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Conference Paper

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Publication date:
2024

Permanent link:
https://doi.org/10.3929/ethz-b-000684348

Originally published in:
Systems and Control Transactions 3

Systems & Control Transactions

Research Article
Foundations of Computer Aided Process Design (FOCAPD 2024)
Breckenridge, Colorado, USA. July 14-18, 2024
Peer Reviewed Conference Proceeding

Towards Designing Sector-Coupled Energy Systems Within Planetary Boundaries

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ABSTRACT

The transition to net-zero greenhouse gas emissions requires a rapid redesign of energy systems. However, the redesign may shift environmental impacts to other categories than climate change. To assess the sustainability of the resulting impacts, the planetary boundaries framework provides absolute limits for environmental sustainability. This study uses the planetary boundaries framework to assess net-zero sector-coupled energy system designs for absolute environmental sustainability. Considering Germany as a case study, we extend the common focus on climate change in sustainable energy system design to seven additional Earth-system processes crucial for maintaining conditions favorable to human well-being. Our assessment reveals that transitioning to net-zero greenhouse gas emissions reduces many environmental impacts but is not equivalent to sustainability, as all net-zero designs transgress at least one planetary boundary. However, the environmental impacts vary substantially between net-zero designs, highlighting that design choices exist to address transgressions of planetary boundaries.

Keywords: Energy Systems, Life Cycle Assessment, Modelling, Optimization, Carbon Capture, Environment, Sector-coupling

INTRODUCTION

The energy system needs to be redesigned to reduce greenhouse gas emissions to net-zero. The redesign is commonly guided by energy systems models in optimization studies [1]. A common finding in energy system optimization studies is the rise of sector coupling to integrate low-carbon electricity into sectors such as mobility and heating [2–5]. Combined with environmental life-cycle assessment (LCA) [6], energy system modeling and optimization can account for climate change and additional environmental impacts.

In LCAs of the energy system transition, reducing the climate change impact of energy systems has been shown to result in burden-shifting, i.e., environmental impacts shift from climate change to other categories, such as in land use, resource depletion, toxicity, and ecosystem diversity [7, 2]. However, traditional LCA commonly adopts a comparative approach, where the environmental impacts of systems are assessed in relation to a reference system [8]. While such traditional LCAs show relative differences in impacts, they do not quantify the severity of shifting environmental impacts.

Recently, metrics were introduced to assess environmental trade-offs and provide critical limits by so-called absolute environmental sustainability assessment [8]. Such methods connect life-cycle assessment with absolute environmental sustainability assessment (for a review, see [8]). A popular example is the application of the planetary boundary framework [9–11] to life-cycle assessment [12, 13]. The planetary boundaries framework defines safe operating spaces for climate change and 8 additional Earth-system processes critical to maintaining an Earth-system state that is beneficial for humans. A recent assessment [11] finds that the planetary boundaries are transgressed for 6 Earth-system processes: climate change, change in biosphere integrity, biogeochemical flows of phosphate and nitrogen, land-system change, freshwater change, and novel entities. Only 3 processes remain within boundaries: stratospheric ozone depletion, ocean acidification, and atmospheric aerosol loading. Hence, it is crucial to consider planetary boundaries in the sustainable design of future energy systems.

In pioneering work, absolute environmental sustainability assessments going beyond climate change have been applied to energy systems [14] but typically consider only one sector, such as power [15–17] or building heat systems [18]. Hence, the impact of sector coupling on absolute sustainability is poorly understood. Here, we conduct an absolute environmental sustainability assessment for net-zero sector-coupled energy systems via the planetary boundaries framework.

PLANETARY BOUNDARIES IN ENERGY SYSTEM MODELING

Energy system modeling and optimization frameworks vary in model complexity depending on the application. For (inter)national sector-coupled energy system models, linear or mixed-integer linear programming formulations are commonly selected to represent techno-economic constraints [19].

In addition to techno-economic constraints, environmental impacts are included via LCA in models of sector-coupled energy systems from international [3, 4] to national scale [5, 2]. Previous LCA studies [2–5] found environmental burden-shifting resulting from the energy transition, e.g., increasing the use of land, water, and resources.

