Energy Strategy Reviews 45 (2023) 101012

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Potentials of direct air capture and storage in a greenhouse gas-neutral European energy system

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ARTICLE INFO

Keywords:
Direct air capture and storage (DACCS)
Carbon dioxide removal (CDR)
Negative emission technology (NET)
Energy system modeling
GHG neutrality

ABSTRACT

Negative emission technologies will likely be needed to achieve the European Commission's goal of greenhouse gas neutrality by 2050. This article investigates the potential of reducing greenhouse gases in the atmosphere via the DACCS pathway, i.e., to capture CO_2 from the ambient air and permanently store it in geological formations. Since the capture of CO_2 from ambient air is energy-intensive, this study particularly models the integration of DACCS plants into a greenhouse gas-neutral European energy system. The model results show that DACCS in Europe 2050 could cost between 160 €/t_{CO2} and 270 €/t_{CO2} with very conservative techno-economic assumptions and between 60 €/t_{CO2} and 140 €/t_{CO2} using more progressive parameters. Annually capturing 5% of Europe's 1990 emissions with a fully electric DACCS system would increase the capacities of onshore wind by 80–119 GW_{el} and PV by 85–126 GW_{el}. In the model results, Sweden, the Iberian Peninsula, Norway, and Finland incorporate the essential characteristics for a successful deployment of capturing and storing CO_2 from ambient air: Sufficiently large geological CO_2 storage capacities and relatively low-cost, vacant renewable power generation potentials. The low DACCS costs could minimize the cost of combating climate change and prevent the implementation of more expensive mitigation strategies. On the other hand, a DACCS-based climate protection strategy is fraught with the risks of CO_2 storage leaks, acceptance problems for the additional required expansion of renewable energies, and premature depletion of global CO_2 storage potentials.

1. Introduction

The United Nations Sustainable Development Goals name climate change a major challenge for our and future generations [1]. To reduce the impact of climate change, the Paris Agreement [2] sets the target to keep the global temperature increase preferably below 1.5 °C compared to pre-industrial times. To achieve this objective, the European Commission (EC) presented its "European Green Deal" in 2019 [3], which aims to achieve an economy with net-zero greenhouse gas (GHG) emissions in 2050 in the European Union (EU).

Various studies conclude that despite rigorous decarbonization efforts across sectors, negative emission technologies (NETs) will likely be needed to achieve net-zero GHG emissions by 2050 [4–6]. In the Special Report on Global Warming of 1.5 °C by the Intergovernmental Panel on Climate Change (IPCC), all analyzed 1.5 °C pathways with limited or no overshoot include carbon dioxide removal (CDR) of the order of 100–1000 Gt_{CO2} in the 21st century [7]. CDR is likely necessary since some economic processes like cement production or social habits like meat consumption are related to the generation of GHG emissions. It is neither from a technical nor from a political viability perspective possible to (completely) substitute these with emission-free alternatives. As a consequence, a need for strategies to compensate for the remaining emissions emerges.

There are a variety of NETs that can be used to remove CO_2 from the atmosphere. Minx et al. (2018) [8] classify the different technical approaches in a taxonomy and identify seven major groups of NETs: afforestation and reforestation (AR), biochar, soil carbon sequestration (SCS), enhanced weathering on land and in oceans (EW), ocean fertilization (OF), bioenergy combined with carbon capture and storage (BECCS), and direct air capture and storage (DACCS). Previous studies carried out with integrated assessment models (IAMs) have focused mainly on the options of afforestation, reforestation, and BECCS [7]. However, there are concerns regarding both sustainability and competition for food and water associated with biomass-based strategies [9,

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https://doi.org/10.1016/j.esr.2022.101012
Received 30 June 2022; Received in revised form 28 October 2022; Accepted 20 November 2022
Available online 1 December 2022

10]. Therefore, technical options that chemically remove CO_2 from the atmosphere rather than through photosynthesis are increasingly a topic of discussion. Facilities that use chemical solvents and sorbents to remove CO_2 directly from the ambient air are called direct air capture (DAC) plants. If the captured CO_2 is permanently stored, this overall process is referred to as DACCS. Geological formations such as depleted oil and gas fields or saline aquifers can serve as long-term CO_2 storage. If powered by carbon-neutral energies, DACCS has the potential to lower the CO_2 concentration in the atmosphere. Compared to conventional carbon capture and storage (CCS), DACCS has the advantage that CO_2 can be captured independently of the location and the process of a point source. Therefore, it can capture distributed emissions, such as transport or aviation. The major challenge for DAC technologies to become integral to a climate protection strategy is the high energy consumption for capturing CO_2 from the ambient air. Since the CO_2 concentration in the atmosphere is low – 421 ppm (parts per million) as measured by the Mauna Loa Observatory Hawaii in May 2022 [11] – large volumes of air must be processed, and a substantial amount of energy must be used to extract the CO_2 [12]. In order to guarantee a beneficial impact of the DAC technologies, this additional energy demand would have to be accompanied by further expansions of renewable power technologies and may compete with other electrification strategies.

Today, DAC has been mainly researched from a technological perspective. Fasihi et al. (2019) [6] provide a comprehensive literature review on the techno-economic properties of DAC plants and make projections for the development of these parameters up to the year 2050. Their analysis focuses on relevant parameters from an energy system perspective without analyzing the interactions between DACCS and the system level. Few studies have analyzed DACCS in the context of energy systems using a model-based approach. Existing works [5,13–16] use IAMs or energy system models that take a global perspective or cover long time horizons, such as until 2100. This spatial and temporal broadness in their modeling approaches entails relatively low spatial or temporal resolutions. However, to achieve GHG neutrality, DACCS technologies will most likely need to be integrated into energy systems that have high shares of weather-dependent renewable energies. Taking into account the interactions or competition with other energy demands for these fluctuating sources requires using models with high technological, spatial, and temporal resolution. Modeling DACCS in such a setup allows for a more realistic economic analysis.

The EC aims to become GHG-neutral by the year 2050. This paper examines the integration of DACCS plants into a European energy system to serve potential CDR needs in Europe. Ultimately, the GHG balance must be globally even to limit the temperature increase. This implies that European CO_2 emissions could be offset beyond Europe's borders in regions with favorable conditions. Nevertheless, DACCS plants outside Europe need to be integrated into the respective conditions of the energy system at hand. In this respect, the analyses in this paper are a case study for offsetting GHG emissions through DACCS locally. They can provide insight into fundamentally beneficial energy systems for using DACCS.

The central research questions of this article are:

- What is the techno-economic carbon dioxide removal potential of DACCS in a GHG-neutral European energy system?
- What are the implications of DACCS deployment on the power sector?
- Which European countries offer the most favorable conditions for DACCS?

These research questions are addressed using a new extension of the energy system model *Enertile*. From this approach, several practical implications can be derived. By taking an economic system perspective, this analysis provides insights on DACCS primarily for policymakers, who allocate research funding and establish legislative regulations as part of climate change mitigation strategies.

2. Methods and data

2.1. Methods

The techno-economic potential of DACCS in Europe is determined using a novel extension of the energy system model *Enertile* [17]. *Enertile* is a software package aimed at analyzing the cost-optimal energy supply for a given geographical region. The regional focus of previous analyses has been on Europe [18–21]. However, the model has also been used for studies in China [22] and the Middle East and North Africa [23].

Enertile is a bottom-up optimization model for large, coupled energy systems. The objective of the model is to minimize the cost of energy conversion, transmission, and storage up to the year 2050. The model covers the interlinked supply of electricity, heat, hydrogen, and synthetic fuels. Exogenous and endogenous demands of these energy forms have to be met by optimizing capacity expansions of relevant infrastructures and their hourly dispatch. Taxes and levies are not included in *Enertile*, as the model focuses on an overall economic perspective and not on individual market actors and their behavior. All investments related to capacity expansions are assigned a weighted average cost of capital (WACC) of 2%. A more detailed and formal description of the linear optimization problem in the base version of *Enertile* is given in Refs. [18,19,23–25].

Technologically, spatially, and temporally highly resolved electricity generation potentials of the renewable technologies ground-mounted photovoltaics (PV), roof-top PV, onshore wind, offshore wind, and concentrated solar power (CSP) are key characteristics of the model Enertile. For these technologies, installable capacities, hourly generation profiles, and electricity generation costs are determined on a grid with an edge length of 6.5 × 6.5 km across Europe. The determination of renewable energy potentials includes techno-economic parameters of the individual renewable power generation technologies, re-analysis weather data of the year 2010 [26], land use data [27], and geographic information such as elevation and slope [28]. Appendix Csummarizes the most important techno-economic input parameters of the individual renewable technologies. In sum, this results in a detailed picture of the potential of renewable energies used in energy system optimization. More detailed documentation of the potential calculation can be found in Refs. [23,29–31].

The central extension of *Enertile* in this paper provides a model representation of capturing and permanently storing CO_2 from ambient air to include DACCS technology in the optimization decisions. There are two mechanisms in the model that allow to evaluate DACCS technology within an energy system economically. Both approaches are shown in Fig. 1. Firstly, the model is offered a selling price for captured and stored CO_2. In cost optimization, *Enertile* decides how much CO_2 it will capture and store at that given price. This mechanism can represent potential CO_2 compensation demands from the sectors of agriculture, industry, transport, residential, and services. The CO_2 compensation demand is indirectly introduced to the model in the form of a selling price that reflects the willingness to pay for captured and sequestered CO_2 of these demand sectors. Technically, the sale of sequestrated CO_2 reduces the energy system cost in the objective function. The model installs and uses additional electricity supply infrastructure and DAC and sequestration units as long as incurred costs are covered by the revenues of selling the compensated CO_2. The last ton of compensated CO_2 provided and sold creates marginal costs at the applied sales price. Applying different sales prices in different model runs generates supply curves for CDR via the DACCS pathway. These supply curves interrelate with the rest of the energy system in the scenario design. Secondly, an exogenous CDR demand is directly imposed on *Enertile*. The model installs and uses additional electricity supply infrastructure and DACCS units until the specified demand is met. This CDR demand represents the remaining emissions from other sectors. Both approaches are used to investigate different aspects of DACCS potentials in Europe.

