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Carbon dioxide removal enables climate planetary boundary compliance in cost-effective energy-industry transition pathways

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Abstract

Several planetary boundaries have already been breached, including climate change. The 1.5°C climate target has been set and widely accepted as the main target. However, the safe and just climate planetary boundary has been identified at around 350 ppm atmospheric CO₂ concentration and ca. +1 W m⁻² radiative forcing, which can be translated into a 1.0°C level. In this research, we show pathways for the energy-industry transition until 2100 to reach the safe and just climate planetary boundary by deploying fossil fuel phase-out and large-scale carbon dioxide removal (CDR). We aim to quantify the energy and economic efforts required to rebalance Earth's climate to 1.5°C and 1.0°C. We study several diverse CDR technology portfolios regarding their energy supply impact and expected financial burden. We find that raising ambitions to 1.0°C based on a highly electrified system with low-cost renewable electricity requires less than 5% additional primary energy compared to 1.5°C scenarios, including CDR portfolios heavily relying on direct air capture and carbon sequestration. The ratio of total annual system cost to gross domestic product (GDP) can be significantly reduced from 6% today to 1.5%, while raised ambitions to 1.0°C would require up to 0.25% of global GDP in addition.

Keywords

Planetary boundary; Climate change; Transition; Carbon dioxide removal; Pathway

1 Introduction

Planetary boundaries are seen as the safe operating space for humanity on Earth^{1,2}. At least six out of nine planetary boundaries have been breached³, including the climate planetary boundary, yet carbon dioxide (CO₂) emissions are further increasing^{4,5}. The safe and just climate planetary boundary has been identified at an atmospheric CO₂ concentration of around 350 ppm and an anthropogenic radiative forcing of +1 W m⁻²⁶⁻⁸, which would refer to a temperature target of ca. 1.0°C⁹. Limiting the global temperature anomaly to 1.5°C is part of the 2015 Paris Agreement¹⁰, so despite the ambition of the agreement, it is not compliant with the safe and just climate planetary boundary. As of 2025, the atmospheric CO₂ concentration reached 423 ppm and radiative forcing was at +2.97 W m⁻²⁸.

Reaching the 1.5°C target is most likely impossible without overshoot¹¹⁻¹³. Rebalancing the Earth's climate to 1.5°C, therefore, already necessitates carbon dioxide removal (CDR)^{14,15}. A restoration of the climate within the planetary boundary around 1.0°C will most likely require substantial CDR deployment. CDR is to be understood as the (permanent) removal of CO₂ from the atmosphere, and as such to be differentiated from carbon capture and sequestration (CCS) which aims to avoid fossil emissions¹⁶. Almost all of current CDR comes from afforestation projects, while so-called novel CDR including direct air capture and sequestration (DACCS)¹⁷, bioenergy with carbon capture and sequestration (BECCS)¹⁸, or others^{19,20}, currently only contribute minor shares¹⁵. Removing other greenhouse gases (GHG) such as methane (CH₄) is not yet seen as an impactful option^{21,22}, while emission reduction of the short-lived GHG may be the more efficient way to reduce its climate impact²³.

CDR had been an important factor in the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC)²⁴. An assessment of the most ambitious scenario in the AR6 database can be found in supplementary information 1 note 1. Scenarios used in the AR6 largely rely on CDR to offset remaining gross CO₂ emissions to achieve net zero emissions when targeting 1.5°C²⁵. The biggest benefit of CDR, however, may lie in climate restoration. While the less prominent 2°C target of the Paris Agreement was a result of science-based, minimum long-term climate stability, the 1.5°C target was adopted rapidly due to political reasons²⁶. The target was finally chosen over the 1.0°C target by vested interests and status quo maintenance²⁷. CDR, if not prominently used to offset remaining fossil emissions, would become a key concept for raised ambitions towards a safe and just climate target.

While planetary boundaries have attracted increasing research attention, they are mostly used to describe the unsustainability of the current state²⁸. Forward-looking studies are rare, and cover food supply²⁹, resource intensity within planetary boundaries for high standards of living³⁰, the trade-offs arising from reaching planetary boundaries for different sustainable development goals³¹, or the compliance of specific technologies, concepts, or practices with planetary boundaries³²⁻³⁴. Future pathways using CDR to rebalance the climate within safe and just planetary boundaries do not yet exist.

Our research aims to answer two distinct research questions: First, since CDR already needs to be scaled to reach the 1.5°C target, how much additional effort would be needed, in terms of both energy and cost, to raise ambitions and scale the CDR sector to comply with climatic planetary boundaries? Second, what is the impact of different CDR technology portfolios on the feasibility and viability of energy-industry-CDR pathways? The main novelty of our study lies in coupling the CDR sector to an energy-industry transition model in hourly resolution to identify a fully defossilised, stable energy system as the basis of CDR sector scaling. We apply different CDR portfolios reflecting societal preferences²⁰ to identify additional benefits or bottlenecks for the energy supply from the choice of CDR options.

2 Results

To assess the feasibility of achieving climate planetary boundary compliance, we evaluate several key aspects of the transition pathway regarding climate impact, energy supply, CO₂ management, and system economics. Here we present most results for the key time steps 2030, 2050, and 2100. Transition pathway figures and detailed results can be found in supplementary Figures S5-S23.

2.1 Carbon dioxide emissions and climate impact

Although climate change is driven by a variety of GHGs, we concentrate on the CO₂ pathways of the energy-industry-CDR system. The emission pathways are used as inputs to climate modelling via the MAGICC7 climate model^{35,36}. The corresponding MAGICC7 output files can be found via supplementary material 1. The pathways, annual CO₂ emissions, and cumulative CO₂ emissions until end of the century, which can be seen in Figure 1, do not significantly differ within the 1.5°C and 1.0°C scenario groups. The defossilisation target year in 2050 is fixed among all scenarios. Similarly, the CDR demand trajectory was exogenously defined. The used energy-industry system transition model LUT-ESTM^{37,38} can vary the defossilisation within these limitations but only does so in a minor way, while some small differences come from the CDR portfolio modelling with CO₂SMOP (cf. supplementary material 1). Since the CO₂ emission pathways are almost identical for the studied scenario groups, we use the average trajectory of each climate target scenario group to evaluate the climate impact using the online MAGICC7 tool. These average trajectories are used in a baseline average (BaseAvg) scenario instead of the CDR portfolio scenarios, as used in Figure 1.

