

Enablers and barriers of sector-coupled energy systems within planetary boundaries

Jan Marcus Hartmann

jan.hartmann@ltt.rwth-aachen.de

RWTH Aachen University <https://orcid.org/0000-0002-4295-1299>

David Yang Shu

ETH Zurich <https://orcid.org/0000-0003-4096-3883>

André Bardow

ETH Zurich <https://orcid.org/0000-0002-3831-0691>

Niklas von der Assen

RWTH Aachen University <https://orcid.org/0000-0001-8855-9420>

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Enablers and barriers of sector-coupled energy systems within planetary boundaries

Jan Marcus Hartmann^{1,3,4}, David Yang Shu^{2,3}, André Bardow², Niklas von der Assen^{1,*}

Affiliations:

¹Institute of Technical Thermodynamics, RWTH Aachen University, Aachen, 52062, Germany

²Energy and Process Systems Engineering, Department of Mechanical and Process Engineering, ETH Zurich, Zurich, 8092, Switzerland

³These authors contributed equally to this work.

⁴Lead contact: jan.hartmann@itt.rwth-aachen.de

*Corresponding author: niklas.vonderassen@itt.rwth-aachen.de

Summary

Energy systems must transition toward absolute environmental sustainability across all impact categories. However, energy systems are commonly designed focusing solely on the impact category climate change. To address this challenge, we optimize the greenfield design of the German energy system in 2050, encompassing the coupled power, heat, and private passenger mobility sectors, while penalizing the transgression of sustainability thresholds derived from the planetary boundaries. We find that sustainable energy system designs are achievable when sustainability thresholds are determined based on the economic value of the energy system. However, stricter sustainability thresholds, which may result from data uncertainties or the choice of allocation method, are transgressed in the atmospheric aerosol loading and phosphorus cycle categories due to impacts from the private passenger mobility sector and material supply. Sustainable energy systems thus require reductions in private passenger mobility demand and material-related environmental impacts, as well as sufficient carbon dioxide storage, particularly if sustainability thresholds prove to be more stringent.

Keywords

Energy system design, absolute environmental sustainability, mathematical optimization, planetary boundaries, safe operating space, life cycle assessment, sector coupling, minimal system cost, carbon capture and storage

1. Introduction

Energy systems supplying electricity, heat and mobility, contribute more than 73 % of global greenhouse emissions.¹ Global efforts to reduce energy-system-related greenhouse gas emissions mitigate the energy system's climate change impact, but may shift its impact toward other environmental impact categories.² It remains unclear whether environmental impact-shifting compromises sustainability across other environmental impact categories. Given the extensive effort of the energy system transition, as well as the long lifetimes of energy system infrastructure, it is imperative to ensure an economically efficient and environmentally sustainable supply of energy across all impact categories.

One approach to find economically efficient and sustainable energy systems is to perform an absolute environmental sustainability assessment³ for given cost-optimal energy system designs.⁴ Absolute environmental sustainability assessment compares the environmental impact of the energy system against system-specific sustainability thresholds. System-specific environmental impacts are commonly determined via life cycle assessment⁵, a standardized, holistic method to assess multiple environmental impacts of an anthropogenic system along its entire life cycle. System-specific sustainability thresholds can be derived from the planetary boundary framework⁶, which defines a safe operating space for multiple environmental impact categories, representing the sustainability threshold for the total anthropogenic environmental impact within each respective category. As the safe operating space is defined for all anthropogenic systems, a share of safe operating space must be allocated to the anthropogenic system under study, e.g. the energy system, to obtain system-specific sustainability thresholds from the planetary boundary framework.³ This allocation is typically based on human-centric theories of distributive justice.⁷ One approach is to allocate the share of safe operating space based on the economic value generated by the anthropogenic system under study.⁸

Previous absolute environmental sustainability assessment studies of cost-optimal energy system designs focus on individual sectors of the energy system, such as the power^{9–11} or mobility sector¹², as well as on multi-sector-coupled energy systems¹³, covering a range of geographical and temporal scopes. Stranddorf et al.⁹ and Guillot and Assoumou¹¹ conduct an absolute environmental sustainability assessment of the electricity generation in the European Union until 2050, while Vasquez-Ibarra et al.¹⁰

conduct an absolute environmental sustainability assessment of the electricity generation in Chile until 2060. Lechtenberg et al.¹² perform an absolute environmental sustainability assessment for the private passenger mobility sector in the European Union until 2050. Shu et al.¹³ assess the German energy system until 2045 including the coupled power, residential and industrial heating, and private passenger mobility sectors. In these studies, the assessed energy system designs are obtained by cost-optimization of energy system models, while respecting constraints related to policies, emission targets or technology restrictions. The environmental impact of cost-optimal energy system designs is subsequently assessed against the allocated share of safe operating space. None of the investigated cost-optimal energy systems designs qualified as absolute environmentally sustainable.

However, the share of safe operating space can be directly included in the optimization problem as a constraint or part of the objective function, simultaneously enabling absolute environmental sustainability and cost optimization.^{14,15} Algunaibet et al.¹⁶ first minimize the sum of share of safe operating space transgressions by the United States' power sector in 2030 and subsequently minimize its costs for fixed transgressions. Weidner et al.¹⁷, Li et al.¹⁸, and Ehrenstein et al.¹⁹ employ the same approach for the European Union's residential heat sector in 2050, the Chinese power and methanol sector in 2050, and the United Kingdom's private passenger mobility sector in 2018, respectively. Negri et al.²⁰ minimize the sum of share of safe operating space transgressions by the European Union's power sector until 2100 and subsequently report the resulting costs. Guillot et al.²¹ minimize the total costs of the European Union's power sector until 2050 while constraining the sector's environmental impact by the share of safe operating space for selected planetary boundary categories. The abovementioned absolute environmental sustainability and cost optimization studies overwhelmingly find that cost-optimal energy system designs are generally not absolutely sustainable.

The absolute environmental sustainability and cost optimization studies focus either on singular sectors of the energy system^{16,21} or singular sectors that are extended by selected technologies, such as Negri et al.²⁰, who include carbon dioxide (CO₂) removal technologies; Li et al.¹⁸, who include methanol production; or Ehrenstein et al.¹⁹ and Weidner et al.¹⁷, who include hydrogen production and electricity generation.