In addition to these two methods to incentivize CO_2 capture and

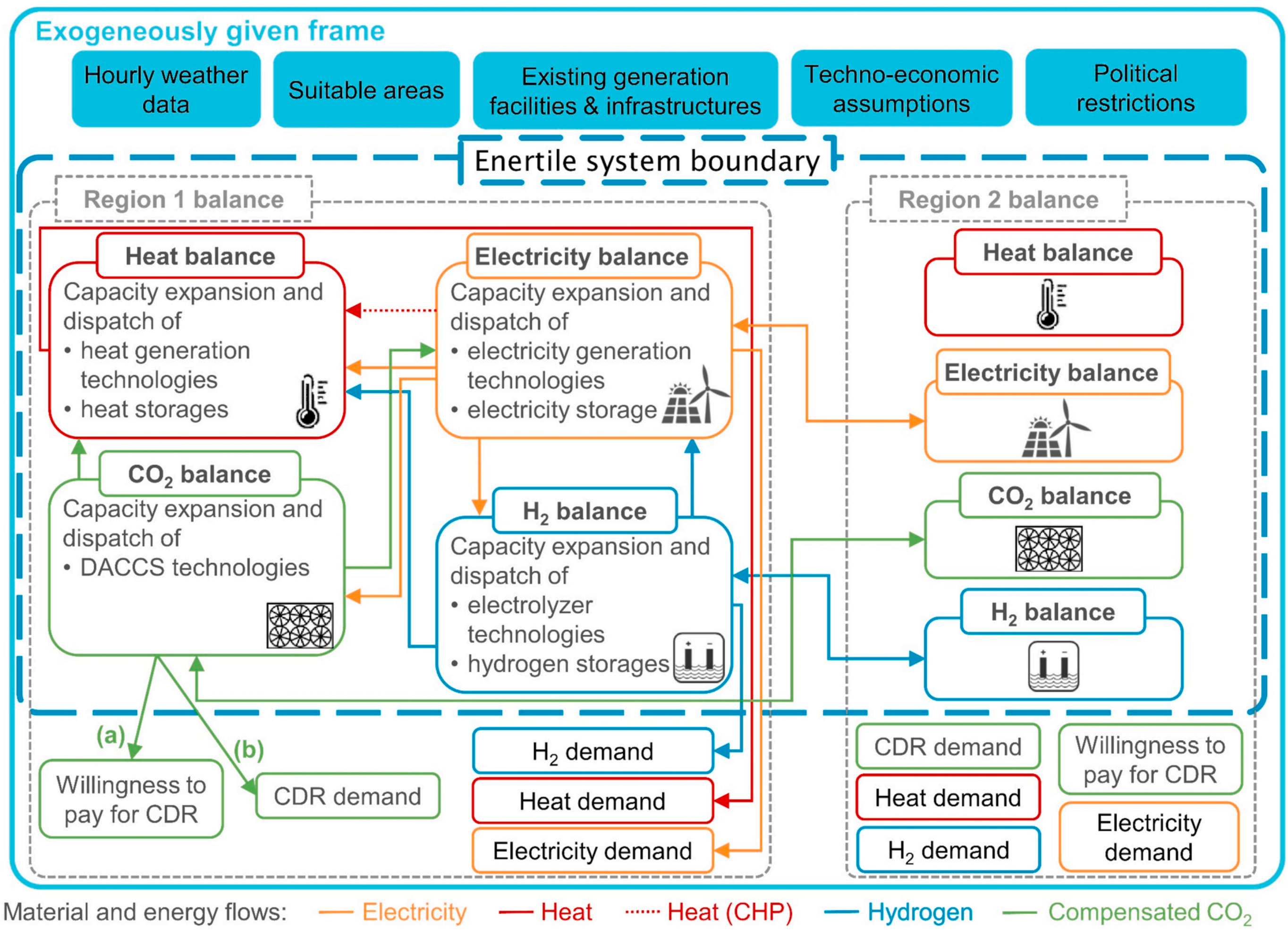

Fig. 1. Simplified representation of energy and material flows in the energy system model *Enertile*. The model extension for this article is the CO_2 balance. Model endogenously, *Enertile* decides on the compensation of CO_2 emissions from the use of fossil fuels for electricity and heat generation and on the exchange of compensated CO_2 between model regions. Model exogenously CO_2 capture and storage can be incentivized through two mechanisms: a) through a selling price of carbon dioxide removal (CDR) in €/t_{CO2} that represents the willingness to pay for compensated CO_2 of demand sectors. b) through explicitly specified CDR demands in t_{CO2}.

storage exogenously, model endogenous CO_2 compensation demands may arise. Fossil technologies can be used by *Enertile* to meet given electricity and heat demands. The emissions released in these processes create a CO_2 compensation demand that must be met through the DACCS pathway. In this way, GHG neutrality of the conversion sector is ensured. The decision of whether this combined electricity and heat supply strategy with fossil fuel utilization and CO_2 emission compensation is used to meet exogenously given energy demands is subject to cost minimization.

To generate negative emissions provided by DACCS technologies, costs and energy demands arise within *Enertile*. The DACCS pathway is modeled as a black box requiring electricity as input and providing captured and sequestrated CO_2 from ambient air as an output (cf. Fig. 1). Potential heat requirements of the DAC technology are accounted for using electricity equivalents. In the modeling, it is conservatively assumed that an electric heater provides this heat (cf. section 2.2.5).

Since CO_2 mixes rapidly in the atmosphere [32], DAC units are not geographically bound to emission sources. In the modeling, it is assumed that DACCS plants can be operated close to suitable geological CO_2 reservoirs or advantageous locations for renewable power generation across Europe. To provide this regional flexibility in *Enertile*, compensated CO_2 can be exchanged between the balances of model regions (cf. Fig. 1). For example, emissions released in Austria can be captured from the ambient air and sequestered in Norway.

Enertile has a high temporal and spatial resolution. Renewable energy potentials are determined on a grid with a tile size of 42.25 km^2. The spatial resolution for the balancing of energy supply and demand in the optimization is mostly at the country level. The definition of model regions is shown in Appendix B. Geographically covered are the member states of the EU, Norway, Switzerland, the United Kingdom, and other Balkan states. For simplicity, the geographic area covered in the scenario calculations is referred to as "Europe" in the remainder of this paper. For the analyses in this article, the year 2050 is considered in hourly resolution. The modeling approach uses perfect foresight, i.e., the model has perfect information about all time steps considered when determining the system cost minimum.

2.2. Data

2.2.1. Scenario design

The analysis of DACCS potentials in Europe is based on the scenario framework *long-term scenarios* of the German Federal Ministry for Economic Affairs and Energy [33]. In this framework, a research consortium has investigated highly ambitious GHG reduction pathways for the European economic system up to the year 2050. This analysis framework is appropriate because the DACCS option can be studied alongside other extensive GHG mitigation measures. This approach considers that the electricity demands of DACCS plants will be integrated into an electricity system that is exposed to high loads caused by the electrification of applications on the one hand but is also more flexible through sector coupling options on the other. By calculating different scenario variants on this basis, ceteris paribus model responses to CDR requirements can be evaluated.

The energy demands in the sectors industry, transport, residential, and services are taken from the electrification scenario ("TN-Strom") and are the basis for the calculations of the energy supply and provision of compensated CO_2 in *Enertile* for this article. In this scenario, GHG emission reductions in the demand sectors are realized through the electrification of processes and applications whenever possible. This strategy includes, for example, the use of trolley trucks in heavy-duty transport and the use of electrode boilers to provide process heat in industry. This strategy to reduce GHGs across sectors results in relatively high electricity demands that must be met in *Enertile* (cf. section 2.2.2).

For the conversion sector in 2050, it is assumed that electricity, heat in heat grids, and hydrogen must be provided GHG-neutral. Therefore, fossil-based electricity and heat generation technologies are prohibited in the model parameterization, except for the utilization of waste. The gross electricity production from non-renewable waste in the scenario runs is fixed to estimates of waste utilization in power generation in the year 2018 [34]. The resulting emissions of waste-to-energy in the conversion sector must be compensated using DACCS; this results in a model-endogenous CDR demand (cf. Fig. 1).

In other sectors, certain emissions remain in the selected scenario, which have to be compensated either inside or outside of Europe to achieve GHG neutrality. These remaining emissions include, for example, process-related CO_2 emissions in the cement industry or GHG emissions in agriculture from livestock farming, soil fertilization, or rice cultivation. To analyze the DACCS potential in Europe, the two incentive mechanisms for CO_2 capture and storage in *Enertile* presented in section 2.1 are used:

- In the case where a selling price for compensated CO_2 is offered to the model, different variants for the parameterization of the DAC technology (cf. section 2.2.5) and different selling prices are investigated. Three parameter variants for DAC are distinguished: *Current2020*, *Cons2050*, and *Base2050* (cf. section 2.2.5). As a result, a CDR supply curve is calculated for each DAC parameter variant. The results obtained using this approach are presented in section 3.1.
- In the case where the model needs to meet explicit CDR demands, the analysis focuses on three main scenarios. The scenarios differ in the model's degree of freedom to meet CDR demands. One, the *No CDR demand scenario* defines an anchor point for a scenario comparison. No exogenous CDR demands are specified in this scenario, and the model only needs to compensate for endogenous CO_2 emissions. Two, in the *Loc bound scenario,* each country must offset its emissions. In this scenario, there is no CDR exchange between model regions. Three, in the *Loc opt scenario*, the model can decide on the location of the carbon capture in a cost-optimal way. In this scenario, Norway, for example, can meet CDR demands from Austria if this decision results in lower system costs. In all cases, geological CO_2 storage potentials must not be violated (cf. section 2.2.6). The *Loc opt,* and *Loc bound scenarios* are calculated using two different DAC parameterizations: *Cons2050* and *Base2050* (cf. section 2.2.5). Region-specific CDR demands are defined in section 2.2.3. The complete scenario tree for this approach is specified in Table 1. The corresponding results are shown in section 3.2.

2.2.2. *Energy demands*

The exogenous energy demands from the sectors of industry, transport, residential, and services are central assumptions of the scenario design with a strong influence on the energy supply optimization. The energy demands for electricity, heat, and hydrogen in the model regions are adopted from the electrification scenario "TN-Strom" of the *long term scenarios* [33]. A flat distribution grid loss of 5.5% is applied to the electricity demands of the demand sectors for the supply optimization, while losses on the transport grid are calculated endogenously. The district heating demands are subject to heat grid losses of 10%.

Fig. 2 summarizes the final energy demands covered in the supply optimization in *Enertile* for the year 2050 in all model regions. Despite significant efficiency improvements in applications, the electricity demand increases to 4699 TWh in 2050. This is due to new electricity consumers such as e-mobility. The European heat demand in heat grids amounts to 524 TWh in 2050. The hydrogen demand increases to 619 TWh because processes such as steel production are converted to the use of hydrogen in the scenario design.

Table 1
Scenario variants for the analysis method where DACCS is incentivized by explicit CDR demands. The *No CDR demand* scenario serves as a reference without exogenously specified carbon dioxide removal demands. In this scenario, only the model endogenous CO_2 emissions from waste-to-energy have to be captured and stored.