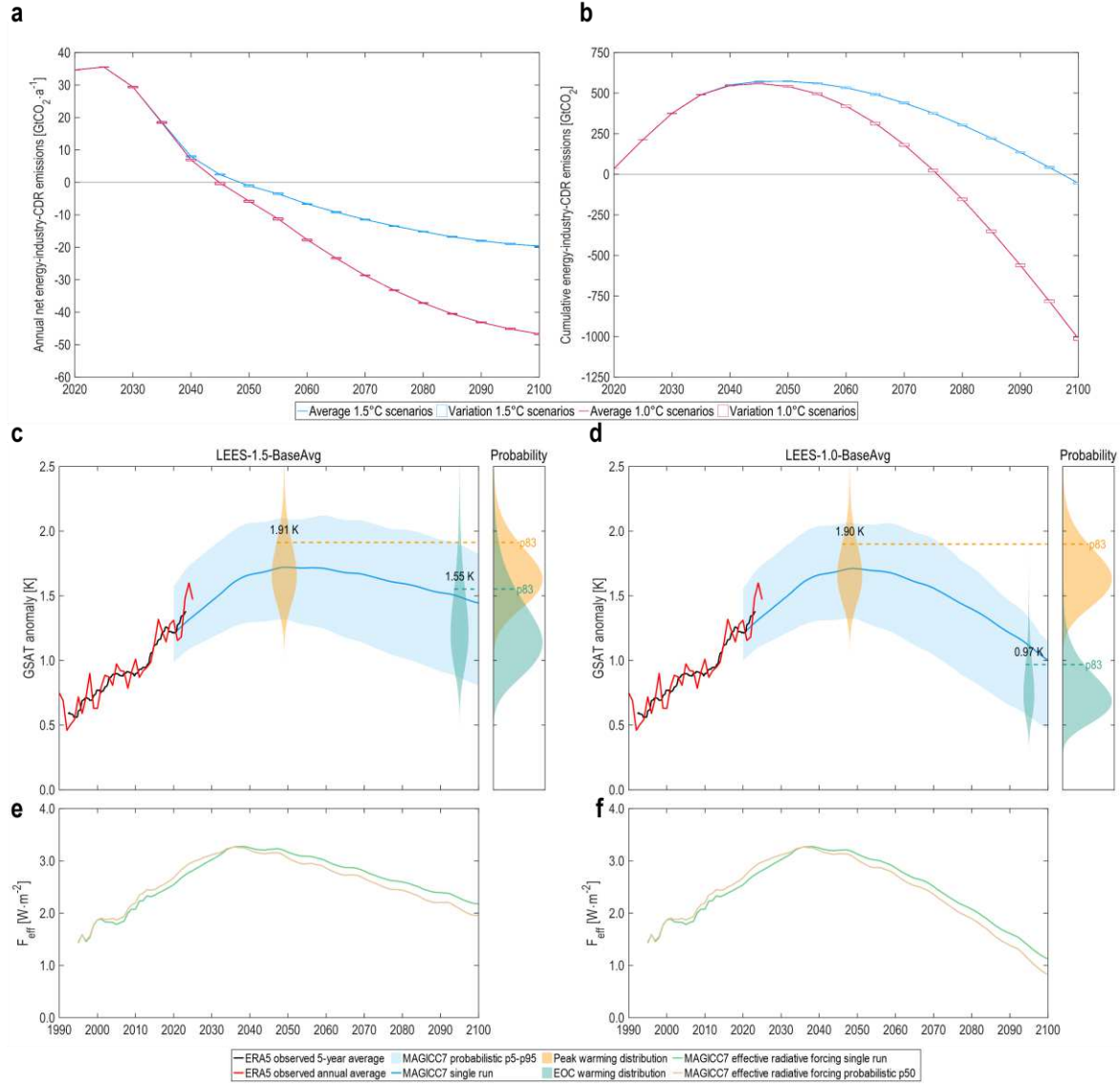


Figure 1. Emission trajectories and climate impact of the investigated scenarios. Average annual net CO₂ emissions (a) and cumulative CO₂ emissions (b) of the energy-industry-CDR system scenarios excluding AFOLU emissions and respective absolute variations (min-max spread) of the investigated scenarios per climate target. (c-d) Climate impact of the average emission trajectories shown on top expressed as representative baseline average scenario (BaseAvg) for the 1.5°C scenarios' (c) and 1.0°C scenarios' (d) CDR portfolio variations. The panels show the MAGICC7 single run results and peak and end-of-century warming probability density and 83.3rd percentile (p83) values of the probabilistic runs as the likely range to keep the GSAT below these levels. (e-f) Effective radiative forcing (F_{eff}) values for both the single and probabilistic run (50th percentile, p50, thereof) of MAGICC7 for the 1.5°C scenario (e) and 1.0°C scenario (f). Probability details for radiative forcing are not provided in the MAGICC7 online version. EOC – end of century, eff. rad. forcing – effective radiative forcing, prob. – probabilistic.

For the validation of climate planetary boundary compliance, we use two values. The first is the global GSAT anomaly. As mentioned in the Introduction, the planetary boundary for atmospheric CO₂ concentration of 350 ppm corresponds to a climate target of ca. 1.0°C. The second value is the effective (anthropogenic) radiative forcing with a climate planetary

boundary threshold of ca. 1 W m^{-2} . MAGICC7 defines both 1.5°C and 1.0°C pathways as C2 scenarios, meaning a high overshoot of 1.5 K.

The overshoot may be kept below 1.91 K for the 1.5°C scenarios, and below 1.90 K for the 1.0°C scenarios as of the probabilistic scenario runs. The single run results in a peak warming of ca. 1.72 K for the 1.5°C and 1.0°C simulations. The defossilisation pathway chosen by LUT-ESTM is very similar for both scenario groups, and most CDR scaling happens after 2050; therefore, the very similar peak warming result is not surprising. With the upscale of CDR after 2050, the warming trajectories begin to clearly differ. For the 1.5°C average scenario, the end-of-century warming of the probabilistic runs is likely below 1.55 K, while the single run results in 1.44 K. The 1.0°C average scenario achieves a warming which is likely below 0.97 K, while the single run achieves exactly the targeted 1.0 K.

In the case of effective radiative forcing, no probability density details are provided. The probabilistic p50 of the 1.5°C average CO_2 trajectory simulations leads to 1.95 W m^{-2} , and the single run results in 2.18 W m^{-2} . For the 1.0°C scenario case, the probabilistic p50 reaches 0.83 W m^{-2} , and the single run achieves 1.12 W m^{-2} . Based on these results, we consider the 1.0°C scenario pathways as compliant with the climate planetary boundary within the limitations of the used climate model.

2.2 Energy supply structure and demand

One expected and often discussed key limitation for CDR, especially with a focus on DACCS, is the ability to supply the entire energy-industry system and an additional large-scale CDR sector with renewable energy³⁹. Although the CDR sector may add significant energy demand to the system, the supply of all energy demand is not at risk at any time. The structure of energy supply is shown in Figure 2 for the supply of electricity and heat as the two most important energy carriers, as well as the structure of the final energy demand and primary energy demand.

