes that international cost can be realized in MENA countries until 2030. However, the actual cost reductions are to be realized until 2030 depend on a broad variety of factors such as realized learning rates and installation of new capacities (Junginger, 2005), but these factors are very uncertain. Thus, Fig. 5 shows turnkey cost estimations for PV systems and wind turbines given in different publications from 2014 and newer. The respective values have been transformed to monetary values related to the year 2017. The median costs for 2030 shown in this graphic are used for the calculations in this paper (i.e., 579 €/kW for PV systems and 1194 €/kW for wind turbines). Annual cost for operation and maintenance (O&M) are given relative to the turnkey cost; values of 1% for PV systems and 2.5% for wind turbines are derived from actual values given in IRENA (2018).

Egypt and Morocco provide electricity from hydropower. Cost related to hydroelectric power generation are highly project specific and depend strongly on the construction costs for dams. In general, larger projects can provide electricity for lower costs (IRENA, 2018). In Egypt, the Assuam dam produces the majority of hydroelectric power and its economics are stated to be very beneficial (Biswas, 2002; Oxford Business Group, 2019). Morocco operates several stations, with Al Wahda dam showing the largest installed capacity in Morocco and the second largest in Africa. Due to the lack of detailed information available on investment costs and capacity factors, generic LCOE of 40 €/MWh are assumed, which are at the lower end of the LCOE range presented in IRENA (2018).

The cost of electricity generated by fossil fuel fired power plants depend on the cost of the plant itself and the fuel cost. Costs and efficiencies for these power plants are shown in Table 9. As these technologies are mature, no significant difference between 2017 and 2030 in costs and efficiencies are expected. The annual electricity produced in power plants burning fossil fuel

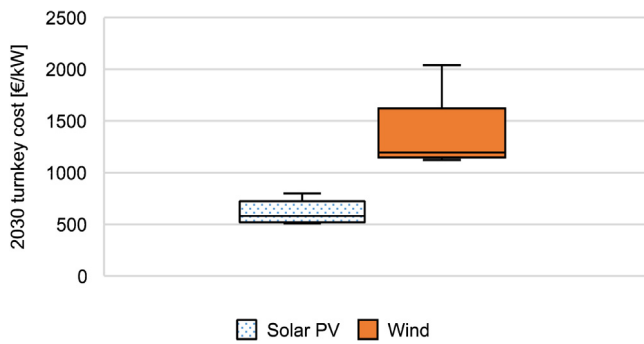


Fig. 5. Turnkey cost of PV systems and wind turbines in €₂₀₁₇ values related to the year 2030.

Source: Data from Fraunhofer (2015), Joint Research Centre of the European Commission (2014), International Renewable Energy Agency (2014), Graham et al. (2018) and Vartiainen et al. (2015).

Table 10

Average full load hours of power plants in MENA countries derived from Arab Union of Electricity (2018).

Country	Average full load hours of power plants
Algeria	5232 h/a
Egypt	4002 h/a
Jordan	4389 h/a
Libya	3989 h/a
Morocco	4335 h/a
Saudi Arabia	4892 h/a
Tunisia	3948 h/a

is derived from Arab Union of Electricity (2018) derived average full load hours are shown in Table 10. Fig. 4 shows the share of electricity produced per power plant technology in 2017. The share of electricity produced from different fossil fuel energy is assumed to remain similar until 2030.

Cost estimations of fossil fuels for 2030 vary widely between different scenarios and sources. For example, the US Energy Information Administration (EIA) project oil prices between 7 and 29 €/GJ (35 – 201 \$/bbl) for 2030 (U.S. Energy Information Administration, 2017). This huge variation arises from differences in assumptions about future development e.g. in world economy, technologies, demographics, resources, political strategies, etc. (U.S. Energy Information Administration, 2017). Due to these uncertainties, the energy cost for 2017 are utilized as a reference for 2030 as well. The crude oil price plus an average crack spread for oil refining make the oil cost to be 9.8 €/GJ (60 \$/bbl) (British Petroleum, 2018). Natural gas prices are globally not uniform and show differences between regions and no MENA gas prices

Table 11

Oil extraction cost in MENA countries (existing oil fields).

Source of information	Knoema (2018)	Chernyshev (2018)	Remme et al. (2007)		Karl (2010)	Own assumption
			From	Up to		
Type of cost	Marginal	Marginal	Extraction cost		Extraction cost	
Algeria	1.0 €/GJ (6.1 \$/bbl)	2.2 €/GJ (13.4 \$/bbl)	0.7 €/GJ (4.3 \$/bbl)	1.7 €/GJ (10.7 \$/bbl)	1.8 €/GJ (11.0 \$/bbl)	1.5 €/GJ (9.2 \$/bbl)
Egypt	1.6 €/GJ (9.8 \$/bbl)		0.7 €/GJ (4.3 \$/bbl)	1.7 €/GJ (10.7 \$/bbl)		
Libya	1.1 €/GJ (6.7 \$/bbl)		0.7 €/GJ (4.3 \$/bbl)	1.7 €/GJ (10.7 \$/bbl)		
Saudi Arabia	0.7 €/GJ (4.3 \$/bbl)	0.4 €/GJ (2.4 \$/bbl)	0.5 €/GJ (3.0 \$/bbl)	1.9 €/GJ (11.6 \$/bbl)		
Tunisia			0.7 €/GJ (4.3 \$/bbl)	1.7 €/GJ (10.7 \$/bbl)		

Table 12

Gas extraction cost in MENA countries (existing gas fields, cost are also given in energy equivalent to 1 bbl oil).

	Remme et al. (2007)		Karl (2010)	Own assumption
	From	Up to		
Algeria	0.4 €/GJ (2.4 \$/bbl)	0.5 €/GJ (3.1 \$/bbl)	1.1 €/GJ (6.7 \$/bbl)	1 €/GJ (6.1 \$/bbl)
Egypt	0.4 €/GJ (2.4 \$/bbl)	0.5 €/GJ (3.1 \$/bbl)		
Libya	0.4 €/GJ (2.4 \$/bbl)	0.5 €/GJ (3.1 \$/bbl)		
Saudi Arabia	0.2 €/GJ (1.2 \$/bbl)	0.3 €/GJ (1.8 \$/bbl)		

are available. Thus, an average of natural gas prices from UK, Netherlands, and Germany are taken as a reference because a significant share of natural gas in Europe comes from Libya and Algeria. Natural gas cost are estimated to be 4.8 €/GJ (energy equivalent 29 \$/bbl) (British Petroleum, 2018).