Scenario name	Model's degree of freedom to meet CDR demands	DAC parametrization	CDR demand
No CDR demand	n.a.	*Base2050*	none
Loc opt - DAC Cons2050	*Loc opt*, i.e., cost-optimal location	*Cons2050*	active
Loc opt - DAC Base2050	*Loc opt*, i.e., cost-optimal location	*Base2050*	active
Loc bound - DAC Cons2050	*Loc bound*, i.e., each country must offset its emissions	*Cons2050*	active
Loc bound - DAC Base2050	*Loc bound*, i.e., each country must offset its emissions	*Base2050*	active

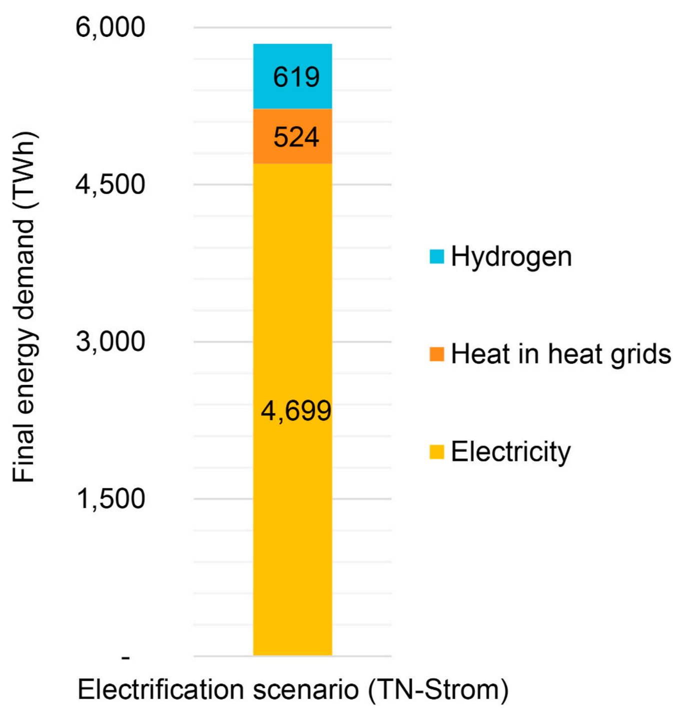

Fig. 2. Energy demands of the demand sectors industry, transport, residential, and services in 2050 for all model regions in the electrification scenario (TN-Strom) of the *long term scenarios* [33] framework. In *Enertile*, the demands for electricity, heat in heat grids, and hydrogen are met by energy supply optimization.

2.2.3. *Carbon dioxide removal demands*

In the case where DACCS in the model is induced by a fixed CDR demand, assumptions are needed as to how high this CO_2 compensation demand is. In the analysis of this paper, the estimation of the CDR demand for each scenario region is based on the countries' GHG emission level[1] of 1990 in CO_2 equivalents [35,36]. It is assumed that 5% of the 1990 emissions have to be compensated in 2050. Based on the figures of [35,36], this results in a total European CDR demand of 288 Mt_{CO2}/a. Fig. 3 visualizes the regional distribution of the assumed CDR demands in the case where (a) each model region must compensate for its emissions[2] (*loc bound*) and (b) no spatial constraints are imposed for offsetting emissions (*loc opt*).

2.2.4. Renewable energy source potentials

An important input to supply-side energy system optimization is the potential of renewable energy sources (RES). Fig. 4 shows the result of the renewable potential calculation described in section 2.1: aggregated techno-economic generation potentials of the different renewable technologies as a function of the generation costs. The figure shows that the renewable electricity generation potential included in the cost minimization of the European energy supply system is about 14,000 TWh. The potential of about 6000 TWh has a levelized cost of electricity (LCOE) of 35 €/MWh; the potential of 8000 TWh is available at an LCOE of about 50 €/MWh. Onshore wind and ground-mounted PV dominate the low-cost potential in Europe in 2050. Offshore wind, roof-top PV, and concentrated solar power (CSP) have smaller potentials and higher generation costs.

2.2.5. Direct air capture technology

DAC is a relatively new technology, with currently 19 plants operating worldwide [37]. Climeworks launched the largest DACCS plant to date, with a CO_2 capture capacity of 4000 t_{CO2}/a in Iceland in 2021 [38]. The technology is, therefore, subject to greater uncertainties regarding its development. Viebahn et al. (2019) [39] analyze the current development stage of different DAC technologies and classify low-temperature DAC systems (LT DAC) with a technology readiness level (TRL) of 6 and high-temperature DAC systems (HT DAC) with a TRL of 5.

Fasihi et al. (2019) [6] reviewed the literature on DAC and found that the stated or estimated energy consumptions and costs of the technology vary widely. To account for the high uncertainty and different data in the literature regarding the techno-economic development of DAC technologies until the year 2050, three parameter sets, *Base2050*, *Cons2050*, and *Current2020,* varying in cost, energy demand, and lifetime, are defined for the analysis in this paper in Table 2. The *Current2020* parameter set represents state-of-the-art DAC systems as currently reported [6]. This parameterization assumes that DAC technology will not be substantially developed in the future and serves as a lower bound. Based on a log-linear learning curve approach and techno-economic parameters assumed for 2020, Fasihi et al. (2019) [6] estimate the evolution of capital expenditures (CAPEX) for DAC until the year 2050. In the *Cons2050* parameter set, CAPEX are estimated to be 222 €/t_{CO2} a for HT DAC and 199 €/t_{CO2} a for LT DAC. In the *Base2050* parameter set, CAPEX are decreased to 93 €/t_{CO2} a for HT DAC and 84 €/t_{CO2} a for LT DAC. Fasihi et al. (2019) [6] also assume an increase in lifetime and a decrease in energy demand as a result of technological learning until 2050. However, in their DAC parameter scenarios, the authors only differentiate the investments – but not the energy consumption and lifetime – between their "base" and "conservative" scenarios. In this work, the *Cons2050* scenario is calculated with half the learning rate in energy consumption (5%/10 a electricity consumption, 7.2%/10 a heat consumption) and half the increase in lifetime (5 a) compared to the original data. The *Base2050* scenario in this paper adopts the "base" scenario from Fasihi et al. (2019) [6]. Breyer et al. (2020) [40] caveat that these future cost levels can only be achieved via technological learning if DAC systems are scaled up early in the energy system. Fixed operating expenditures (OPEX) are assumed to be 4% of CAPEX for all parameter sets. Since the electricity costs are included and optimized endogenously in the model *Enertile*, no other variable costs are assumed. Since HT DAC systems are reported to have higher costs, we only consider LT DAC systems in this paper.

For both HT DAC and LT DAC, the major part of a DAC plant's energy demand is heat for dissolving captured CO_2 from solvents or sorbents. While for HT DAC primarily natural gas has been used for the heat supply so far, the literature for LT DAC shows different heat sources – waste heat being the most economically attractive one [6]. This paper examines DACCS plants in deep decarbonization scenarios. This limits the selection of suitable or available heat sources. Fasihi et al. (2019) [6] elaborate that natural gas and renewable synthetic methane are not sustainable or efficient for supplying heat in DAC plants. Renewable heat sources such as solar thermal, geothermal, or biomass may be suitable; however, their potential is bound to certain regions and, in the case of biomass, is limited by land use restrictions. Waste heat is locally bound too and, in GHG-neutral energy systems, subject to increasing competition for utilization. Consequently, electricity-based heat supply is expected to become an important decarbonization measure (e.g. Refs. [41–43]). Aiming at robust results, the modeling approach in this paper conservatively assumes full electric DAC systems. It is conservatively assumed that heat is provided by electric heaters and heat demands of DAC plants are converted into electricity demands. Depending on the parameter set, an LT DAC system requires between 1339 kWh_{el} and 2088 kWh_{el} of electricity to capture one ton of CO_2. A lifetime between 20 and 30 years is assumed in the respective parameter sets.

2.2.6. CO_2 sequestration technology and storage capacities

Deep geological formations into which CO_2 can actively be injected by wells are important for DACCS. Zhang and Song (2014) [44] assume a sequestration site is suitable if it stores the CO_2 for at least 1000 years with a leakage rate of less than 0.1% per year. The captured CO_2 is preferably compressed and injected in a supercritical state into 800 m to 2000 m deep geological formations like deep saline aquifers, hydrocarbon fields, or coal fields [44,45]. Depending on the sequestration site, different trapping mechanisms exist to store CO_2 in the gaseous, liquid, or supercritical state. Low-permeability cap rock is a prerequisite for all storage sites, as it traps the moving CO_2 underneath and prevents leakage before other optional trapping mechanisms, such as mineral trapping, can come into play [44].

The EU GeoCapacity project [46] performed a GIS-based assessment of geological formations including the most interesting sequestration sites deep saline aquifers, hydrocarbon fields, and coal fields in 25 European countries [45]. Based on the results of Navigant (2019) [47], the total CO_2 sequestration potential of the scenario regions – including the EU 27 member states, Norway, United Kingdom, Switzerland, and countries of the Balkan Peninsula – account for 134 Gt_{CO2}. Deep saline aquifers account for the largest share of storage capacity with about 80% [46]. The total storage potential of the scenario regions is shown in Fig. 5. For the 2050 analysis in this paper, the total capacity is divided by 100 years, as capacity may be needed before and after 2050. This results in an annual storage potential of more than 1 Gt_{CO2}/a and would be sufficient to store a quarter of the EU's annual emissions in 2018 [36].

CO_2 sequestration costs highly depend on the type of storage site. NAVIGANT (2019) [47] estimates storage costs between 1 €/t_{CO2} for low-cost onshore depleted oil or gas fields and 22 €/t_{CO2} for high-cost offshore saline aquifers. Based on additional literature [6,48], final

[1] Without land use, land-use change, and forestry (LULUCF).

[2] Given the framework conditions of this study, Austria, Switzerland, the Czech Republic, the Baltic States, and the Benelux Union do not have sufficiently large geological CO_2 storage potentials to meet their own CDR demands (cf. section 2.2.6). In order to keep the sum of annual CO_2 capture volumes between the *loc bound* and *loc opt* scenarios equal, exceeding CDR demands in these regions are shifted to the country with the largest geological storage potential: Norway offsets about 15 Mt_{CO2} more than its own demand in the loc bound scenarios.