Focusing on individual sectors that are extended by selected technologies is insufficient to adequately represent cross-sectoral interactions and system effects, resulting from, e.g., the electrification of heat and mobility sectors. Therefore, considering sector-coupled energy systems is crucial as sector-coupling can increase overall system efficiency²² and can decrease environmental impacts.²³

Balanza et al.²⁴ therefore include the share of safe operating space into the modeling constraints for optimizing a European sector-coupled energy system that includes the power, residential heat and industrial heat sector, as well as CO₂ capture and storage infrastructure for electricity generation from natural gas and waste. Balanza et al.²⁴ find that an absolutely sustainable energy system is only feasible through the reduction of final energy demand. These findings might be exacerbated when including the private passenger mobility sector, which is a major driver of final energy demand.²² Conversely, the evolution of life cycles across energy system sectors arising from the expansion of renewable energy technologies and alternative material production pathways may mitigate some of the environmental impacts in future sector-coupled energy systems.²⁵ Thus, a comprehensive analysis of sustainable sector-coupled energy systems needs to account for the major final energy demand drivers along with the evolution of environmental impacts of a transitioning economy.

Here, we perform a greenfield absolute environmental sustainability and cost optimization study of a sector-coupled energy system. We minimize total systems costs while penalizing transgressions of the share of safe operating space by the energy system's life cycle environmental impacts. As a representative industrialized nation, we employ an energy system model for Germany in 2050, encompassing the power, industrial and residential heat, and private passenger mobility sectors, along with transmission and storage of electricity, and CO₂ capture and storage infrastructure for the energy-system-wide mitigation of CO₂ emissions. Our study considers the evolution of global life cycles based on prospective scenarios and provides the first detailed analysis of enablers of and barriers to absolutely sustainable energy systems encompassing all planetary boundary categories except novel entities, which had to be excluded due to missing life cycle impact assessment methods.⁸

Our results show that an absolutely sustainable energy system design may be feasible for a share of safe operating space allocated based on the economic value generated by the energy system, quantified by total final consumption expenditure and total gross

value added, and assuming sufficient CO₂ storage capacity. However, the share of safe operating space allocated to the sector-coupled energy system may be smaller, due to uncertainties in the underlying data used for calculating the share of safe operating space or due the choice of allocation method. We therefore systematically determine energy system designs for smaller shares of safe operating space and find that the impact on atmospheric aerosol loading exceeds its respective share of safe operating space first, followed by the impact on the phosphorus cycle. A detailed multi-tier life cycle contribution analysis shows that these environmental impacts mainly result from private passenger mobility-related emissions and material supply. Reducing private passenger mobility demand and material-related environmental impacts can thus counterbalance uncertainties in CO₂ storage capacity and the allocation of the share of safe operating space, thereby supporting the development of sustainable and cost-optimal energy systems.

2. Results

2.1. Absolute environmental sustainability and cost optimization

We perform a greenfield absolute environmental sustainability and cost optimization of the German sector-coupled energy system in 2050. We find that absolutely sustainable energy system designs may exist for a share of safe operating space that is allocated to the energy system based on economic value represented by either total final consumption expenditure (0.54 %) or total gross value added (1.11 %) (Figure 2). The designs based on total final consumption expenditure and total gross value added are nearly identical with regard to the technologies employed to meet final energy demand (Figure S2) and are both relying on sector-coupling through electrification of the private passenger mobility and heat sectors (Figure 1, Figure S1). Hereafter, percentage ranges are reported as total final consumption expenditure - total gross value added, while a single value indicates the same share in both designs. Private passenger mobility demand is mainly met by battery electrical vehicles (82 %), with the remaining demand supplied by compressed natural gas vehicles (18 %). The demand for residential heat is reduced by 34 - 32 % through thermal insulation of buildings, while 61 - 62 % is met by residential heat pumps. The industrial heat demand for low-temperature heat is mostly covered by industrial heat pumps (95 %). Of mid-temperature and high-temperature heat, 79 - 78 % and 89 % of the demand, respectively, are met by natural gas boilers, and 9 % and 11 %, respectively, by district natural gas boilers, with the remaining demand for mid-temperature industrial heat being supplied by electrode boilers (12 - 13 %). The electricity demand is primarily supplied by onshore wind (47 - 49 %), natural gas combined cycle power plants (37 - 36 %) and photovoltaics (14 - 13 %). Both designs rely on similar levels of energy imports, mainly in the form of natural gas, with 1251 TWh and 1205 TWh of natural gas being imported in the designs based on total final consumption expenditure and total gross value added, respectively. Additionally, both designs rely on comparable electricity storage capacities, with 4.6 GWh and 4.5 GWh installed in the designs based on total final consumption expenditure and total gross value added, respectively (Figure S3).