Algeria, Libya, and Saudi Arabia show high reserve-to-production (R/P) ratios for natural gas with 48, 124, and 72 and crude oil with 21, 153, and 61 (British Petroleum, 2018). Thus, production capacity could be expanded to supply additional domestic demand. As the countries are also members of the Organization of the Petroleum Exporting Countries (OPEC) and are bound to OPEC's targets for international export, no additional return can be expected for additionally extracted fossil energy. Therefore, the cost for oil and gas in these countries are not related to international oil and gas prices but set through the gas extraction cost. For considered net fossil energy exporting countries cost of 1.5 €/GJ (9 \$/bbl) for oil and 1 €/GJ (energy equivalent 6 \$/bbl) for natural gas are assumed, which represent domestic extraction cost (Tables 11 and 12).

A high share of the electricity generation costs for renewable energy technologies is due to the installation of the systems as running costs are comparatively low. Thus, the weighted average cost of capital (WACC) has a strong impact on the resulting electricity cost. Here a WACC of 7% is assumed for projects today and in 2030. This value is higher than the WACC for internationally operating utilities being ca. 3.5% in 2013 (PricewaterhouseCoopers, 2018) as WACC are usually higher in MENA countries (International Renewable Energy Agency, 2014).

5.3. GHG emissions

Up-, mid-, and downstream emission data for oil and its products, for natural gas and for coal is available from a range of different sources. Most detailed studies for upstream emissions analyse

Table 13

Crude oil upstream methane and GHG emissions given in ARG4 (IPCC 2007) GWP potentials (100 year) (Malins et al., 2014; Cowi Consortium, 2015).

	Crude name	Production GHG emissions [gCO ₂ e/MJ]	Production methane emissions [t _{CH₄} /t _{crude}]	Refining GHG emissions [gCO ₂ e/MJ]
Algeria	Other Algerian	15.4	0.17%	8.6
Algeria	Saharan Blend	12.8		
Egypt	Egyptian Medium/Light	8.9		
Libya	Libyan Heavy	8.9		
Libya	Libyan Light	8.3		
Libya	Libyan Medium	13.6		
Saudi Arabia	Arab Light	5.5		
North Africa		11.12		

the emissions per source (i.e., per oil and gas field separately). In this paper country specific GHG emissions are considered.

The ICCT study (Malins et al., 2014) assessed the upstream emissions of fossil fuel feedstock consumed in the EU, considering emissions of different types crude oils coming from different origins. These results are based on the oil production GHG emission estimator (OPGEE). Country specific emission data is shown here for two crude oils from Algeria, one from Egypt, three from Libya, and one from Saudi Arabia. Thus this investigation covers more countries relevant in this investigation than source (Cowi Consortium, 2015) which is used later in the context of natural gas.

This study here assumes that crude oil producing countries use their own crude oil. If information is available on more than one type of crude oil, average values are derived as no data is available on corresponding shares used per country. If no country specific value is given, a standard value for North Africa is applied. Table 13 shows upstream methane and GHG emissions in GWP₁₀₀ (IPCC AR4) values.

Refining of crude oil is a complex process that produces marketable products such as fuel oil. This includes removing impurities such as sulphur, separating the crudes into different fractions and converting long chain hydrocarbons into shorter ones. The fact that manifold products are provided by the refining process makes the allocation of emissions to single products difficult. Here refining related GHG emissions of 8.6 g_{CO₂e}/MJ given in GWP₁₀₀ (IPCC AR4) are used that are related to diesel production (Edwards et al., 2014). The value is approximately similar in GWP₂₀ and GWP₁₀₀ (IPCC AR5) terms as over 99% of GHG emissions are caused by CO₂ emissions (United States Environmental Protection Agency, 2013).

Emission data for natural gas produced in major EU supplier countries are published in Cowi Consortium (2015). The GHGenius model is used to estimate GHG emissions and considers well drilling, testing and servicing, and gas extraction, as well as, gas processing while including methane losses at all stages. Here values for Algeria and Libya are directly taken from source (Cowi Consortium, 2015). For other countries – as they export only small amounts or even import natural gas – no reliable information is available on domestic production. But Morocco is connected to Algeria through the Maghreb Europe pipeline and Tunisia with Algeria through the Trans-Mediterranean pipeline. Therefore, it is assumed that Moroccan and Tunisian natural comes from Algeria. For the remaining countries, the mean value from Algerian and Libyan natural gas is taken as an estimate. For Egypt this assumption seems reasonable due to geographical proximity of the gas fields. This is also true for Saudi Arabia as GHG emissions of natural gas produced in the neighbouring country Qatar lays in the same range (Cowi Consortium, 2015). Table 14 shows upstream methane and GHG emissions given in GWP₁₀₀ (IPCC AR4) values. Thus, Libyan gas causes higher GHG emission as it requires substantial processing due to a high CO₂ content.

Table 14

Natural gas upstream methane and GHG emissions given in ARG4 (IPCC 2007) GWP potentials (100 year) (including processing) (Cowi Consortium, 2015).

	GHG emissions [gCO ₂ e/MJ]	Methane emissions [m ³ _{CH₄} /m ³ _{naturalgas}]
Algeria	12.6	2.0%
Libya	16.2	0.7%

Table 15

Downstream emissions per fuel type derived from Edwards et al. (2014) and ÖKO Institut (2011) and own calculations.

