



Research paper

Life cycle-based environmental impacts of energy system transformation strategies for Germany: Are climate and environmental protection conflicting goals?

T. Naegler^{a,*}, J. Buchgeister^b, H. Hottenroth^c, S. Simon^a, I. Tietze^c, T. Viere^c, T. Junne^a

^a Department of Energy Systems Analysis, Institute of Networked Energy Systems, German Aerospace Center (DLR), 70563 Stuttgart, Germany

^b Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT), 76133 Karlsruhe, Germany

^c Institute for Industrial Ecology (INEC), Pforzheim University of Applied Sciences, 75175 Pforzheim, Germany

ARTICLE INFO

Article history:

Received 8 August 2021

Received in revised form 15 March 2022

Accepted 17 March 2022

Available online xxxx

Keywords:

Energy system modeling

Scenarios

LCA

Environmental impacts

Climate protection

Environmental protection

ABSTRACT

In the development of climate-friendly energy system transformation strategies it is often ignored that environmental protection encompasses more than climate protection alone. There is therefore a risk of developing transformation strategies whose climate friendliness comes at the expense of higher other environmental impacts. Consequently, an assessment of environmental impacts of energy system transformation strategies is required if undesired environmental side effects of the energy system transformation are to be avoided and transformation strategies are to be developed that are both climate and environmentally friendly. In this paper, ten structurally different transformation strategies for the German energy system were re-modeled (in a harmonized manner). Five of these scenarios describe pathways for a reduction of direct, energy related CO₂ emissions by 80%, the other five by 95%. Life cycle-based environmental impacts of the scenarios were assessed by coupling the scenario results with data from a life cycle inventory database focusing on energy and transport technologies. The results show that the transformation to a climate-friendly energy system reduces environmental impacts in many impact categories. However, exceptions occur with respect to the consumption of mineral resources, land use and certain human health indicators, which could increase with decreasing CO₂ emissions. The comparison of environmental impacts of moderately ambitious strategies (80% CO₂ reduction) with very ambitious strategies (95% CO₂ reduction) shows that there is a risk of increasing environmental impacts with increasing climate protection, although very ambitious strategies do not necessarily come along with higher environmental impacts than moderately ambitious strategies. A reduction of environmental impacts could be achieved by a moderate and – as far as possible – direct electrification of heat and transport, a balanced technology mix for electricity generation, by reducing the number and size of passenger cars and by reducing the environmental impacts from the construction of these vehicles.

© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Climate change is certainly one of the most pressing global ecological challenges of our time. Globally, energy-related greenhouse gas (GHG) emissions account for around three quarters of total GHG emissions (Lamb et al., 2021). Consequently, there is a great deal of research into strategies for decarbonizing the energy supply, both at regional and national level, but also worldwide, in order to keep the global temperature increase below 2 °C (or even 1.5 °C) compared to pre-industrial levels. Climate-friendly energy systems are based primarily on technologies that no longer use

fossil fuels, e.g. from renewable sources. However, it cannot be ruled out per se that those transformation strategies may lead to higher environmental impacts elsewhere, i.e., that there may be some trade-offs between climate and environmental protection.

Bottom-up energy system models (ESMs) with a high technological detail are often used to develop technically feasible and economically viable transformation strategies for the energy (and transport) system which make it possible to achieve the climate protection goals that have been set. In general, the focus of such analyses is on reducing direct (on-site) CO₂ emissions from the operation of the technologies under consideration.

On the other hand, Life Cycle Assessment (LCA) is an established and widely used tool for assessing the environmental impacts across all life cycle phases of a product or process from the extraction of raw materials to the construction, operation, and

* Corresponding author.

E-mail address: tobias.naegler@dlr.de (T. Naegler).

end of life of plants (Hellweg and Milà i Canals, 2014). Thereby, LCA quantifies all relevant physical elementary flows of a product system that provides a service or function described by its functional unit (e.g. provision of an amount of electricity) (Hauschild, 2018). Furthermore, the broad spectrum of impact categories considered in LCA (e.g. impacts on human health, resources and the ecosystem) complements the mostly one-dimensional consideration of environmental implications, namely climate change contribution, of energy scenarios to date (Pauliuk et al., 2017).