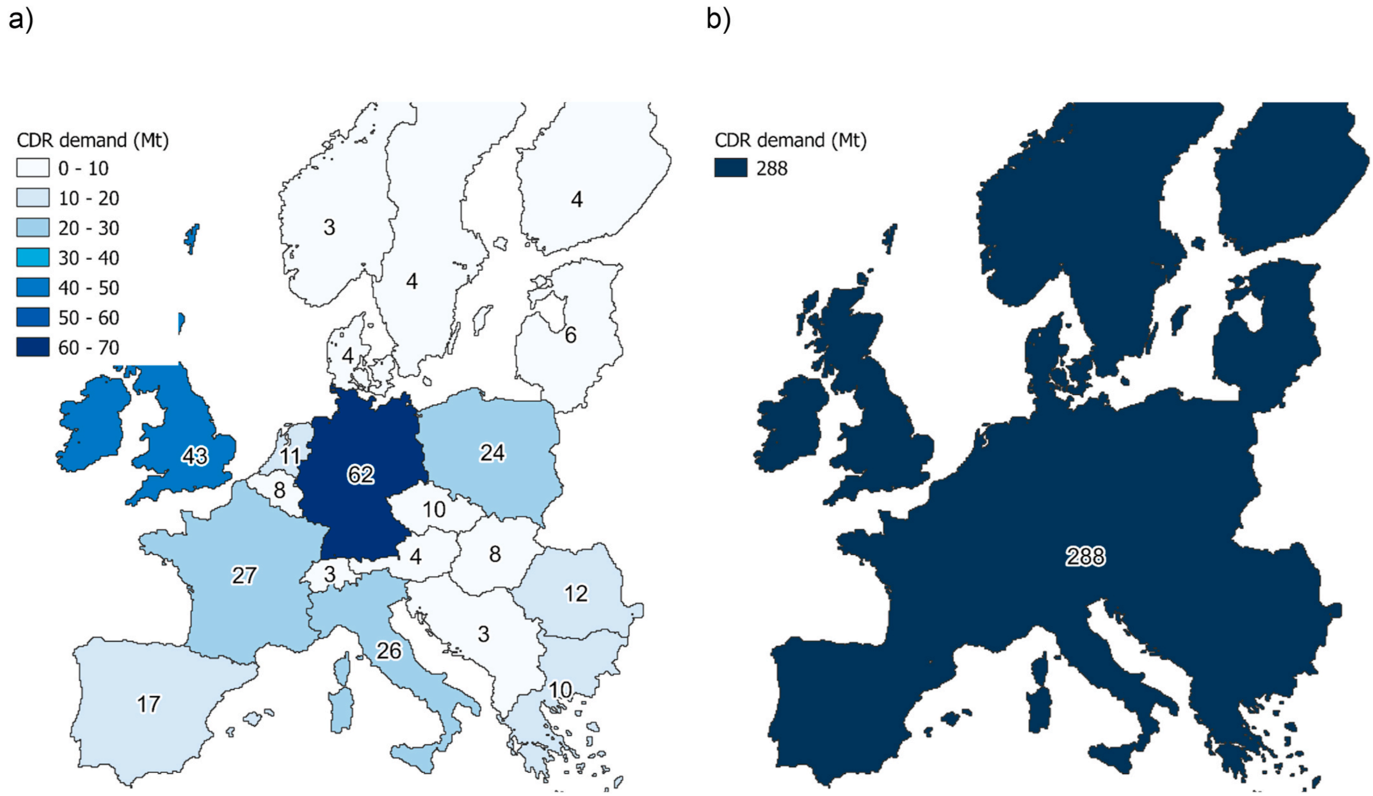

Fig. 3. The assumed CDR demands in 2050 equal 5% of 1990 GHG emissions [35,36]. a) *Loc bound:* Each model region must offset its emissions. b) *Loc opt*: The CDR demand must be met within Europe, but the optimizer decides on the location of DACCS.

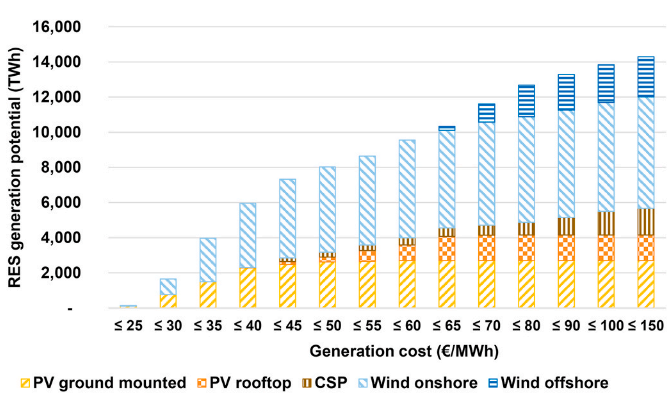

Fig. 4. Aggregated renewable electricity cost-potential curve for Europe in 2050 [33].

OPEX of 10 €/t_{CO2} for CO_2 sequestration are assumed in this study.

3. Results

The techno-economic DACCS potential in a GHG-neutral European energy system is analyzed using both modeling approaches presented in section 2.1. The results of the CDR sales instance supplied by DACCS units are presented in section 3.1. European supply curves of captured and sequestrated CO_2 and a cost decomposition are shown. The results of meeting explicit CO_2 removal demands via the DACCS route are shown in section 3.2. This methodological approach is used to analyze the regional distribution of CO_2 removal among European countries and to show the impacts of DACCS on the conversion sector.

3.1. Methodology approach a – carbon dioxide removal sales instance for DACCS units

3.1.1. European supply curves for carbon dioxide removal by direct air capture and storage

Fig. 6 shows the model results of the DACCS supply curves for Europe

Table 2
DAC parameter sets used in the energy system optimization model *Enertile*.

Scenario	CAPEX (€/t_{CO2}h) [a]	OPEX		Electricity demand (**kWh$_{el}$/t_{CO2}**)	Lifetime **(a)**	Data source
		Fix (% of CAPEX)	**Variable** (€/t_{CO2})			
Base2050	672,000	4	0	1339	30	[6]
Cons2050	1,592,000	4	0	1685[b]	25[b]	[6] [b]
Current2020	5,840,000	4	0	2088	20	[6]

[a] To receive the CAPEX, the reported investments – e.g., 199 €/t_{CO2} a for the conservative parameter set – were multiplied by 8000 full load hours (FLH) based on results for large-scale DAC systems in Fasihi et al. (2019) [6] and Breyer et al. (2020) [40].

[b] In their DAC parameter scenarios, Fasihi et al. (2019) [6] differentiate only the investments – but not the energy consumption and lifetime – between the scenarios Base and Conservative. In this work, the *Cons2050* scenario is calculated with half the learning rate in energy consumption (5%/10 a electricity consumption, 7.2%/10 a heat consumption) and half the increase in lifetime (5 a) compared to the original data.

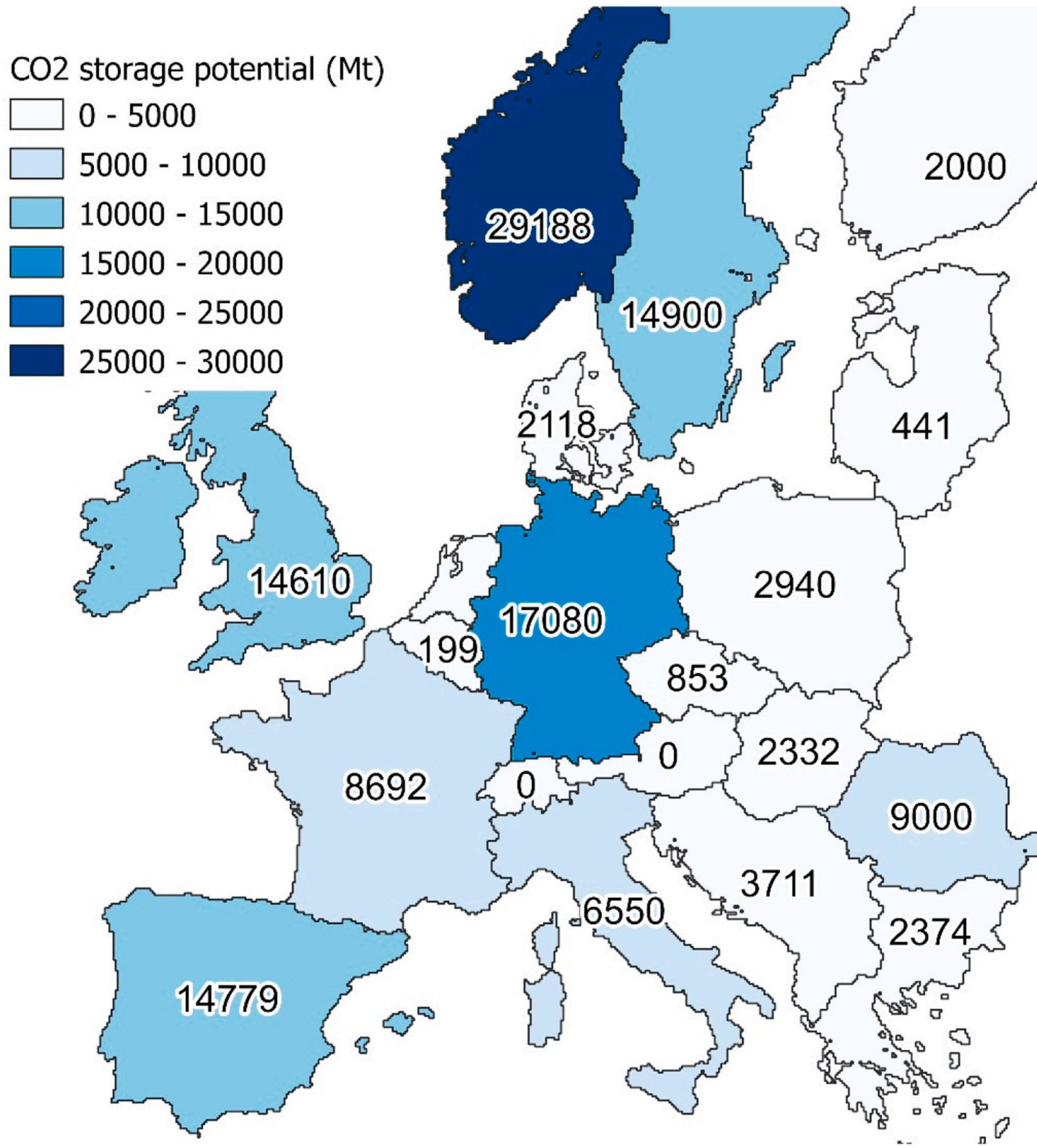

Fig. 5. Regional CO_2 storage potentials for all scenario regions. Own illustration based on data from Refs. [46,47].

in 2050. Three different techno-economic parametrizations of the DAC technology are distinguished. The CDR supplies via the DACCS pathway are an economic European optimum conditioned by regional CO_2 storage potentials and hourly electricity generation costs. The supply curves in Fig. 6 represent CDR quantities for GHG emissions external to the conversion sector. However, the endogenous CO_2 compensation for waste-to-energy is part of the optimization, accounts for additional 37 Mt_{CO2}/a of CDR requirement, and explains the gap between the maximum values of the supply curves and the upper limit of the annual CO_2 storage capacity.

For all three DAC parametrizations, the optimization results show increasing CDR amounts with increasing sales prices. This means that with a higher willingness to pay for compensated CO_2 in other sectors, additional DACCS plants with higher marginal costs come into play. Assuming that only one-hundredth of the available geological CO_2 storage potential may be used annually and applying the parameter projections for low-temperature DAC plants until 2050, DACCS costs are in the ranges of 60–90 €/t_{CO2} for the *Base2050* DAC parameter set and 80 to 140 €/t_{CO2} for the *Cons2050* DAC parameter set. For an upper benchmark, if the presently published key performance indicators of DAC plants are used, DACCS costs in the range of 160–270 €/t_{CO2} are obtained for the *Current2020* parameter set. At the upper end of sales prices of 90 €/t_{CO2} (*Base2050*), 140 €/t_{CO2} (*Cons2050*), and 270 €/t_{CO2} (*Current2020*), the respective supply curves reach the predefined maximum annual CO_2 storage capacity.