	Fuel oil	Natural gas	Coal
	Emissions in g/MJ _{fuel}		
CO ₂	72.0	45.0	79.0
CH ₄	0.003	0.004	0.002
N ₂ O	0.003	0.003	0.005

Coal is a globally traded energy carrier originating from a large number of regions. GHG emissions associated with its use therefore show a wide range (Whitaker et al., 2012). Globally, above 93% of GHGs are emitted through its burning in power plants and ca. 6% in mines. Remaining emissions are low with ca. 1% and are caused through ocean, river, rail, or road transport (Oberschelp et al., 2019). Within the MENA region, coal is only produced and used in Morocco. Upstream emissions through mining are derived from Oberschelp et al. (2019) and result to 0.10 g/MJ CO₂ and 0.32 g/MJ methane.

Midstream emissions encompass transportation from the well to the power plants. Emissions from transportation are not considered for oil as the energy density is high and the transport distances are comparatively short. Natural gas transport is considered via pipelines and associated energy consumption is assumed to 0.05 MJ/(MJ 1000 km) in Libya derived from industry data and 0.03 MJ/(MJ 1000 km) in all other countries being the IPCC default value (Cowi Consortium, 2015). Methane losses are accounted for with 0.02%/1000 km derived from Cowi Consortium (2015). Transport distances are estimated via mean distances in the countries given as $\sqrt{\text{surface area of country}/2}$ with the surface area from reference (The world bank, 2019b). The coal transport chain including the transport of coal on the ocean and its domestic transport on rail and road cause 3.19 g/MJ CO₂ and 0.32 g/MJ methane (Oberschelp et al., 2019).

Downstream emissions account for the use of fuel oil, natural gas, and coal for electricity generation. In the MENA region, a variety of different power plant types are used. Unfortunately, country specific information is unavailable for non-CO₂ emissions. Thus, Table 15 shows generic emissions from different fuels. The various efficiencies of the power plants are summarized in Table 9. The share of electricity produced by type of power plant is presented in Fig. 4.

Electricity production from PV and wind turbines are associated with GHG emissions caused primarily during manufacturing, but also assembly, and operation of associated systems. As

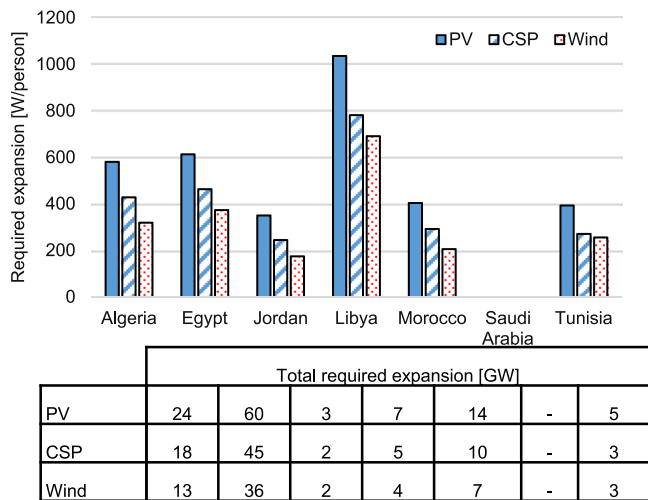


Fig. 6. Required expansion of RE capacity between 2017 and 2030 to fulfil RE share targets by one single RE technology.

manufacturing is an international undertaking and only limited parts are produced in the MENA countries itself, international GHG values are used to estimate associated emissions. For electricity production by wind turbines a value of $6 \text{ g}_{\text{CO}_2\text{e}}/\text{kWh}$ is assumed (Mendecka and Lombardi, 2019). This value corresponds to the median for onshore wind turbines with typical nameplate capacities between 2.5 and 5 MW per turbine and the deviation from the median is small with $5\text{--}8 \text{ g}_{\text{CO}_2\text{e}}/\text{kWh}$ (1st–3rd quartile) (Mendecka and Lombardi, 2019). A variety of PV technologies exist that are associated with different GHG emissions. However, associated average values lay in a similar range with $37 \text{ g}_{\text{CO}_2\text{e}}/\text{kWh}$ for systems applying mono-silicon modules and $24 \text{ g}_{\text{CO}_2\text{e}}/\text{kWh}$ if cadmium telluride (CdTe) modules are applied. Here $31 \text{ g}_{\text{CO}_2\text{e}}/\text{kWh}$ are assumed being average value for different technologies (Peng et al., 2013). Electricity from other RE such as hydropower cause GHG emissions lower or in a similar range as electricity from PV (Amponsah et al., 2014). Thus, GHG emissions caused through PV systems are taken as reference if not stated otherwise.

6. Results

Based on the methodology outlined in Section 4 and the data elaborated in Section 5, the implications on the power sector in 2030 are shown below assuming the RE power targets are satisfied. On this basis, it will be examined whether current activities fulfil the targets and how the objectives are to be classified in relation to the Paris Agreement.

The investigation is based on the assumption of increasing electricity demand. Assumptions on the growth are shown in Table 16 (Kost, 2015). Thus, compared to historical developments a declining increase is expected until 2030. While Egypt and Morocco are expected to grow by around $5\%/a$ until 2028 and Libya by as much as $9.4\%/a$, Saudi Arabia is anticipated to approach a rather saturated state with $2.3\%/a$ being in line with latest developments (Arab Petroleum Investments Corporation, 2018).

6.1. RE electricity and capacity expansion

Power generation from RE in 2030 is assessed under the RE share and capacity targets that are individually set by the MENA countries (chapter 2). Table 17 shows the required amount of electricity produced from RE if the respective countries fulfil the

defined RE share targets. The values are in the range of 8 TWh for Jordan and 144 TWh in Egypt. High values can reflect high electricity demand, high RE ambitions, or a combination of both. The required RE electricity generation per person varies between $0.8 \text{ MWh}/\text{person}$ in Jordan and $2.2 \text{ MWh}/\text{person}$ in Libya. For comparison, Germany targets ca. $5.2 \text{ MWh}/\text{person}$ in 2030.

The second column of Table 17 compares the required amount of RE electricity in 2030 with the expected electricity growth until 2030. For Egypt, Jordan and Libya the growth in electricity demand significantly exceeds the amount of RE electricity in 2030. Therefore, more electricity from non-RE sources will be necessary in 2030 than today. New fossil fuel based power plants will be necessary under the currently valid RE share targets. RE electricity in 2030 and the growth of electricity in Algeria, Morocco and Tunisia are in the same range and so capacity expansion is potentially possible without the installation of new non-RE power plants. This implies – among other things – that the current power plants can still be in operation also in 2030.