The combination of the two methods, energy system modeling on the one hand and LCA on the other, allows to capture shifts of environmental impact from one life cycle stage to another (e.g. from the operation of a power plant to its construction): LCA has become increasingly popular in recent years as a means of assessing environmental impacts that go beyond the traditional system boundaries of ESMs. Hertwich et al. (2015) were among the first to conduct a dynamic life cycle assessment of different global scenarios with a focus on the electricity sector using the Technology Hybridized Environmental-Economic Model with Integrated Scenarios (THEMIS). THEMIS has also been used to consider the impacts of future power generation, including storage and the grid (Berrill et al., 2016), and has been coupled with various global Integrated Assessment Models (IAMs) for ex-post assessment (Luderer et al., 2019; Pehl et al., 2017). In addition to the applications of THEMIS, which had mainly a global focus, numerous other studies have assessed the environmental impact of the electricity sector in different geographical regions (García-Gusano et al., 2017, 2016; Xu et al., 2020; Shmelev and van den Bergh, 2016; Sokka et al., 2016; Raugei et al., 2020; Gargiulo et al., 2020). However, these studies focus only on the electricity sector. They did not consider the important interlinkages between sectors, such as the increasing electrification of transport and heat and the resulting potential shift of environmental impacts between sectors.

So far, the environmental assessment of multi-sectoral scenarios has been limited to a few studies. For example, Volkart et al. (2017) assessed three energy scenarios for 2035 for Switzerland and found that ambitious climate policy is accompanied by adverse side-effects regarding metal depletion and ecosystem damages but performs better regarding life cycle-based GHG emissions and fossil fuel demand. In another study, Volkart et al. (2018) analyzed three global energy scenarios until 2050 and showed that ambitious climate policy may induce challenges in terms of water and land use. Blanco et al. (2020) conducted an ex-post assessment of six European scenarios focusing on the introduction of power-to-methane (PtM) technologies. The authors illustrated that the introduction of PtM may be associated with slightly higher life cycle-based GHG emissions and fossil fuel demand but leads to a reduction of most of the other indicators assessed. Finally, Junne et al. (2020b) developed the FRamework for the assessment of environmental Impacts of Transformation Scenarios (FRITS) and applied it to two energy scenarios for Germany up to 2050. The authors found that ambitious climate policy may exacerbate abiotic resource depletion, land use, and some ecosystem and human health impacts.

Furthermore, previous studies have shown that a shift from conventional to renewable energy supply also shifts the environmental impacts from the use phase (primary emission phase of fossil energy technologies) to the manufacturing phase (primary emission phase of renewable energy and storage technologies) (Rauner and Budzinski, 2017; Junne et al., 2020b). These results demonstrate the importance of taking a life cycle perspective when determining environmental impacts.

The aforementioned studies provide important insights into potential life-cycle based environmental impacts of energy scenarios in other countries and world regions. The novel contribution and main objective of this study is the systematic comparison

life cycle-based environmental impacts of ten structurally significantly different energy system transformation strategies for the energy (and transport) system with a high degree of sector coupling for Germany. The analyzed strategies have been developed in recent years by renowned research institutions. In this study, boundary conditions such as useful energy demand and transport services have been harmonized among the scenarios and the scenarios were re-modeled with the same energy system model in order to allow an unbiased comparison of impacts. The scenarios also describe differently ambitious transformation paths: Five of the scenarios (the “moderately ambitious scenarios”) reduce direct CO₂ emissions by approximately 80% (1990–2050). The other five “highly ambitious scenarios” reduce direct emissions by 95%. This corresponds to the range of official GHG reduction targets for Germany at the beginning of the underlying project.

In addition to the overarching research question mentioned above, the study also addresses the following specific research questions:

- Which environmental co-benefits and adverse side effects are associated with ambitious pathways for a climate-friendly transformation of the German energy system? Which technologies and which life cycle phases may cause adverse side effects?
- How do environmental impacts of different transformation strategies for Germany differ—and what are the causes for those difference at the sector or technology level?
- Is there a conflict of objectives between climate and environmental protection? Does very ambitious climate protection (95% reduction of direct CO₂ emissions) result in higher environmental impacts than moderately ambitious scenarios (80% emission reduction)?
- Which sectors are the main drivers for future environmental impacts?

To the best of our knowledge, this paper represents the first study to examine life cycle-based environmental impacts for the coupled energy and transportation system in Germany. Furthermore, there has been no systematic, harmonized comparison of the environmental impacts of different transformation strategies from different studies that were originally developed with different approaches, models, CO₂ reduction objectives, etc. for any other country in the world. In this respect, the paper also breaks new ground. Finally, the paper presents the first systematic comparison of the environmental impacts of different transformation strategies for the energy system, which show different degrees of ambition in terms of GHG mitigation.

The analysis can thus contribute to the identification and development of strategies for the climate-friendly transformation of the German energy system, which also prove to be no-regret strategies with regard to environmental protection.