3.1.2. Cost components of DACCS

Fig. 7 shows the cost decomposition of the DACCS supply curve for the *Cons2050* DACCS technology parametrization. The cost decomposition shows that the dominant cost component for compensating for CO_2 emissions with DACCS is energy costs. With increasing CDR sales prices – and therefore increasing CO_2 compensation amounts – the share of electricity costs for DAC increases from 65% of DACCS costs at a sales price of 90 €/t_{CO2} to 74% at a sales price of 140 €/t_{CO2}. This increase in

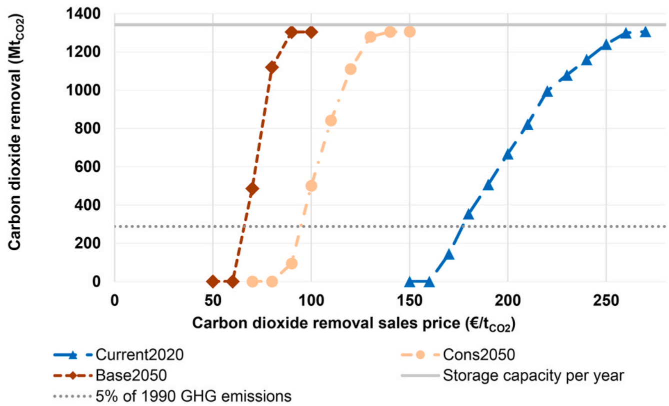

Fig. 6. Aggregated European DACCS supply curves in 2050 for three different DAC parametrizations. The upper limit of the annual capture volume is set by the geological storage potential. As an order of magnitude, 5% of 1990 GHG emissions are plotted.

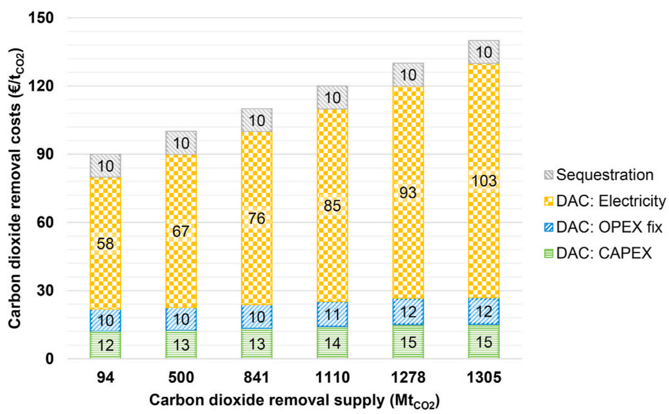

Fig. 7. Cost decomposition of carbon dioxide removal (CDR) for the DACCS supply curve using the *Cons2050* DAC parameter set.

electricity costs is due to exploiting increasingly expensive RES sites (cf. Fig. 4) as electricity demands for DACCS increase. Annuitized CAPEX and fixed OPEX of DAC only show moderate increases with increasing CDR sales prices. Depending on the sales prices, these fixed cost components of the DAC unit account for 19%–24% of the total DACCS cost for the *Cons2050* DAC parameter set. Sequestration costs are assumed to be flat and account for 10 €/t_{CO2} for all points on the supply curve.

The cost decompositions of the *Base2050* and *Current2020* DACCS parametrization scenarios show structurally similar results compared with the *Cons2050* case. For all parametrizations considered, electricity is the dominant cost component of DACCS costs.

3.2. Methodology approach B – meeting explicit regional carbon dioxide removal demands via the DACCS pathway

3.2.1. Regional DACCS potential usage

Fig. 8 shows the regional distribution of CDR via the DACCS route in the scenarios *Loc opt - DAC Base2050* and *Loc opt - DAC Cons2050*. It shows that if the optimizer is given the choice of where to perform DACCS to compensate for European GHG emissions, units are operated only in Sweden, Norway, Finland, the Iberian Peninsula, and the Baltic States. These countries offer sufficient CO_2 sequestration potentials in combination with idle and relatively low-cost renewable electricity generation potentials. In Finland and the Baltic States, the predefined maximum annual sequestration volume is reached in both scenarios. Many countries currently contributing substantially to Europe's GHG emissions, such as Germany, the United Kingdom, France, and Italy (cf. Fig. 3), do not have favorable conditions to permanently remove CO_2.

The regional distribution of CO_2 capture and storage differs between the two DAC parameterizations. In the *Base2050* DAC parameter scenario, the highest amount of GHG emissions is offset on the Iberian Peninsula amounting to 148 Mt_{CO2}/a. In the parameter scenario *Cons2050* DAC with higher specific investments for DAC plants and higher specific energy consumption for CO_2 capture, the optimizer shifts the capturing of about 50 Mt_{CO2}/a from the Iberian Peninsula to Scandinavia. This shift is especially related to the disproportional increase in specific investments in the *Cons2050* scenario: while the specific investments of DAC units are increased by 137% compared to the *Base2050* scenario, the energy demand per ton of CO_2 captured is only increased by 26%. In consequence, the average full load hours of the DACCS plants in the optimization result increase from 4878 h in the *Loc opt - DAC Base2050* scenario to 6,633 h in the *Loc opt - DAC Cons2050* scenario. By increasing the full load hours, the increased annuities of the specific investments can be allocated to more hours and thereby reduce the specific DACCS costs. This allocation of the higher investments to more operating hours competes with increased power procurement costs during these additional hours. The renewable expansion results in Figs. 9 and 10 show that these higher full-load hours of DAC units can be realized by onshore wind rather than PV. Therefore, with higher specific investments of DACCS units, the optimizer reduces the expansion of PV capacity on the Iberian Peninsula and increases onshore wind capacity in Scandinavia instead.

3.2.2. Impacts of DACCS on the conversion sector

Energy costs are the main component of CDR costs using DACCS technology. This section describes the impacts of DACCS deployment on the electricity system. Fig. 9 shows the electricity generation, and the associated installed generation capacities in Europe in 2050 for the *No CDR demand* scenario and the change in these quantities for all scenarios with CDR demands defined in Table 1. In the reference case of the *No CDR demand* scenario, onshore wind and PV are the dominating electricity generation technologies. Together, they account for 72% of electricity generation and 78% of the installed electricity generation capacity in Europe in 2050.

CO_2 compensation in Europe substantially increases the installed power generation capacities of renewable energies. Compared to the *No CDR demand* scenario, all scenarios with an exogenously given CDR demand of 288 Mt_{CO2}/a show a 5%–8% increase in power generation capacity. The DAC parameterization has a higher impact on the extent of additional installed capacity than regional constraints on CO_2 capture and storage. Additional electricity generation capacity requirements in the *DAC Cons2050* scenarios range between 206 GW (*Loc opt)* and 228 GW (*Loc bound*), while in the *DAC Base2050* scenarios, they range between 159 GW (*Loc opt*) and 182 GW (*Loc bound*). In both parametrization cases – *DAC Cons2050* and *DAC Base2050* – the free choice of location for offsetting CO_2 emissions within Europe reduces the additional electricity generation capacity by only one percentage point. The capacity expansion for power generation mainly affects onshore wind and PV. Onshore wind capacity increases between 80 GW (*Loc bound - DAC Base2050*) and 119 GW (*Loc bound - DAC Cons2050*); PV capacity increases between 85 GW (*Loc opt - DAC Base2050*) and 126 GW (*Loc bound - DAC Cons2050*). In the *DAC Cons2050* scenarios, the offshore wind capacity is increased by 1 GW; in the *DAC Base2050* scenarios, offshore wind capacity is not increased at all. With the underlying costs assumptions, offshore wind is too expensive to be expanded substantially given the amount of compensated CO_2 required in these scenarios; for higher CRD demands, offshore wind might play a greater role.

Fig. 10 shows the regional distribution of the potential utilization of the technologies ground-mounted PV, onshore wind, and offshore wind for the scenario *No CDR demand.* In addition, it shows the regional changes in installed electricity generation capacities of these technologies in scenarios with exogenous CDR demands. The figure illustrates that already in the *No CDR demand* scenario, the renewable electricity

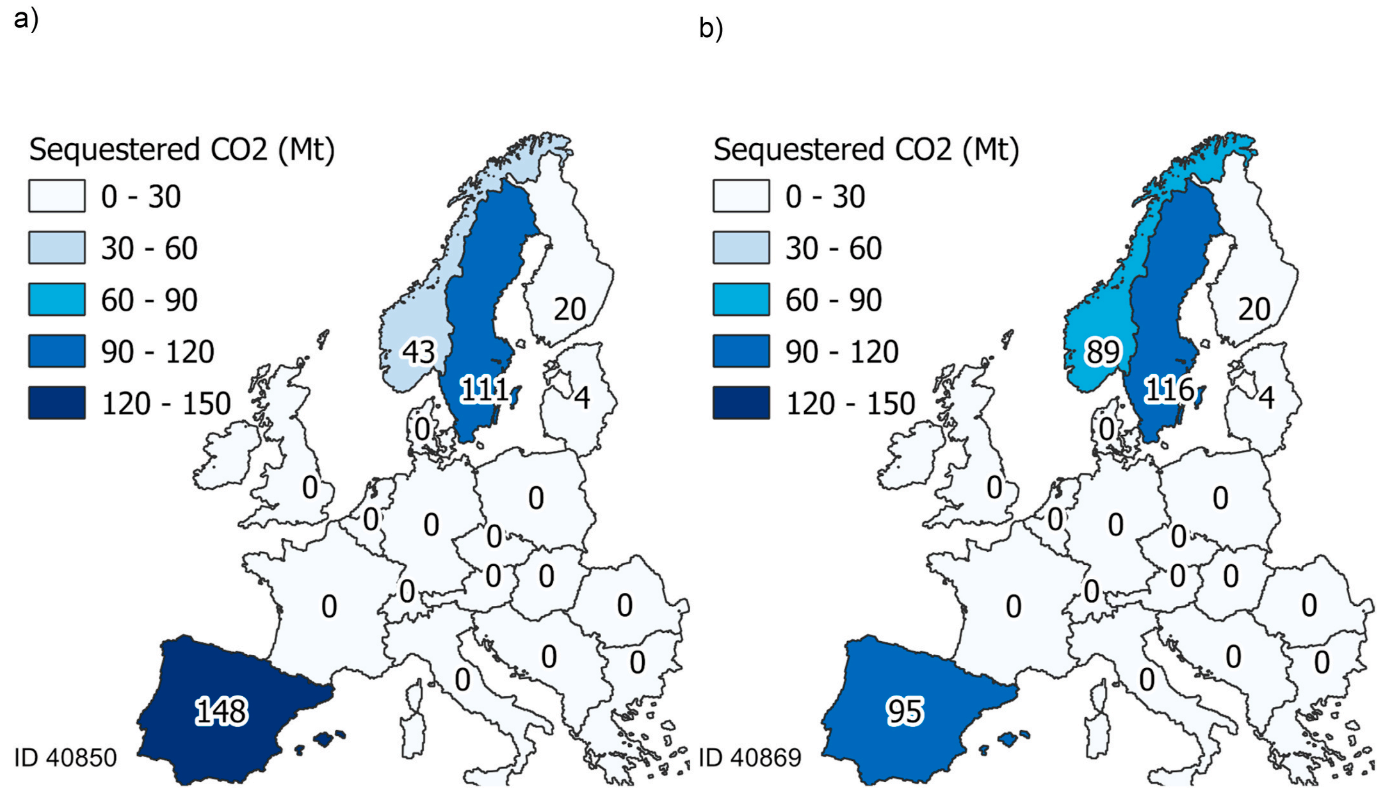

Fig. 8. Captured and sequestered CO_2 in the scenarios *Loc opt - DAC Base2050* and *Loc opt - DAC Cons2050*. In addition to the model endogenous CDR demands caused by emissions from waste-to-energy within the conversion sector, both scenarios assume that 5% of the 1990 greenhouse gas emissions need to be removed from the atmosphere annually. The total annual CDR demand in the scenarios is about 325 Mt_{CO2}. The optimizer has the choice of where to install and utilize DACCS units across Europe.