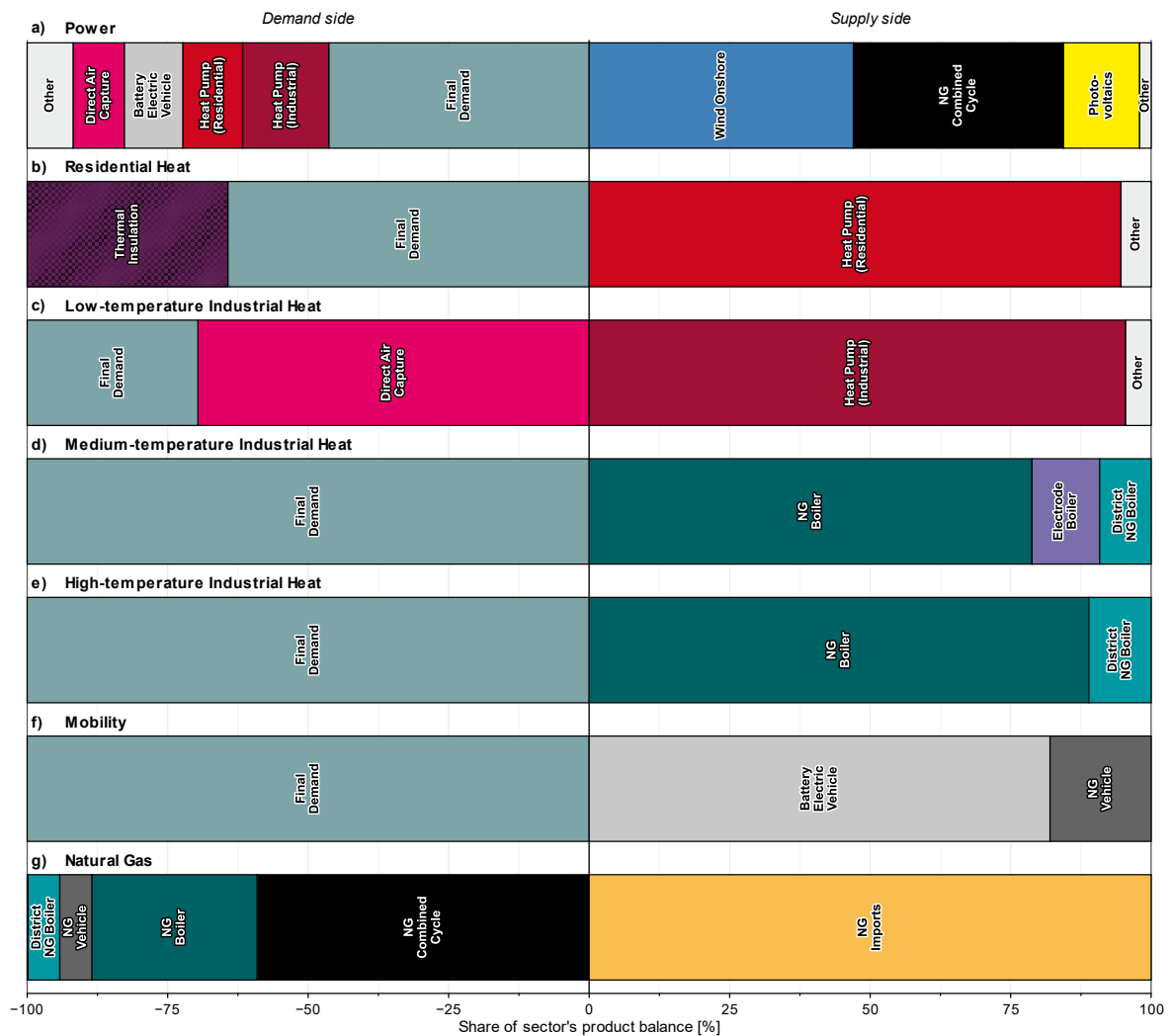


Figure 1: Shares of each sector's product balance: The design, based on total final consumption expenditure for Germany in 2050, relies on sector coupling through electrification of the private passenger mobility and heat sectors. Shares are normalized separately for demand-side and supply-side contributions in each sector, such that the negative and positive contributions each sum to 100%. Thermal insulation measures are shown as hatched demand-side reductions. Abbreviation: NG, natural gas.

Post-combustion carbon capture and direct air capture of CO₂ with subsequent permanent storage of CO₂ are employed in both designs to maintain the climate change impact within the allocated share of safe operating space (Figure S3). Post-combustion capture and storage reduces the CO₂ emissions of natural gas combined cycle power plants, which provide firm power supply. Additionally, direct air capture and storage mitigates the climate change impact from residual CO₂ emissions, such as emissions from natural gas combustion to meet mid- and high-temperature heat demand, and from compressed natural gas vehicles.

The design based on total final consumption expenditure increases the deployment of direct air capture (+14 %) and post-combustion capture (+12 %) capacity compared to

the design based on total gross value added, to meet the stricter share of safe operating space for climate change. As a consequence, the annual CO₂ storage capacity increases by 13 %, from 265 Mt CO₂ to 301 Mt CO₂ (Figure S3). Apart from reducing climate change impact, the capture and storage of CO₂ reduces the impact on ocean acidification and change in biosphere integrity. The associated CO₂ capture and storage is the main driver of the 2 % increase of total energy system design costs of the design based on total final consumption expenditure in comparison to total gross value added (Figure S3).

When the allocated share of safe operating space is reduced below the share of safe operating space based on total final consumption expenditure, absolutely sustainable energy system designs exist until a share of safe operating space of 0.48 %. However, at 0.47 %, the impact on atmospheric aerosol loading transgresses the share of safe operating space, and at 0.17 %, the impact on the phosphorus cycle additionally transgresses the share of safe operating space (Figure 2). While impacts on climate change, ocean acidification and change in biosphere integrity are limited through the deployment of CO₂ capture and storage, no technologies are included in the model to mitigate impacts on atmospheric aerosol loading and the phosphorus cycle. Therefore, energy system demands cannot be met while reducing impacts on atmospheric aerosol loading and the phosphorus cycle below a minimum level (Figure 2).

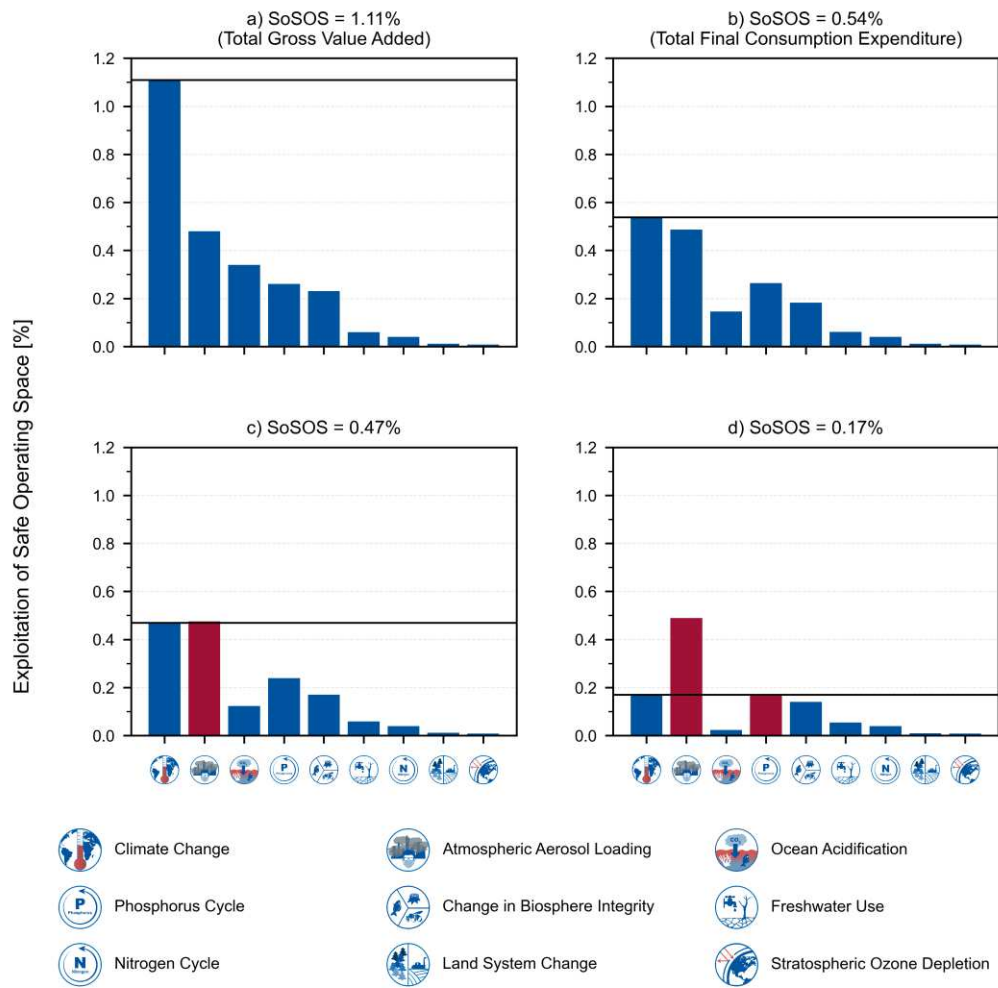


Figure 2: Absolutely sustainable energy systems exist for Germany in 2050 for allocated shares of safe operating space (SoSOS) based on total gross value added (GVA) and total final consumption expenditure (FCA). At a SoSOS of 0.47 % and 0.17 %, the impact on atmospheric aerosol loading and the phosphorus cycle transgress the SoSOS, respectively. The design optimization comprises all planetary boundary categories except novel entities.