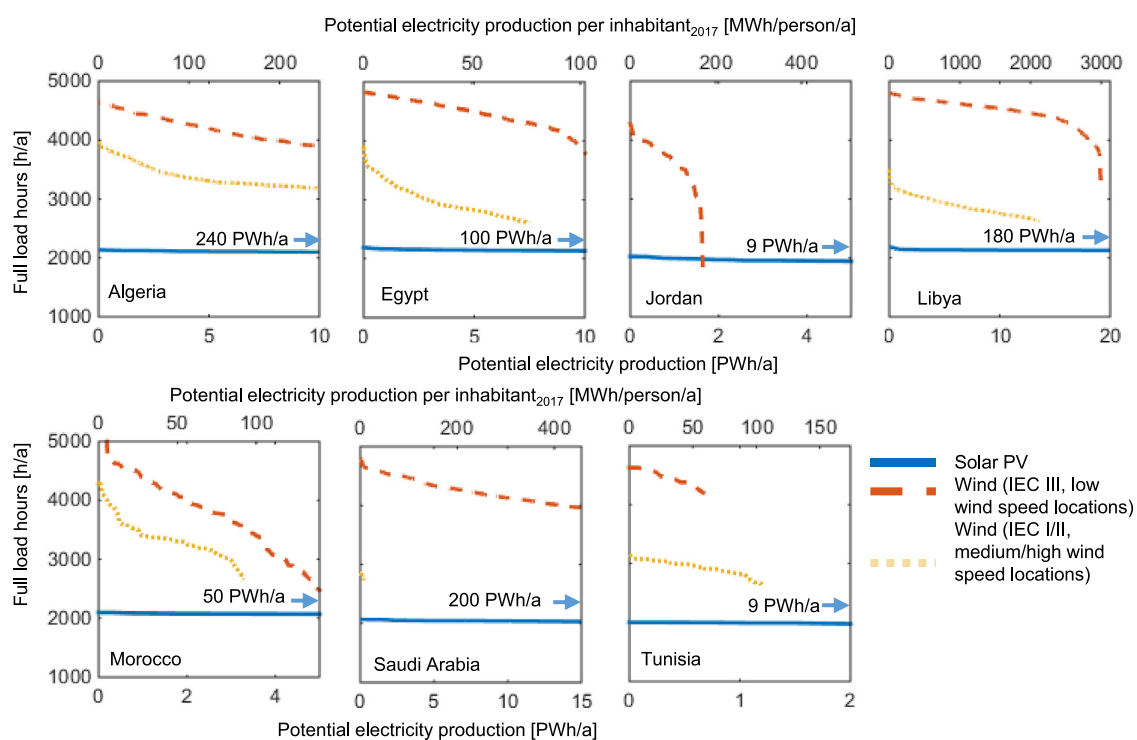
Fig. 6 shows the capacity installations of RE technologies necessary to fulfil the 2030 RE share targets. The shown capacities reflect the case that the overall desired electricity from RE would be produced by one RE technology only. For example, expansion of 24 GW PV systems in Algeria would lead to the RE share target of 37% in 2030 and no expansion would – in theory – be necessary from other RE technologies. Full load hours are selected according to Fig. 7 (i.e. locations with highest full load hours respectively lowest LCOE are selected first).

The highest expansion is necessary in the next 12 years in Egypt with 24 GW PV, 18 GW CSP, or 13 GW wind capacity, as most RE energy is needed here. This equals an average expansion of $2 \text{ GW}/a$ PV, $1.5 \text{ GW}/a$ CSP, or $1.1 \text{ GW}/a$ wind capacity. For comparison, in Germany 1.7 GW of PV (pv magazine, 2019) and 6.6 GW of wind capacity (Bundesverband WindenErgie, 2017) have been installed in 2017 and Germany covers one third of Egypt's surface area and has a comparable number in population. According to Table 5 Egypt plans the commissioning of ca. 1.5 GW of RE capacity in the next several years. Thus, RE capacity expansion needs to increase significantly to reach the self-defined targets. The situation is similar in Algeria and Tunisia, where the current capacity expansion needs to increase by approximately one order of magnitude. Compared to that, Jordan and Morocco might reach the self-committed RE targets if the current speed of capacity expansion continuous. Fig. 6 also shows the required expansion normalized by the number of inhabitants in 2017. In Libya, most RE capacities would need to be installed per person, followed by Egypt and Algeria.

Table 18 compares 2030 RE capacity targets – values are not available for Egypt, Jordan and Morocco – against RE share targets. According to Table 18, RE capacity targets are well in line with the RE share targets in Algeria and Tunisia. I.e. if RE capacity targets are achieved also the RE share targets are achieved. Libya's RE capacity targets are not sufficient to reach the RE share target which are already comparatively low with 13% in 2030. Saudi Arabia did not publish RE share targets. However, if Saudi Arabia fulfils the RE capacity targets roughly 35% of electricity will be produced from RE in 2030. This value is similar to the RE share targets set by Algeria, Tunisia, and Egypt. Targeted RE electricity production in Saudi Arabia by 2030 exceeds the growth in electricity demand by 68% and therefore the shutdown of existing power plants is likely. This shutdown might also include the shutdown of old power plants exceeding their technical life time anyway within the years to come. According to Table 5 Saudi Arabia currently plans to commission ca. 2 GW in upcoming years – a similar continuous expansion will reach the 2030 capacity targets of solar PV. However, currently capacities of planned CSP and wind projects are too low to reach the RE capacity targets.

Table 16
Historical and projected electricity generation in MENA countries.