In previous work, we considered the environmental impacts of the German sector-coupled energy transition to net-zero operational greenhouse gas emissions [20]. Our work revealed increases in up to 7 of 16 impact categories compared to the status quo, e.g., resource depletion of minerals and metals may increase up to four times. However, the degree of burden-shifting can be reduced by design choices: Carbon capture and storage is found to be a lever to steer environmental impacts.

While the identified burden-shifting highlights potential areas of concern, the relative increase in impacts does not reveal if the increase contributes to a transgression of limits of absolute sustainability. Absolute assessments via planetary boundaries aim to overcome this limitation and have been conducted for a single sector of the energy system [14–17]. As these studies are limited to a sector or geographical region and the safe operating space applies to all human activities, downscaling is required, where a share of the safe operating space is allocated to the assessed system [21]. Typically, the safe operating space is allocated by one or a combination of the following principles: egalitarian, utilitarian, or acquired rights. All of the energy-related studies [15–18] apply downscaling by population to account for the geographical scope, and some further apply downscaling by economic principles or acquired rights.

METHODS

Absolute environmental sustainability assessment via planetary boundaries

Here, we assess the absolute sustainability of the net-zero designs for the German sector-coupled energy system identified in previous work [20]. We apply the planetary boundaries framework using the impact assessment method provided in [13]. Note that novel entities are excluded from our assessment, as they are not quantified in [13]. However, in [11], the planetary boundary for novel entities is considered transgressed if any synthetic chemical is released into the environment without adequate safety testing. Hence, the boundary is likely transgressed for the energy system.

As the geographical and sectorial scope is limited in the case study, we allocate a share of the global safe operating space to the German energy system. We first apply downscaling by population based on egalitarian principles to account for the geographical scope. Thus, a share of the total safe operating space is allocated to Germany based on its share of the global population in 2021 [22]. We subsequently apply downscaling by grandfathering to account for the sectorial scope. For the grandfathering, we limit the share of the German safe operating space that the energy system can occupy to the share of environmental impacts caused by the energy system in the reference year (2016). The share of environmental impacts in the reference year is estimated compared to the total German impacts determined using a global input-output database [23]. As an additional reference, we include the share of safe operating space based on gross domestic product in 2021 [24] instead of population. We thus identify environmental impacts exceeding absolute limits for sustainability.

Energy system model description

The net-zero sector-coupled energy systems are designed via a modeling and optimization framework with integrated LCA[1] [25] based on the life-cycle inventory database ecoinvent 3.5 (APOS) [26].

The system boundary of the energy system includes the electricity sector, the private mobility sector, and the heating sector for buildings and for industry on three temperature levels. In addition, we include CCS technologies and a direct air capture technology to enable CO_2 emission avoidance and CO_2 removal (Table 1).

As the functional unit, we select the supply of all

[1] git-ce.rwth-aachen.de/secmod

exogenous end-use demands for electricity, mobility, and heat. Additionally, we constrain operational greenhouse gas emissions to reach net-negative emissions of -29 Mt CO_2-eq. in 2045, assuming that the energy system contributes to balancing hard-to-abate emissions, e.g., in agriculture. A detailed description is available in [20].

Table 1: Technologies considered in the energy system case study based on [2, 20].

electricity	**heating**
biogas-to-power	**building**
geothermal	natural gas boiler (district)
hard coal	natural gas boiler
hydrogen fuel cell	electrode boiler
lignite	energetic rehabilitation
natural gas combined cycle (NGCC)	heat pump
natural gas turbine	oil boiler
nuclear	**industry, low-temp.**
oil	natural gas boiler (district)
photovoltaics	natural gas boiler
run-of-river	electrode boiler
waste-incineration	heat pump
wind, offshore	**industry, medium-temp.**
wind, onshore	natural gas boiler (district)
other non-renewables	natural gas boiler
lithium-ion battery	electrode boiler
pumped hydro storage	**industry, high-temp.**
	natural gas boiler (district)
	natural gas boiler
private mobility	**carbon capture & storage**
battery electric	direct air capture
compressed natural gas	cement industry
diesel	CO_2 pipeline
gasoline	NGCC
hydrogen fuel cell	steel industry
plug-in hybrid	geological storage CO_2
power-to-X	**transmission**
power-to-diesel	220 kV power line
power-to-hydrogen	380 kV power line
power-to-methane	upgrade 220 to 380 kV

The multi-period investment decisions are determined in a rolling-horizon optimization, minimizing total annualized cost with investments every 5 years for a foresight horizon of 10 years. We apply a linear programming formulation for the design problem, assuming linear input-output relationships in energy conversion, continuous equipment sizing, and linear investment and operating costs.