2.2. Multi-tier contribution analysis for atmospheric aerosol loading and the phosphorus cycle

The impact on atmospheric aerosol loading in the design based on total final consumption expenditure mostly originates from the private passenger mobility sector (64 %) (Figure 3). Emissions in the private passenger mobility sector are mainly associated with the manufacturing of vehicles and associated material supply. Additionally, the private passenger mobility sector causes direct emissions impacting atmospheric aerosol loading, with 14 % of overall emissions being non-exhaust direct emissions due to tire, break and road wear.

The second largest contributor to atmospheric aerosol loading is the power sector responsible for 25 %, which is mostly associated with emissions from material and fuel supply, manufacturing of power technology infrastructure, and direct emissions from the combustion of natural gas.

Across all sectors, material and fuel supply is the main driver of impacts on atmospheric aerosol loading (57 %), with steel (20 %), aluminum (6 %) and copper (4 %) being the most impactful materials. The supply of natural gas causes 10 % of the impact. The impact of materials and fuels originates mainly from emissions associated with the material's life cycle, i.e. from mining operations (11 %) and metals processing (20 %), as well as from the energy and fuel supply (16 %) that is used to power material and fuel life cycles.

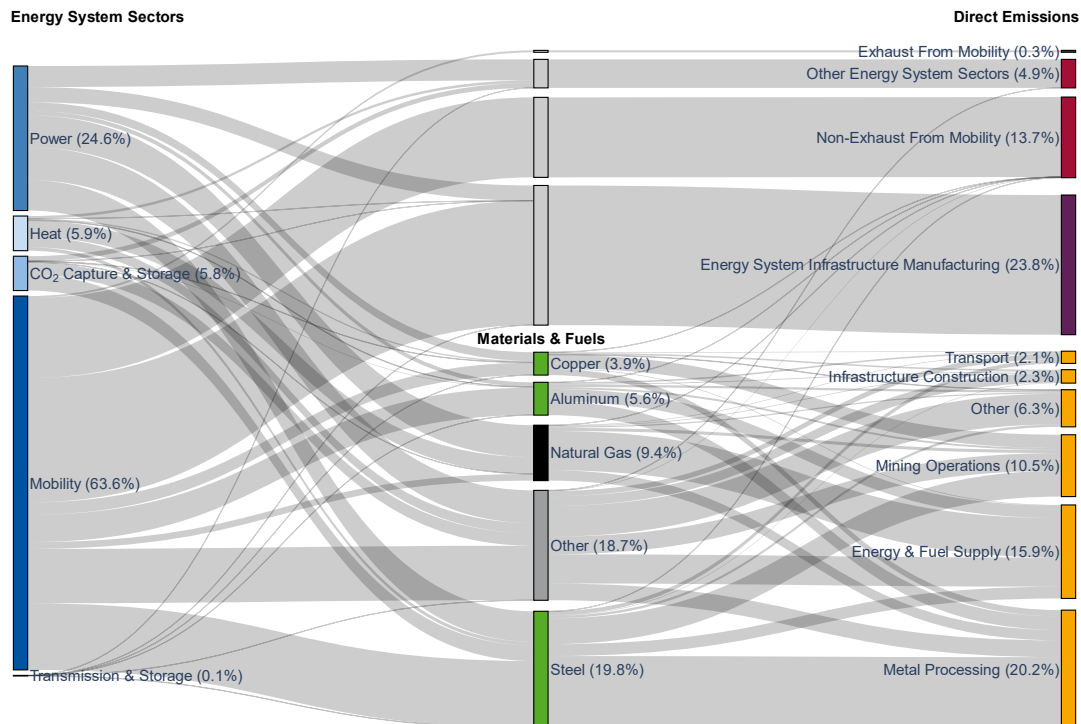


Figure 3: Multi-tier contributions to the atmospheric aerosol loading impact of the design based on total final consumption expenditure for Germany in 2050: Impacts on atmospheric aerosol loading originate mainly from emissions related to the private passenger mobility sector and to material supply. Colors indicate the source of contributions: blue – energy system sectors; green – materials; black – fuels; grey – other materials and fuels; red – direct emissions from the energy system; purple – energy system infrastructure manufacturing; orange – material and fuels production. Contributions below 2 % to the impacts of materials, fuels, and their production are aggregated under “Other”.

Designs in which the share of safe operating space is transgressed due to impacts on atmospheric aerosol loading demonstrate stronger sector-coupling through electrification and differ from non-transgressing designs primarily in the shares of technologies employed to meet electricity demand: Electricity generation from photovoltaics is replaced by electricity from offshore wind and natural gas combined cycle power plants to reduce material-related impacts (Figure S2). The larger deployment of offshore wind increases the installation of electricity storage, whereas the larger deployment of natural gas power plants increases the installation of CO₂ capture and storage to mitigate climate change impact (Figure S3).

Similarly, the private passenger mobility (67 %) and power (24 %) sectors are responsible for most of the impact on the phosphorus cycle in the design based on total final consumption expenditure (Figure 4). Again, the impact from private passenger mobility and power sector originates mainly from material supply and from the manufacturing of the sector’s technology infrastructure. Materials and fuels (79 %)

are the dominant driver of the phosphorus cycle impact across all sectors, with copper (22 %), steel (12 %), gold (12 %) and aluminum (10 %) being the most impactful materials. Most of the impact associated with materials originates from treatment processes, especially for mining residues during raw material extraction, i.e. to treat sulfidic tailings (54 %), or spoil from hard coal and lignite mining (13 %).