generation potentials in Central Europe are largely exhausted. Especially in Germany, Denmark, the Czech Republic, the British Isles, and the Benelux Union, the potentials for onshore wind and ground-mounted PV are fully exploited. In the *Loc opt* scenarios, the cost optimization, therefore, mainly selects locations at the "edges" of Europe for the installation of DACCS plants. In these scenarios, onshore wind and ground-mounted PV capacities are expanded mainly on the Iberian Peninsula, Sweden, and Norway. These locations have both a CO_2 storage potential (cf. Fig. 5) and – equally important – idle and relatively cheap renewable electricity generation potentials. In the *Loc bound* scenarios, there too is a focus of onshore wind and PV expansions on the Iberian Peninsula, in Sweden, Norway, and Finland, but the concentration of the renewable capacity expansion in these regions is not as pronounced. The exploitation of the available renewable potentials is more evenly distributed across Europe. This is based on the scenario-specific restriction that each region must capture and store its own CDR quantity. The required electricity can either be generated within the respective region by renewable energies or imported from other regions. However, imports are limited by transmission grid capacities and are subject to losses. An expansion of the transmission grid is possible in the optimization but is associated with costs. In the optimization result, regions like the Iberian Peninsula or Norway, therefore, export more electricity in the *Loc bound* scenarios than in the *Loc opt* scenarios. On the other hand, regions like Germany and the British Isles, which have already exhausted their potentials for onshore wind and ground-mounted PV in the *No CDR demand* scenario, compensate for the additional energy demands in the *Loc bound* scenarios through their trade balances. Germany imports electricity for CO_2 capture from other European countries. The British Isles reduce their electricity and hydrogen exports to mainland Europe to meet the increased domestic electricity demand. In contrast, Poland is particularly increasing its PV capacity to meet its CDR demand.

All four scenarios with exogenously specified CDR demands show a reduced utilization of hydrogen as a seasonal storage medium in the conversion sector compared to the *No CDR demand* scenario. Fig. 9 shows that the hydrogen utilization for electricity generation decreases by between 22 TWh_{el} in the *Loc opt - DAC Base2050* scenario and 37 TWh_{el} in the *Loc bound - DAC Cons2050* scenario. Since both electrolysis and DAC technologies have electricity as the main cost driver in this modeling, these technologies compete for low-cost renewable energy and mutually limit one another's uses. As more renewable energy is produced, the need for hydrogen reconversion decreases, while in times of high renewable supply more electricity is used in DAC facilities.

3.2.3. Regional DACCS costs

Fig. 11 shows the regional cost of DACCS in the scenarios *Loc bound - DAC Cons2050* and *Loc bound - DAC Base2050*. Using the methodology approach in which explicit CDR demands must be met, DACCS costs are obtained by evaluating the shadow prices[3] in the optimization results. The regional cost results for the *Loc bound - DAC Cons2050* scenario show that Europe may be categorized into four region clusters: The first cluster consists of Finland, the Iberian Peninsula, Sweden, and Norway and shows the lowest DACCS costs between 90 €/t_{CO2} and 92 €/t_{CO2}. The second cluster consists of the British Isles, Denmark, Poland, and France. This cluster has DACCS costs between 98 €/t_{CO2} and 101 €/t_{CO2}. Germany, Bulgaria and Greece, Hungary and Slovakia, the Netherlands, the Balkan States, and Romania form the third cluster with DACCS costs between 104 €/t_{CO2} and 110 €/t_{CO2}. Italy has the highest DACCS cost compared to all other regions, with 119 €/$t_{CO2,}$ and is the only

[3] The shadow prices represent the marginal costs of a constraint, in this case the regional CRD demand, and are retrieved from the dual value of this constraint in the optimization result.

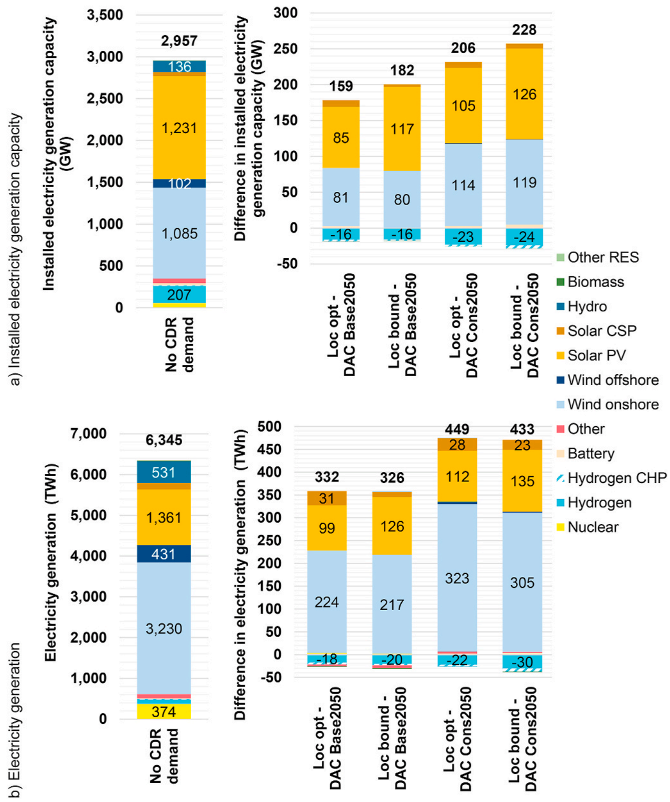

Fig. 9. Technology-specific installed electricity generation capacities (a) and electricity generation quantities (b) in the European power sector in 2050. The results of the *No CDR demand* scenario and the deviations in the scenarios with CDR demand, as defined in Table 1, are distinguished.

representative of the fourth cluster. In the *Loc bound - DAC Base2050 scenario*, the clusters are not equally clear-cut and the regional differentiation of DACCS costs is weaker overall. The average DACCS costs in Europe 2050 are 104 €/t_{CO2} in the *Loc bound - DAC Cons2050* scenario and 70 €/t_{CO2} in the *Loc bound - DAC Base2050* scenario.

In the *Loc opt* scenarios with an optimization of the DACCS site selection, uniform marginal DACCS costs arise in all model regions for a given CO_2 capture quantity. The optimization approach prevents arbitrage opportunities between the regions. In the *Loc Opt - DAC Base2050* scenario, an effective CDR demand of 325 Mt_{CO2} (including the GHG emission compensation for power-to-waste) results in marginal DACCS costs of 66 €/t_{CO2} in Europe; in the *Loc Opt - DAC Cons2050* scenario, it is 94 €/t_{CO2}. The total European CDR demand in these *Loc opt* scenarios is met by the five model regions with the lowest marginal DACCS costs in the *Loc bound* scenarios.

4. Discussion

While NETs are still in their infancy today, they can significantly change pathways to GHG neutrality: cheap NETs may prevent more expensive GHG mitigation strategies. Therefore, the discussion below compares the optimization results for DACCS to existing literature: First, to other DACCS studies (4.1); second, to other NET studies (4.2); and third, to other GHG mitigation studies in general (4.3). Section 4.4 discusses the limitation of chosen methodological approach and gives an outlook.

4.1. Comparison of the optimization results to other DACCS studies

Fuss et al. (2018) [49] provide a comprehensive literature review on the costs and potentials of NETs. One NET group the review covers is DACCS. The reviewed literature shows a wide CDR cost range from 30 to 1000 \$/t_{CO2} for DACCS. Due to different boundary conditions in existing studies, the authors emphasize that cost comparisons for DAC are difficult. Based on their understanding of the literature, Fuss et al. estimate the reasonable cost range of widely deployed DACCS plants within 100–300 \$/t_{CO2} [49]. Fasihi et al. (2019) [6] calculate CO_2 capture costs of LT-DAC for Moroccan conditions in a range of 32–54 €/t_{CO2} in 2050, depending on the availability of cost-free waste heat. If waste heat can be deployed, together with low water demand and high modularity, this causes the cost superiority of LT-DAC over HT-DAC technology [6]. Breyer et al., 2020 [40] find that by optimizing operating hours and using low-cost heat, DACCS costs can decrease to around 40 €/t_{CO2}. Lackner and Azarabadi (2021) [50] calculate DACCS cost well below 100 \$/t_{CO2} and close to 50 \$/t_{CO2} if a progressive capacity expansion is assumed. According to a comparative technical assessment of Sabatino et al. (2021) [50], costs for CO_2 capture of less than 200 \$/t_{CO2} are possible for various LT-DAC technologies under optimized process conditions. The company Climeworks currently offers negative emissions using already existing DACCS plants for 1000 €/t_{CO2} [51]. The system cost minimization results in this manuscript show DACCS costs in Europe 2050 ranging within 60–140 €/t_{CO2} with progressive techno-economic assumptions and 160–270 €/t_{CO2} with a conservative parameter set. These DACCS costs are, therefore, of the order of magnitude in the current literature. While existing studies were either rather technically oriented or had a high-level perspective using integrated assessment models, this study closes the gap and focuses on the integration of DACCS into a renewables-based European energy system.