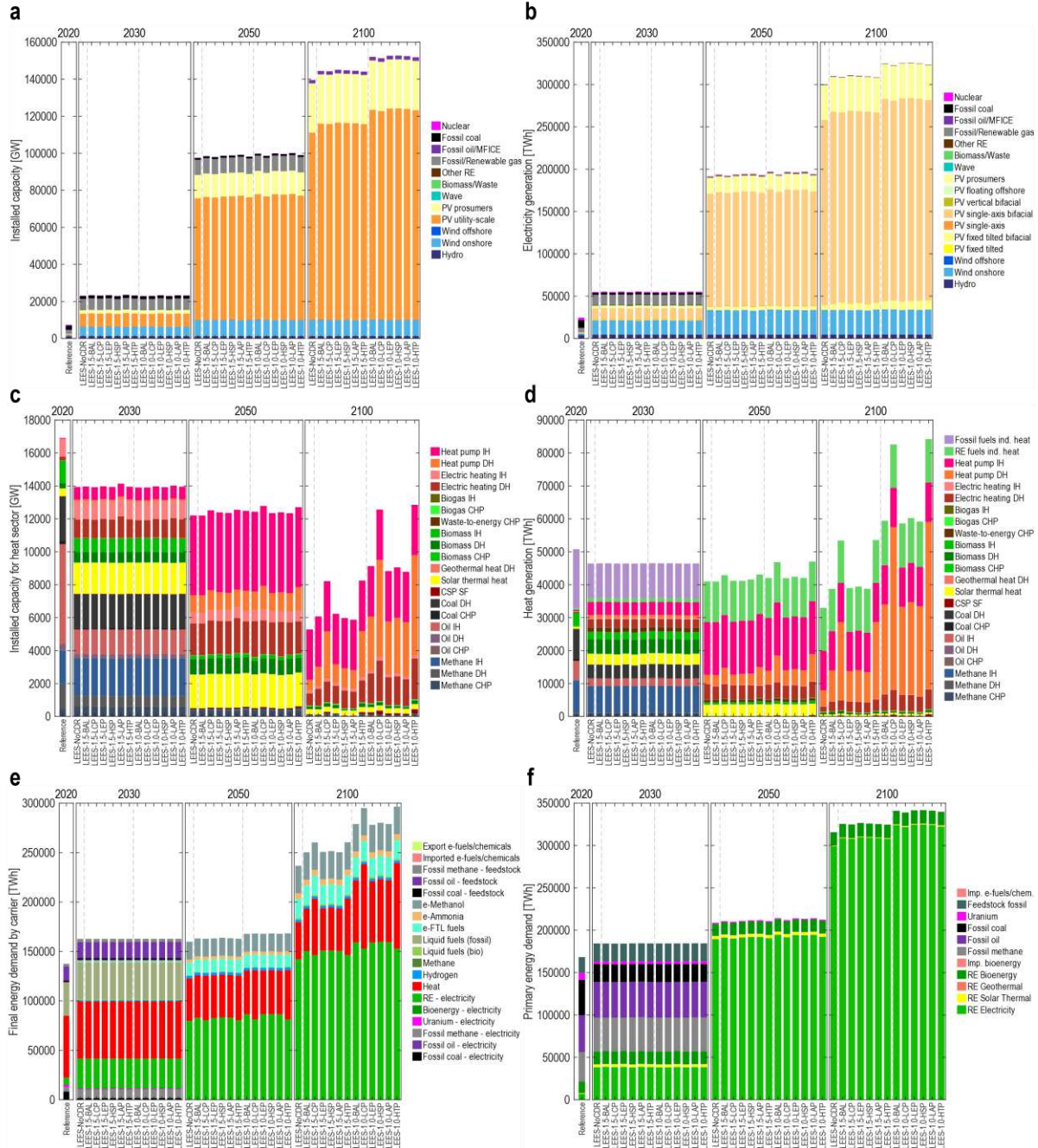


Figure 2. Global development of the supply structure of electricity and heat, and final energy demand for the reference year 2020 as well as 2030, 2050, and 2100. (a) Installed capacity of technologies for electricity generation. Utility-scale solar PV includes fixed-tilt mono-/bifacial, single-axis tracking mono-/bifacial, vertical bifacial, and floating offshore solar PV. (b) Electricity generation by technology. (c) Installed capacity of technologies for heat generation. (d) Heat generation by technology. (e) Final energy demand by carrier. (f) Primary energy demand by fuel or energy type. MFICE – multi-fuel internal combustion engine, IH – individual heat, DH – district heat, CHP – combined heat and power, CSP SF – concentrated solar thermal power heat collectors with semi-parabolic linear Fresnel reflector, ind. – industrial (high temperature) heat, RE fuels ind. heat – renewable energy fuels (e-methane, e-hydrogen, biomass/biogas) for industrial heat, Exp. e-fuels/chem. – exported e-fuels and chemical e-feedstocks, e-FTL – liquid Fischer-Tropsch e-fuels.

The general structure of electricity generation changes only marginally with different CDR portfolios. Utility-scale solar PV becomes the dominant source of renewable electricity by

2050, both in installed capacity and electricity generation. The total installed solar PV capacity in the 1.0°C scenario group differs between 139.0 TW_p and 140.6 TW_p in 2100. Compared to the NoCDR scenario with 127.5 TW_p total installed solar PV capacity, the CDR sector increases the demand for solar PV by 11.5-13.1 TW_p. The remaining thermal capacities in 2050 and afterwards are parts of the legacy system and forced capacities for grid stability, while gas turbines and combustion engines can be powered by e-fuels and e-hydrogen. Solar PV also dominates the electricity generation. Following today's trend, bifacial solar PV becomes the dominating technology, while the single-axis tracking system setup outperforms the fixed-tilt system setups in terms of cost of electricity generation. Wind power remains an important pillar of the future system in the Northern hemisphere, namely North America, Europe, Eurasia, and Northeast Asia. The sunbelt, however, in a best-policy cost optimisation, may almost fully transform into a Solar-to-X Economy⁴⁰.

In contrast to electricity generation, the heat supply shows more significant differences. A striking difference is observed in the installed capacities of electric heaters and heat pumps for district heating (DH). For both temperature target scenario groups, two scenarios or CDR portfolios are standing out: LCP (low cost) and HTP (high technology readiness). As shown in detail in the following subsection, these CDR portfolios heavily rely on concentrated CO₂, which means either DACCS or BECCS CDR routes. Since the availability of sustainable biomass is very limited, the model must install significant capacities of DAC to supply the required CO₂. DAC requires low-temperature heat for the release of CO₂ from the sorbent. The most cost-effective way to provide this heat beyond waste process heat is through heat pumps, which can make use of very low-cost renewable electricity while keeping the additional electricity generation capacities small. This is a structurally distinct result from state-of-the-art analyses that include a more limited representation of technological diversity. The variety of technologies represented shape the feasibility of large-scale DACCS, while heat pumps specifically circumvent the contested heat demand of solid-sorbent DAC. Heat pumps dominating in all regions are mostly supported by direct electric heaters, which are not as efficient as heat pumps, but have an advantage in low investment cost. Larger shares of electric heaters can be found in Eurasia and Northeast Asia, while biomass heating has a larger share in South America. The total heat supplied by large-scale heat pumps may reach ca. 50 PWh (180 EJ) in 2100, around the total heat supply of the reference system in 2020, although this number also includes non-CDR heat demand.

When looking at the final energy demand structure, one can see two dominating energy demand types. The first one is electricity, mostly driven by raising standards of living and the consequential rise in power sector demand. The second demand type is heat, which transforms from the biggest demand type as of today to the second biggest after electricity. Heat demand may be significantly reduced by rising standards and efficiency gains, both in industrial and building environments. Deploying different CDR portfolios causes differences in both electricity and heat demand, depending which CDR options are used. Interestingly, one can

notice that the two scenarios with higher heat demand (LCP, HTP) show slightly lower electricity demand, although the increase in heat demand outweighs the reduction in electricity demand, leading to a higher final energy demand in total. Despite the higher heat demand of DACCS-based CDR portfolios, the primary energy demand is almost not affected. The 1.0°C scenarios require 339.1-341.8 PWh (~1221-1230 EJ) of primary energy, which is on average 15.3 PWh (~55 EJ) or 4.7% more than for the 1.5°C scenarios. Efficient, large-scale heat pumps are, therefore, indispensable for DACCS-based CDR deployment. While CDR is already necessary for reaching the 1.5°C target, we find that compliance with the climate planetary boundary can be achieved with less than a 5% increase in primary energy demand.

2.3 Carbon dioxide management

CO₂ management combines concepts to avoid (CCS), circulate (CCU), or remove (CDR) CO₂ to or from the atmosphere. The framework aims to distinguish how CO₂ is handled, and which concepts evolve as the dominating driver for CO₂ handling. Figure 3 shows the extent of CO₂ management, how much CO₂ is used as a raw material for which sector and details the CDR sector in terms of source of CO₂ and CDR portfolio.