CASE STUDY RESULTS

Transition pathways depend on key technology options, such as the availability of green electricity imports or DAC as a carbon dioxide removal technology. DAC opens a design space with solutions spanning between the cost-optimal and the minimally-required deployment of CO_2 sequestration that still meets greenhouse gas emission targets.

Here, we assess the absolute environmental sustainability assessment of a conservative scenario from [20] that excludes electricity imports into the energy system. Further, we consider 3 sub-scenarios where CO_2 storage is 1) unconstrained (min-TAC), 2) constrained to a minimum (min-storage), and 3) constrained to an intermediate value (compromise).

The net-zero energy systems outperform the fossil system from the initial year of the transition horizon in at least 6 of 9 impact categories (Figure 1). Only for the nitrogen cycle, impacts increase beyond the level of 2016 in all net-zero designs. Additional burden-shifting occurs only in scenarios with minimal CO_2 sequestration, where the impacts increase in atmospheric aerosol loading and in freshwater use compared to the reference in 2016. However, the absolute sustainability assessment reveals that the burden-shifting for freshwater use does not result in a transgression of the safe operating space.

In the other Earth system processes, the net-zero designs reduce impacts, sometimes substantially, e.g., in ocean acidification (-91 %), climate change (-90 %), the phosphorus cycle (-86 %), change in biosphere integrity (-82 %), and land system change (-57 %).

However, no net-zero energy system stays within all planetary boundaries when downscaling is applied based on population. In particular, all energy systems transgress boundaries for the nitrogen cycle and atmospheric aerosol loading, while some further exceed boundaries for climate change, change of biosphere integrity, and ocean acidification. The designs obtained for the compromise scenario and the scenario with minimal CO_2 sequestration exceed boundaries for climate change despite reaching net-zero operational greenhouse gas emissions due to greater infrastructure intensity with embedded emissions.

The transgression is particularly large for the nitrogen cycle, where the boundaries are exceeded by a factor of 4.2 on average across the three net-zero designs due to massive investments in battery electric vehicles, power-to-methane, and insulation material for energetic rehabilitation.

While all three net-zero designs transgress at least 2 planetary boundaries and are therefore unsustainable, the designs differ substantially in their environmental impact (Figure 1): On average, the energy system occupies 77 % of the safe operating space for the case minimizing total annualized cost with unconstrained CO_2 sequestration (min-TAC) but by up to 190 % for the case with minimal CO_2 sequestration (min-stor). The results indicate that design choices, such as the availability of flexible negative emission technologies, can reduce transgressions.

The results vary depending on the choice of downscaling methods, which involves distributive justice considerations and introduces subjectivity into the assessment [21]. Therefore, we include downscaling by gross domestic product instead of population as an additional reference.

Downscaling by gross domestic product instead of population quadruples the safe operating space due to Germany's large per-capita gross domestic product. For downscaling by gross domestic product, an energy system design within the modeled planetary boundaries seems possible if CO_2 sequestration is unconstrained (Figure 1, min-TAC). However, downscaling by economic indicators is controversial [21]. In general, the downscaling method requires careful consideration in the interpretation of results.

CONCLUSIONS AND OUTLOOK

Global greenhouse gas emissions must decline rapidly to limit human-induced climate change. In addition to climate change, other sustainability challenges must be addressed simultaneously.

The planetary boundaries framework defines a safe operating space for human activities for 8 Earth-system processes in addition to climate change. The planetary boundaries thus impose additional constraints on the design space of sustainable energy systems that are commonly neglected.

