



Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling

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Received: 17 July 2018 / Accepted: 27 January 2019 / Published online: 13 February 2019

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Abstract

Pathways for achieving the 1.5–2 °C global temperature moderation target imply a massive scaling of carbon dioxide (CO₂) removal technologies, in particular in the 2040s and onwards. CO₂ direct air capture (DAC) is among the most promising negative emission technologies (NETs). The energy demands for low-temperature solid-sorbent DAC are mainly heat at around 100 °C and electricity, which lead to sustainably operated DAC systems based on low-cost renewable electricity and heat pumps for the heat supply. This analysis is carried out for the case of the Maghreb region, which enjoys abundantly available low-cost renewable energy resources. The energy transition results for the Maghreb region lead to a solar photovoltaic (PV)-dominated energy supply with some wind energy contribution. DAC systems will need the same energy supply structure. The research investigates the levelised cost of CO₂ DAC (LCOD) in high spatial resolution and is based on full hourly modelling for the Maghreb region. The key results are LCOD of about 55 €/t_{CO₂} in 2050 with a further cost reduction potential of up to 50%. The area demand is considered and concluded to be negligible. Major conclusions for CO₂ removal as a new energy sector are drawn. Key options for a global climate change mitigation strategy are first an energy transition towards renewable energy and second NETs for achieving the targets of the Paris Agreement.

Keywords Negative emission technology · CO₂ direct air capture · Energy transition · 100% renewable energy · Maghreb

1 Introduction

Recent research clearly indicates that 1.5–2 °C global temperature moderation pathways include fast and deep defossilisation of all energy sectors globally. However, past and present greenhouse gas (GHG) emissions are not compatible with directly achieving the target.

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Negative carbon dioxide (CO₂) emission technologies (NETs) are required to achieve the ambitious targets of the United Nations Framework Convention on Climate Change 21st Conference of the Parties, the Paris Agreement, (UNFCCC 2015) within this century. Kriegler et al. (2017) quantified the negative emission demand at around 10 Gt_{CO₂} in the 2050s, reaching about 20 Gt_{CO₂} later in the second half of the twenty-first century, which implies a need to start scaling up the NET capacities in the late 2030s and for massive investments in the 2040s.

Most integrated assessment models (IAMs) strongly rely on bioenergy carbon capture and storage (BECCS) while typically ignoring CO₂ direct air capture (DAC), as recently documented by Rogelj et al. (2018) and criticised by Williamson (2016) and further confirmed by the Intergovernmental Panel on Climate Change (IPCC) SR1.5 (2018). Nevertheless, the substantial obstacles for BECCS (Harper et al. 2018; Fajardy and Dowell 2018; Fridahl and Lehtveer 2018; King and Bergh van den 2018) may not allow a massive scale-up, since huge land areas are needed due to very low area efficiency, rise of water stress issues, low energy return on energy invested induce a burden for the entire energy system, the high cost of bioenergy-based solutions and last but not least societal barriers are expected to be substantial. And last but not least, BECCS as a base generation technology would have not much added value for an energy system mainly based on low-cost variable renewable energy (VRE) (Dowell and Fajardy 2017), i.e. solar photovoltaics (PV) and wind energy, which require flexibility and not an inflexible base generation. Recent research clearly indicates that future energy systems will be mainly based on very high shares of VRE, as pointed out by Jacobson et al. (2017), and can be even lower in cost than the present energy system as further emphasised by Breyer et al. (2018). The IPCC SR1.5 report (IPCC 2018) confirmed for the first time that 100% renewable energy (RE)-based systems shall be seriously taken into account. Brown et al. (2018) pointed out the technical feasibility and economic viability of 100% RE systems, in particular for the power sector. Sustainable bioenergy solutions are confirmed by most researchers in the field of high renewable shares (Breyer et al. 2018; Brown et al. 2018; Child et al. 2018), but not by all (Jacobson et al. 2017). A common view has been developed that full hourly resolution of energy system description is a required methodology of the best possible validation of results for highly renewable energy systems (Breyer et al. 2017a, 2018; Brown et al. 2018; Pursiheimo et al. 2018; Jacobson et al. 2018). The long underestimated role of VRE in climate change mitigation (Breyer et al. 2017a) may explain why electricity-based DAC solutions have not been much regarded in IAMs. However, recent progress in adopting real-world development in VRE, as initiated by Creutzig et al. (2017), may trigger more focus on DAC and also on IAMs for evaluating a more balanced solution space in the near future. This paper aims to examine the feasibility of renewable electricity-based DAC solutions.

DAC technology is on the rise in the debate on suitable NET options (Williamson 2016; Goepfert et al. 2012; Workman et al. 2011; Smith et al. 2016). DAC can combine several key features, in particular an excellent area footprint for large-scale deployment, no major conflicts with land use and an excellent match to the renewable electricity-based energy system of the future (Fasihi M, Efimova O, Breyer Ch. Techno-economic assessment of CO₂ direct air capture plants, submitted), which will be mainly based on solar PV and wind energy (Jacobson et al. 2017; Breyer et al. 2018). This implies additional key advantages, such as very low-cost energy supply, good energy system integration, access to areas of excellent energy resources and the potential to decouple the locations of DAC and electricity generation, if needed.

In the following sections, this research will focus on the Maghreb region with its excellent preconditions for low-cost RE and vast tracks of unused land. The preferred RE supply for DAC also matches the electricity supply in the region as supported by respective energy system

transition analyses. The DAC cost is mainly presented for 2040 and 2050 considerations as the estimated scale-up years of the technology. It is emphasised that this analysis is the first to the knowledge of the authors based on full hourly and high spatial resolutions of the entire DAC system so that a deeper understanding of the required system design can be gathered.

2 Methodology

The LUT Energy System model of LUT University is used to analyse RE-based DAC systems in the Maghreb region. The LUT model combines full hourly resolution and coverage of the world structured into 145 regions (Breyer et al. 2017a, 2018; Ram et al. 2017a), whereof the Maghreb region is highlighted in this research. This section is divided into the methodology for all relevant DAC aspects and a brief overview on the LUT Energy System Transition modelling.

2.1 CO₂ direct air capture system modelling

Low-temperature solid-sorbent CO₂ DAC units have been used in this system modelling according to Fasihi et al. (Fasihi M, Efimova O, Breyer Ch. Techno-economic assessment of CO₂ direct air capture plants, submitted). Such a system consists of a single unit with solid sorbent to capture and release CO₂ through temperature swing adsorption (Kulkarni and Sholl 2012). Several companies, such as Climeworks and Global Thermostat, are already running pilot or commercial plants of such technology (Climeworks 2018; Global Thermostat 2018; Ping et al. 2018). The DAC units require electricity and heat at about 100 °C for CO₂ capture and regeneration. The heat is provided by means of electrical compression heat pumps (HP) and can be balanced or stored in thermal energy storage (TES) before consumption. Depending on the applied technology, water moisture in the air could be also captured as a by-product of the system. As illustrated in Fig. 1, fixed tilted and single-axis tracking PV power plants and wind power plants are used for electricity generation. Stationary batteries are used to balance the electricity output and extend the period of power availability. The specifications of the power sector and other components for the years 2040 and 2050 are provided in Tables 1 and 2, respectively.

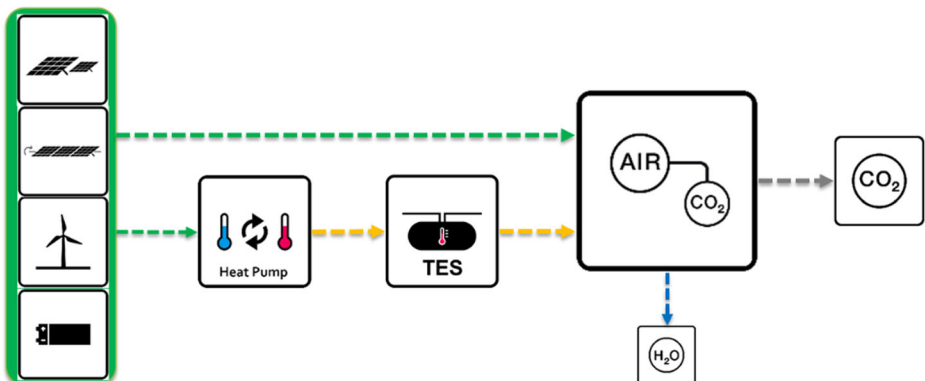


Fig. 1 The hybrid PV-wind-battery-DAC value chain

Table 1 Power sector key specifications

Device	Unit	2040	2050	Ref.
PV fixed tilted				ETIP-PV (2017); Breyer et al. (2018)
Capex	€/kW _p	300	246	
Opex _{fix}	€/kW _p	8.8	7.4	
Lifetime	Years	40	40	
PV single-axis tracking				ETIP-PV (2017); Bolinger and Seel (2016); Breyer et al. (2018)
Capex	€/kW _p	330	271	
Opex _{fix}	€/kW _p	10	8	
Lifetime	Years	40	40	
Wind energy (onshore)				Breyer et al. (2018)
Capex	€/kW _p	940	900	
Opex _{fix}	€/kW _p	18.8	18	
Lifetime	Years	25	25	
Battery				Breyer et al. (2018); Hoffmann (2014); Schmidt et al. (2017); Kittner et al. (2017)
Capex	€/kWh _{el}	100	75	
Opex _{fix}	€/(kWh·a)	2.5	1.875	
Opex _{var}	€/kWh	0.0002	0.0002	
Cycle efficiency	%	95	95	
Energy to power ratio	h	6	6	
Lifetime	Years	20	20	