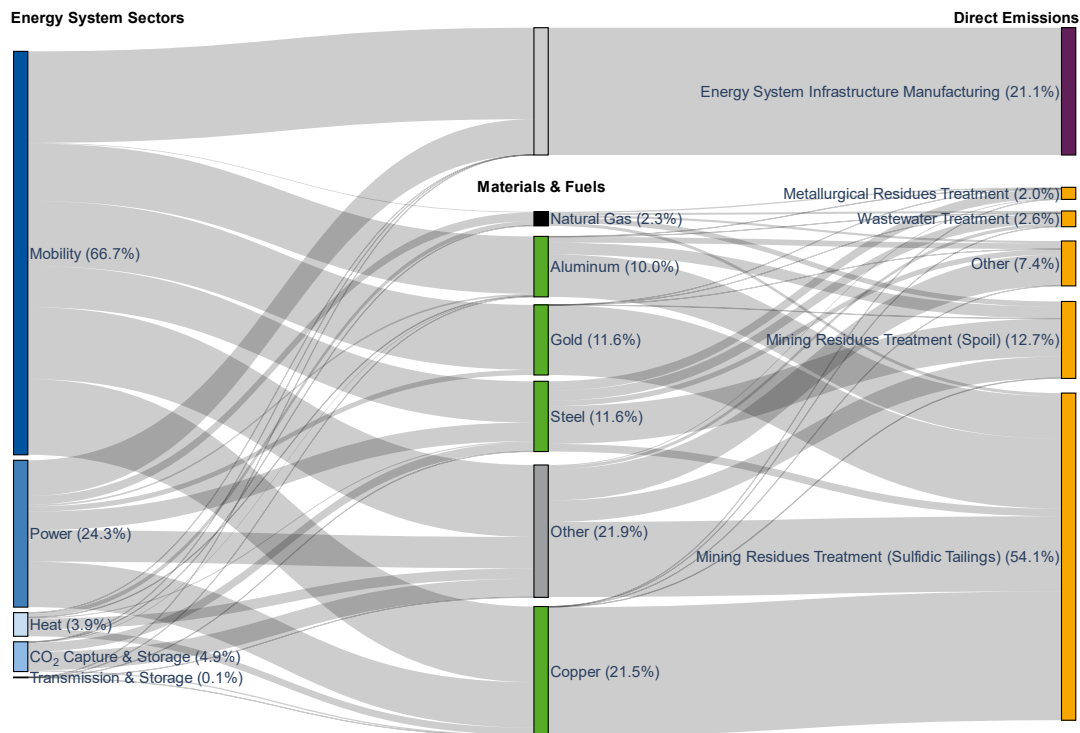


Figure 4: Multi-tier contributions to the phosphorus cycle impact of the design based on total final consumption expenditure for Germany in 2050: Impacts on the phosphorus cycle are mainly driven by material-related emissions in the life cycles of the private passenger mobility and power sectors and can be traced back to the treatment of mining residues during raw material extraction. Colors indicate the source of contributions: blue – energy system sectors; green – materials; black – fuels; grey – other materials and fuels; purple – energy system infrastructure manufacturing; orange – material and fuels production. Contributions below 2 % to the impacts of materials, fuels, and their production are aggregated under “Other”.

Most CO₂ emissions from natural gas combustion in combined cycle power plants are mitigated through post-combustion carbon capture and storage. Therefore, the impact on climate change, ocean acidification and change in biosphere integrity is mainly caused by direct CO₂ emissions from combustion processes within the heat and private passenger mobility sectors (Figure S4-6). However, these impacts are partially offset by direct air capture and storage.

In conclusion, impacts on atmospheric aerosol loading and the phosphorus cycle related to the private passenger mobility sector, especially due to direct emissions and emissions from manufacturing, as well as, material-related impacts are the main

drivers of the share of safe operating space transgressions in these impact categories and hence constitute barriers to absolute sustainability of energy systems.

2.3. Sensitivity analysis for material-related environmental impacts, private passenger mobility demand, and CO₂ storage capacity

A decrease in material-related impacts only slightly reduces impacts on atmospheric aerosol loading and the phosphorous cycle and, consequently, only marginally lowers the transgressing share of safe operating space: For instance, a 25 % reduction in material-related impacts of primary and secondary steel, aluminum, and copper decreases the transgressing share of safe operating space from 0.47 % to 0.44 % for atmospheric aerosol loading and from 0.17 % to 0.16 % for the phosphorus cycle (Figure 5a). Both transgressing and non-transgressing energy system designs are nearly identical to the designs without a decrease in material-related impacts, i.e., the base case (Figure S7-9).

In contrast, a reduction in private passenger mobility demand decreases the transgressing shares of safe operating space proportionally: For example, a 10 % reduction in private passenger mobility demand results in a 10 % decrease in the share of safe operating space where a transgression occurs. Reductions in private passenger mobility demand also decrease total system costs proportionally (Figure 5b). Energy system designs with and without reductions in private passenger mobility demand (base case) are nearly identical, for both transgressing and non-transgressing designs (Figure S10-12). Yet, energy system designs that satisfy lower private passenger mobility demand require less electricity generation capacity, import less natural gas and therefore rely on less CO₂ capture and storage capacities.