The paper is organized as follows: In the following methods section (Section 2), the procedure for a harmonized remodeling of transformation strategies for Germany is explained (Section 2.1). Section 2.2 shortly introduces FRITS that is used to estimate life cycle-based environmental impacts of the scenarios. In Section 3, results of the analysis are presented. Here, the focus is on a comparison of environmental impacts of moderately and highly ambitious climate protection scenarios (Section 3.1) the identification of the end-use sectors responsible for the impacts (Section 3.2), and a discussion of results for the environmental footprint, an aggregated environmental indicator (Section 3.3). In the discussion (Section 4), shortcomings and further methodological developments of the approach are identified (Section 4.1) and the results are compared – if appropriate – with results from similar studies (Section 4.2). Section 5 summarizes the results, draws conclusions for researchers and the public, summarizes research gaps and identifies possible future developments.

Table 1
Overview of scenario studies used as starting point for the analysis.

This study		Assumptions for supply side strategies taken from			
Scenario number	Reduction of direct CO ₂ emissions	Scenario name in original study	Involved research institution(s)	Reference	year
Scen I	80%	Energiewende-Szenario	GWS, Prognos, DIW, FhG ISI, DLR	Lutz et al. (2018)	2018
Scen II	80%	Basis	FhG ISI, ifeu, Consentec	Pfluger et al. (2017)	2017
Scen III	80%	Langfristszenario A	DLR, FhG IWES, IfNE	Nitsch et al. (2012)	2012
Scen IV	80%	Klimaschutz-Szenario 80	Öko-Institut, FhG ISI, H.-J. Ziesing	Repenning et al. (2015)	2015
Scen V	80%	80/gering/H2/ nicht beschleunigt	FhG ISE	Henning and Palzer (2015)	2015
Scen VI	95%	Klimaschutz-Szenario 95	Öko-Institut, FhG ISI, H.-J. Ziesing	Repenning et al. (2015)	2015
Scen VII	95%	100% Szenario	J. Nitsch	Nitsch (2014)	2014
Scen VIII	95%	GreenEE	FhG IWES, ifeu, CONSIDEO, D. Karl Schoer SSG	Günther et al. (2017)	2017
Scen IX	95%	Optimales System	enervis energy advisors GmbH	Klein et al. (2017)	2017
Scen X	95%	Technologiemix 95%	ewi Energy Research and Scenarios GmbH	Bründlinger et al. (2018)	2018

2. Methods

The first step of the analysis is the post-modeling of 10 different transformation scenarios for the German energy system, in which key boundary conditions were harmonized to ensure comparability (see Section 2.1). In a second step, life-cycle-based environmental impacts are determined for these (re-modeled) transformation strategies using the framework for the assessment of environmental impacts of transformation scenarios FRITS (Section 2.2). The approach presented here therefore goes beyond the original scenarios summarized in Table 1 by (a) re-modeling the scenarios in a harmonized manner and (b) estimating life-cycle-based environmental impacts for the transformation pathways, unlike the original studies.

2.1. Harmonized remodeling of transformation strategies of the German energy system

The basis for the analysis of life cycle impacts of transformation strategies are scenario data from the harmonized re-modeling of ten different transformation strategies for the German energy system with multi-sector perspective (electricity, heat, transport) up to 2050. The following section summarizes the re-modeling approach. Details of the re-modeling approach can be found in Naegler et al. (2021) (and its supplementary material). A detailed documentation of the re-modeled scenarios can be found on Zenodo (<https://zenodo.org/record/5992432> and <https://zenodo.org/record/5993177>).

In a first step, ten different transformation strategies for Germany (Lutz et al., 2018; Pfluger et al., 2017; Nitsch et al., 2012; Repenning et al., 2015; Henning and Palzer, 2015; Nitsch, 2014; Günther et al., 2017; Klein et al., 2017; Bründlinger et al., 2018) were selected from the literature (see Table 1). The selected scenarios describe transformation strategies for the entire energy system (including heat and transport) for Germany until 2050 with high technological detail. The first five of the selected original scenarios achieve a reduction in energy related (direct) CO₂ emissions of approximately 80% (see Table 1), the second five scenarios reductions of 95%–100%. All selected scenarios were analyzed in terms of their supply side strategies, i.e. their assumptions on technology and fuel market shares in the year 2050 for electricity, heat, and fuel generation as well as technology and fuel market shares in freight and passenger transport.

In the second step, those selected supply side strategies were set as boundary conditions for a remodeling of the scenarios through a soft coupling of the scenario generator tool MESAP/PlaNet (Schlenzig, 1999) with the electricity market model flexible (Qussous et al., 2019). The energy system models explicitly consider operation, construction (and replacement after their

technical lifetime) of all technologies for power and heat generation (incl. CHP), the generation of synthetic H₂, CH₄, biogenic and synthetic liquid fuels, as well as the passenger car and freight transport sectors. It furthermore explicitly models considers plants to generate electricity as well as synthetic fuels and gases (P2X) outside Germany for respective imports to Germany. Thus, from a technical point of view, the explicitly modeled system comprises both the energy supply and transport system, and from a geographical point of view includes necessary infrastructures for electricity and P2X imports to Germany.