4.2. Comparison of DACCS to other negative emission technologies

Besides DACCS, Fuss et al. (2018) [49] review other NETs. This section compares this detailed literature evaluation on the costs and potentials of six other NETs to the DACCS results obtained in this paper. One, AR describes the creation of new forests and the regeneration or recreation of former woodlands. This approach uses photosynthesis to convert and store atmospheric CO_2 in additional biomass, i.e., trees. For AR, the authors of the review estimate costs in 2050 in the range of 5–50 \$/t_{CO2} with a global carbon removal potential of 0.5–5 Gt_{CO2}/a. Two, Biochar is produced via pyrolysis, i.e., the thermal decomposition of organic material in a low-oxygen environment. In Fuss et al.'s review, Carbon removal by biochar production and storage in soils have estimated costs within a range of 30–120 \$/t_{CO2} at a global potential of 0.5–2 Gt_{CO2}/a. Three, SCS describes ways of land management in order to increase carbon absorption or decrease carbon losses of soils. SCS is associated with costs of 30–120 \$/t_{CO2} and a global carbon removal potential of 2–5 Gt_{CO2}/a. Four, EW on land and in oceans artificially accelerates the natural weathering of rocks. Rock material is ground to speed up the chemical reaction of atmospheric carbon dioxide with water and air. For EW, Fuss et al. estimate costs of 50–200 \$/t_{CO2} and a global potential of 2–4 Gt_{CO2}/a. Five, OF is a type of geo- or climate engineering that is based on the deliberate addition of plant nutrients to the upper ocean waters. It is in an attempt to remove CO_2 from the atmosphere by increasing phytoplankton production. Fuss et al. consider OF to have an extremely limited potential and give, therefore, no reasonable cost range. Six, BECCS provides negative emissions by combusting sustainable biomass in industrial or power plants and subsequently capturing and storing the resulting carbon dioxide. Fuss et al. estimate the costs of BECCS in the range of 100–200 \$/t_{CO2} with a global carbon removal potential of 0.5–5 Gt_{CO2}/a. The DACCS costs identified in Fig. 6 tend to be higher than or equal to the costs of alternative NETs in the literature.

However, according to Fuss et al. (2018) [49], all alternative NETs come with negative side effects that are not captured in their costs: For EW, local air pollution and heavy metal pollution in soils are anticipated. SCS and biochar are permanently at risk of a rapid release in case of a turnaround in land management decisions. With increasing scale,

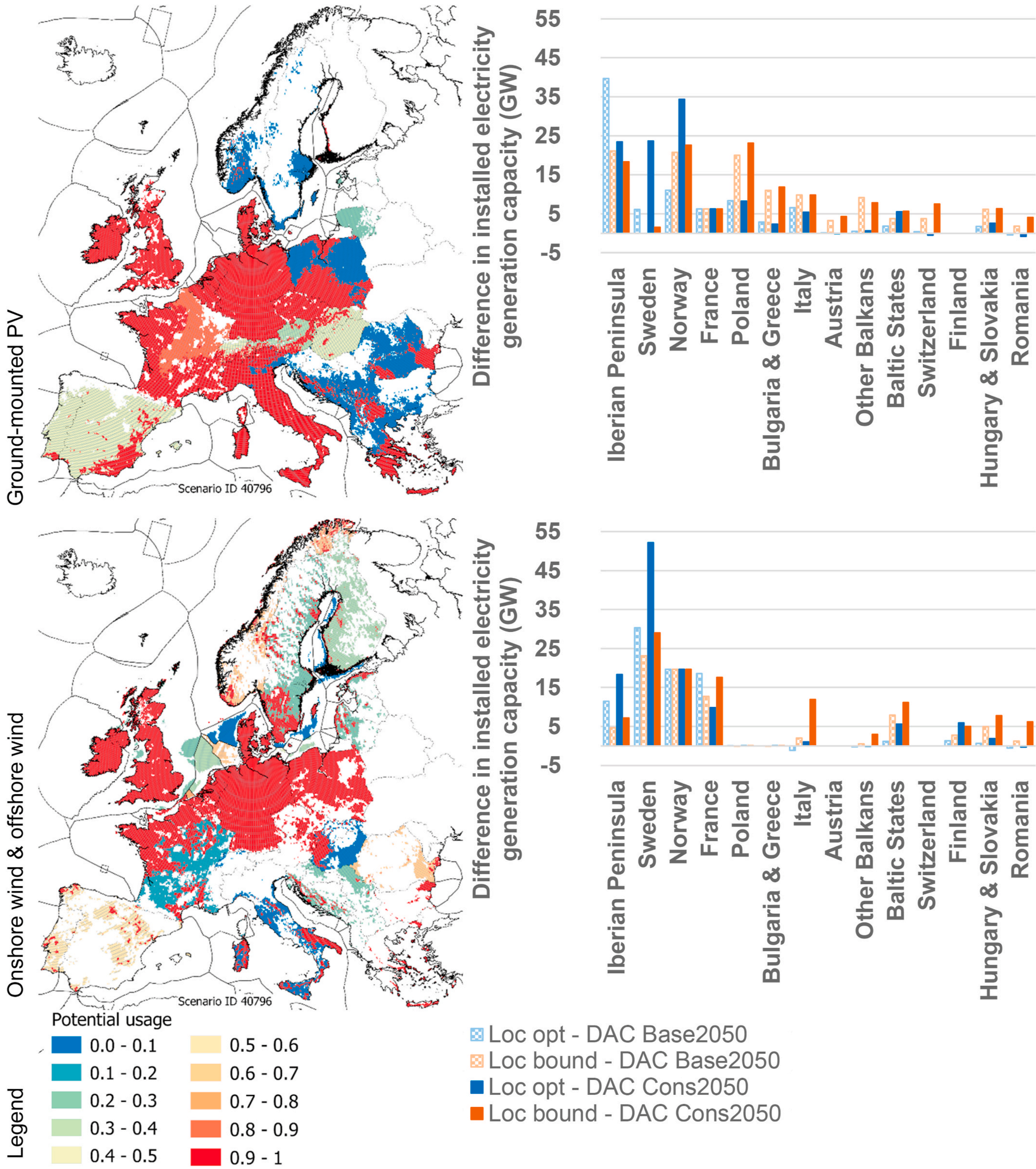

Fig. 10. Potential utilization of the technologies ground-mounted PV, onshore wind, and offshore wind in the *No CDR demand* scenario in 2050. Deviations in installed wind and PV capacities from the *No CDR demand* scenario are shown for scenarios with CDR demand.

BECCS and AR programs involve substantial demand for land. Changes in land use could result in direct and indirect GHG emissions and impacts on biodiversity and soil nutrition. As DACCS is a relatively new technology, literature has not yet systematically discussed its risk of negative side effects.

4.3. Comparison of DACCS to other CO_2 abatement options

In addition to offsetting unavoidable remaining emissions, DACCS could play a role in GHG-neutral energy systems when alternative mitigation strategies have higher costs. Below, two approaches are presented to compare the costs of DACCS to other abatement strategies

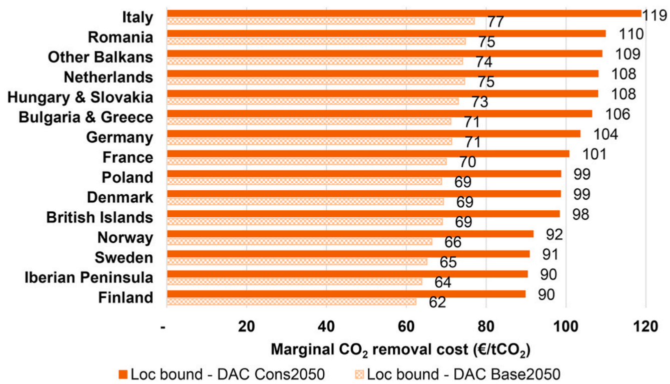

Fig. 11. Regional DACCS costs in the scenarios *Loc bound - DAC Base2050* and *Loc bound - DAC Cons2050*. DACCS costs are obtained by evaluating the shadow prizes of CDR demand constraints in the optimization results. Austria, Switzerland, the Czech Republic, the Baltic States, and the Benelux Union are excluded because these regions do not have sufficiently large CO_2 storage potential to store their emissions (cf. section 2.2.3).

in the literature. The reference for this comparison is the maximum DACCS costs of 270 €/t_{CO2} in Europe in 2050, shown in the DACS supply curves in Fig. 6. The first approach relies on so-called marginal abatement cost curves (MACCs). MACCs sort various GHG mitigation options according to their costs and show the corresponding saving potential. Gerbert et al. (2018) [52] developed such a curve with measures to achieve a 95% GHG reduction in Germany. Across sectors, it shows mitigation options above 270 €/t_{CO2} with an annual saving potential of 60 Mt_{CO2}. The transport sector has the greatest savings potential within these high-cost options. The most expensive measure in this MACC is the use of synthetic hydrocarbons for electricity generation with abatement costs of 400 €/t_{CO2}. Della Vigna et al. (2021) [53] show comparable curves taking a global perspective. Assuming a ramp-up of currently available abatement technologies until 2030, the study estimates a GHG emission abatement potential of about 2 Gt_{CO2} above costs of 270 €/t_{CO2}. This study sees options with high abatement costs primarily in the buildings and transport sectors. The MACCs in the literature show that most GHG abatement options are less expensive than DACCS. However, there is a substantial portion of abatement strategies significantly more expensive than the DACCS costs identified in this paper. The second approach uses the modeling results of mitigation pathways developed in the latest IPCC report [54]: calculations with global models find median CO_2 prices of 578 \$/t_{CO2} for pathways reaching GHG neutrality by mid-century. This CO_2 price level is significantly above the DACCS costs in this paper.

One central challenge for DACCS is the low CO_2 concentration in the atmosphere (cf. section 1). Conventional CCS technologies, therefore, capture emissions at point sources such as power or industrial plants with higher CO_2 concentrations in the flue gas. Wilberforce et al. (2020) [55] estimate the costs of post-combustion CCS in power plants in 2050 in the range of 30–270 \$/t_{CO2}, depending on the type of the power plant. In addition to capture costs, PSCC increases the electricity production costs by 0.01–0.05 \$/kWh compared to a reference power plant [55]. For industrial applications, Leeson et al. (2017) [56] project PSCC costs for avoided CO_2 in 2050 to 40 \$/t_{CO2} for iron and steel production, 42.9 \$/t_{CO2} in refineries, and 19.9 \$/t_{CO2} in cement plants. The IEA [37] lists several current post-combustion CCS projects generally focused on energy production and processing rather than industry. However, the scenario design for this paper prohibits power plants with direct CO_2 emissions in 2050. Literature values of PSCC costs in industry are lower than the DACCS costs obtained in this paper. Since PSCC is not a NET, it is not entirely accurate to compare PSCC and DACCS solely by their costs. PSCC can only reduce (in case of carbon capture and sequestration) or postpone (in case of carbon capture and use, e.g., in synthetic fuel production) fossil CO_2 emissions. In contrast, DACCS can reduce the CO_2 concentration in the atmosphere. As PSCC is locally bound to point sources, it additionally requires the transport of captured CO_2 to a storage site. However, for processes where CO_2 emissions are unavoidable, PSCC and DAC could compete for market shares in terms of capture costs and efficiency [6].

4.4. Limitations of the analytical approach and outlook

In this paper, the central analytical approach to assessing DACCS potentials is cost minimization of the European energy supply system. This approach has structural limitations. Although certain interactions with demand sectors are modeled, e.g., load shifts in charging e-mobiles, it is a partial model, and there is no detailed interaction with other parts of the economy. Furthermore, the modeling approach assumes perfect competition in markets, which does not occur in reality. A well-known characteristic of optimization models is the so-called "penny-switching" effect. It means that small changes in parameterization can lead to fundamentally different results.

A key limitation in computer-based models is computational power. Therefore, aggregations are necessary. For example, the regional resolution in the optimization is limited to national states. Possible power system bottlenecks within a region are therefore not taken into account. This may impact the locations of DACCS plants.