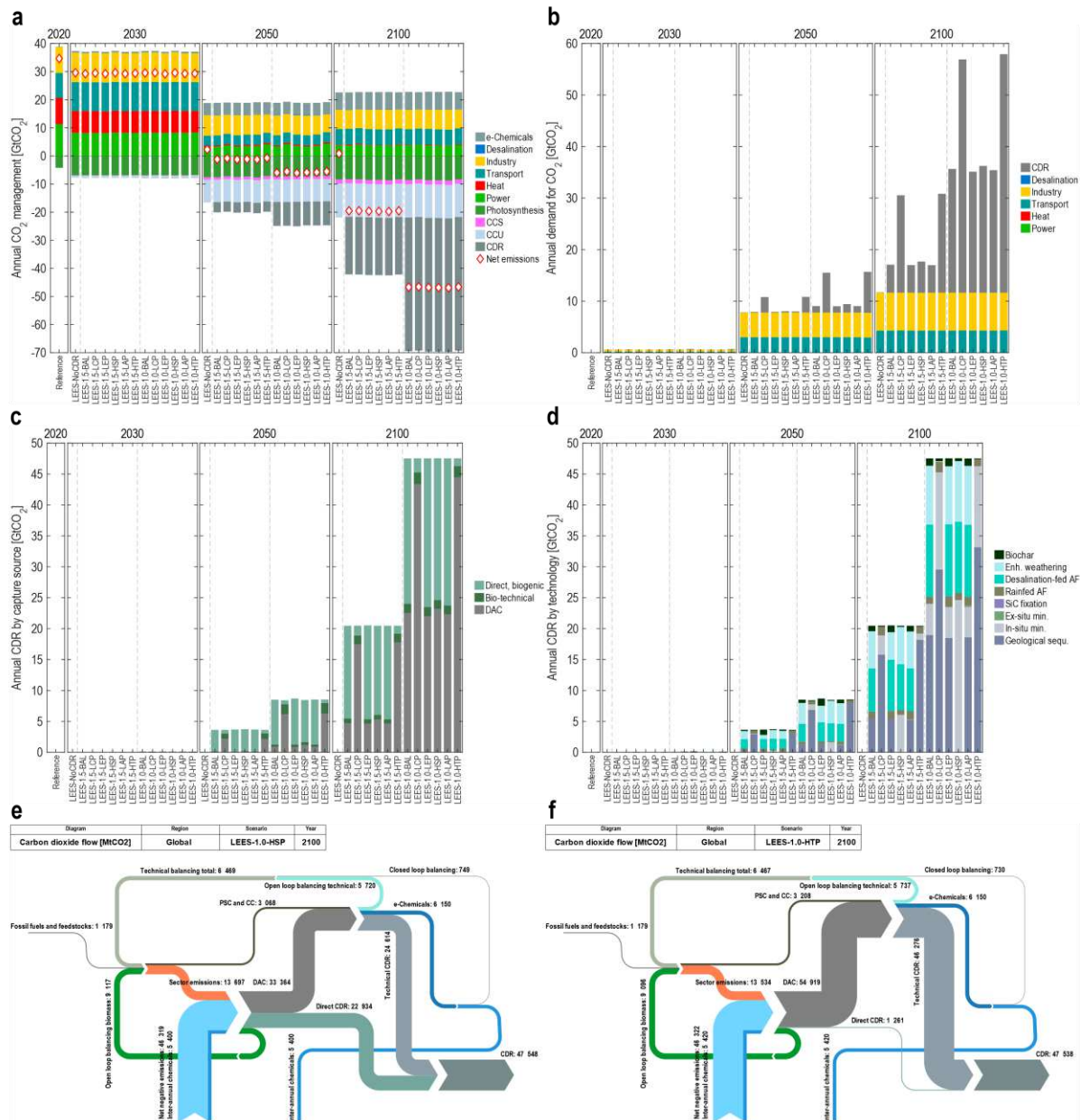


Figure 3. Global CO₂ management structure development and CDR sector structure for the reference year 2020 as well as 2030, 2050, and 2100. (a) CO₂ management distinguishing positive and negative emissions. Positive emissions are indicated by sector and negative emissions are indicated by CO₂ management or sequestration type. Photosynthesis describes the growth of biomass for energetic use, with re-emission in the same year. Growth of biomass for pulp and paper (P&P) industry with subsequent point source capture, biomass for biochar, and growth of forests is included in the CDR bar. Net emissions indicate balanced positive and negative emissions. **(b)** Annual demand of CO₂ as raw material, e.g. for e-fuels and e-chemicals, as well as for CDR. **(c)** Origin of CO₂ for the CDR sector by capture source. Distinguished are technological capture from the atmosphere via DAC (DACCS), bio-technical capture from the atmosphere with photosynthesis as the primary and point source capture as the secondary capture process (BECCS), and direct sequestration from the atmosphere without a primary or secondary technological capture process (direct sequestration), including afforestation and biochar. **(d)** CDR by technology, indicating the CDR portfolio. On- and offshore options for geological sequestration and in-situ mineralisation are not specifically shown. **(e)** Simplified CO₂ flows of the energy-industry CDR system in 2100 for the LEES-1.0-HSP scenario as example for a balanced direct sequestration (direct atmospheric and bio-technical) and DACCS. **(f)** Simplified CO₂ flows of the energy-industry-CDR system in 2100 for the LEES-1.0-HTP scenario as an example for significant

dominance of DACCS. Enh. – enhanced, AF – afforestation, min. – mineralisation, sequ. – sequestration, PSC – point source capture, CC – carbon capture.

Annual CO₂ management shows two distinct trends. The first is the shift from largely positive emissions as of the reference system to a largely balanced system after defossilisation in 2050. It becomes clear why defossilisation is a more striking term over decarbonisation, as the evolving use of e-fuels, e-chemicals, and the continued use of bioenergy lead to a processing of ca. $\pm 20 \text{ GtCO}_2 \text{ a}^{-1}$, while positive and negative emissions are largely balanced, leading to a net-zero energy-industry system. In 2050, the CDR sector already starts to scale and offsets minor residues of unbalanced emissions, an artefact of allowed model tolerances in addition to non-captured mineral CO₂ of cement production plants resulting from point source capture inefficiency. The second trend that one can notice is the shift from a net-positive towards a net-negative emissions system after 2050, caused by the scaling of CDR, leading to a net removal of CO₂ from the atmosphere. This can be seen based on the net emissions, which indicate a near net-zero emission system in 2050 for the 1.5°C scenarios, while a 1.0°C pathway may already achieve a net-negative emission system.

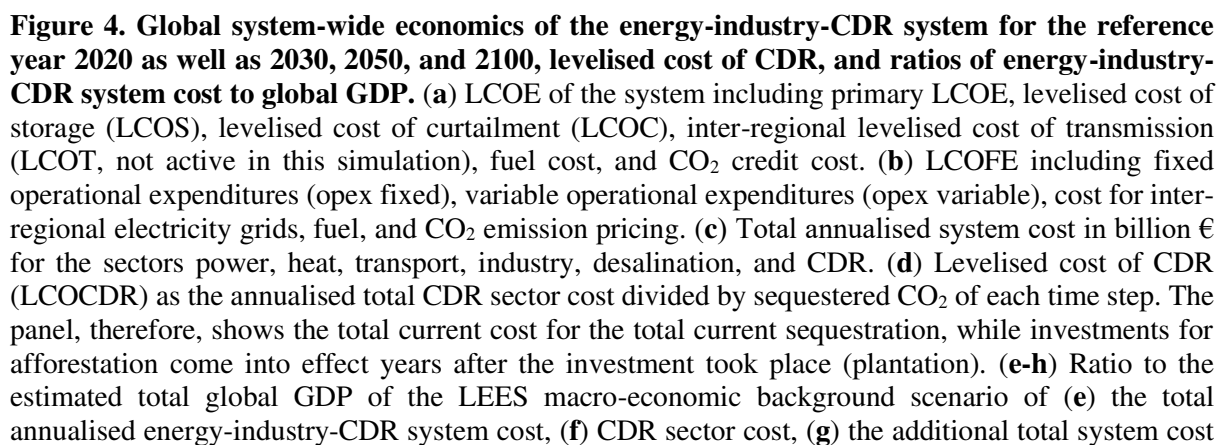
Depending on the CDR portfolio, the role of CDR for CO₂ demand compared to other sectors of the energy-industry system is quite different in 2050. As mentioned before, the LCP and HTP portfolios depend heavily on DACCS, and therefore, already require significant amounts of CO₂ in 2050 supplied from capture technologies. With the limited availability of sustainable biomass, and the optimisation to use biomass in other sectors, largely for industrial heat supply, the role of bio-technical CO₂ sources for the CDR sector only plays a minor role for all CDR portfolios. If sequestration does not happen to large shares via direct or biogenic sequestration (afforestation, enhanced weathering, biochar), DAC is the dominating source to supply CO₂ for the CDR sector. For the 1.5°C scenarios, direct and biogenic sequestration cover about three quarters of CO₂ sourcing, while for the 1.0°C scenarios DAC contributes at least half of the CO₂. This can also be noticed in the CO₂ flows. While direct CDR (afforestation, enhanced weathering, biochar) covers almost $23 \text{ GtCO}_2 \text{ a}^{-1}$, technical CDR (DACCS, BECCS via biomass loop and PSC) covers more than $24 \text{ GtCO}_2 \text{ a}^{-1}$ for the HSP scenario. A DACCS-heavy portfolio such as the HTP would result in a total DAC capacity of almost $55 \text{ GtCO}_2 \text{ a}^{-1}$, of which more than $46 \text{ GtCO}_2 \text{ a}^{-1}$ is designated to supply CDR. In a 1.0°C compliant energy-industry system, CDR largely outweighs the CO₂ demand for transport and industry and may be the main driver of a future DAC industry.