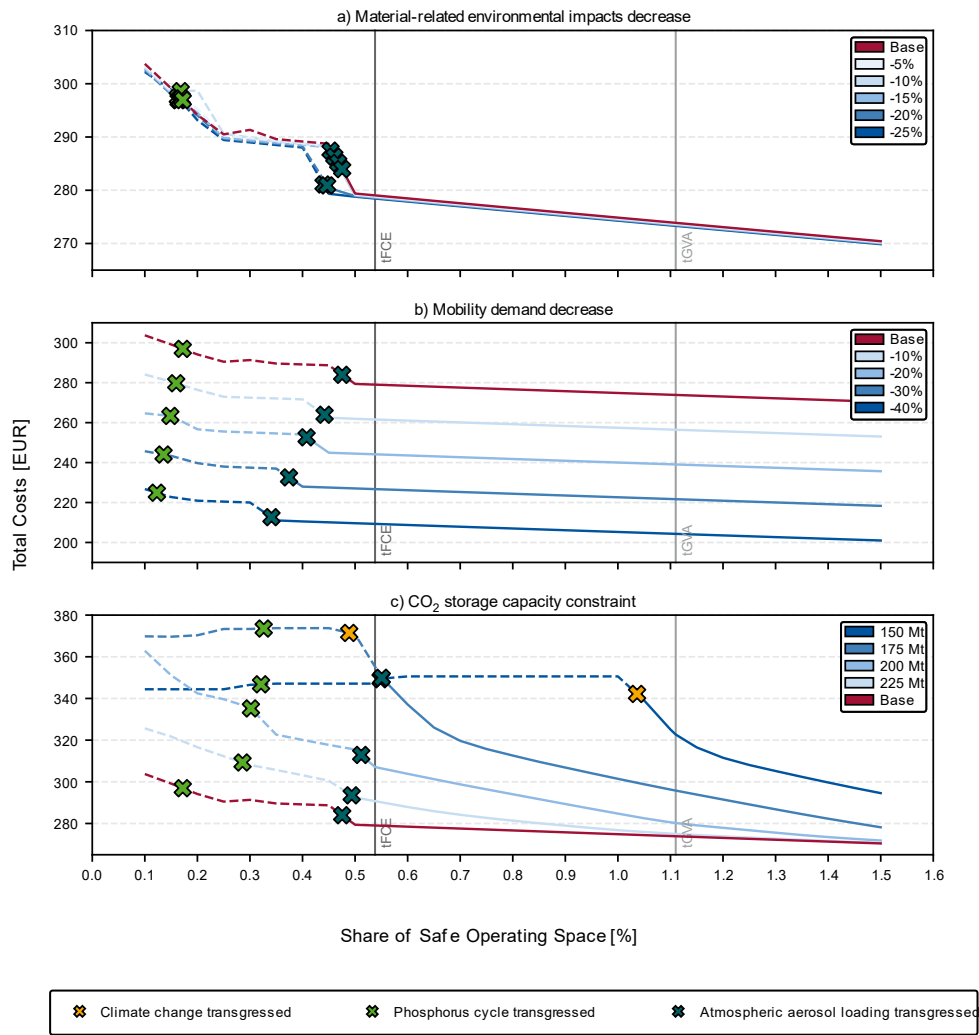


Figure 5: Decreasing material-related environmental impacts only slightly extends sustainability to tighter shares of safe operating space, whereas reducing private passenger mobility demand results in a substantially greater extension. In contrast, constraining carbon dioxide storage capacity has the opposite effect, limiting sustainability at larger shares of safe operating space. Solid lines indicate no transgression of the share of safe operating space in any planetary boundary category, whereas dashed lines indicate transgression in at least one category. Abbreviations: tFCE, total final consumption expenditure; tGVA, total gross value added.

The designs based on total gross values added and total final consumption expenditure require 265 Mt and 301 Mt of annual CO₂ storage capacity, respectively, when CO₂ storage capacity is unconstrained. For more stringent CO₂ storage capacity constraints below 179 Mt CO₂ annually, environmentally sustainable designs exist only for the larger share of safe operating space based on total gross value added, as the share of safe operating space based on total final consumption expenditure is transgressed for climate change. Below an annual storage capacity of 146 Mt CO₂ annually, no environmentally sustainable designs exist with respect to either threshold (Figure 5c). Consequently, CO₂ capture and storage enables and is strictly required for absolute sustainability. Compared to the base case designs, where CO₂ storage

capacity is unconstrained, energy system designs that obey an increasingly stricter constraint on CO₂ storage capacity display increasingly higher total system costs and an increasingly greater electrification of the heat and the private passenger mobility sectors (Figure S13, Figure S16). In the private passenger mobility sector, compressed natural gas vehicles are substituted by plug-in hybrid vehicles (Figure S14, Figure S17). Additionally, increasingly stricter constraints on CO₂ storage capacity shift electricity generation from natural gas combined cycle power plants toward higher shares of renewables, particularly toward onshore and offshore wind (Figure S14, Figure S17). The shift to renewables induces an expansion of electricity storage capacities for firm power supply by approximately two orders of magnitude (Figure S15, Figure S18).

3. Discussion

Absolutely sustainable energy system designs may exist for a share of safe operating space allocated based on the energy system's generated economic value, i.e. based on total final consumption expenditure and total gross value added. However, allocating the share of safe operating space solely on the basis of economic value may not capture the true value of energy systems: Energy is a necessary input for all other economic sectors and therefore enables their economic value generation.²⁶ While indirect economic value generated through energy use is reflected in total final consumption expenditure and total gross value added, this indirect accounting does not capture the non-substitutability of energy.

Moreover, energy systems are the main driver of life cycle environmental impacts in many economic sectors.²⁷ Therefore, reducing the energy system's environmental impacts simultaneously reduces the environmental impacts of other sectors. These environmental co-benefits are not explicitly captured by the allocated share of safe operating space. Internalizing currently unaccounted-for external costs associated with environmental impacts could shift economic value from other sectors to the energy sector that causes these environmental impacts.²⁸ This would provide a more comprehensive representation of the energy sector's importance for both economic value generation and environmental impact reduction within the share of safe operating space.

The sustainable energy systems identified rely on renewable electricity generation and on sector-coupling technologies. However, the sustainable energy systems still rely on imported fossil natural gas for firm power supply and to meet demands for medium- and high-temperature industrial heat. This reliance remains robust even when natural gas prices are doubled, although natural gas use declines across sectors (Figure S20-22) and total energy-system costs increase (Figure S19). The natural gas imports could be substituted by other energy imports, such as biogas, electricity, hydrogen, or other electricity-based fuels, reducing environmental impacts and risks associated with the natural gas supply chain. Imports of biogas and other bio-based fuels could reduce the impact on climate change, ocean acidification and biosphere integrity by replacing fossil CO₂ emissions with biogenic CO₂. This replacement can reduce the need for CO₂ capture to address climate change impact, while enabling CO₂ removal when biogenic

CO₂ is captured and stored. Yet, biogas shifts environmental impacts to other categories linked to agriculture, such as freshwater use, land-system change and the nitrogen and phosphorus cycle.²⁹ In this study, impacts on freshwater use, land-system change and the nitrogen cycle remain well below the share of safe operating space, suggesting that a partial substitution of imports with biogas could be beneficial. Still, a partial substitution of imports with biogas could exacerbate impacts on the already critical phosphorus cycle. Additionally, biogas supply is limited, and expanding production may raise costs and compete with other agricultural systems, for example food production.²⁹

Electricity imports can substitute electricity generation from natural gas combined power plants (Figure S24-25). This substitution reduces the need for post-combustion CO₂ capture and storage and hence the required CO₂ storage capacity (Figure S26). After substituting natural gas combined power generation, increasing electricity imports substitutes material-intensive renewable electricity generation technologies (Figure S25) and therefore associated electricity storage needs (Figure S26), resulting in reduced transgression levels for the share of safe operating space (Figure S23) and reduced costs (Figure S26).