For all ten remodeled scenarios, the same set of drivers (GDP, population) and demand development in the different sectors were used as boundary conditions. This harmonized re-modeling ensures that the re-modeled scenarios differ only with respect to technical supply side strategies for the energy system transformation, whereas (useful) energy demand and annual mileage per transport mode are identical in all remodeled scenarios. The re-modeled scenarios comprise complete energy balances, the required infrastructures (electricity generation & storage, heat, P2X and biofuel generation) as well as the development of the vehicle fleet until 2050. Furthermore, annual new (gross) infrastructure additions and the number of new vehicles registrations are calculated endogenously. More details can be found in Naegler et al. (2021).

For the purpose of this study, the five re-modeled scenarios reaching a CO₂ emission reduction of 80% (SCEN I–SCEN V) are collectively referred to as “moderately ambitious scenarios”. The scenarios SCEN VI–SCEN X achieve a reduction of 95% and are called the “highly ambitious scenarios”. The analyses in the following study will mainly focus on typical characteristics of the two ambition classes of scenarios. Note that the original scenarios from Nitsch (2014), Günther et al. (2017) and Klein et al. (2017) reach a CO₂ emission reduction of 100% by 2050. For the purpose of this study, the targets of the corresponding re-modeled scenarios VII, VIII and IX were somewhat relaxed (to 95%) in order to achieve similar emissions as Scen VI and Scen X.

2.2. Estimation of life cycle based environmental impacts with FRITS

The estimates of the annual gross new infrastructure demand (incl. new vehicles) and technology operation (annual electricity, heat and fuel generation, annual mileage in the transport sector) are the relevant boundary conditions for FRITS in order to obtain life cycle-based impacts of entire transformation strategies for Germany for the period 2000–2050. A detailed description of FRITS can be found in Junne et al. (2020b). Here, only a short summary is given, as well as differences and further developments compared to Junne et al. (2020b) are presented. An illustration

Table 2
List of environmental indicators used in this study.

Category	Indicator	Unit	Reference
Climate Change	Climate change	kg CO ₂ eq	Fazio et al. (2018)
Ecosystem quality	Freshwater and terrestrial acidification	mol H ⁺ eq	Fazio et al. (2018)
	Freshwater ecotoxicity	CTUe	Fazio et al. (2018)
	Freshwater eutrophication	kg P eq	Fazio et al. (2018)
	Marine eutrophication	kg N eq	Fazio et al. (2018)
	Terrestrial eutrophication	mol N eq	Fazio et al. (2018)
Human health	Carcinogenic effects	CTUh	Fazio et al. (2018)
	Non-carcinogenic effects	CTUh	Fazio et al. (2018)
	Ionizing radiation	kg U ²³⁵ eq	Fazio et al. (2018)
	Ozone layer depletion	kg CFC-11 eq	Fazio et al. (2018)
	Photochemical ozone creation	kg NMVOC eq	Fazio et al. (2018)
	Respiratory effects, inorganics	disease incidence	Fazio et al. (2018)
Resources	Fossils	MJ	Fazio et al. (2018)
	Minerals and metals	kg Sb eq	van Oers et al. (2020)
	Land use	points	Fazio et al. (2018)
	Dissipated water	m ³ water eq	Fazio et al. (2018)
Aggregated	Environmental Footprint 2.0	dimensionless	Fazio et al. (2018), European Commission (2018)

of the workflow in FRITS can be found in the supplementary material.

Expanded life cycle inventory database and data adaptations

The core of FRITS is the life cycle inventory (LCI) database ecoinvent v.3.3 (system model allocation, cut-off) (Wernet et al., 2016), which provides process data regarding environmental impacts for many products and services. Additional LCI data for missing or outdated energy and transport technology data sets is integrated into the database in order to extend the perspective on technologies in the scenarios, which are essential for achieving high GHG reductions, and/or will have a specific role for Germany in the future. Additional data comprise LCI data sets on P2X technologies (Liebich et al., 2021), bioenergy cultivation and usage (Schebek et al., 2013; Haase and Rösch, 2019), electricity storage (Immendoerfer et al., 2017; Spanos et al., 2015; Bouman et al., 2016; Weber et al., 2018; Tietze et al., 2017), PV systems (UVEK, 2018), power lines (Jorge et al., 2012; Arvesen et al., 2014), solar thermal heating systems (Arden, 2017), electric heat pumps (Greening and Azapagic, 2012), electrolyzers (Koj et al., 2017), H₂ storage (Benitez et al., 2021) and on various vehicle types (cars and trucks) (Cox, 2018; Miotti et al., 2017; Mottschall and Bergmann, 2013; Breemers et al., 2010; Wulf et al., 2018; Simons and Bauer, 2015 and supplementary material). An overview on the LCI data sets used in this study and the mapping of LCI data sets to technologies in the ESM can be found in the supplementary material.