According to Fasihi et al. (Fasihi M, Efimova O, Breyer Ch. Techno-economic assessment of CO₂ direct air capture plants, submitted), to capture 1 metric tonne of CO₂ from the ambient air in 2050, on average, 182 kWh of electricity and 1102 kWh of heat are needed. These electricity and heat demands are periodical. However, in a large-scale modular system, the timing of DAC units could be adjusted for somewhat more steady electricity and heat demands for the system as a whole. This would lead to lower electricity and heat storage demands. In addition, the change in the available electricity or heat would not affect all the units as they could be switched on and off, one by one. A coefficient of performance (COP) of 3 has been

Table 2 DAC and heat sector key specifications

Device	Unit	2040	2050	Ref.
CO ₂ direct air capture plant				Fasihi et al. (Fasihi M, Efimova O, Breyer Ch. Techno-economic assessment of CO ₂ direct air capture plants, submitted)
Capex	€/(t _{CO2} ·a)	234	196	
Opex	% of capex p.a.	4	4	
Lifetime	Years	30	30	
Electricity demand	kWh _{el} /t _{CO2}	203	182	
Heat demand	kWh _{th} /t _{CO2}	1286	1102	
Electrical compression heat pump				DEA (2016)
Capex	€/kW _{th}	554	530	
Opex _{fix}	€/kW _{th}	2	2	
Opex _{var}	€/kWh _{th}	0.00163	0.00161	
Lifetime	Years	25	25	
COP	–	3	3	
Thermal heat storage				Breyer et al. (2017b)
Capex	€/kWh _{th}	20	20	
Opex _{fix}	€/kWh _{th}	0.3	0.3	
Cycle efficiency	%	0.9	0.9	
Self-discharge	%/h	0.2	0.2	
Energy to power ratio	h	12	12	
Lifetime	Years	30	30	

assumed for the heat pump, as a global average number. However, a higher COP is also achievable for the climate of the Maghreb region.

Equations (1)–(4) below are used to calculate the levelised cost of electricity (LCOE), the levelised cost of heat (LCOH), the levelised cost of CO₂ DAC (LCOD) and the subsequent value chain. Abbreviations are as follows: capital expenditures, Capex; annuity factor, crf; annual operational expenditures, Opex; fixed, fix; variable, var; annual CO₂ production output of DAC plant, Output_{CO₂}; full load hours per year, FLh; electricity demand of DAC plant per t_{CO₂} produced, DAC_{el.input}; heat demand of DAC plant per t_{CO₂} produced, DAC_{th.input}; fuel costs, fuel; efficiency, η ; coefficient of performance of heat pumps, COP; weighted average cost of capital, WACC; lifetime, N . A WACC of 7% is used for all the calculations in this study.

$$\text{LCOE} = \frac{\text{Capex} \cdot \text{crf} + \text{Opex}_{\text{fix}}}{\text{FLh}} + \text{Opex}_{\text{var}} + \frac{\text{fuel}}{\eta} \quad (1)$$

$$\text{LCOH} = \frac{\text{Capex} \cdot \text{crf} + \text{Opex}_{\text{fix}}}{\text{FLh}} + \text{Opex}_{\text{var}} + \frac{\text{fuel}}{\eta} + \frac{\text{LCOE}}{\text{COP}} \quad (2)$$

$$\text{LCOD} = \frac{\text{Capex}_{\text{DAC}} \cdot \text{crf} + \text{Opex}_{\text{fix}}}{\text{Output}_{\text{CO}_2}} + \text{Opex}_{\text{var}} + \text{DAC}_{\text{el.input}} \cdot \text{LCOE} + \text{DAC}_{\text{th.input}} \cdot \text{LCOH} \quad (3)$$

$$\text{crf} = \frac{\text{WACC} \cdot (1 + \text{WACC})^N}{(1 + \text{WACC})^N - 1} \quad (4)$$

2.2 LUT Energy System Transition model

A linear programming model, called the LUT Energy System Transition model (Breyer et al. 2018; Bogdanov and Breyer 2016), was designed and developed to analyse 100% RE systems for the period of 2015 to 2050 in 5-year time steps using a multi-nodal approach. The model can be used to examine the effects of combining various RE and energy storage technologies to match a load demand throughout a year. The main objective of the model is to minimise the total annualised system costs by optimising elements of an energy system. The energy model enables the simulation of an energy system for different geographical areas, from local to global scale. Weather data with hourly temporal and $0.45^\circ \times 0.45^\circ$ (roughly $50 \times 50 \text{ km}^2$) spatial resolutions have been utilised based on National Aeronautics and Space Administration (NASA) data (Stackhouse 2008, 2009) which have been reprocessed by the German Aerospace Center (Stetter 2012). Two samples of high spatially–temporally resolved data, representing solar single-axis tracking PV and onshore wind for Morocco, are shown in Fig. 2. The model includes four technological categories: electricity generation, energy storage, energy sector bridging and electrical power transmission. All technologies work in a chain to balance the energy system for every hour of a year. A list of RE technologies for electricity generation, energy storage technologies and transmission options for the power sector is presented in Fig. 3. It is important to highlight that the model can be applied to all energy sectors, such as seawater desalination, heating, transport and industry. So far, the model has been utilised for power, desalination and non-energetic industrial gas sectors (Breyer et al. 2017a; Kilickaplan et al. 2017). The desalination sector meets the necessary water demand through the optimised use of seawater reverse osmosis and multiple-effect distillation plants.

The non-energetic industrial gas sector covers the required non-energetic gas demand for industry using synthetic natural gas (SNG) and bio-methane.

The system also includes prosumers that can provide their own electricity using rooftop solar PV and battery storage. The prosumers can contribute a maximum of 20% towards total electricity demand in the power sector. It is defined that the total prosumer demand should be met over the transition period, but not in the first time step. The maximum share of prosumers can go up by the following share starting from 2020, or the first year of positive PV prosumers economics: 6%, 9%, 15%, 18% and 20%. If self-generation is profitable for prosumers during the first time step, the share will increase accordingly in the next time step. Otherwise, the maximum share remains unchanged. It should be noted that a constraint has been applied to block new fossil fuel and nuclear power installations after 2015. An exception is applied for gas turbines, since their fossil fuel can be gradually shifted to renewable forms of methane. However, the current capacities can be involved in electricity generation until the end of their lifetimes. Another constraint is that the share of RE-installed capacity, from the total generation capacity, can only increase by a maximum of 4% per year. The first 5-year time step, however, is limited to a 15% limit. The reason for having this constraint is to avoid excessive disruption to the power system. A further description of the model, mathematical equations and technical and financial assumptions can be found in (Breyer et al. 2018; Bogdanov and Breyer 2016).

3 Results

This section is divided into results for the CO₂ DAC system modelling and the energy system transition towards full sustainability in the power sector for the Maghreb region.

3.1 CO₂ direct air capture system modelling

The results for the CO₂ DAC system modelling for the case of the Maghreb region are presented in the following, mainly for the two decisive cost years of 2040 and 2050, and highlighting some of the most relevant system aspects of the full hourly modelling. As depicted for the case of Morocco (Fig. 2), the input data for solar PV and wind energy are in full hourly resolution, and the data are used in that resolution for every $0.45^\circ \times 0.45^\circ$ of area, which enables not only a high temporal but also high spatial resolution.