The CDR composition by technology reveals that the DACCS-heavy CDR portfolios largely deploy geological sequestration. For the 1.0°C cases, in-situ mineralisation also plays an important role, as some deployment limits are reached for geological sequestration. The HSP portfolio does not use any geological sequestration, and all DACCS is realised via in-situ mineralisation. Rainfed afforestation only plays a minor role in all portfolios, which is a consequence of limited potential in most regions. Desalination-fed afforestation shows a large potential, and due to favourable scores for cost, energy demand, and (net) area demand, is deployed to significant shares. Similarly, enhanced weathering is a relatively low-cost, secure,

and not energy-intensive sequestration option. Biochar also shows a rather limited potential compared to the full CDR demand, and therefore, is deployed in many portfolios, but only has smaller shares for sequestration.

2.4 System economics

Besides the technical feasibility, the economic viability of the studied pathways is an important measure. In this context, we evaluate the key system economics of levelised cost of electricity (LCOE) as an indicator of the production cost of the most important energy carrier, levelised cost of final energy and non-energy use (LCOFE) as an indicator for the cost of the total final energy and feedstock supply, and the total annualised system cost as an indicator for the overall monetary efforts that come with the transition pathway. Figure 4 also shows the levelised cost of CDR (LCOCDR), giving insights on the specific costs of CO₂ sequestration, and several economic values as a ratio to the estimated total GDP to evaluate the economic burden in relation to the total economic power.



compared to a system without CDR, and **(h)** additional system cost for raised ambitions from 1.5°C to 1.0°C. Note that lines may overlap.

Both LCOE and LCOFE are insignificantly affected by the different scenarios. The LCOE drops from 96.4 € MWh⁻¹ in 2020 to an average of 34.5 € MWh⁻¹ in 2050 and 17.2 € MWh⁻¹ by 2100, with almost no variation between the studied scenarios. Scenarios with a higher solar PV share achieve slightly lower LCOE. The LCOFE stands at 50.4 € MWh⁻¹ in 2020 and increases to an average of 66.0 € MWh⁻¹ in 2030. This increase is a combination of investments for RE and continued use of fossil energy, as RE investments increase the capex share, and fossil fuels come with high fuel and CO₂ cost. A full defossilisation by 2050 enables an average LCOFE of 62.1 € MWh⁻¹, and until 2100, an average LCOFE of 35.2 € MWh⁻¹ is possible. Switching to RE, therefore, leads to some short-term increase in LCOFE but brings along strong cost reductions in the long term. Nevertheless, this switch can still be seen as beneficial, as the assumed rise in fuel and CO₂ cost would lead to significantly higher LCOFE by 2050. Interestingly, CDR portfolios with the highest DACCS share lead to the lowest LCOFE.

The LCOFE finally follows the trajectory of the total annualised system cost. The biggest contributor to the long-term reduction of total annualised system cost is the power sector, enabled by very low-cost renewable electricity. Without the CDR sector, a strong reduction in total annualised system cost would be possible. However, the need for CDR comes at significant additional cost. In 2050, the CDR sector of the 1.5°C scenarios is responsible for 2.5% (LCP, HTP) up to 6.6% (HSP) of the total system cost, while the LAP portfolio makes up the highest total system cost. For 1.0°C scenarios, the CDR sector is already responsible for 5.6% (LCP) up to 13.2% (LEP) of the total annualised system cost, while the latter is also the scenario with the highest total cost. In 2100, CDR is responsible for a minimum of 10.8% of total system cost (LCP, HTP, 1.5°C scenarios) up to 28.6% (BAL, 1.0°C scenarios). On average, achieving the climate planetary boundary may come at an annualised cost share of 25.9%.

While these results indicate a large cost share to achieve the climate planetary boundary, we should put it into perspective of the total global economic power, the total GDP. Currently, humankind invests ca. 5.8% of total GDP into the energy-industry system before taxes and subsidies⁴¹. Continuing the use of fossil fuels may rise this ratio to slightly above 6% in the near future. A strong defossilisation, however, decouples economic growth and related growth in energy demand from rising total annualised system cost, and a strong reduction of the energy-industry-CDR system cost to GDP ratio cannot be dismissed. Even deploying large-scale CDR to rebalance Earth's climate within planetary boundaries, the ratio drops to ca. 1.5% by end of the century. Driven by very low-cost renewable electricity, humankind is facing an unprecedented abundance of cheap energy supply at significantly lower cost for society compared to today. If we only put the total CDR sector cost into relation to the total GDP, one can see that rebalancing Earth's climate is possible for less than 0.6% of the global GDP. This can also be noticed when looking at the LCOCDR, which, after peaking around 2040, strongly decreases to less than 80 € tCO₂⁻¹ by 2100. The LCP and HTP portfolios are even able to

achieve less than 50 € tCO₂⁻¹. The initial peak is caused by the afforestation option, which requires large upfront investments with low sequestration volumes as a result, but as forests grow, the costs can be driven down significantly. Overall, the sequestration-weighted average LCOCDR is less than 100 € tCO₂⁻¹ for all scenarios. The LEP portfolios tend to be the more costly options, while LCP and HTP similarly achieve the lowest LCOCDR.

If we set the additional cost of the energy-industry-CDR system to the no CDR scenario into relation with the GDP, one would expect the same ratio as the CDR sector cost to GDP, as we would assume that CDR adds cost to the basic system. However, this is not the case. The more expensive scenario groups can achieve a lower GDP ratio in this regard, which indicates that the CDR sector contributes to an overall cheaper energy-industry system by offering additional system flexibilities, leading to an overall more efficient use of resources. The additional sector coupling, therefore, has positive effects on the underlying system. However, the two cheaper scenario groups (LCP, HTP) show the opposite effect, where the total system cost compared to a no CDR scenario is higher than the CDR sector ratio itself. In these cases, the underlying system is confronted with additional burdens, making it more expensive. In all cases, the additional system cost compared to a no CDR scenario can be kept below 0.45% of the global GDP.

In terms of additional cost, we also look at the additional cost for raised ambitions. As of today, the 1.5°C climate target is in focus. The additional costs to raise ambitions from 1.5°C to 1.0°C are very low. When comparing each CDR portfolio's total annualised system cost of the 1.0°C scenario with the respective 1.5°C scenario's cost, the additional cost relative to the global GDP is quite similar at less than 0.25%. Achieving climate planetary boundary compliance is, therefore, well within the economic viability.

3 Discussion

To reach a safe and just climate future, planetary boundaries must be considered in greater depth for emission-climate pathways modelling. Our results assess the techno-economic impacts of deploying a significant CDR sector to increase climate ambitions from a 1.5°C target to a 1.0°C target. Beyond general insights, we discuss three main findings in the context of climate planetary boundary compliance.