A number of adaptations were made to the LCI data (see also Junne et al., 2020b for details): In order to correctly allocate environmental impacts in time between construction and operation, the data sets of construction and operation of the plants were separated in the LCI database. The technology and fuel mix for electricity generation used in upstream processes in the various regionally differentiated electricity markets of the LCI database was adjusted to the respective electricity generation technology mixes for ten different world regions from the 2.0 °C scenario from Teske et al. (2019) and Teske et al. (2021) (for more details, see Junne et al., 2020b). To avoid double counting in the foreground system, all inputs of energy carriers directly modeled within the scenario were excluded from background data sets connected to the scenario. Double counting in the background system of the database is avoided for electricity supply at the level of the German market for electricity in the ecoinvent database by deleting all electricity producing activities from the market (Junné et al., 2020b). The avoidance of double counting of heat and transport activities could not be achieved with this approach. Thus, the total level of environmental impact is somewhat

overestimated. Assumptions about the efficiency of conversion technologies were harmonized between the LCI database and the energy system model. The impacts from the operation of the technologies were adjusted according to the ratio of efficiency according to MESAP/PlaNet and efficiency according to the LCI data. This approach allows efficiency improvements of all relevant energy, assuming a linear relationship between in- and outputs during operation to be taken into account.

The LCIs of the energy and transportation technologies in the adapted database are the starting point for a life cycle impact assessment (LCIA) of those technologies. LCIA is mainly based on the ILCD/Environmental Footprint 2.0 2018 methodology (Fazio et al., 2018), with modifications of the abiotic resource indicator “minerals and metals” in the “resource” impact category according to van Oers et al. (2020). An overview over the full set of indicators used here can be found in Table 2 and in the supplementary material.

Besides the indicators for the single impact categories also an aggregated single score indicator known as Environmental Footprint is applied in this study. The aggregation is done via a normalization based on global impacts in the year 2010 (Sala et al., 2017; Crenna et al., 2019) and a weighting step (Sala et al., 2017).

Section 3 will primarily present results for the environmental impacts of the scenarios in 2050, but also addresses cumulative 2020–2050 values. Both presentation methods have their justification, although they have advantages and disadvantages: Focusing on the target system 2050 also provides some kind of outlook beyond 2050, if it can be assumed that the system will not change drastically after the transition period until 2050. However, it ignores the significantly different environmental impacts of the pathways (2020–2050) towards the target system. In contrast, the cumulative environmental impacts focus on the *complete path* toward the target system. As all scenarios start from the same starting point (the year 2020), the scenarios are quite similar until about the mid-2030s. In the following years, depending on the scenario, various investments are made that are associated with environmental impacts due to construction and operating processes. In the cumulative representation, the differences in environmental impacts between the strategies are therefore significantly smaller than in the representation for 2050. Furthermore, cumulated results cannot be extrapolated into the future beyond 2050.

Calculation of life cycle-based environmental impacts for the entire scenario and allocation to end-use applications

LCA refers to a functional unit that is the unified comparison parameter of the energy systems under study. The functional