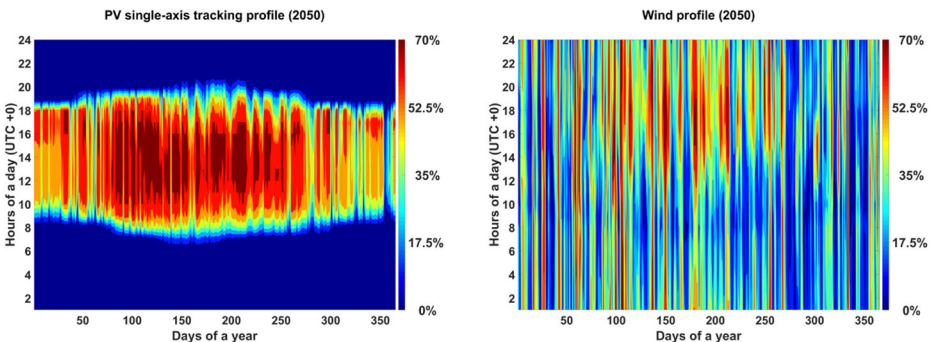


Fig. 2 Aggregated feed-in profiles for solar single-axis tracking PV (left) and onshore wind (right) for Morocco. The weather data used are real data from the year 2005, used for the years in the future. The percentage values show the actual yield of the plants normalised to the nameplate capacity

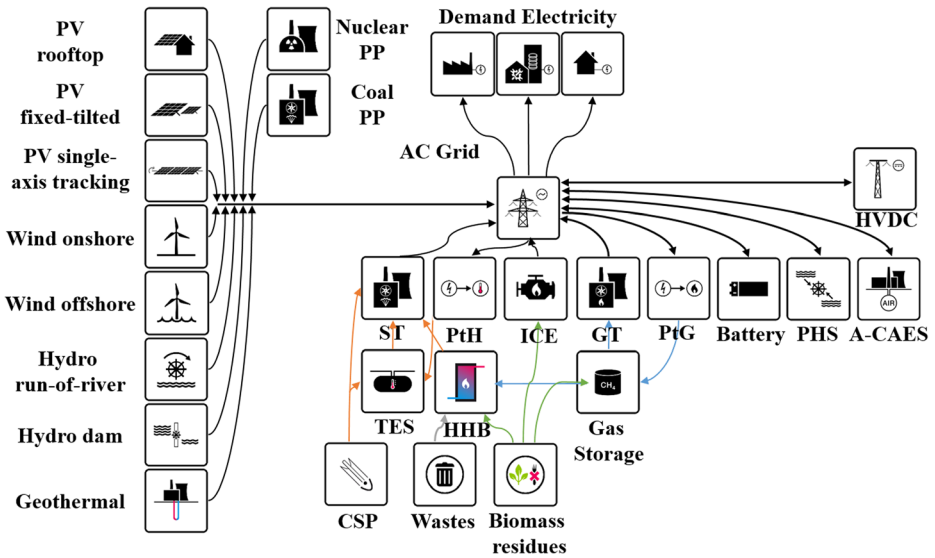


Fig. 3 The schematic diagram of the LUT Energy System Transition model for the power sector (Breyer et al. 2018). Power plants (PP), alternating current (AC), high-voltage direct current (HVDC), steam turbine (ST), power-to-heat (PtH), internal combustion engine (ICE), gas turbine (GT), pumped hydro energy storage (PHS), adiabatic compressed air energy storage (A-CAES), thermal energy storage (TES), hot heat burner (HHB), concentrating solar thermal power (CSP)

The steep cost decline of solar PV systems and supporting battery systems leads to very high solar PV electricity supply shares for the CO₂ capturing system, which is visualised in Fig. 4. Such systems can be regarded as a special type of Power-to-X facilities (Vidal Vázquez et al. 2018), which could be denoted as Power-to-CO₂ or in short PtCO₂, as used in several of the following diagrams. Since the relative cost decline of solar PV and battery systems is significantly steeper than that for wind energy, one can also observe a relative shift towards higher solar PV shares of optimised electricity supply plants from 2040 to 2050.

The dominating solar PV electricity supply share is enabled by both very low-cost solar PV systems and battery systems, since battery systems are mainly used to increase the moderate solar PV full load hours (FLh) to levels close to base generation conditions. This implies that about 50% of electricity supply for DAC system components (mainly DAC itself and HP units for low-cost heat supply) is provided by discharging batteries, which had been charged before by solar PV systems. Figure 5 visualises this for the case of 2050. Thermal energy storage, which is also part of the total DAC system design, helps further lift the total DAC system FLh as a means of further cost reduction.

The substantial relative capex requirements of DAC units lead consequently to high DAC FLh for overall optimised levelised cost of CO₂ DAC (LCOD), which can be achieved by a very high utilisation of the DAC capacity. The same can be observed for the operation of HP units, for the same reason. Battery systems enable the almost continuous operation of the DAC and HP units, whereas low-cost TES helps to further optimise the relative capacity demand, in particular for the HP units. The cost-optimised FLh for operating the DAC and HP units are visualised in Fig. 6. Almost no difference for cost-optimised FLh could be observed for the cost years 2040 and 2050, which emphasises the substantial need for high FLh for least cost solutions. DAC FLh were expected to be more flexible in 2050 than in 2040, as the capex

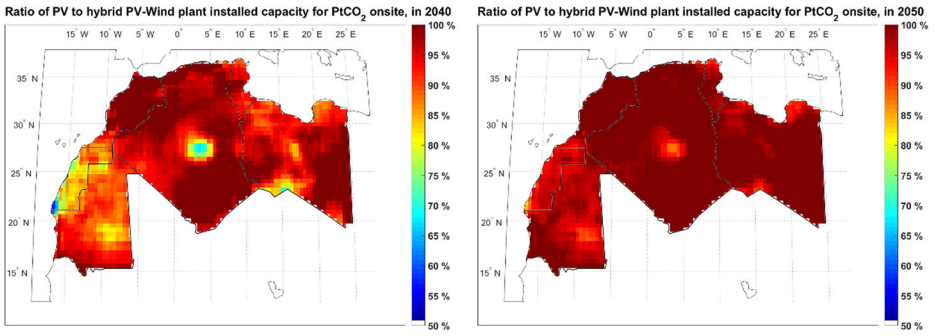


Fig. 4 Ratio of PV generation to total hybrid PV-wind plant electricity generation for 2040 (left) and 2050 (right)

decreases. However, no significant change in FLh is observed as the energy production cost experiences a sharper decline. Thus, running the system with high FLh still remains a priority. These results again document the crucial role of low-cost batteries for the entire DAC system design, since this component enables the close to baseload generation of energy supply for the entire DAC system.

The close to baseload generation of energy supply for the DAC units implies the combination of several flexibility options in the DAC system design. The utilised flexibility options are:

- DAC units do not have to be run on baseload;
- HP units do not have to be run on baseload;
- TES units buffer heat and help reduce the HP capacity;
- Battery units store solar electricity and enable close to baseload system operation;
- Curtailed electricity allows more PV generation capacity for higher total FLh.

Figure 7 shows the curtailed electricity which cannot be used for capturing CO₂ in the cost-optimised case. Lower curtailment, due to whatever measure, would lead to a higher cost. The difference in curtailment between 2040 and 2050 is not significant. However, some changes can be observed depending on the relative supply share of wind energy. Also, the reduced relative cost of curtailment has an impact, as a consequence of further reduced solar PV LCOE.

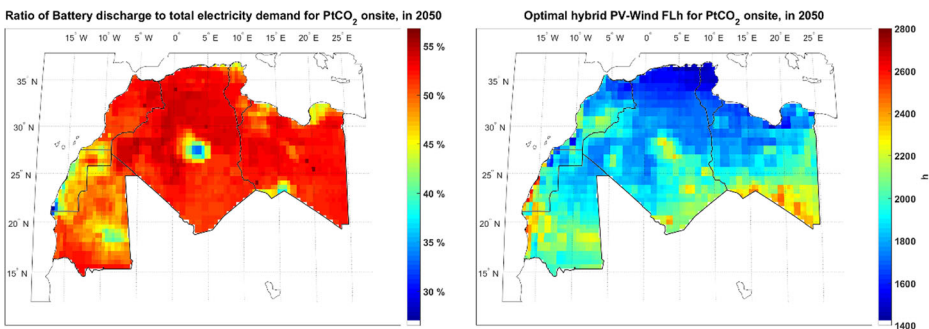


Fig. 5 Ratio of discharged electricity from batteries to total DAC system demand (left) and full load hours of optimised hybrid PV-wind systems for overall energy supply (right) for the cost year 2050

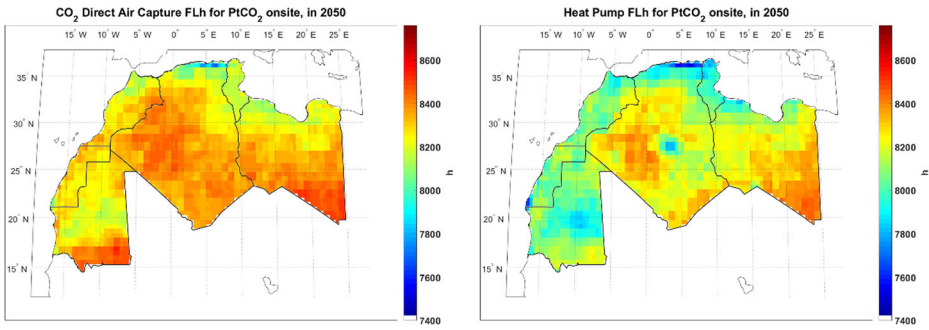


Fig. 6 Full load hours of CO₂ DAC units (left) and heat pump units (right) used for heat supply for the cost year 2050

The full hourly operation of a cost-optimised DAC system in a sample node is depicted in Fig. 8. The almost stable electricity generation conditions finally lead to close to baseload operation of the DAC units which are only run at lower capacity utilisation during the night hours in wintertime. Batteries enable a close to 24/7 operation mode of the DAC units, which can be partly achieved for several months in a row during summertime. This is also a time when some curtailment of electricity generation is part of the cost-optimised operation. The HP units are run in a very similar mode as the DAC units. During all hours of curtailment, the HP units run on full capacity, so no further thermal energy can be stored in the TES during that time and further power-to-heat capacities would also increase the cost.