Country\year	1990 ^a	2015 ^a	2030	Growth after 2015 ^b
Algeria	16 TWh (0.6 MWh/person)	69 TWh (1.7 MWh/person)	137 TWh	4.7% p.a.
Egypt	42 TWh (0.7 MWh/person)	182 TWh (1.9 MWh/person)	412 TWh	5.6% p.a.
Jordan	4 TWh (1.0 MWh/person)	19 TWh (2.1 MWh/person)	36 TWh	4.4% p.a.
Libya	10 TWh (2.1 MWh/person)	38 TWh (6.0 MWh/person)	109 TWh	7.3% p.a.
Morocco	10 TWh (0.4 MWh/person)	31 TWh (0.9 MWh/person)	67 TWh	5.2% p.a.
Saudi Arabia	69 TWh (4.2 MWh/person)	338 TWh (10.7 MWh/person)	465 TWh	2.1% p.a.
Tunisia	6 TWh (0.7 MWh/person)	20 TWh (1.7 MWh/person)	32 TWh	3.2% p.a.

^aInternational Energy Agency (2018).^bDerived from Arab Union of Electricity (2018), information on population from The world bank (2019c)**Fig. 7.** Full load hours from solar PV and wind turbines vs. technical potentials of electricity production.**Table 18**
Targeted power generation in 2030; RE capacity targets vs. RE share targets.

	Electricity from RE in 2030 (Compliance with RE capacity targets Table 4)				Achievement of RE share targets through capacity targets ^a	RE share in electricity generation (Compliance with 2030 RE capacity targets Table 4)
	PV	CSP	Wind-turbine	Total		
Annual electricity in TWh/a						
Algeria	29	6	19	53	104%	39%
Egypt	-	-	-	-	-	-
Jordan	-	-	-	-	-	-
Libya	2	1	3	6	56%	6%
Morocco	-	-	-	-	-	-
Saudi Arabia	33	73	62	164	-	35%
Tunisia	9	-	14	9	95%	29%

^aA value smaller 100% indicates that RE capacity targets are too low to achieve RE share targets vice versa.

Table 17

Power generation from renewable energies in 2030 according to RE share targets.

	Electricity from RE in 2030 (Compliance with RE share targets Table 3)	2030 RE electricity normalized by increase of electricity demand between 2015 and 2030
Algeria	51 TWh (1.2 MWh/person ^b)	93%
Egypt	144 TWh (1.5 MWh/person ^b)	78%
Jordan	8 TWh (0.8 MWh/person ^b)	60%
Libya	11 TWh (2.2 MWh/person ^b)	18%
Morocco	35 TWh (1.0 MWh/person ^b)	122%
Saudi Arabia	–	(168%) ^a
Tunisia	9 TWh (0.8 MWh/person ^b)	102%

^aValue based on RE share derived from RE capacity targets.

^bRelated to population in 2017 with data from [The world bank \(2019c\)](#).

6.2. Cost

6.3. Use of (RE) resource

Electricity production uses finite RE resources (e.g. limited by land resources). The resulting technical potentials for RE electricity production are shown in [Fig. 7](#) given as end points of the graphs. The potentials are presented for wind turbines of IEC III (low mean wind speeds) and IEC I/II (medium to high wind speeds) as well as for PV systems. These technical potentials for electricity production correlate with the size of the countries; i.e., countries with a large surface area such as Algeria, Egypt, and Saudi Arabia show higher potentials in the range of hundred PWh/a for all three technologies together. For smaller countries such as Jordan and Tunisia several PWh/a result. In general, the potential for electricity from PV systems exceeds the potential from wind by a factor of 5 and more. The potential per person ranges from nearly several hundred MWh/(person a) in Tunisia to several ten GWh/(person a) in Libya.

[Fig. 8](#) shows the related full load hours in a descending order. While the full load hours of PV systems only slightly decrease with an increasing exploitation of the potential (x-axis), the wind systems show a sharper decrease. The reason is that the difference in between wind availability differs more significantly than the solar irradiation.

The technical potential for electricity production exceeds the electricity consumption by two to three orders of magnitude. The expected generation of electricity in 2030 lays in the range of hundreds of TWh/a in larger countries and several TWh/a in smaller countries ([Table 16](#)). Thus, the RE targets for 2030 can be satisfied without a strong utilization of the available potential. RE capacities could be installed in locations with very beneficial RE availability and still high potentials with similar beneficial conditions would remain untouched.

First, the costs for electricity production are discussed on the basis of LCOE for individual technologies in 2030. Then, aggregated national electricity cost and changes related to the fulfilment of RE targets are discussed.

- PV power generation. [Fig. 8](#) shows spatially resolved LCOE estimations for 2030 for electricity from PV systems. The respective LCOE varies between 28 and 47 €/MWh being a factor of 1.5 between lowest and highest cost. There is a

clear trend that areas with the highest cost category (34 to 47 €/MWh) are in the northern regions of Morocco, Algeria, and Tunisia. Remaining cost categories show only small deviations (28 to 34 €/MWh). As a general trend, lower generation cost can be achieved in southern areas due to higher solar radiation in average. Production from PV for as low as ca. 30 €/MWh can be realized in a range of several PWh for all considered countries.

- Wind power generation. [Fig. 9](#) shows spatially resolved LCOE estimates for 2030 for electricity production from wind turbines. In general, costs for electricity from wind turbines is higher compared to PV systems and starts at ca. 40 €/MWh at beneficial locations. The distribution of the respective LCOE covers a wide range from 38 to 222 €/MWh. Areas with highest cost between 94 and 222 €/MWh are located in the north of Morocco, in the west of Jordan and at the south-west coast of Saudi Arabia. Lowest LCOE can be found at the southern coast of Morocco and in the central region of Algeria. However, regions with low costs are scattered and each of the considered countries except for Jordan show locations in the cost category from 45 to 55 €/MWh. There is no clear trend between low wind locations and high or low cost. Jordan and Saudi Arabia show predominantly locations with low wind locations.
- Fossil fuel power generation. [Fig. 10](#) shows estimations on electricity production by power plants burning fossil fuel energy. The LCOE clearly reflects if a country is a net-fossil energy importer or exporter.
 - In net-exporting countries, electricity generation costs ca. 30 €/MWh or even down to approximately 20 €/MWh for electricity production in combined cycle power plants. The fuel costs contribute roughly 31% for the more efficient combined cycle power plants and with up to 60% for turbines. Due to lower specific energy cost for natural gas compared to oil, the costs are slightly lower for natural gas fired power plants.
 - For net-importing countries, the LCOE are significantly higher: fuel oil and natural gas fired power plants show costs between 76 and 108 €/MWh and between 49 and 58 €/MWh, respectively.