Our first finding is a confirmation of previous studies. Low-cost renewable electricity along deep electrification has been identified as a key enabler for sustainable futures before^{37,42}. While this fact becomes increasingly clear, the opportunities that lie on the table resulting from an abundance of low-cost renewable electricity, specifically from solar PV, still seem underestimated. Solar PV experts are sure that the success story of this technology has just started^{43,44}, while it is also said that solar PV may have passed a 'tipping point', at which the dominance of solar PV may be inevitable even without active climate policies⁴⁵. In combination with low-cost battery technologies, which are no longer constrained by resource availability⁴⁶, an unprecedented abundance of sustainable energy supply lies ahead of

humankind. This fact is not yet reflected in one of the leading reports on future energy systems, the IEA's World Energy Outlook, which is known to continuously underestimate the growing role of solar PV⁴⁷. Also, many integrated assessment models (IAMs) underestimate solar PV deployment due to outdated cost assumptions, insufficient representation of technological learning, and lack of detailed modelling of electrification and power-to-X⁴⁸. Our results indicate that the availability of RE is not a bottleneck for reaching the climate planetary boundary, even in CDR portfolios that heavily rely on DACCS. On the contrary, RE is a key enabler for ambitious climate targets, which should be reflected more in transition pathway and climate target studies with ambitious defossilisation and high electrification.

The second important finding is the role of DACCS for CDR portfolios and reaching ambitious climate targets. While 1.5°C scenarios may be possible with a minimum share of DACCS, reaching the climate planetary boundary will most likely rely on large shares of DACCS. A selective assessment of IAM scenarios in the latest State of CDR report¹⁵ indicates that almost all assessed scenarios include DACCS, however, it plays a non-dominant role in most cases, while BECCS and afforestation are the leading CDR options. As the report mentions, the choice of DAC technology (low-temperature solid-sorbent versus high-temperature aqueous solution) may have a significant impact on the choice of CDR route. Our results contradict the general statement of the report that DACCS may be constrained by the energy intensity of DAC, while coupling DACCS with RE should be seen as a prerequisite rather than a limitation. The opportunity arising from an abundance of low-cost renewable electricity coupled with efficient heat pumps can be seen in the cost-effectiveness of scenarios largely relying on DACCS. Large-scale BECCS, which is still the default main option in IAMs, will exceed various limitations regarding sustainability⁴⁹ and area demand⁵⁰, and as a consequence, biodiversity, since the default amounts of large-scale BECCS development will only be possible by dedicated energy crop cultivation. Although we acknowledge that DAC technology still faces some challenges for large-scale industrial scaling⁵¹, showing respective alternative pathways that do not overly rely on BECCS are important for industry and policymakers to gain insights with what is possible if the right incentives exist. It has been shown that an industrial scaling of DACCS per se should not be a limitation⁵². In addition to the capture process of DAC, the sequestration path is also important. Usually, a generic DACCS route is implemented in energy models and IAMs that by default assume geological sequestration. In-situ mineralisation is almost always entirely overlooked, although the sequestration potential is significant⁵³.

The third finding is the economic opportunity that lies ahead, both in terms of a sustainable supply of society's energy needs and the additional monetary effort required to rebalance Earth's climate within the planetary boundary. Our results regarding CDR sector cost in relation to global GDP confirm earlier findings by Mühlbauer et al.²⁰. Typically, it is assumed that the transition towards a sustainable energy system comes at additional cost, often expressed as GDP loss^{54,55}. Our results based on a stringent defossilisation, lowering the cost-

to-GDP ratio significantly, rather indicate a gain in available GDP, as less money must be spent for more energy used with increasing GDP. Although GDP alone is not a fully inclusive metric for human welfare, it indicates that a sustainable energy supply combined with a climate restoration within the planetary boundary is achievable at significantly lower societal economic burden. Furthermore, the additional GDP cost ratio for raised ambitions from 1.5°C to 1.0°C is very small, implying that climate restoration does not come at significant additional cost. By increasing climate ambition, the projected loss in global average GDP per capita could be reduced by approximately 3.3-8.6% for a globally differentiated climate response⁵⁶. Assuming additional mitigation costs of approximately 0.25% of GDP to achieve the 1.0°C target, the resulting net societal economic benefit would be around 3.0-8.3% of global GDP. This rough estimate is intended to illustrate that, beyond reducing costs, stronger climate action could generate a net socio-economic benefit in addition to other positive effects that support human well-being and the long-term flourishing of civilisation.

Although we aim for comprehensive modelling, our research is subject to some limitations. Most importantly, we are not able to cover sensitivity analysis within the scope of this study. Important sensitivities may cover the cost reductions of RE sources, as well as key technologies such as water electrolyzers and DAC. The cost trajectories assume an ambitious cost decline based on best policy conditions. For DAC, the choice of technology in our study fell on the low-temperature solid-sorbent option. The technical and, more importantly, economic feasibility of reaching climate planetary boundary with a more energy-intensive high-temperature DAC option will be an interesting aspect of a future study. Regarding reaching the climate planetary boundary, the effect of delayed defossilisation with the need of CDR to offset residual fossil emissions should be studied to evaluate the limitations for reaching the climate planetary boundary within the 21st century. Our research has a very specific scope on the climate planetary boundary, and we do not consider the eight other planetary boundaries. Future research should explore ways to include an assessment of other planetary boundaries in energy-industry-CDR transition pathways.

4 Conclusions

In this study we provide an assessment of energy-industry transition pathways including carbon dioxide removal to provide negative emissions to rebalance Earth's climate within the safe and just planetary boundary associated with a climate target of 1.0°C. Several technology portfolios of carbon dioxide removal options have been evaluated regarding their techno-economic impact on the overall system transition.

Our findings support the following key conclusions: First, our assessment supports previous findings that solar photovoltaics may emerge as the leading energy source of the 21st century. In addition to being the main driver for the energy-industry transition, the low-cost renewable electricity available in abundance is also a key enabler for climate restoration. Second, direct air capture and carbon sequestration may play a key role in climate restoration. Solid-sorbent

direct air capture coupled with highly efficient heat pumps and low-cost renewable electricity does not overburden the energy system. Third, the economic premium is manageable. Rebalancing Earth's climate within the safe and just planetary boundary requires less than 0.6% of global gross domestic product, while raising ambitions from 1.5°C to 1.0°C requires less than 0.25% of global gross domestic product additionally. If considering the gain of gross domestic product from a safer climate future, resources invested in carbon dioxide removal would lead to a net gain in gross domestic product.

The opportunities resulting from the abundance of low-cost renewable electricity are becoming increasingly clear, while this study provides a new point of view regarding planetary boundary compliance in energy-industry transition pathways. We provide a first step for forward-looking compliance of scenarios within planetary boundaries. Large-scale carbon dioxide removal may evolve as a main pillar besides the energy and industry transition.

5 Methods and data

All assumptions described in this section are integrated in a larger framework around the *LUT Energy System Transition Model (LUT-ESTM)*^{37,38}, which has been expanded to include a detailed representation of the CDR sector. Figure 5 shows the model interaction, data, and information flow within the LUT energy-industry-CDR modelling framework.