The spatial distribution of the electricity supply cost of the DAC systems is visualised in Fig. 9 for the LCOE of the hybrid PV-wind system, as are the levelised cost of storage (electricity) and the LCOE of the DAC system for the case in 2050. It is shown that the cost of the electricity generation system is as important as the cost of the electricity storage system, since both contribute roughly equally to the total electricity supply cost, which is the consequence of the dominating solar PV supply share. One can see that excellent electricity supply sites can be found in the entire Maghreb, but most often in the south, such as the south of Libya, the south of Algeria or the south of Morocco. This may indicate some fundamental seasonal influence for close to baseload generation conditions. This observation can be seen in the electricity generation cost, and more pronounced in the cost of delivered electricity.

The levelised cost of CO₂ DAC (LCOD) is finally the key metric for cost-optimised CO₂ capture. Figure 10 shows the cost breakdown of LCOD for one of the very good areas in the Maghreb region for the conditions of the years 2040 and 2050.

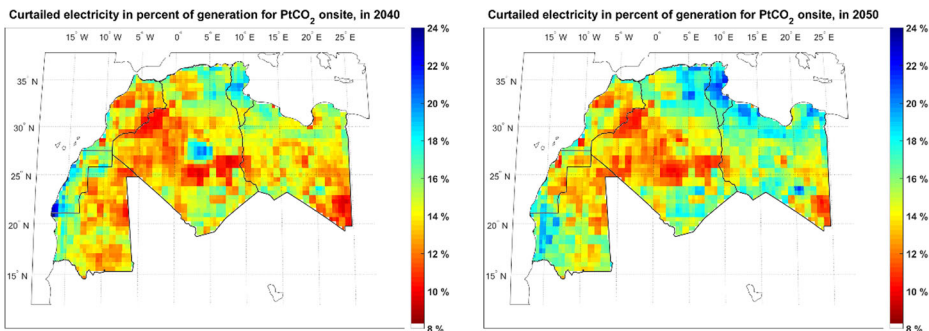


Fig. 7 Curtailed electricity in the DAC system for 2040 (left) and 2050 (right)

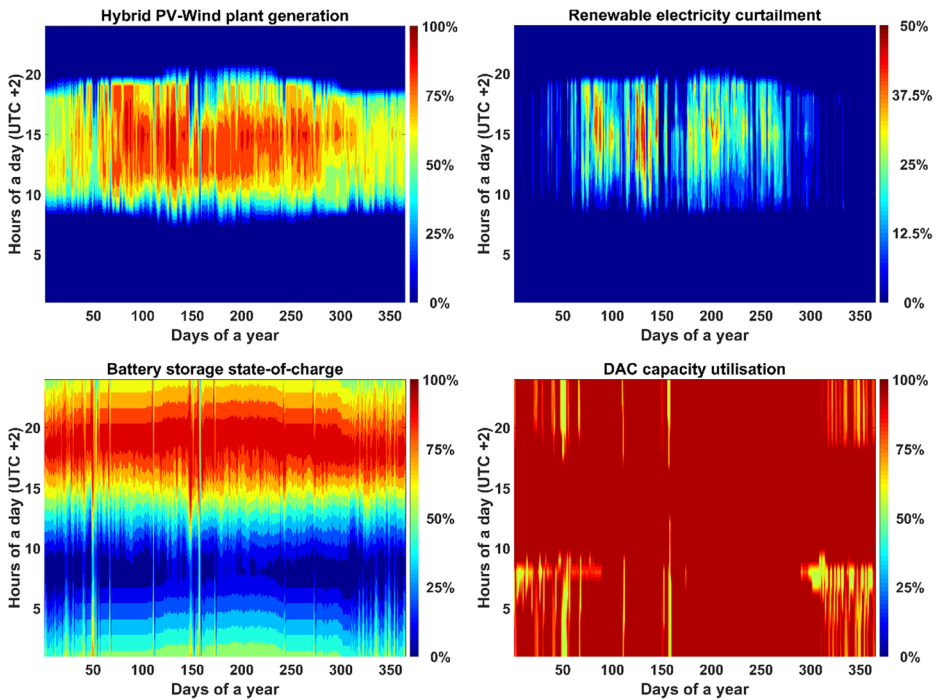


Fig. 8 Hourly resolved operation mode of DAC system components for a cost-optimised site for hybrid PV-wind electricity generation (top left), curtailed electricity (top right), battery state-of-charge (bottom left) and DAC utilisation (bottom right) for 2050 conditions

The spatial distribution of the LCOD is plotted in Fig. 11 for the cost years 2040 and 2050. The spatial distribution is relatively stable between the two years of assumptions, whereas the absolute cost goes down at almost the same pace for most areas. It can be noticed again that the least cost sites are in the south of Libya and the south of Algeria. Some excellent wind sites are still competitive for 2040 conditions but further lose ground for 2050 conditions. The spatial distribution in the LCOD is strongly linked to the strength of the resource availability and respective LCOE; thus, most coastal areas suffer from seawater-induced solar irradiation disturbance, which is less relevant for inner land sites. This explains the excellent solar resource conditions in the south of Libya and south of Algeria and as a consequence of very low LCOE can be also found in low LCOD. At excellent sites, it is possible to capture CO₂ for around 70 €/t_{CO2} in 2040 and for about 55 €/t_{CO2} in 2050, respectively. Although a different technology, but as the latest insight from DAC companies, Carbon Engineering expects to reduce their CO₂ capture costs to below 100 €/t_{CO2} just by regulating their business through construction of limited plants (Keith et al. 2018). Thus, our projected carbon capture cost of 70–80 €/t_{CO2} for a developed market in 2040 seems to be within the expected range, as the LCOD would benefit both from lower energy costs and lower capex achieved by cumulative installed capacity and expected learning rates.

Figure 12 shows the local annual CO₂ capture strength for all given conditions and the additional area restriction that not more than 10% of the local area can be utilised for solar PV or wind energy plants. For the condition of this study (mix of PV and wind, DAC FLh and energy consumption and losses), all additional DAC system components may require about

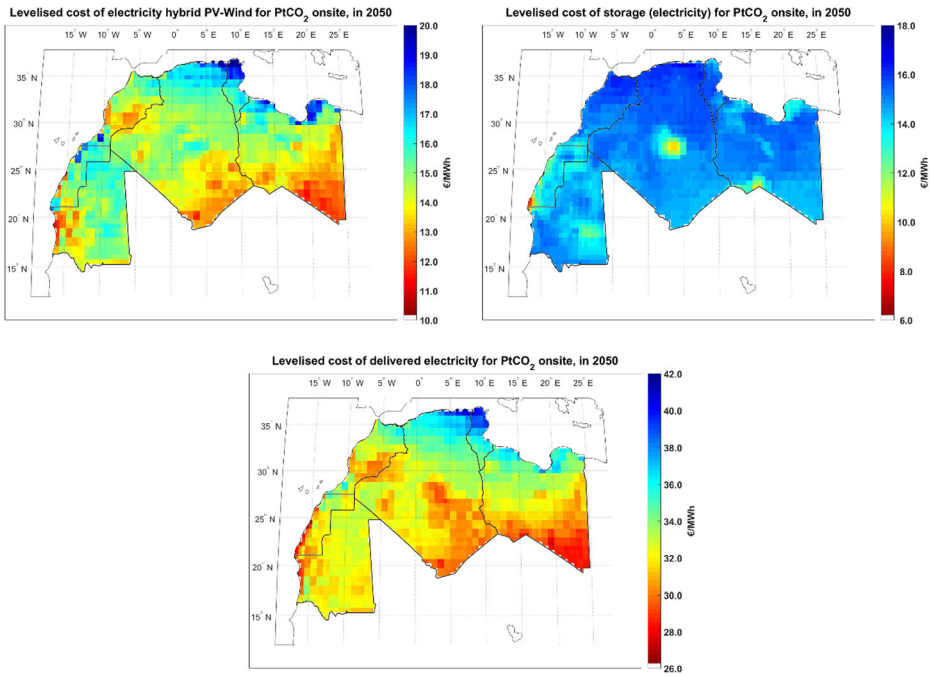


Fig. 9 LCOE of the hybrid PV-wind systems (top left), levelised cost of storage (electricity) (top right) and the LCOE of delivered electricity for the DAC systems (bottom) for the case in 2050