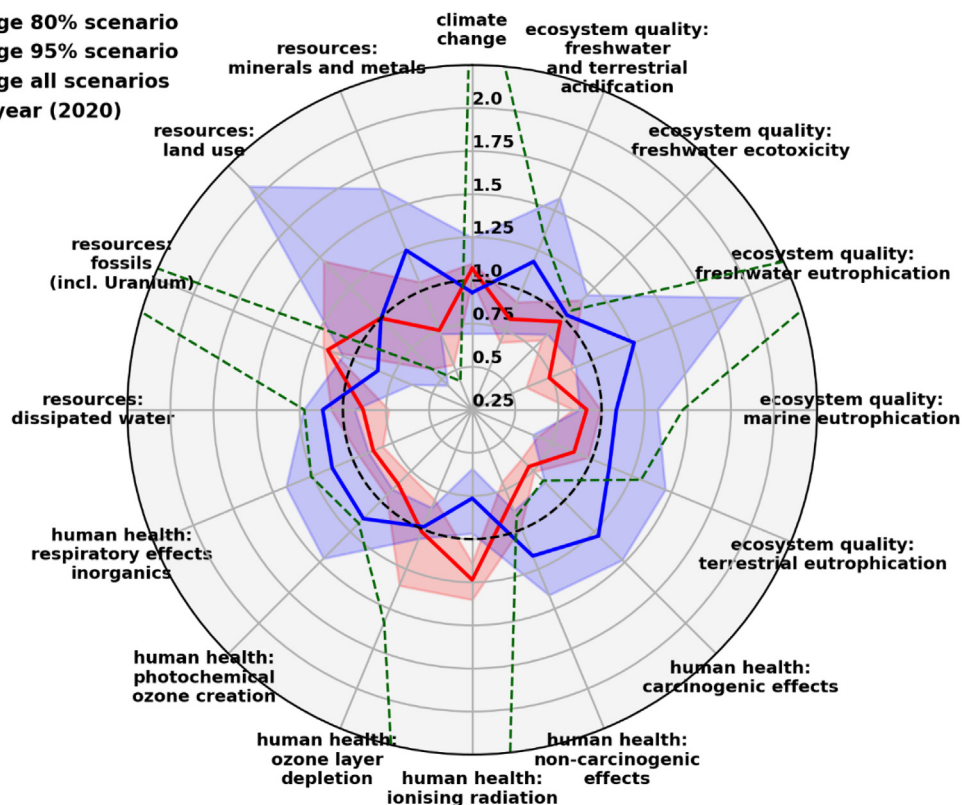


Fig. 1. Comparison of life cycle environmental impacts of 80% and 95% CO₂ emission reduction strategies in 2050. Impacts are normalized to the average impact of all scenarios in 2050 (black dashed line). Red line and red shaded area: mean normalized impacts and range of normalized impacts of 80% strategies. Blue line and blue shaded area: The same for 95% strategies. Green dashed line: Values for reference year 2020, normalized to average of all scenarios in 2050.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

unit of the analysis represents the annual useful energy demand including electricity, heat and transport mileage in Germany. Depending on the configuration of the energy system this functional unit is met by different technologies. The share of each technology is expressed by the reference flow. The reference flows per scenario are separated in construction and operation flows of each technology. Construction flows are calculated from the (gross) new installations (in kW/a) or new registrations (in vehicles/a) and the construction of the plants or vehicle (per kW or per unit), respectively. Operation flows are calculated in kWh or for cars in person kilometer (pkm) and trucks in ton kilometer (tkm) and refer to the annual energy output (or the annual mileage for vehicles) according to the scenario.

The resulting technology-specific environmental impacts (construction and operation separated) are summed to obtain impacts for the entire scenario. Impacts on end-use level are calculated as follows: Impacts from end-use technologies (e.g. electric heat pumps used to generate space heat in the residential sector or gas boilers for industrial process heat) are fully allocated to the respective end-use sector. Additionally, impacts of technologies from the conversion sector (e.g., generation of electricity, district heating, hydrogen, synthetic gas and fuels, biofuels) are allocated to end-use sectors according to the end-use sectors' shares of consumption of these energy sources. Since energy carriers that are produced in the conversion sector are partly consumed again in the conversion sector (e.g. hydrogen in fuel cell combined heat and power plants), this allocation has to be iterative until a complete allocation to the end-use sectors has been achieved.

3. Results

3.1. Comparison of life cycle-based environmental impacts of ambitious and very ambitious transformation strategies

Fig. 1 summarizes the environmental impacts of all scenarios for 2050 as well as the development of the impacts between 2020 and 2050 for each indicator. All impact values are normalized to the average impact of all ten scenarios in 2050. The solid red line is the average normalized impact of all 80% scenarios. The red shaded area indicates the range of (normalized) results for all 80% scenarios. The blue line and the blue area show the corresponding results for the 95% scenarios. The dashed green line shows the results for the base year 2020, also normalized using the average of all scenarios in 2050. This means that if the green line is below one for an indicator, then environmental impacts in this category are on average higher in 2050 than in 2020. This indicates undesired side effects of the transformation. If, on the other hand, the green line is above one, then a climate-friendly transformation strategy has positive side effects compared to the average over all scenarios with regard to this indicator.

As can be seen in **Fig. 1**, the transformation of the energy system is accompanied by a strong decrease in some environmental impacts between 2020 and 2050 (indicated by a green dashed line well above 1). This is in particular the case for “resources: fossils”, “human health: ionizing radiation”, “ecosystem quality: freshwater eutrophication” and – trivially – for “climate change”. These are the expected improvements e.g. from replacing nuclear and fossil-fired power plants with renewable electricity generation.