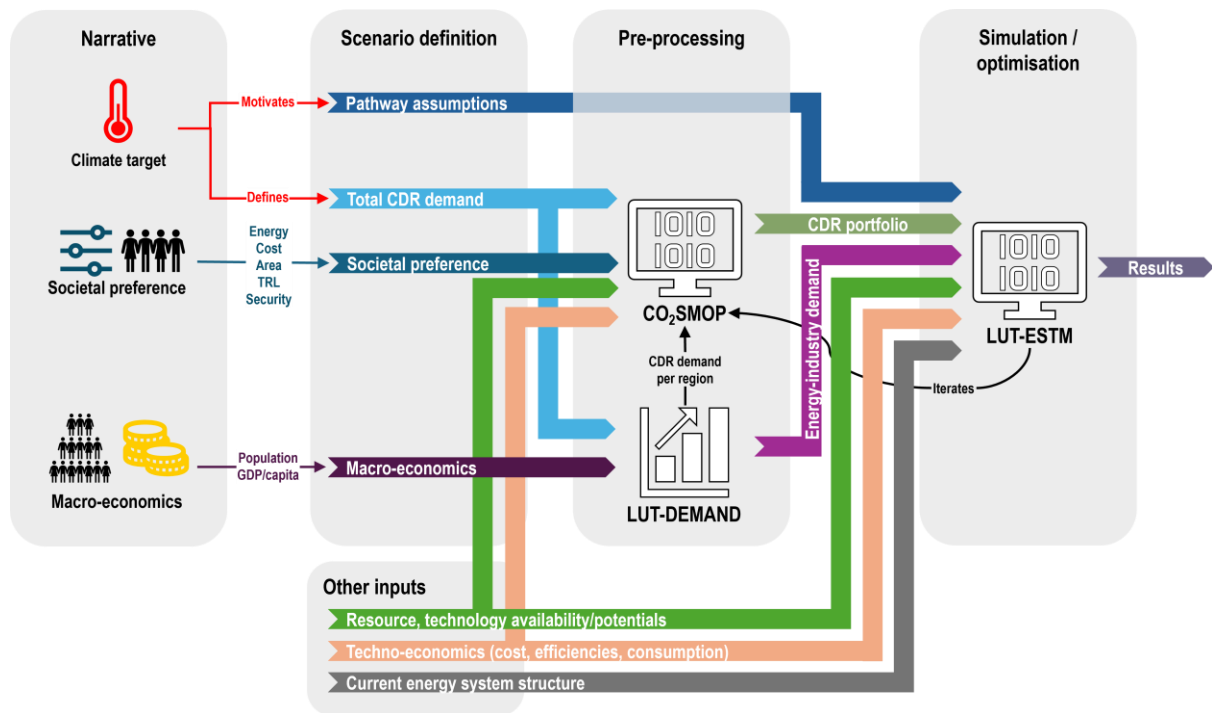


Figure 5. Overview of the LUT energy-industry-CDR modelling framework. Information flow starts from narrative formulation, which is the basis for the scenario definition, via pre-processing of scenario-specific data with pre-processing models, to the final simulation of the energy-industry-CDR system. Other inputs are in this study independent from the scenario definition. The current energy system structure includes currently installed capacities and age structure of the legacy system.

The following subsections explain the preparation of data and assumptions for the scenario setup. Each subsection refers to respective data and models used.

5.1 Global carbon dioxide removal demand

In contrast to IAMs, which are usually directly linked to simplified climate models, energy system models such as LUT-ESTM require an exogenous input for the CDR demand. The estimation of the CDR demand is done using a simplified method considering the most important parameters that influence the total (global) CDR demand (see supplementary material 1 note 3).

The central drivers are the GHG emissions of the energy-industry system within the 21st century. Residual emissions are offset against the remaining CO₂ emission budget to reach respective climate targets of the IPCC AR6 to identify a CO₂ budget overuse. Furthermore, a deep defossilisation of the future energy-industry system also leads to the virtual elimination of aerosol emissions, known to have a cooling effect on Earth's climate. If aerosol emissions are eliminated, this cooling effect may lead to an additional warming contribution to be offset via CDR. Besides the emissions from the energy -industry system, agriculture, forestry, and other land use (AFOLU) emissions are also considered in the CDR demand estimation. Baseline is the IPCC AR6 C2 scenario group (high overshoot), of which a medium emission projection has been created and adapted to available MAGICC7 templates to allow for historical and current climate vetting (cf. supplementary material 3). AFOLU emissions include CO₂, CH₄, and N₂O emissions.

The method includes the non-linear Earth system feedback for radiative forcing of CO₂ emissions, as well as perturbed airborne fractions. The estimation leads to a total global CDR demand of 377 GtCO₂ for aerosol warming compensation, 724 GtCO₂ for rebalancing the climate to 1.5°C after a temperature overshoot, and 1682 GtCO₂ to rebalance Earth's climate within the planetary boundary of 1.0°C.

5.2 Carbon dioxide removal portfolio modelling

CDR portfolios per region are created using an advanced version of the previous LUT-CDR tool²⁰. The purpose is to identify the most valuable portfolio of CDR options optimised for societal preferences. The model optimises the deployment of CDR options for annual sequestration rates between 2020 and 2100, following a given CDR demand ramping, applying a multi-objective linear optimisation for the best possible portfolio in line with the given societal preferences.

Societal preferences for large-scale CDR may be cost, energy, security (permanence), area, or technology readiness. Each of the preferences is assigned a weight to create a sensitivity among the societal preferences. The weight of the prioritised preference is set to 92%, while each other preference has a weight of 2%. Table 1 shows an overview of the portfolios applied in this study.

Table 1. Overview of CDR options portfolios including the respective underlying narrative. Portfolios and narratives are chosen based on Mühlbauer et al.²⁰.

CDR portfolio	Abbreviation	Narrative
Balanced	BAL	Society has no preference and all weights are equal.
Low cost prioritisation	LCP	Society prefers cost-optimal solutions with lowest burden on economy and socio-economics.
Low energy prioritisation	LEP	Society prefers options with the lowest possible energy demand, reducing the need for RE, leading to less visual impact.
High security prioritisation	HSP	Society prefers durable sequestration options with high permanence of once sequestered CO ₂ without the danger of re-emission and long-term burden of re-sequestration need.
Low area prioritisation	LAP	Society prefers CDR options with an overall low net area ^a impact, i.e. built-up area or monocultures for energy crops, which might contradict with food supply and biodiversity.
High TRL prioritisation	HTP	Society prefers CDR options that are proven to work, so that future energy-industry-CDR system planning can be done based on mature technology choices.

^a For the definition of net and gross area, please refer to Keiner et al.⁵⁰

Available CDR options²⁰ comprise of geological sequestration (on-/offshore)^{57,58}, in-situ mineralisation (on-/offshore)^{53,59,60}, ex-situ mineralisation (industrial waste feedstock)^{61,62}, electricity-based silicon carbide⁶³, enhanced weathering^{60,64}, biochar^{65,66}, desalination-fed afforestation⁶⁷, and classic rainfed afforestation⁶⁸. The optimisation of the CDR portfolios assigns each option a score between 0 and 1 for each time step, where 1 is assigned to the option with the highest/lowest respective value and 0 to the option with the lowest/highest value. The objective of the portfolio model is to optimise the deployment of CDR options to minimise the overall score of deployed CDR to maximise compliance with the specified societal preference. A description of the portfolio model is available in the supplementary note 4, and a visualisation of the CDR portfolios per major region can be seen in supplementary Figures S2 and S3 (supplementary information 1).

The optimisation considers the available potential of all CDR options. As detailed in the supplementary note 5, the potentials are obtained via a bottom-up method, identifying a local potential in a 0.45° x 0.45° global resolution, cumulating the potential for the respective region. For options with a cumulative potential (geological sequestration, in-situ mineralisation), an “extraction” rate in reference to the reserve-to-production (R/P, total reserves to annual production) ratio of the oil and gas industry is chosen. Typical oil and gas R/P ratios are around 50 years, or 2% a⁻¹ extraction rate⁶⁹. Without specific data for CDR, a more conservative ratio of 1% a⁻¹ is applied.