The applied model has a techno-economic focus. Public perception and technology acceptance can only be reflected to a very limited extent. In reality, there may be barriers that prevent the exploitation of the derived DACCS potential in this work. Dütschke et al. (2015) [57] found that real CCS projects raised public concerns. The societal objection may result in existing geological storage potentials not being used. Furthermore, due to favorable conditions, cost minimization concentrates DACCS units in a few countries. This leads to substantial increases in renewable power generation capacity in these regions. In reality, there may be opposition to additional wind power plants for CO_2 compensation for other countries.

In this paper, flat CO_2 sequestration costs are assumed. Future work could develop and consider a pricing mechanism for the finite resource of geologic storage.

This study focuses on the integration of DACCS plants into a GHG-neutral European energy system. However, DACCS has the advantage that it can reduce CO_2 concentration regardless of the emission source. Breyer et al. (2019) [58] show that the global south, in particular, has low-cost DAC potential. The integration of DACCS plants into non-European energy systems remains a task for future studies.

5. Summary and conclusions

Negative emission technologies will likely be needed to achieve the climate protection goals of the European Commission by 2050. This article investigates the potential of reducing GHGs in the atmosphere via the DACCS pathway. Since the capture of CO_2 from ambient air is energy-intensive, this study particularly considers the integration of DACCS plants into a GHG-neutral European energy system. The analyses were conducted using a new model extension of the energy system optimization model *Enertile*. Relying on a high technological, temporal and spatial resolution for renewable energy potentials, this modeling approach considers for the first time the interactions of DACCS with weather-dependent power generation technologies, flexible and inflexible power consumers, and sector coupling technologies in the context of the European energy system. Applying different evaluation approaches, the European techno-economic DACCS potential is determined and examined.

Literature shows that there are large geological CO_2 storage capacities of over 100 Gt_{CO2} in Europe. How long this storage capacity could last depends on the rate at which GHGs are extracted from the atmosphere and stored underground. If current emissions of about 4 Gt_{CO2}/a

[36] must be removed every year, the CO_2 storage potential is exploited after 27 years. If yearly GHG emissions were reduced to 5% of 1990 emissions, the compensation of these remaining emissions through capture and storage would be possible for over 350 years.

The model results show that there is a potential for DACCS in the framework of a GHG-neutral European energy system. Assuming – in a very conservative approach – that the techno-economic properties of DAC technology do not improve by 2050 and limiting the annual CO_2 capture amount to a hundredth of the geological storage potential (about 1 Gt_{CO2}/a), the cost range for DACCS in the optimization results is between 160 €/t_{CO2} and 270 €/t_{CO2}. This cost range marks the upper limit of DACCS costs in Europe 2050 in the model results. By contrast, assuming technological progress of DAC plants, DACCS costs could be in the range of 60 €/t_{CO2} to 140 €/t_{CO2} by 2050.

The model results show that energy supply is key for the deployment of DACCS units. Firstly, energy costs are the dominant cost driver in CDR costs via DACCS. Secondly, the capture of CO_2 from ambient air is associated with substantial energy demands. Applying fully electric DAC systems and using current projections of the technological development of DAC and CO_2 storage technologies, the removal of about 288 Mt_{CO2}/a (i.e., 5% of European GHG emissions in 1990) increases the electricity demand in 2050 by 385 TWh_{el} to 495 TWh_{el} in Europe. This increase in electricity demand for DAC can be met by a 5%–8% increase in renewable power generation capacities compared to an energy system without exogenously specified CDR demands. The capacity expansion for power generation mainly increases onshore wind and PV capacities. These required increases in power generation capacity are critical because the expansion of renewables on the path to GHG neutrality in the underlying scenario is enormous in any case. Especially in Germany, Denmark, the Czech Republic, the British Isles, and the Benelux Union, the potentials for onshore wind and ground-mounted PV are fully exploited before the energy demands for DACCS are taken into account. Germany and the British Isles, in particular, are characterized by high absolute CO_2 emissions in the past.

If cheaper heat sources – e. g., waste heat or geothermal energy – were available, lower DACCS costs and a lower additional expansion of renewable power generation technologies would be possible.

The model results show that – given a free choice of location – cost optimization favors Finland, Sweden, Norway, and the Iberian Peninsula for CO_2 capture and storage. These countries on the periphery of Europe are characterized by large geological CO_2 storage capacities and relatively low-cost, vacant renewable power generation potentials. These two characteristics are key for the future deployment of DACCS.

Even applying a conservative set of input parameters, the resulting costs for DACCS appear to be very competitive compared to the abatement costs of other climate change mitigation strategies across sectors. Many alternative CO_2 abatement strategies have been estimated to cost more than 270 €/t_{CO2} and are thus more expensive than the DACCS cost calculated in this article. This can be interpreted from two perspectives: On the one hand, from a cost-minimization perspective, DACCS could be a valuable option for minimizing the cost of combating climate change. It would essentially act as a backstop technology, pushing the necessity of using more expensive options into the future for at least several decades. On the other hand, there are substantial risks when pursuing a strategy that relies heavily on DACCS for fighting climate change, e.g., risks associated with CO_2 storage leakages, the acceptance of the required additional renewable energy capacities, or the chance that DACCS might be used excessively while still relying on fossil fuels, exhausting global storages too quickly. From this perspective, there are valid arguments that DACCS should be reserved for the compensation of unavoidable emissions, e.g., from agriculture and for cleaning up legacy emissions. Nonetheless, even from that perspective, the economic pressure for using DACCS will likely increase once costlier decarbonization options have to be pursued. From both perspectives, it is essential to research, understand, and evaluate DACCS options in greater detail and to decide and regulate their role in the strategies to fight climate change.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Credit author statement

Benjamin Lux: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft & review. Niklas Schneck: Software, Investigation. Benjamin Pfluger: Writing – original draft, Supervision. Wolfgang Männer: Writing - review. Frank Sensfuß: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors are indebted to Joshua Fragoso García, Christoph P. Kiefer, Christoph Kleinschmitt, Christiane Bernath, Gerda Deac, and Katja Franke for their modeling, expertise, and feedback.

Appendix

A Abbreviations

Table A.1
Abbreviations.

Abbreviation	Explanation
AR	Afforestation and reforestation
BECCS	Bioenergy with carbon capture and storage
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CSP	Concentrating solar power
DAC	Direct air capture
DACCS	Direct air capture and storage
EC	European Commission

(*continued on next page*)

Table A.1 (*continued*)

Abbreviation	Explanation
EU	European Union
el	Electrical
e-fuels	Electricity-based fuels
EW	Enhanced weathering
FLH	Full load hours
GHG	Greenhouse gas
HT DAC	High-temperature direct air capture
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized cost of electricity
LT DAC	Low-temperature direct air capture
NET	Negative emission technology
O&M	Operation and maintenance cost
OF	Ocean fertilization
OPEX	Operating expenditure
ppm	Parts per million
PV	Photovoltaics
RES	Renewable energy source
SCS	Soil carbon sequestration
TRL	Technology readiness level
WACC	Weighted average cost of capital

B Model regions

Fig. B.1. Map of model regions in *Enertile*.

Table B.1
Definition of regions as used in *Enertile*.

Enertile region code	Countries	Term used in the text
AT	Austria	Austria
CH	Switzerland	Switzerland
DE	Germany	Germany
FR	France	France
IBEU	Spain, Portugal	Iberian Peninsula
BEU	Belgium, Luxembourg	Benelux Union
HUK	Hungary, Slovakia	Hungary & Slovakia
UKI	United Kingdom, Ireland	British Islands
PL	Poland	Poland
BUG	Bulgaria, Greece	Bulgaria & Greece
BAK	Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Kosovo, Montenegro, Albania, North Macedonia	Other Balkans
BAT	Estonia, Lithuania, Latvia	Baltic States
CZ	Czech Republic	Czech Republic
DK	Denmark	Denmark
IT	Italy	Italy
NO	Norway	Norway
RO	Romania	Romania
SE	Sweden	Sweden
NL	Netherlands	Benelux Union

C Key assumptions for the renewable potential calculation

The onshore wind potential calculations take 59 different turbine configurations into account. In 2050, hub heights in the range of 80–160 m and specific area outputs in the range of 270–500 W/m^2 are considered. Table C.1 shows specific investments, fixed operation and maintenance costs, and technical lifetimes of representative combinations. The full data set is available online [31].

Table C.1
Hub height, rotor diameter, specific investments, fixed operation and maintenance costs, and technical lifetimes of 8 representative onshore wind turbines in the potential calculation for 2050 [31].

Turbine	Hub height (m)	Specific area power (W/m^2)	Specific investment (€/kW$_{el}$)	Fixed operation and maintenance cost (€/kW$_{el}$)	Technical lifetime (a)
1	120	270	1293	23.21	20
2	120	280	1277	22.97	20
3	120	290	1261	22.73	20
4	140	350	1229	22.89	20
5	150	280	1374	25.37	20
6	150	350	1262	23.70	20
7	160	270	1423	26.41	20
8	160	350	1294	24.49	20

The offshore wind potential calculations take 16 different turbine configurations into account. In 2050, hub heights in the range of 100–120 m and specific area outputs in the range of 370–450 W/m^2 are considered. Table C.2 shows specific investments and fixed operation and maintenance costs of representative combinations. The full data set is available online [31].

Table C.2
Hub height, rotor diameter, specific investments, fixed operation and maintenance costs, and technical lifetimes of 3 representative offshore wind turbines in the potential calculation for 2050.

Turbine	Hub height (m)	Specific area power (W/m^2)	Specific investment (€/kW$_{el}$)	Fixed operation and maintenance cost (€/kW$_{el}$)	Technical lifetime (a)
1	120	370	3559	66.51	20
2	120	380	3542	66.27	20
3	120	390	3526	663	20

Table C.3 shows specific investments, fixed operation and maintenance costs, and technical lifetimes of the solar technologies considered in the renewable potential calculation.

Table C.3
Specific investments, fixed operation and maintenance costs, and technical lifetimes for different solar technologies in 2050;

	Specific investment (€/kW$_{el}$)	Fixed operation and maintenance cost (€/kW$_{el}$)	Technical lifetime (a)
Technology			
Ground-mounted PV	500	5,00	20
Roof-top PV	764	11,00	20
CSP	2410	40,00	30

Table C.4 shows land use factors of all relevant technologies in the renewable potential calculation.

Table C.4
Land use factors in the potential calculation of renewable electricity generation technologies.

Category	Roof-top PV	Ground-mounted PV	CSP	Onshore wind
Barren	0%	16%	12%	18.0%
Cropland	0%	2%	2%	14.4%
Forest	0%	0%	0%	10.8%
Grassland	0%	2%	2%	18.0%
Savannah	0%	2%	12%	18.0%
Shrubland	0%	2%	12%	18.0%
Snow and ice	0%	4%	0%	10.8%
Urban	16%	0%	0%	0.0%
Water	0%	0%	0%	0.0%
Wetlands	0%	0%	0%	0.0%

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