Imports of hydrogen or other electricity-based fuels could satisfy medium- and high-temperature heat demand, or other energy demands. However, using electricity-based fuels such as hydrogen instead of electricity introduces efficiency penalties for electrochemical conversion and therefore likely increases costs and environmental impacts in comparison to electricity imports, with consequences for the energy system's absolute sustainability.³⁰ The choice of imported energy carriers in future energy systems thus not only impacts system costs and design, but also environmental impacts and therefore the absolute sustainability of energy systems.

This study assumes that the evolution of global supply chains follows the SSP2-NDC scenario, where SSP2 refers to a "Middle-of-the-Road" shared socio-economic pathway and NDC to a policy implementation corresponding to a mean average surface temperature increase of 2.0-2.5°C by 2100 under this socio-economic pathway.³¹ Achieving this scenario requires the implementation of additional climate policies. However, even if these additional policies are not implemented and current policies are maintained under the same socio-economic pathway, absolute sustainability remains achievable, albeit with a greater need for CO₂ storage capacity

(Figure S31-33). Conversely, implementing more stringent climate policies consistent with limiting the temperature increase to 1.5°C, while maintaining the current socio-economic pathway, can reduce overall costs (Figure S27) while simultaneously decreasing the required CO₂ storage capacity (Figure S28-30).

If the share of safe operating space is reduced below the value based on total final consumption expenditure, the allocated share of safe operating space is first exceeded by impacts related to atmospheric aerosol loading, followed by impacts on the phosphorus cycle. Impacts on atmospheric aerosol loading and the phosphorus cycle originate mainly from material-related impacts and emissions related to private passenger mobility demand. The study highlights the need to investigate these often-overlooked impact categories, and develop mitigation measures addressing the emissions from material life cycles and from the private passenger mobility sector. The underlying life cycle inventories should be reviewed, as environmental impacts depend strongly on data from a few direct-emitting processes. For example, impacts on the phosphorus cycle largely depend on emissions associated with the treatment of sulfidic tailings. Although the impacts on atmospheric aerosol loading and the phosphorus cycle are assessed at a global level in this study, these impacts can have significant regional implications.⁶ Future research should therefore expand absolute environmental sustainability and cost optimization studies to incorporate regional, system-specific sustainability thresholds and impacts for atmospheric aerosol loading, the phosphorus cycle, and other impact categories, to ensure regionally-specific deployment of mitigation measures.

Primary and secondary materials such as steel, aluminum, and copper contribute substantially to environmental impacts in the critical categories atmospheric aerosol loading and phosphorous cycle. Reducing material-related impacts can therefore shift transgressions in these critical impact categories to lower shares of safe operating space. Reductions can be achieved by lowering environmental impacts along the material's life cycle, by reducing the energy system's demand for materials, by shifting from primary to secondary materials through recycling, or through a combination of these approaches. However, a reduction in material-related impacts alone only mildly shifts the share of safe operating space at which transgressions occur, as other large contributors to environmental impacts remain unaddressed, including the manufacturing of energy infrastructure.

A reduction of private passenger mobility demand can have a larger effect than the reduction of material-related impacts, with additional co-benefits for overall system costs. For example, a reduction of the material-related impact by 25 % has the same effect, as a reduction of the private passenger mobility demand by 10 % (Figure 5). Additionally, a decrease in private passenger mobility demand lowers the required supply of electricity and natural gas imports, thereby reducing the need for CO₂ storage capacity. Private passenger mobility demand can be reduced through a shift from private passenger transport to shared or public transport.^{32,33} An expansion of shared transport would entail an increase in passengers per vehicle while reducing environmental impacts and costs. A shift toward public transport would result in an expansion of transport infrastructure, which is currently not included in the energy system model nor in the allocation of the share of safe operating space. Demand reduction represents a comparatively straightforward mitigation measure that can significantly reduce costs, environmental impacts and required CO₂ storage capacity, even at relatively low levels of reduction. Demand reduction strategies are generally feasible with available technologies and can decrease the need for emission sequestration.

The capture and storage of CO₂ is a crucial enablers of sustainable energy systems to mitigates impacts on climate change, ocean acidification and change in biosphere integrity. However, limited availability of CO₂ storage capacity may prevent absolute sustainability, as climate change becomes the limiting impact category. We estimate the CO₂ storage capacity available to the German energy system in 2050 by applying the same allocation factors used to derive the share of safe operating space to global CO₂ storage capacity estimates of the IPCC³⁴ (30 Gt yr⁻¹ in 2050) and Zhang et al.³⁵ (16 Gt yr⁻¹). For those allocated CO₂ storage capacities, only the larger storage capacity determined based on total gross value added enables sustainable designs (Figure S34). Consequently, CO₂ storage capacity may be a bottleneck for sustainable energy systems. Given limited social acceptance and potential technical uncertainties of capacity expansion, a precautionary approach is therefore needed to limit reliance on CO₂ capture and storage.

This study indicates that environmentally sustainable energy systems may be feasible in a greenfield design. However, this conclusion relies on uncertain assumptions: the allocation of a sufficiently large share of safe operating space to the energy system,

the large-scale use of limited CO₂ storage capacities, the transition of energy system infrastructure, and the prospective evolution of global life cycles. To mitigate these uncertainties, a combination of measures is required across impact categories. Measures include demand reduction, e.g. for private passenger mobility, reductions in material-related environmental impacts, and additional mitigation measures along the energy system's life cycle, such as process improvements and emission sequestration technologies.

4. Methods

4.1. Goal & Scope

The goal of this study is to identify cost-optimal, sector-coupled energy system designs whose life cycle environmental impacts remain within an allocated share of safe operating space. In addition, the study examines key enablers and barriers to achieving absolute sustainability in energy systems.

The scope of the study comprises the greenfield design of the German energy system in 2050 covering the coupled sectors for power, residential heating, industrial heating and private passenger mobility from cradle-to-grave, i.e. from raw material extraction via construction and operation to end-of-life. The energy system meets the demand for electricity, residential heat, industrial heat on low (below 100°C), medium (between 100-400°C) and high temperature levels (above 400°C), and for private passenger mobility in 2050 in Germany.

4.2. Energy system model

For this study, we adapt the model of the sector-coupled German energy system presented in detail by Shu et al.² The model is developed using the modeling and optimization framework SecMOD³⁶ for multi-energy systems with integrated life cycle assessment. The greenfield design problem of the energy system is represented as a linear optimization problem with a spatial resolution of 18 nodes and node-specific temporal profiles of electricity, private passenger mobility, residential and industrial heating demands, with an aggregated temporal resolution of 8 typical periods with 24 hourly time steps each.