5.3 Macro-economic demand scenario modelling

The basis of the energy demand estimation is the macro-economic narrative, composing economic development and population of the future. Energy demand estimation is done using the LUT-DEMAND tool as described by Keiner et al.⁷⁰. The economic scenario in this study is the LUT late economic equality scenario (LUT-LEES), which describes a steady increase in gross domestic product (GDP) per capita, while standards of living are not yet fully aligned globally by 2100. The LUT-LEES is comparable to the global average GDP per capita of the shared socioeconomic pathway 2 (SSP2)^{70,71}. The population projection is chosen to be the medium projection of the United Nations (UN medium)⁷², which reaches ca. 9.6 billion people by 2050 and ca. 10.2 billion people by end of the century.

LUT-DEMAND uses a bottom-up approach to estimate the future energy demand. Historic data on energy and material consumption for all sectors (power, heat, transport, industry, desalination) form the basis on which a trendline is projected in relation to the relevant factor (GDP per capita, average ambient temperature, etc.). The model allows for certain parameters to be adjusted to follow a narrative for future energy demand development, such as efficiency improvements for space heating, phase-out of biomass for cooking, industrial heat improvements. The model then follows the principle of ‘trendline approximation’, i.e. the values of single countries approximate the abovementioned trendline with future change in the macro-economic assumptions to filter current differences assuming a future alignment of living standards, general availability of goods and consumer products, as well as behavioural alignments. The output of LUT-DEMAND for energy service demand and final energy demand (FED) forms input data for LUT-ESTM.

5.4 Applied scenarios

The scenarios applied in this study are a combination of the climate target and CDR portfolios to identify the feasibility of an ambitious 1.0°C climate target with different underlying CDR portfolios, as well as to appraise the additional efforts of a 1.0°C climate target versus the established 1.5°C climate target. Table 2 shows an overview of the applied portfolios. The overall macro-economic narrative is that global standards of living approximate by 2100 but are not yet fully aligned (cf. subsection 4.3).

Table 2. Overview on the combination of temperature targets and CDR portfolios to applied scenarios in this study. The macro-economic scenario (LEES) and population estimation do not vary among the scenarios (cf. subsection 4.3).

Temperature target	CDR portfolio	Abbreviation
No target	NoCDR	LEES-NoCDR
1.5°C	BAL	LEES-1.5-BAL
	LCP	LEES-1.5-LCP
	LEP	LEES-1.5-LEP
	HSP	LEES-1.5-HSP
	LAP	LEES-1.5-LAP
	HTP	LEES-1.5-HTP
1.0°C	BAL	LEES-1.0-BAL

	LCP	LEES-1.0-LCP
	LEP	LEES-1.0-LEP
	HSP	LEES-1.0-HSP
	LAP	LEES-1.0-LAP
	HTP	LEES-1.0-HTP

The range of scenarios aims for an analysis of the feasibility based on different directions of societal preference and present extreme cases. In addition to 1.5°C and 1.0°C climate targets, a scenario without CDR deployment is used as a reference to assess the impact of a large-scale CDR sector on the energy supply structure of the energy-industry system, as well as on the overall economics if no CDR would be deployed. This scenario is included for comparison purposes only and is not validated regarding the respective climate impact.

5.5 Integrated system modelling

The final step of the LUT energy-industry-CDR modelling framework amalgamates all narratives, data, parameters, and scenarios for the transition simulation using LUT-ESTM (see supplementary note 2). LUT-ESTM is a myopic transition model with the objective to cost-optimize the supply of energy, while it considers given constraints within the transition pathway regarding the use of technologies, allowed fossil emissions, etc. For a schematic overview of the model including energy and data flows see supplementary note 2.

The model includes all relevant RE sources in different system setups: Solar PV (rooftop, fixed-tilt, single-axis tracking, monofacial, bifacial, vertical, floating offshore), wind power (onshore, offshore), hydropower (run-of-river, reservoir), wave power, geothermal, and concentrating solar thermal power. Conventional power plants (PP) and combined heat and power (CHP) plants include those powered by fossil fuels (coal, lignite, natural gas), nuclear, biomass, or waste. In the case of biomass an emphasis lies on the sustainable availability of residues⁷³ and no energy crop cultivation is allowed. Internal combustion engine generators (ICE) are mainly powered by oil-based fuels, and gas turbines mainly by natural gas, whereas both are enabled as multi-fuel generators in the future to be powered by electricity-based methane (e-methane) or electricity-based hydrogen (e-hydrogen), with the latter for new investments from the 2030s onwards. The use of biomass is limited within sustainable limits for each region⁷³.

Energy storage is available in the form of electro-chemical batteries (prosumer, utility-scale, vehicle-to-grid), pumped hydro energy storage (PHES), adiabatic compressed air energy storage (A-CAES), and several thermal energy storage (TES) options. CH₄ and H₂ storage are central energy storage options, with the output not limited to a single sector. Heat conversion technologies are available as fossil fuel or biomass boilers (prosumer, district heating), as well as direct electric heating and heat pumps (prosumer, industrial heat supply, district heating).

The use of CO₂ to produce electricity-based chemical feedstocks (e-chemicals) or e-fuels (Fischer-Tropsch fuels, e-methanol, e-methane) is supplied either by direct air capture (DAC)

or as point source capture (PSC) at industrial processes (pulp and paper, cement), power plants (fossil, biomass) and waste incinerators. The demand of concentrated CO₂ for the CDR sector can be satisfied via DAC (DACCS) or biomass-PSC (BECCS) to ensure the link to the atmosphere. CDR options with direct sequestration (EW) or biogenic capture (AF_{DF}, AF_{RF}, BC) do not need a CO₂ capture process but take the CO₂ directly out of the atmosphere.

A central part of LUT-ESTM is a wide availability of power-to-X technologies required for an extensive Power-to-X Economy⁷⁴: power-to-heat transformers, seawater desalination (potable water, AF_{DF}), electrolyser, Haber-Bosch synthesis (e-ammonia), methanol synthesis (e-methanol), Fischer-Tropsch synthesis (liquid e-fuels), methanation (e-methane), power-to-steel, power-to-aluminium, and e-mobility.

Data for LUT-ESTM are based on a bottom-up method. Resource profiles are based on 151 regions (see supplementary Figure S1) and then aggregated to 9 major regions to avoid lumping resources with the most favourable conditions⁷⁵. In this study, each of the 9 major regions is assumed to be self-sufficient, without inter-regional fuel or power trade. LUT-ESTM starts by compiling all input data. In a first simulation step, the prosumer sub-model is run, which affects the power and heat demand to be supplied by the centralised system. In the second step, the centralised energy system model is run with the target to minimise the overall system cost. After simulation, all results are compiled and analysed. A detailed explanation of LUT-ESTM and a summary of applied constraints is provided in the supplementary note 2, including assumptions for non-uniform weighted average cost of capital (WACC). Specific techno-economic input assumptions can be found in supplementary information 2. The input values are in 2019€, but the model applies an inflation adjustment with a factor of 1.21 to 2024€. Therefore, results are presented in 2024€.

The validation of the climate impact of calculated pathways is done using the online tool for the reduced complexity climate model MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change, available at <https://live.magicc.org>)^{35,36}.

Declaration of competing interests

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 study.

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Data availability statement

Research data are available in the supplementary materials. The extended supplementary figures (see supplementary information 1 for details) and supplementary information 3 can be found in an online repository via the identifier: 10.5281/zenodo.22041775

During peer review, the files can be accessed using the following private review link:

https://zenodo.org/records/22041775?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6IjVkJmJFhNzQyLWl0NjAtNDczOC1iYTcxLWFiNzU5MDc5MzBhNyIsImRhdGEiOnt9LCJyYW5kb20iOiI5YTA2NDIxODI5MTliYjA2ZWQ0ODRmMmQzYzdmNzZkMiJ9.qjluDhGjmJ2jHsl5o_E0-1JzGKvrC5RYRyg3yp7GopypXAKZbJKDQS643xA5iUOYY9VJyFwXnSMuKpQU0UL-jQ

This link and yellow highlighted text will be removed and the dataset made publicly accessible upon acceptance.

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