Here, we evaluate the environmental impacts of net-zero energy system designs considering the planetary boundaries. In particular, we consider net-zero designs of the sector-coupled energy system of Germany, a representative industrial economy. Our case study reveals a

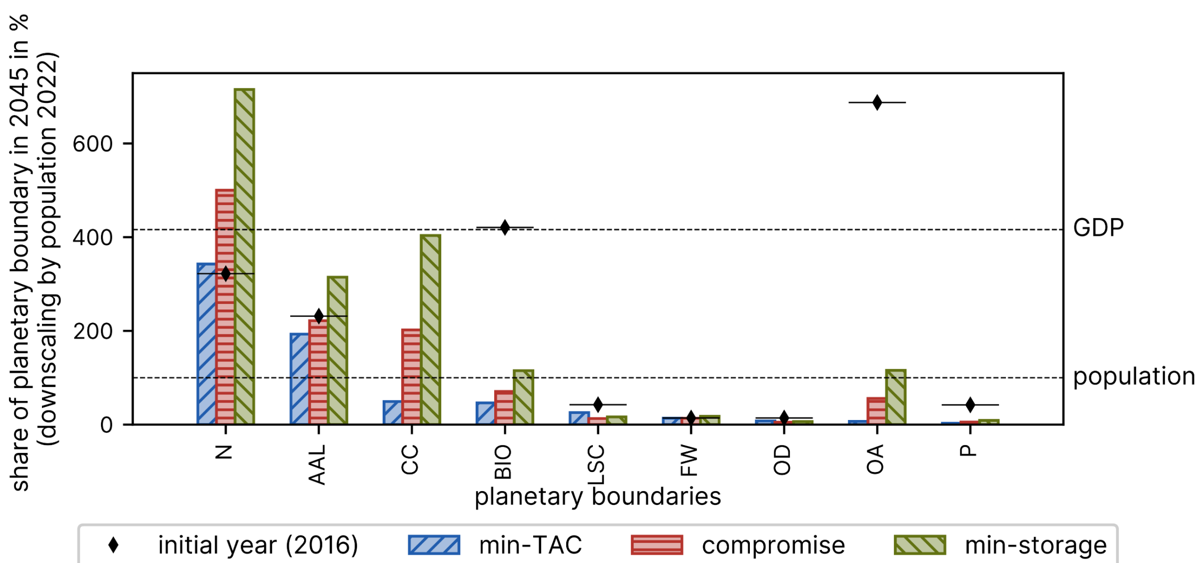

Figure 1. Share of safe operating space occupied by sector-coupled energy system designs with net-zero operational greenhouse gas emissions for the German energy transition in 2045 aiming for minimal cost (min-TAC) or minimal CO_2 sequestered (min-storage), and an intermediate solution (compromise). Downscaling of the global safe operating space to the share of safe operating space allocated to the German energy system is based on 1) the population of Germany in 2021 and 2) on the energy system's share of the total environmental impacts in Germany in the original year of the transition horizon (2016) (population). As a reference, downscaling based on gross domestic product in 2021 instead of population is indicated as well (GDP).

The share of safe operating space occupied by the energy system in the reference year (2016) is marked (♦) for comparison with the energy systems in 2045.

abbreviations: nitrogen cycle (N), atmospheric aerosol loading (AAL), climate change (CC), change in biosphere integrity (BIO), land-system change (LSC), freshwater use (FW), stratospheric ozone depletion (OD) , ocean acidification (OA), phosphorous cycle (P)

Novel entities are excluded, as they are not quantified in [13]. However, in [11] the planetary boundary for novel entities is considered transgressed if any synthetic chemical is released to the environment without adequate safety testing. Hence, the boundary is likely transgressed for the energy system.

transgression of at least 2 planetary boundaries for all net-zero designs. At the same time, the transgressions vary substantially across designs, indicating opportunities to address transgressions via design choices.

The present work demonstrates the need to include all planetary boundaries in the design of sustainable energy systems. This perspective leads to multiobjective optimization for design space exploration to determine technological barriers and supply chain contributions to environmental impacts. We thus aim to identify enablers of energy systems within planetary boundaries, which will be presented in future work.

ACKNOWLEDGEMENTS

DS has received funding from the pilot project DemoUpCARMA, funded and supported by the Swiss Federal Office of Energy and the Federal Office for the Environment. AB acknowledges funding by the Swiss Federal Office of Energy's SWEET programme as part of the project PATHFNDR.

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