10–15% relatively more space in 2050 using individual footprints for the components and their composition in a concrete DAC system. The total CO₂ capturing potential for optimised DAC systems in the Maghreb region for the given constraints rises from 131 Gt_{CO2} per year to 155 Gt_{CO2} per year from 2040 to 2050, which is not only driven by the assumed efficiency increase of the DAC units, but also partly due to a higher solar PV share. This share has a significantly higher electricity generation potential per area than wind energy (Bogdanov and Breyer 2016). The difference of local CO₂ capturing potential per unit of area is also mainly a

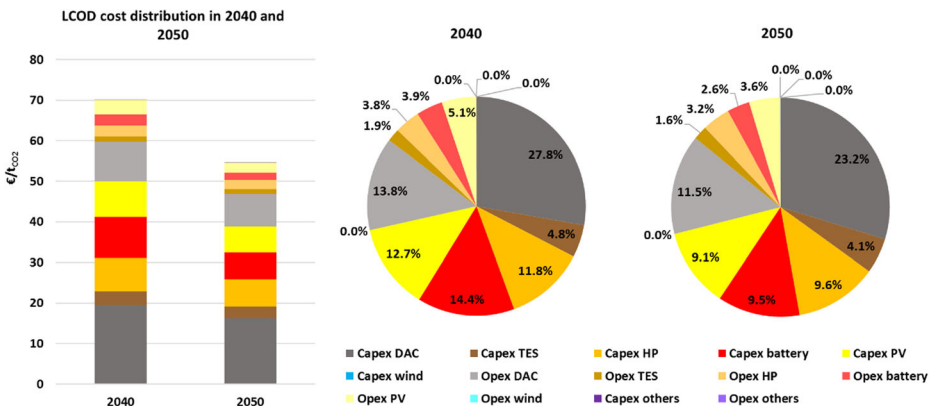


Fig. 10 Cost breakdown of captured CO₂ in terms of LCOD for 2040 and 2050 as bar (left) and pie (right) diagrams

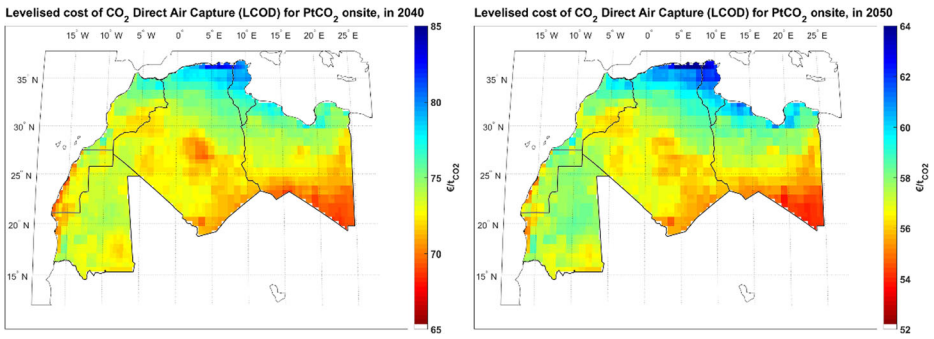


Fig. 11 Levelised cost of CO₂ DAC (LCOD) in the Maghreb region for 2040 (left) and 2050 (right) assumptions

consequence of the relative solar PV and wind share of the hybrid PV-wind plant, and the set 10% area constraint.

The trend line for CO₂ capturing cost expressed in LCOD is visualised in Fig. 13 in the form of an industrial cost curve, i.e. the least cost sites are selected first and the CO₂ capture potential is added, site by site. This allows better identification of the least cost sites and provides a profile in a cost vs volume relation.

The plateau cost levels of CO₂ DAC in the Gt_{CO₂} scale are around 105 €/t_{CO₂}, 70 €/t_{CO₂} and 55 €/t_{CO₂} for 2030, 2040 and 2050, respectively. A very substantial cost reduction from 2030 to 2040 is projected by the obtained results along with a significant further cost reduction from 2040 to 2050. This cost projection also implies some cost reduction of DAC units and a respective learning curve as shown in Fasihi et al. (Fasihi M, Efimova O, Breyer Ch. Techno-economic assessment of CO₂ direct air capture plants, submitted). The CO₂ capturing potential of the Maghreb region grows significantly from 2030 to 2050, which is driven by the assumed energetic efficiency increase of the DAC units, and also by the applied area constraint of 10% of available area. This area constraint does not change over time, and there is a gradual shift to higher solar PV electricity supply shares, which require substantially less land per generated electricity compared to wind energy. It is worth noting that the annual CO₂ capturing potential in the Maghreb region restricted to about 10% (including all DAC system components not more than 15%) of the area exceeds the annual global CO₂ removal demand of 10–20 Gt_{CO₂} according to Krieglner et al. (2017) by roughly one order of magnitude.

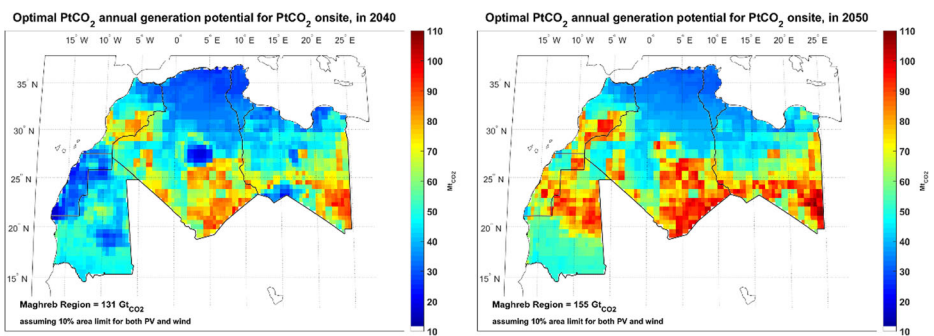


Fig. 12 CO₂ capture potential of DAC systems for 2040 (left) and 2050 (right) conditions in the Maghreb region for a 10% area constraint for the electricity supply sub-systems. The granularity is based on the 0.45° × 0.45° resolution of the input data

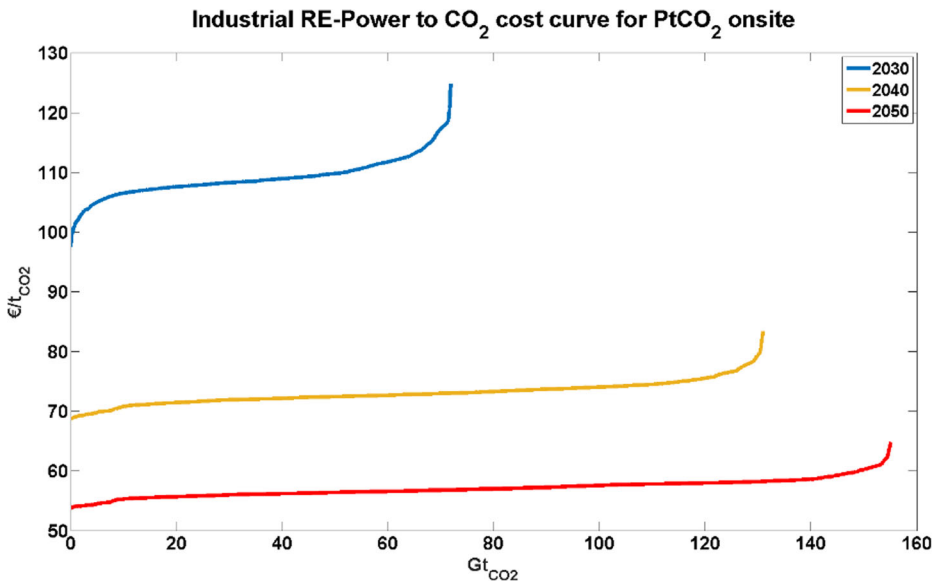


Fig. 13 Industrial cost curves for captured CO₂ in the Maghreb, indicated for the years 2030, 2040 and 2050. The potential for captured CO₂ in gigatonnes represents annual values of CO₂, which could be captured for the applied constraints

3.2 Energy system transition in the power sector

The current power sector in the Maghreb region is almost fully dependent on fossil fuels. Fossil natural gas plays the most important role, followed by oil and coal. However, the need for renewable energy becomes more and more crucial due to limited fossil resources, and increasing population and electricity demand. In this section, a transition towards a 100% renewable-powered energy system, based on solar PV and wind power in particular, is examined. The results indicate that a net installed capacity of 200 GW and a net electricity generation of 440 TWh are needed for an entirely RE-based power system for the Maghreb region (Morocco, Algeria, Tunisia, Libya) by 2050. A brief summary of the energy transition results is provided below. More detailed results for all countries in the Maghreb region can be found also in Ram et al. (2017a, b, c, d, e, f).