Comparing the LCOE for electricity produced using RE and fossil fuel energy, the picture is quite clear.

- For net-fossil energy exporting countries, power plants burning natural gas or fuel oil produce electricity for lower LCOE. Neither electricity produced in wind turbines nor from PV systems can compete economically with the low fuel cost being below the global energy price level.
- For net-fossil energy importing countries, the picture is opposite. Especially PV systems provide electricity for lower LCOE in most locations. PV electricity cost are even lower than the fuel cost of all fossil fuel fired power plants. This means that only the operation of fossil fuel fired power plants causes higher cost than generating electricity by PV systems. So even power plants where the capital cost are paid off provide electricity at higher cost. Also, electricity produced from wind turbines located in beneficial wind locations can provide electricity competitive with electricity produced from natural gas.

[Fig. 11](#) shows estimated levelized electricity costs in MENA countries in 2017. Net-fossil energy importing countries produce electricity in 2017 at significantly higher cost in the range of 59 to 65 €/MWh compared to net-fossil energy exporting countries

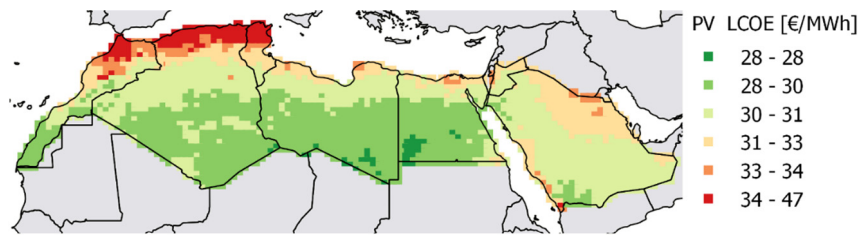


Fig. 8. Estimations of levelized cost of electricity (LCOE) in 2030 produced from solar PV.

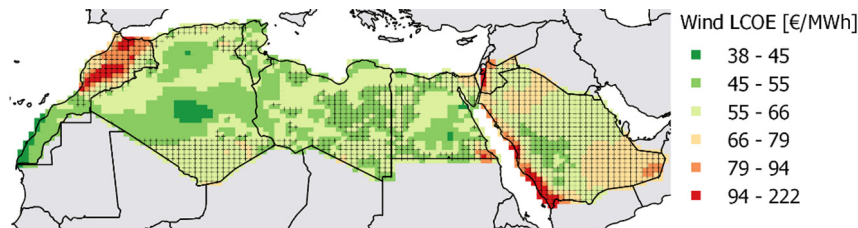


Fig. 9. Estimations of levelized cost of electricity (LCOE) in 2030 produced from wind turbines. Locations marked with a cross indicate where low wind speed turbines are applied.

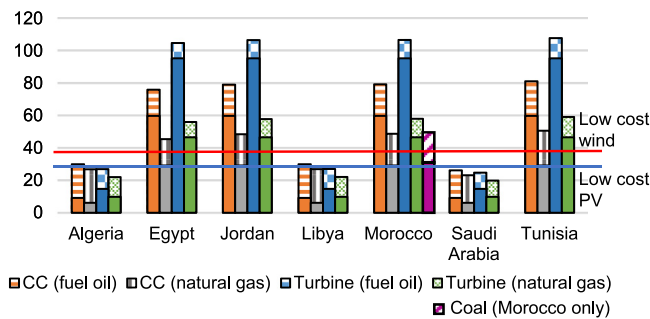


Fig. 10. Estimations of levelized cost of electricity (LCOE) in 2030. CC stands for combined cycle power plants. Dashed parts indicate share of fuel cost.

with 26 to 29 €/MWh. This can be explained by significantly lower fuel cost. Tunisia shows lowest electricity cost from all net-importing countries and nearly all costs are caused through electricity production based on natural gas. Remaining importing countries produce electricity at comparable cost.

Fig. 11 also shows the electricity cost if the RE share targets are fulfilled in 2030 by only one RE option. In the case “PV only RE”, all additionally required RE electricity will be provided by PV systems only and in the case “wind only PV”, all additional RE electricity will come from wind turbines solely. In reality, most likely a mix of both technologies would be utilized. The figure shows that electricity cost in net-fossil energy exporting countries increase while the cost for countries importing fossil fuels increase. The change in the cost indicates how ambitious the RE targets are. For Libya seeking to generate only 13% of their electricity from RE by 2030, the change in the total cost are low. Saudi Arabia and Morocco show ambitious targets and thus the impact on electricity cost are higher. For Saudi Arabia the relative high difference between the cases PV and wind only reflect that Saudi Arabia shows less beneficial wind conditions for power generation.

6.4. GHG emissions

Below the GHG emissions related to electricity production are first discussed on a basis of individual power generation technologies. Then a discussion on national electricity related GHG emissions and changes related to the fulfilment of RE targets follows.

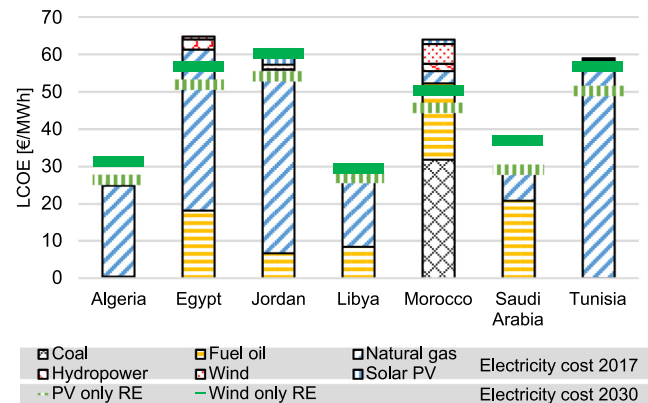


Fig. 11. Estimated total levelized cost of electricity (LCOE) in 2017 and 2030 if RE share targets are satisfied (for Saudi-Arabia a RE share target of 35% is assumed).