For other indicators, however, the impacts increase in the course of the transformation (green dashed line below 1): In

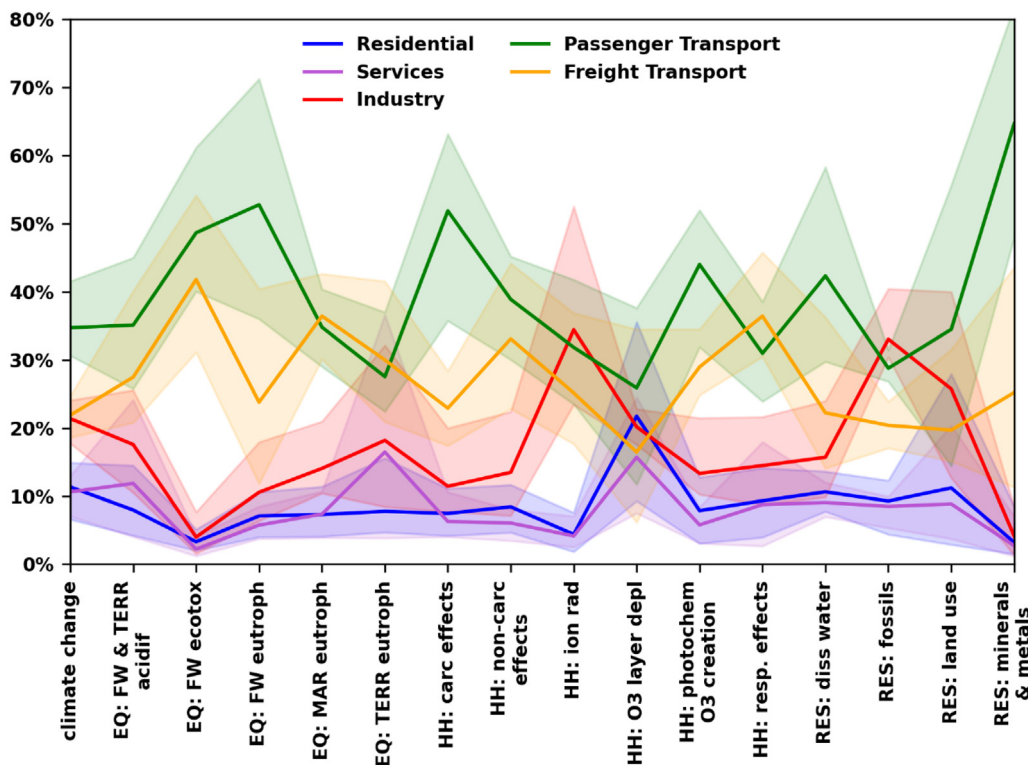


Fig. 2. Relative share of the impact of the end-use sectors residential, industry, service, passenger and freight transport in the total impact for each impact category in 2050. The solid line shows the average of all scenarios. The colored areas show the range of sector shares from all scenarios. EQ: ecosystem quality, FW: freshwater, TERR: terrestrial, MAR: marine, HH: human health, carc: carcinogenic, ion: ionizing, rad: radiation, depl: depletion, resp: respiratory, RES: Resources, diss: dissipated.

the “resource” category, these are “minerals and metals” and “land use”, in the category “human health” carcinogenic and non-carcinogenic effects. The indicator “land use” mainly reflects the land use by the cultivation of crops for bioenergy. The reason for the increase in the “metals” indicator is the growing demand for metals that are currently mined at a high extraction rate compared to currently known reserves. These metals are particularly needed for the construction of vehicles with new drive technologies such as BEVs and FCEVs, but also for PV systems, electrolyzers, etc. Human health is also affected by the construction of BEVs, Hybrids, and FCEVs, as well as PV and Wind power plants, and the cultivation of bioenergy plants.

The red and blue shaded areas in Fig. 1 illustrate that the range of possible environmental impacts within an ambition class – 80% or 95% GHG reduction – is very large with regard to the individual indicators. While there is a strong overlap in the range of 80% scenarios and 95% scenarios, the 95% scenarios show a much larger spread, resulting from a much higher variety in the technical structure of 95% scenarios than for 80% scenarios.¹ Although moderately ambitious scenarios tend to perform better on average for many impact categories, there are always 95% scenarios that perform significantly better than 80% scenarios in particular impact categories.

The comparison of the red and blue lines in Fig. 1 allows to assess the extent to which more ambitious climate protection in the 95% scenarios (blue lines) is associated with a further decline in environmental impacts compared with moderate climate protection (80% scenarios, red line). Interestingly, the 95% scenarios actually perform better on average than the 80% scenarios only in few impact categories: Climate change, ionizing radiation, and resources: fossils (and uranium). These categories are directly

related to the extraction and use of fossil energy sources, which are used to a much lesser extent in the 95% scenarios than in the 80% scenarios. In the other impact categories, it is apparent that the deployment of key technologies in a climate-friendly energy transition are often associated with significant environmental impacts. This concerns in particular technologies for renewable electricity generation, electricity storage, new drive technologies for motor vehicles, and technologies for P2X generation.