The primary electricity generation from various power sources for Algeria and Morocco from 2015 until 2050 is illustrated in Fig. 14. As shown, the power sector in Algeria (Ram et al. 2017c) is dominated by fossil natural gas with a very small fraction of fossil oil and RE for the year 2015. In 2020, solar PV, bioenergy and hydropower contribute almost 15% to total generation, whereas the rest still comes from natural gas. Starting from 2025, RE dominates the total electricity generation with a significant contribution from wind power. However, the ideal conditions for solar PV again push this source above wind in 2030, accounting for 48% of the overall mix. This trend continues upward until the end of the transition period, when PV is the major source of energy with a share of 77%, followed by onshore wind with 21%. An almost similar situation can be observed for the case of Morocco (Ram et al. 2017b). At present, the power sector is dominated by fossil fuels (coal, gas and oil). The share of RE in 2015 is higher in comparison to Algeria, accounting for 10% of total electricity generation. Although hydropower is the leader in terms of produced electricity from RE sources in 2015,

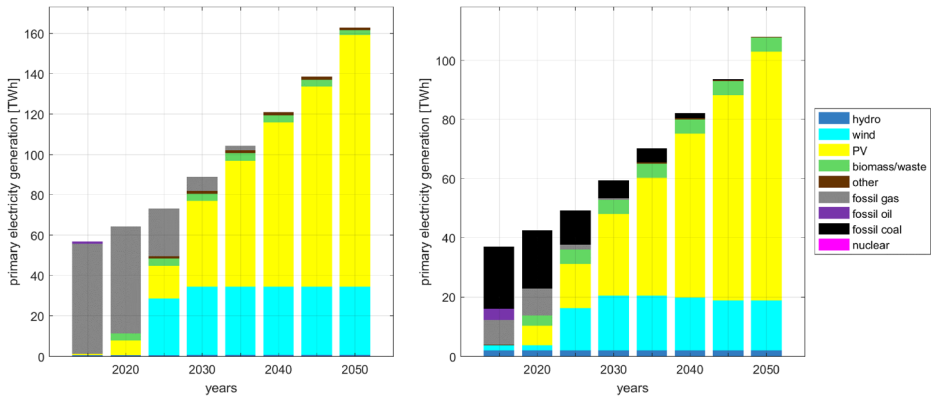


Fig. 14 Net electricity generation for Algeria (left) and Morocco (right) from 2015 to 2050. Diagrams are taken from Ram et al. (2017b, c)

solar PV reaches the highest electricity generation among all RE sources in 2020. The contribution of PV and wind is almost in the same range for the year 2025, followed by bioenergy and hydropower. However, similarly to Algeria, electricity generation from solar PV increases drastically from 2030 to 2050. Similarly, Libya (Ram et al. 2017e), Tunisia (Ram et al. 2017d), Mauritania and Western Sahara (Ram et al. 2017f) experience the same path for the energy transition.

In terms of newly added installed capacities, one can observe a significant amount of wind power capacity installed in both Algeria and Morocco for the year 2025, as shown in Fig. 15. This can be explained by good conditions of wind energy throughout the year and the almost even distribution across the countries. At the same time, onshore wind is quite cost-competitive at the beginning of the transition period. However, as the transition period gets closer to the end, no additional wind power is installed due to outstanding solar PV and battery cost reductions. This is self-explained by the learning curves of solar PV and batteries presented in various studies (Breyer et al. 2017a, 2018; Schmidt et al. 2017; Kittner et al. 2017; ISE 2015; ITRPV 2018). As mentioned in the CO₂ DAC section, energy storage, in particular Li-ion batteries, can lift the solar PV capacity due to its rapid cost decline. Therefore,

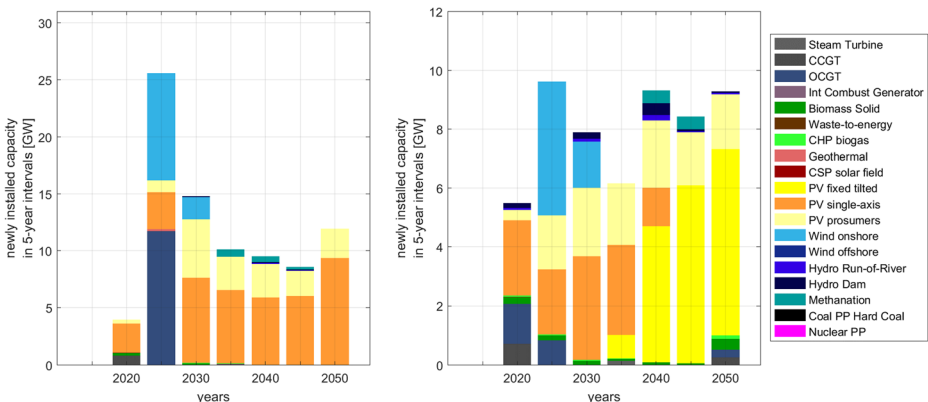


Fig. 15 Newly installed capacities of various power generation technologies for Algeria (left) and Morocco (right) from 2015 to 2050. Diagrams are taken from Ram et al. (2017b, c)

solar PV installed capacity dominates the system from 2030 to 2050 for all Maghreb countries. Focusing on the details, the contribution of different solar PV technologies varies between Algeria and Morocco. Solar single-axis tracking PV is the main PV technology installed in Algeria with 70% share of total PV capacity in 2050. In comparison, single-axis tracking PV has the highest share (60%) in terms of new capacity up to 2035 in Morocco, but fixed tilted PV dominates from 2040 onwards. Excellent conditions of fixed tilted PV during the spring and wintertime lead to higher installed capacity in the last few years. This is because the peak load demand in Morocco is over the spring, summer and winter seasons. However, the higher FLh of single-axis tracking PV for the first few years of the energy transition have been the major hindrance for the fixed tilted PV. Starting from 2035, the very low-cost fixed tilted PV takes the lead concerning the new installed PV capacity. In addition, solar PV prosumers, with almost a 30% share of total capacity, complement the two other PV system technologies. For the case of Tunisia, the model presents very similar results to Morocco. Meanwhile, for the case of Libya, the results are similar to those of Algeria.

Storage technologies play a major role in the high penetration of the VRE system, especially in a lack of large grid interconnections. Among all energy storage technologies, Li-ion batteries are the leading technology in all Maghreb countries (Fig. 16). The reason for the high share of batteries is that the batteries match best with PV to balance the system both in the form of prosumers and in utility-scale battery storage. During the daytime, especially in summer, PV generates more electricity than required by demand. Then, the excess electricity is stored in batteries and used during the peak load. In comparison to battery storage, gas storage is a seasonal storage that can store electricity for longer periods. Thus, the amount of gas storage output in terms of total storage output is much lower than that for batteries. The cost of gas storage capacity is lower than that for batteries. However, the conversion of power-to-gas-to-power is much higher in cost than charging and discharging batteries. The optimised mix of short-term battery storage and long-term power-to-gas (PtG) storage leads to the least cost system solution for 100% RE. Other storage technologies that contribute to the total storage output are as follows: pumped hydro storage (PHS), TES and adiabatic compressed air energy storage (A-CAES).

The overall storage output supplies about 35% and 39% of the total electricity demand in Algeria and Morocco, respectively, by 2050, of which more than 90% is delivered from batteries in both countries. It should be noted that gas storage only contains synthetic natural gas (SNG). Although bio-methane is also stored in gas storage, it is considered as bioenergy generation as shown earlier in Fig. 14.

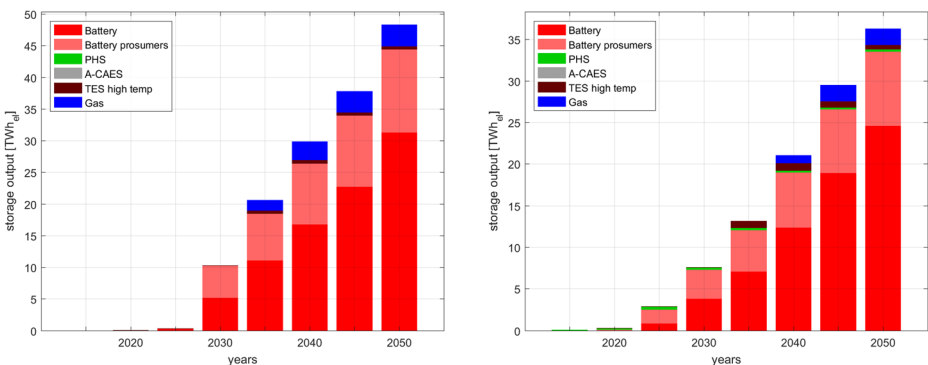


Fig. 16 Net storage output by various storage technologies for Algeria (left) and Morocco (right) from 2015 to 2050. Diagrams are taken from Ram et al. (2017b, c)

The energy system LCOE of the Maghreb region declines noticeably from 2015 to 2050. However, the cost drop is different from one country to another. The highest decrease is observed for the case of Libya, where the cost drops from 125 €/MWh in 2015 to 49 €/MWh in 2050. Algeria and Morocco experience almost similar trends, as depicted in Fig. 17. After a rapid decrease in 2020, the high capital expenditures in new capacities of RE, as shown in Fig. 15, result in again an increase in LCOE in 2025 (Fig. 17). From 2030 onwards, the LCOE decreases gradually until the end of the transition period. The LCOE decreases from 71 to 49 €/MWh in Algeria and from 67 to 51 €/MWh in Morocco during the entire transition period from 2015 to 2050. The LCOE includes all electricity generation, energy storage and curtailment costs. The LCOE in the year 2050 is composed of solar PV, battery storage and wind energy, complemented by some energy storage technologies, bioenergy and hydropower, as visualised in Fig. 17. Moreover, the fuel cost component of LCOE falls significantly from 2015 to 2035 due to the phaseout of existing fossil fuels in the whole region.