Fig. 12 shows GHG emissions caused by electricity generation based on natural gas, fuel oil and coal. Combined cycle power plants show the lowest GHG emissions per unit of electricity because the efficiency is relatively high. Additionally, if natural gas is used instead of fuel oil, resulting GHG emissions are lower. Thus, the lowest GHG emissions of approximately 375 to 395 g_{CO2e}/kWh result from electricity from combined cycle power plants running on natural gas. These values do not differ significantly between different MENA countries. Combined

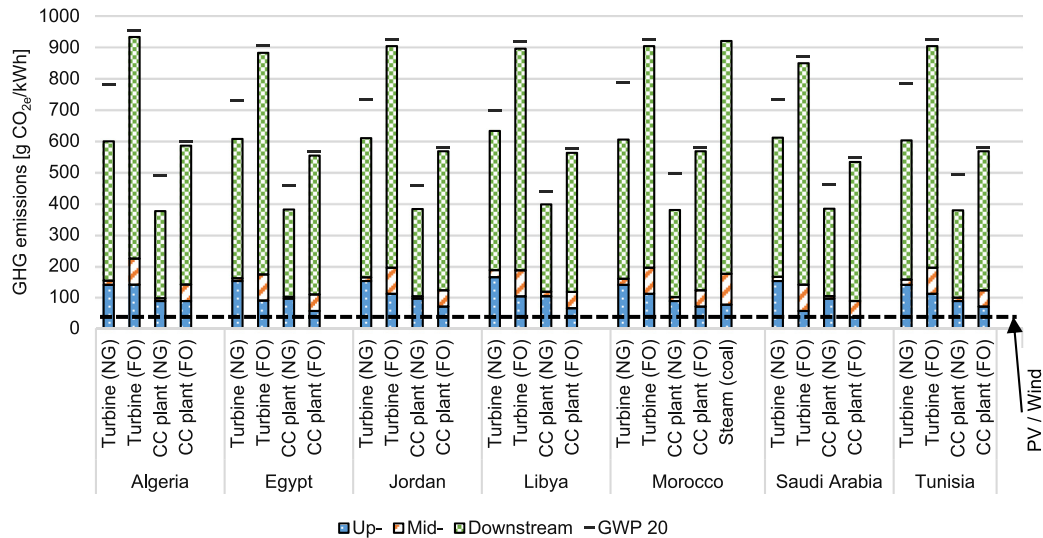


Fig. 12. Estimated greenhouse gas (GHG) emissions for electricity production in turbine or combined cycle (CC) power plants burning natural gas (NG) or fuel oil (FO). Bars are based on Global Warming Potentials (GWP) for 100 years. The line “GWP 20” gives GHG values with a 20 years horizon. The dashed line shows GHG emissions of electricity production from PV/Wind.

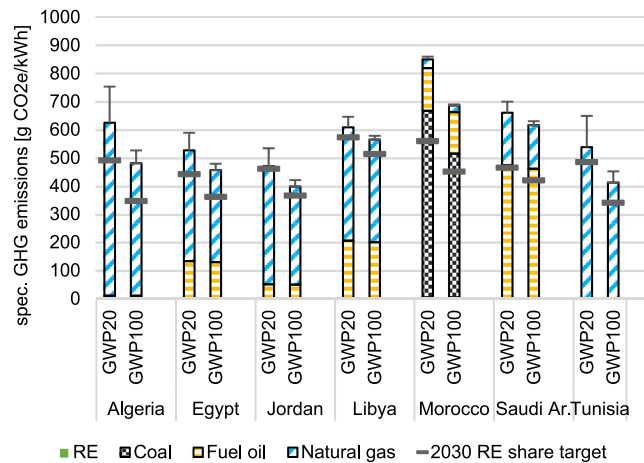


Fig. 13. Estimated GHG emissions for electricity generation and its share by used fuel in 2017. Error bars reflect a +60% methane emissions for production and processing. The line “2030 RE share target” shows GHG emissions in the case that the 2030 RE share targets are met (for Saudi Arabia target of 35% of RE is assumed).

cycle power plants using fuel oil cause similar GHG emissions with 535 to 585 g_{CO_{2e}}/kWh as turbines using natural gas (600 to 610 g_{CO_{2e}}/kWh) in all countries. Turbines on fuel oil and steam power plants in Morocco cause similar emissions of 850 to 920 g_{CO_{2e}}/kWh. If GHG emissions are calculated with GWP 20 values, power plants based on natural gas and fuel oil emit rather similar GHG; i.e., GHG emission “benefits” of using natural gas stay but shrink, if rather near future effects on the climate are considered. As indicated by a dashed line, GHG emissions caused by electricity production by wind or PV systems are substantially lower; 31 g_{CO_{2e}}/kWh and lower.

Fig. 13 shows specific GHG emissions related to the electricity production in 2017 considering GWP for 20 and 100 years. In the case of GWP 20 (100 years) emissions are in the range of 468 g_{CO_{2e}}/kWh (396 g_{CO_{2e}}/kWh) in Jordan and 845 g_{CO_{2e}}/kWh (682 g_{CO_{2e}}/kWh) in Morocco. The emissions related to GWP 100 years are on average ca. 15% lower. Morocco shows highest specific GHG emissions for electricity generation although it has the highest share of electricity from renewable energy with 8% in 2017. Compared to that, electricity production in Tunisia causes among the smallest GHG emissions although only 2% of electricity is produced from RE. This is partly due to the selection of energy

carrier: 45% of electricity in Morocco is produced from coal power plants emitting more than 900 g_{CO_{2e}}/kWh. Only 10% of electricity comes from natural gas power plants emitting 30 to 60% less GHG emissions (for comparison, electricity production in Europe (EU 28) caused on average 407 g_{CO_{2e}}/kWh in 2013 (Moro and Lonza, 2018)). GHG emissions from RE are negligibly low in all countries.