Technologies to convert energy carriers to supply the exogenous demands are represented as input-output models with fixed efficiency and life cycle inventories to model environmental impacts, as documented by Baumgärtner et al.³⁷ and Shu et al.² All considered technologies of each sector, along with storage, transmission, and CO₂ capture, transport, and storage technologies, are presented in Table S1 of the Supplemental Information.

The life cycle inventory database integrated in the model is updated to ecoinvent 3.10.1 (cut-off)³⁸ and adapted using *premise* 2.3.3³⁹ to reflect the evolution of the energy systems and its life cycles in 2050 based on the integrated assessment model *REMIND* 3.5³¹ and the “Middle-of-the-Road” shared socio-economic pathway corresponding to a mean average surface temperature increase by 2.0-2.5°C by 2100 (SSP2-NDC).⁴⁰ We replace the life cycle inventories of passenger vehicle technologies, grid-scale batteries and industrial heat pumps, as described in Section 1.1 of the Supplemental Information. The life cycle inventories are converted into environmental impacts on the planetary boundary categories using the methodology of Hartmann et al.⁸

We design the energy system by minimizing total annualized cost, as proposed by Reinert et al.³⁶, assuming a greenfield design in 2050. In addition to total annualized cost, we introduce penalty terms for the transgression of the share of safe operating space into the objective function. The penalties are chosen to be sufficiently large, such that transgressions only occur when they are unavoidable. We ensure equal weighting across impact categories by applying the same penalty to each category and normalizing it by the respective share of safe operating space. Note that the total costs reported in this publication include only investment and operating costs, while excluding the penalty costs for transgressing the share of safe operating space. All optimization problems are solved using Gurobi.⁴¹

4.3. Share of safe operating space allocated to the energy system

To determine the share of safe operating space that is allocated to the energy system, we use the allocation factors provided by Hartmann et al.⁸, who calculate allocation factors for multiple economic sectors based on the total consumption- or production-based economic value generated by the economic sector, via total final consumption expenditure and total gross value added, respectively. We use the most recent allocation factors available for 2022, following the recommendations derived in our previous work.⁸ The allocation factors account for population, geographical scopes, and temporal scopes.

To determine the allocation factor for the power sector, we consider the allocation factors of German sectors involved in the production of electricity by all available technologies. For the residential and industrial heat sector, we consider the allocation factor for steam and hot water supply in Germany. Additionally, we consider the allocation factor for transmission of electricity in Germany. Hartmann et al.⁸ do not provide allocation factors for private passenger mobility. We thus determine the allocation factor for the private passenger mobility sector based on the economic value generated by sectors supplying the private passenger mobility sector, as described in Section 1.2 of the Supplemental Information. We aggregate the allocation factors across all individual sectors to obtain allocation factors for the German energy system based on total final consumption expenditure (0.54 %) and based on total gross value added (1.11 %).

4.4. Scenario parameters for sensitivity analysis of share of safe operating space

We define scenarios for the three parameters: material-related environmental impacts, private passenger mobility demand, and CO₂ storage capacity. We vary the parameters independently and solve the design optimization problem for a share of safe operating space constrained to values ranging from 0.1-1.5 %.

Material-related environmental impacts are the environmental impacts associated with the material life cycle, which include processes for mining, beneficiation, processing, refining and end-of-life treatment of materials. For material-related environmental impacts, we reduce the impacts associated with the primary and secondary production of steel, aluminum, and copper, by 5 %, 10 %, 15 %, 20 %, and 25 %. As a reference, material-efficiency measures and technological shifts reduce global aluminum and steel demand by 17 % and 24 % in 2060, respectively, in the Clean Technology Scenario compared to a Reference Technology Scenario of a joint IEA–OECD report.⁴² A detailed explanation of the implementation of the material-related impacts parameter can be found in Section 1.3 of the Supplemental Information.

We reduce private passenger mobility demand by 10 %, 20 %, 30 % and 40 % from initial private passenger mobility demand of 657.4 billion vehicle kilometers per year, or 986.3 billion passenger kilometers per year, when considering an average passenger vehicle occupation in Germany by 1.5 passengers.⁴³ As a reference, Gupta et al.³² estimate a minimum private passenger mobility demand of 9.6-12.3 passenger kilometers per person and per day required to meet basic transportation needs, corresponding to 294.3-377.1 billion passenger kilometers per year or a 62-70 % reduction compared to the baseline, assuming a population of 84 million.

We impose constraints on the CO₂ storage capacity ranging from 50 Mt – 400 Mt CO₂. As a reference, the IPCC³⁴ and Zhang et al.³⁵ estimate a maximum global CO₂ storage

capacity of 30 Gt CO₂ and 16 Gt CO₂ per year in 2050, respectively. We allocate a share of global CO₂ storage capacity to the energy system based on the same allocation factors used as for the allocation of the share of safe operating space. When applying the allocation factors based on total final consumption expenditure to the capacities proposed by the IPCC and Zhang et al., this results in an annual capacity of 161.4 Mt CO₂ and 86.1 Mt CO₂, respectively, and for the allocation factor based on total gross value added, this results in an annual capacity of 333 Mt CO₂ and 177.6 Mt CO₂, respectively.

5. Resource Availability

5.1. Lead Contact

Please contact the Lead Contact, Jan Marcus Hartmann (jan.hartmann@ltt.rwth-aachen.de) for inquiries regarding further information and resources.

5.2. Materials Availability

This study uses the open-source Python package *pbaesa*, developed by the authors, which provides methods for planetary-boundary-based absolute environmental sustainability assessment and is described in a separate publication.⁸

5.3. Data and Code Availability

The code for the SecMOD modeling and optimization framework used in this study is publicly available.³⁶ The energy system model is based on the model presented by Shu et al.², with all adaptations made for this study described in the present article. The life cycle inventory data used in the model are either documented in Shu et al.² and in this article, or were obtained from the proprietary ecoinvent database³⁸ and therefore cannot be redistributed.

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Authors contributions

J.M.H.: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing – original draft. D.Y.S.: Conceptualization, Methodology, Supervision, Writing – review & editing. A.B.: Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition. N.A.: Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition.

Declaration of Competing Interests

A.B. has ownership interests in Carbon Minds, a firm that renders services on LCA to industry, and other companies which also provide services to industry using LCA. In 2022, A.B. has served on review committees for research and development at ExxonMobil and TotalEnergies, oil and gas companies that are also active in LCA. All other authors report no competing interests.

Declaration of Generative AI and AI-assisted Technologies

Artificial intelligence tools were used solely to assist with grammar and spelling corrections and to support coding tasks. The authors reviewed, edited and take full responsibility for the final content.

Supplemental Information

Document S1. Supplemental methods, Figures S1–S34, and Tables S1–S2

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