Sector coupling brings further flexibility to the energy system and thus affects the final cost. To give an illustration, PtG can be utilised simultaneously for electricity generation through combined or open-cycle gas turbines to satisfy the electricity demand in the power sector and for gas production to cover the non-energetic industrial gas demand. As a result, the system works more effectively and extra costs for separate processes are eliminated. Seawater desalination can play a similar role in the energy system. However, it had been observed that seawater reverse osmosis (SWRO) desalination plants find their cost optimum near baseload conditions around 8000 FLh throughout the entire energy transition (Caldera and Breyer 2018). The benefits of sector integration are well observed in Algeria and Morocco (Breyer et al. 2017a). The LCOE drops in Algeria from 49.0 €/MWh for the power sector only to 37.7 €/MWh for the integrated sectors, which shows a relative reduction of 23%. For the case of Morocco, the cost reduction is somewhat lower than that of Algeria, showing a 7% decrease from the power sector only to integrated sectors. For both countries, the reduced curtailment cost accounts for the highest cost reduction, at 60% in Algeria and 56% in Morocco. This explains the effects of sector coupling, which allows the system to operate more efficiently. Further, the storage requirement decreases in Algeria due to additional electricity demand for the non-energetic industrial gas and water sectors. However, the demand of the additional sectors in Morocco is much lower than that in Algeria, resulting in a lower decrease in levelised cost of storage.

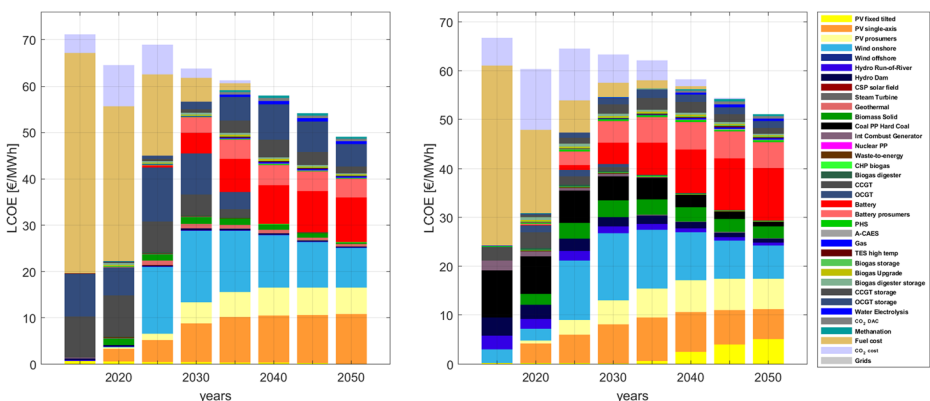


Fig. 17 Composition of LCOE by various power generation technologies for Algeria (left) and Morocco (right) from 2015 to 2050. Diagrams are taken from Ram et al. (2017b, c)

4 Discussion

The results reveal the outstanding potential not only for 100% renewable energy supply in the Maghreb region, but also for huge CO₂ removal in the region. The total LCOE for 100% RE supply of the power sector by 2050 is around 50 €/MWh for the historic cost of the energy transition, but would be around 40 €/MWh if the structure of the energy system achieved in the year 2050 would have been built with an overnight approach in the same year. The power supply for near baseload conditions of the new CO₂ removal sector is lower, at around 30–33 €/MWh in the Maghreb region at the best sites. The reasons for the cost difference are mainly three aspects: (i) the energy supply for an entire country is based on the usage of different sites and on a weighted mix of the 50% best sites in the country (Bogdanov and Breyer 2016); (ii) the load curve of a country has to be matched for all 8760 h of a year, whereas the DAC system does not require this level of energy supply security and is finally run for about 8300 h a year; and (iii) for a national energy system, there are also some higher cost must-run units included, such as waste-to-energy plants for efficiency and additional sustainability reasons (Breyer et al. 2017a, 2018; Ram et al. 2017a; Bogdanov and Breyer 2016).

The new CO₂ removal sector shows several characteristics already known from SWRO desalination, in particular the tendency for high FLh in the least cost operation mode. The FLh for DAC units are around 8300 in the cost-optimised operation, whereas SWRO desalination plants show even a tendency towards almost full baseload operation (Caldera and Breyer 2018). This indicates that not much efficiency gain due to sector coupling, but an almost parallel operation of these energy sectors, can be expected.

The potential energy system impact of the CO₂ removal sector can be very dominant. The electricity generation for the power sector is expected to be around 440 TWh for the Maghreb region in 2050. This demand may be increased by SWRO desalination and non-energetic industrial gas demand by about 115% (Breyer et al. 2017a; Aghahosseini et al. 2016). The global CO₂ removal demand may be around 10 Gt_{CO2} in 2050, which may lead to a contribution of the Maghreb region of 5–10% of this demand due to the excellent resource conditions. The CO₂ capture of 1 Gt_{CO2} by 2050 would require at a top site in the Maghreb region the following DAC system:

- Solar PV power plants of 329.6 GW_p (composed of 187.4 GW_p single-axis tracking and 139.5 GW_p fixed tilted systems), generating 703 TWh of electricity annually at 12.8 €/MWh LCOE primary. The FLh are 2389 (single-axis tracking) and 1830 (fixed tilted).
- Wind power plants of 2.7 GW, generating 9.9 TWh of electricity annually at 26 €/MWh LCOE primary. The FLh are 3660.
- Battery units of 156.3 GW power capacity and 937.6 GWh_{cap} energy storage capacity.
- Heat pump units of 148.3 GW_{th} capacity. The FLh are 8297.
- TES of 1779.5 GWh_{th} energy storage capacity.
- DAC units of 1.04 Gt_{CO2/a} capture capacity, run near baseload. The FLh are 8405.
- The annualised cost for the total DAC system is 55.3 b€, leading to LCOD of 55.3 €/t_{CO2}. The cost breakdown of the annualised cost of the DAC system is PV plants (16.1%), wind plants (0.5%), battery units (15.3%), heat pump (16.3%), TES (7.2%) and DAC units (44.6%).

These results reveal that the CO₂ removal sector would achieve the same size as the total energy system by 2050 in the Maghreb region for 10% of global CO₂ removal and about the

same size as the demand in the power sector for 5% of global CO₂ removal demand. The electricity supply would be almost fully solar PV based, due to cost reasons.

The area demand for 1 Gt_{CO₂} annual capture is estimated to be about 5244 km², thereof 83% for the PV power plants, 6% for the wind power plants, 3% for the HP units and 8% for the DAC units. The specific area demand is assumed to be 75 MW/km² for solar PV (Bogdanov and Breyer 2016), 8.4 MW/km² for wind energy (Bogdanov and Breyer 2016), 1 GW_{th}/km² for heat pumps and 2.5 Mt_{CO₂,cap/a}/km² for DAC units (Fasihi M, Efimova O, Breyer Ch. Techno-economic assessment of CO₂ direct air capture plants, submitted). The area demand is equal to 0.08% of the total area of 6.31 million km² of the Maghreb region; hence, even a 10% global CO₂ removal contribution is negligible in area demand for the Maghreb region. It needs to be mentioned that the DAC systems even produce some water as a by-product of CO₂ capture at least for moderate climate conditions, and the DAC system can be operated in a mode close to being fully automatized.

The CO₂ capturing cost shows a steep decline to about 105 €/t_{CO₂}, 70 €/t_{CO₂} and 55 €/t_{CO₂} for the years 2030, 2040 and 2050, respectively. It can be assumed that some further cost reduction after 2050 can be realised due to further effects of economies of scale and learning curve aspects. It should be also mentioned that the underlying learning curve for the DAC units has to be called rather conservative, since a rather low DAC capacity demand of less than 11 Gt_{CO₂} by 2050 for all CO₂ removal and all carbon capture and utilisation (CCU) activities for power-to-fuels and power-to-chemicals globally is assumed (e.g. a substantial DAC-based CCU potential for power-to-fuels had been identified earlier for the Maghreb region (Fasihi et al. 2017)), as well as a rather moderate learning rate of only 10% (Fasihi M, Efimova O, Breyer Ch. Techno-economic assessment of CO₂ direct air capture plants, submitted). Fasihi et al. (Fasihi M, Efimova O, Breyer Ch. Techno-economic assessment of CO₂ direct air capture plants, submitted) clearly point out that more realistic assumptions, i.e. about 22 Gt_{CO₂} global capturing capacity by 2050 and a 15% learning rate, would lead to an additional DAC capex reduction from 196 €/t_{CO₂}·a to 81 €/t_{CO₂}·a, or an additional reduction of close to 60%. This effect alone would translate to a LCO_D reduction from 55.3 €/t_{CO₂} captured to 45.6 €/t_{CO₂} or about 18% cost reduction.