The error bars in Fig. 13 indicate a case, where methane emissions in the oil and gas industry are 60% higher because it has been shown that the actual methane emissions caused by the oil and gas industry are ca. 60% higher in the US compared to standard values (Alvarez et al., 2018). The dominant source of these clearly increased emissions are potentially abnormal operations (Alvarez et al., 2018). A risk of higher GHG emissions due to methane emissions exists especially for countries with a high share of electricity from natural gas (i. e. Algeria and Tunisia). The impact of methane on the GHG emissions is substantially higher in GWP 20 terms and up to an additional 128 g_{CO_{2e}}/kWh would result for Algeria if methane emissions are 60% higher than assumed.

Fig. 13 also shows the GHG emissions for 2030, if the RE share targets of the countries are fulfilled and the fossil power plant fleet operates similar to 2017. As electricity production

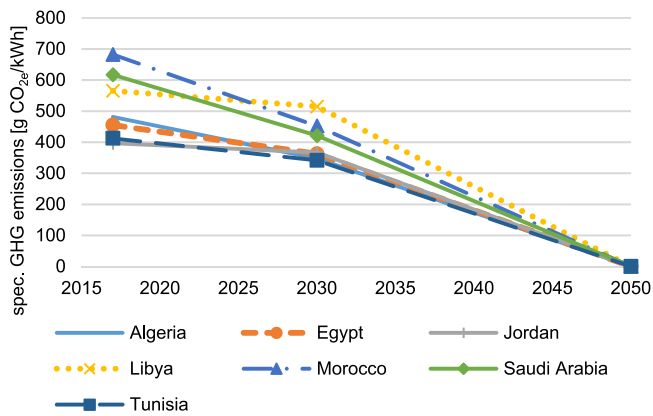


Fig. 14. Estimated GHG emissions (GWP 100) for electricity generation over time; 2017 emissions are derived based on actual data; 2030 assumes that “RE share target” and 2050 that Paris Agreement is met- (for Saudi Arabia target of 35% of RE in 2030 is assumed).

from RE increases in all countries, specific GHG emissions decrease. Electricity production in Algeria, Egypt, Jordan and Tunisia would result in lowest and similar GHG emissions with 440 to 490 g_{CO_2e}/kWh (330 to 350 g_{CO_2e}/kWh) in a GWP 20 (100 year perspective). Morocco, although it targets highest RE share, GHG emissions related to electricity production are still higher due to the operation of e.g. coal fired power plants. GHG emissions caused by RE are below 3% in all countries.

Fig. 14 shows the decline of specific GHG emissions between 2017 and 2030 if the RE share targets are met. For 2050 nearly zero GHG emissions are necessary to fulfil the 2 °C targets of the Paris Agreement (Rockström et al., 2017), that all MENA countries signed. All countries must increase their efforts to decrease GHG emissions of electricity supply drastically after 2030 in order to reach climate change targets. Even Morocco and Saudi Arabia that target the strongest decline in the period 2017–2030 with - 18 and - 15 $g_{CO_2}/kWh/a$ on average, must increase efforts. Increasing the RE targets for 2030 would decrease the pressure for GHG emission mitigation measures afterwards and should therefore be considered.

7. Final consideration

All MENA countries target to expand the use of RE within the power sector. Important drivers are the expected growth in electricity demand requiring an expansion of the power plant park anyway. Additionally, the MENA countries have large areas suitable for an electricity production from RE sources characterized by a beneficial wind respectively solar supply that make low cost electricity production possible. Additionally, electricity based on RE can be produced with low GHG emissions. Thus, RE expansion is a measure to fight climate change.

Within this context, this paper assesses the national renewable power targets and investigates the impact on the current power sector. The following main findings can be drawn from the assessment:

- Current plans target an expansion of RE approximately covering the expected electricity demand growth. Only Libya’s RE targets are significantly lower. However, this must be seen in the context of the current political instability. Also the RE targets in Jordan cover only 60% of the expected demand growth. But the current RE expansion in this country is comparatively high and Jordan is a forerunner in this field in the region.

- The current expansion of RE in Jordan and Morocco are in line with respective RE target for 2030. Saudi Arabia lately announced several RE projects and the expansion is gaining pace. However, in all other countries the increase of expansion must accelerate in order to reach the self-defined targets.
- The technical potential for RE electricity sets no borders. For all countries it is in the range of several PWh/a. Thus, the available potential exceeds the demand by at least one order of magnitude. Therefore, even sufficient locations are available providing very beneficial RE resources if the RE electricity demand is clearly increased significantly and/or electricity is exported. Especially high solar radiation for PV power generation is available in many locations. But, also promising wind locations are available in most countries.
- From an economic point of view, RE technologies provide electricity at lower cost than producing electricity in power plants operated on fossil fuel energy, if international fuel prices need to be paid and if they stay in a similar range as in 2017. Electricity from PV systems and wind turbines costs even less than the cost for fuel oil or natural gas only, i. e. without capital cost for the power plant (combined cycle and turbines). If this holds true also in a detailed, location specific analysis and technical restrictions allow that, the fossil plant should be replaced. From an economic perspective RE targets should be increased if possible. Even if fuel can be produced from domestic resources and fuel cost are in the range of extraction cost, solar PV systems are close to cost parity in 2030.
- Deploying renewable energies for electricity production decreases the specific GHG emissions. However, the choice of fuel has a significant impact. Even though Morocco shows highest ambitions of renewable energy deployment with 52% in 2030, estimated specific GHG emissions are still higher than in many other countries of the region as a substantial share of electricity is produced from coal in Morocco. Other countries like Tunisia mainly use natural gas and show lower ambitions for RE development. However, electricity causes lower specific GHG emissions. Thus, if lower GHG emissions are targeted, higher RE shares but also a switch in fuel can have a significant impact.
- The efforts to decrease GHG emissions must increase significantly in all MENA countries. Planned emission reductions under existing policy targets, even if fulfilled, are not sufficient to reach the targets of the Paris Agreement.

In general, MENA countries should reconsider current renewable energy targets for their electricity sector. Very beneficial resources are available allowing for an economic electricity production from renewable sources of energy. Furthermore, increasing the use of wind and solar power could further reduce the still significant GHG emissions from the electricity sector until 2030 and lead to additional economic benefits for the overall economy.

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