The cost assumptions for the two main electricity supply technologies may be also too high for the conditions of the year 2050, since the PV LCOE reaches about 12 €/MWh in 2050. This is almost the level which has been offered in the most competitive PV tender in Saudi Arabia in the year 2017, when 17.86 USD/MWh (14.3 €/MWh at an exchange rate of 1.25 USD/€) was offered by a consortium of internationally leading PV and power companies (PV-Tech 2017). The potential for solar PV in 2050 should be well below 10 €/MWh, which may reduce the LCO_D by a further 5% or more.

The battery cost may be also further reduced by 2050, since the learning curve cost target would be only one-third compared to the assumed cost, which is equal to an additional cost reduction of about 10%. A power-to-gas-to-power (PtGtP) system was also included in the model as an additional option for seasonal electricity storage. However, for the conditions of the Maghreb region, no considerable capacities of this option were installed in the cost-optimised solution.

In the absence of cost numbers for heat storage at around 100 °C, the cost assumptions for high-temperature heat storage are used, which are most likely too high by at least a factor of 2, and represent a LCO_D reduction of about 5%. The balancing role of heat storage could be different depending on the availability of electricity and heat and the demand period. For a periodical heat demand and a near to baseload electricity availability, heat storage makes it possible to have a smaller HP capacity. On the other hand, for a baseload heat demand, a heat

buffer helps generate the heat when electricity is available. Therefore, by letting the HP run for lower FLh, its capacity would be more than that for the baseload case. In this scenario, the benefit comes indirectly from avoiding DAC shutdowns or scaling up the electricity generation or storage system. The systems in the Maghreb region operate in a condition closer to the second case, whereby most of the storage and balancing is provided by low-cost battery storage.

However, there is also a downside potential for the development of DAC units and respective LCOD. The major risk may be a too slow market deployment of DAC technology, not only for carbon direct removal, as investigated in this research, but also in particular for power-to-fuel and power-to-chemical options needed for defossilising the transport sector and chemical industry. Since DAC units can be used for all these markets, a substantial delay in reducing GHG emissions in these sectors would lead to a delay in capacity increase of substitution solutions, and this would automatically lead to a reduced and delayed DAC capacity demand, and thus a delay in achieving the mentioned DAC capex targets outlined in this research.

Summing up, the possible further cost reductions of the DAC units, PV systems, battery storage and TES account for about 40% of further cost reductions, which would translate from 55.3 €/t_{CO₂} captured to about 32 €/t_{CO₂} captured in a most cost-optimised but possible case in 2050. The applied WACC is 7%, which may be reduced to 5% for low-risk international cooperation activities, and would further reduce the LCOD by about 15% to levels well below 30 €/t_{CO₂} for captured CO₂ by 2050. Substantial ambitionless defossilisation targets for major GHG emitting sectors, in particular the marine- and aviation-based transport sectors and chemical industry, would be a burden for achieving the assumed cost targets. Significant slower market development of DAC systems would delay the expected cost targets, which in most unfavourable conditions may lead to cost levels in 2050, which would be achieved otherwise around 2030.

The results for the Maghreb region also reveal that the CO₂ removal industry may grow to be one of the largest industries on the planet, since the annual turnover may reach 300 to 550 b € per year, based on the results for the Maghreb region, for 10 Gt_{CO₂} of removal per year. This turnover would be roughly equivalent to 0.27–0.50% of the global GDP, assuming a continued real GDP growth of about 2% per year, hence well affordable for the global society if a climate change survival strategy is the clear target of the people of the world.

The scope of this research has been the CO₂ capture by DAC units and is comparable to other research in the applied metric and system boundaries. However, it needs to be mentioned that gaseous CO₂ is not an intrinsic safe material to be stored over the period of many thousands of years. Leakage from geological storage has been studied and is summarised by Leung et al. (2014). They separate the cases for caprock leakage which is in the order of tens of thousands of years and leakage through permeable pathways which causes more concerns. In addition, the injection wells are identified as the most likely leakage pathway. The CO₂ injection also can cause fractures in the geologic formation which happened for caprock in a project in Algeria, and also in the world's biggest storage site in Norway (Montastersky 2013). A leakage rate of already 0.1% per year has been identified as critical (Enting et al. 2008). Hazeldine (2009) describes conditions for leakage of CO₂ injections in geologic formations. Fogarty and McCally (2010) investigate CCS from a medical perspective and raise concerns about risks of CCS for human health. As long as remaining risks and uncertainties can be removed, it may be of interest for all to imply at least one further conversion step from gaseous CO₂ to a compound, i.e. solid material, which shall be chemically inert and which should have a high combustion point, comparable to SiC or carbon fibres. Such a conversion will require further energy and conversion techniques, but is indispensable for responsible long-term

carbon storage. This conversion would be also required for all other CO₂ capture technologies, whether BECCS, point source carbon capture or other options, and therefore no differentiator in the CO₂ capturing industry. Research on CO₂ conversion to stable compounds for long-term storage is currently in its infancy.

All CO₂ capture technologies would need, to some extent, a collection system from distributed units and a buffer unit before utilisation, conversion, transportation or permanent storage of CO₂. Such a system would also have some additional costs and energy demand. It is important to note that the presented cost levels in 2040 and 2050 could be achieved only if the implementation of CO₂ capturing technologies starts in rather small scales in the 2020s in order to stimulate a learning curve. Otherwise, without an early start and learning all the options, there might be more economic barriers to achieve the outlined cost levels.

5 Conclusions

The targets of the Paris Agreement to limit the anthropogenic temperature rise to a 1.5–2 °C increase above pre-industrial levels imply not only net zero GHG emissions and thus a zero GHG emission energy system by the mid-twenty-first century, but also substantial permanent CO₂ removal. This has to be started in the 2030s and massively scaled up in the 2040s and 2050s. CO₂ DAC is among the most promising CO₂ removal technologies, also called negative emission technologies. IAM-based scenarios have neglected this option partly due to limited understanding of the real cost dynamics of RE technologies, and also a high focus on the BECCS option in the past, which raises increasing debate on a more balanced discussion on the various NET options. The water demand of DAC is in practical terms zero and the area demand is very low. Even more importantly, DAC systems can be built on barren land, as shown for the Maghreb region, which is dominated by desert environments. The area demand for 10% of global CO₂ removal demand in 2050 would require less than 0.08% of the Maghreb region for the full DAC system including full energy supply.

The costs for the captured CO₂ have been calculated as 105 €/t_{CO2}, 70 €/t_{CO2} and 55 €/t_{CO2} for the years 2030, 2040 and 2050, respectively, for areas of several tens of Gt_{CO2} annual capturing potential. All calculations are based on full hourly modelling for all included sub-systems, which are mainly solar PV power plants, wind power plants, battery storage, heat pumps, thermal energy storage and DAC units. The DAC units are operated at near baseload conditions for the least cost of captured CO₂. The derived CO₂ capturing cost may be further reduced by about 50%, thereof by 40% pts due to reductions in sub-system costs, mainly DAC units, battery systems, PV systems and TES, and further by 10% pts due to lower than assumed weighted average cost of capital. This is because, in an international cooperation programme, the business risk can be reduced if guarantees are issued by countries.

The results show that CO₂ captured cost could reach levels of about 55 €/t_{CO2} and even lower than 30 €/t_{CO2} for the best conditions in the Maghreb region. Almost all required energy would be solar PV based, which is the least cost source of energy in the applied scenario and abundantly available in the Maghreb region. The additional energy demand of the CO₂ removal energy sector may grow to levels comparable to the entire energy throughput for the energy system. Not much sector coupling benefits are expected due to similar operation modes as found earlier for SWRO desalination plants which are also operated in a least cost mode at near baseload operation. Concerns about risks of geological storage of gaseous CO₂ may require further conversion to solid compounds with additional energy and area demand,

which may not be so costly, as already documented for the sustainable CO₂ removal based on renewable electricity and DAC units.

Key global climate change mitigation strategy options can be derived from the structural insights for the Maghreb region. An energy transition in the power sector leads to very high shares of RE, as a consequence of environmental sustainability, technical feasibility and economic viability. For achieving the targets of the Paris Agreement, NETs are required and CO₂ DACCS represents a very attractive NET option, which can be implemented globally and scaled to very large volumes, if needed.

CO₂ removal may be an outstanding economic opportunity for the Maghreb region due to excellent resource conditions, strong CO₂ removal demand and a strong competitive edge of the Maghreb region for CO₂ removal.

Acknowledgements The authors would like to thank Michael Child for proofreading.

Funding information Open access funding provided by Lappeenranta University of Technology (LUT). This study received financial support from the Lappeenranta University of Technology.

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