3.2. End-use sector shares in total impacts

In the sense of a “polluter pays” principle, the end users of energy services and transport are responsible for the environmental impacts that arise. Therefore, an allocation of the environmental impacts to the end-use sectors industry, services (incl. trade and commerce), households, freight and passenger transport is appropriate (see Section 2.2). Fig. 2 shows the share of each end-use sector in the total impact in 2050 for each impact category. The solid lines depict the average of all scenarios, the colored areas the range across all scenarios. Across all impact categories, the picture is surprisingly consistent—despite the wide range between the scenarios: Most of the environmental impact in 2050 is due to transport activities (freight and passenger traffic). In contrast, the contribution of the residential and services sectors to the overall environmental impacts is rather low and rarely exceeds 10% each of the total impacts in any of the impact categories.

3.3. Environmental footprint results of the transformation strategies

The results of the impacts aggregation to the European Environmental Footprint (EUEF) are shown in Fig. 3. For most scenarios there is significant improvement compared to today’s situation. The four scenarios which perform best in 2050 with

¹ See also scenario documentation on <https://zenodo.org/record/5992432> and scenario data on <https://zenodo.org/record/5993177>

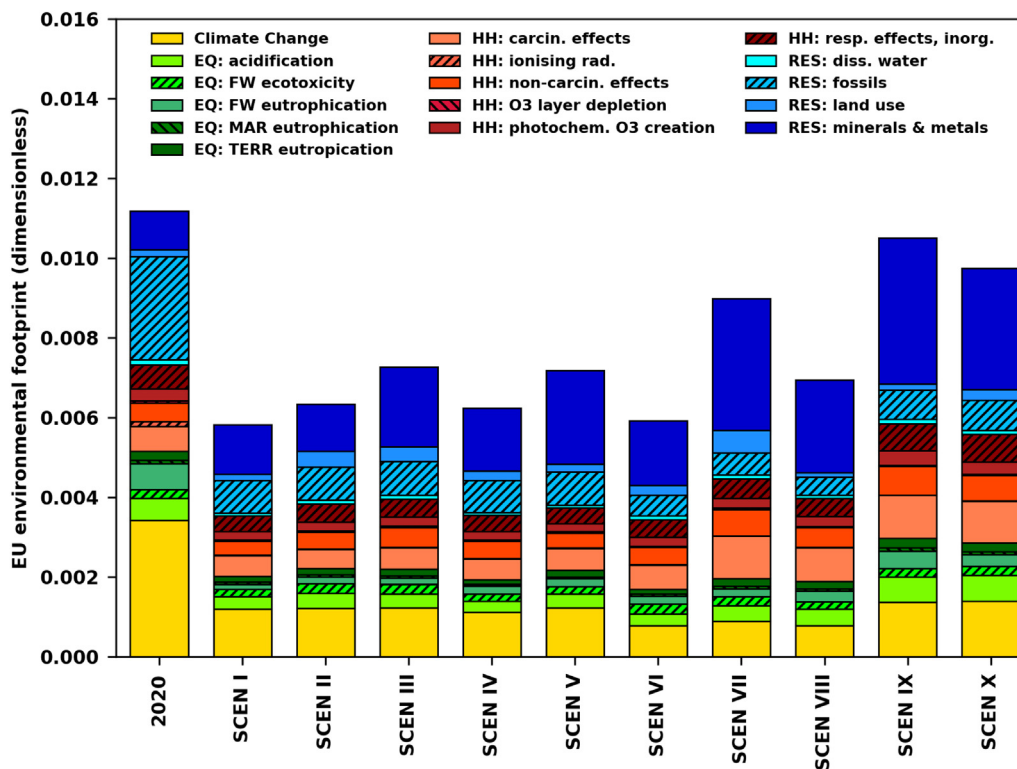


Fig. 3. Comparison of the overall environmental performance of the scenarios (contribution of each indicator to the EU environmental footprint): scenario results for 2050 and results for base year 2020. EQ: ecosystem quality, FW: freshwater, TERR: terrestrial, MAR: marine, HH: human health, carcin.: carcinogenic, rad: radiation, resp: respiratory, inorg.: inorganic, RES: resources, diss: dissipated.

respect to the EUEF are SCEN I (EUEF: 0.0058, reduction of direct CO₂ emissions: 82%), SCEN VI (EUEF: 0.0059, 95% CO₂ emission reduction), SCEN IV (EUEF: 0.0062, 82% reduction), and SCEN II (EUEF: 0.0063, 82% reduction). The three scenarios performing worst with respect to the EUEF are SCEN VII (0.0090), SCEN IX (0.0105) and SCEN X (0.0098). These three scenarios also show the highest cumulated impacts in the last simulation decade. They all belong to the 95% class of scenarios. This finding confirms the result from Section 3.1: Highly ambitious climate protection scenarios do not automatically go hand in hand with more environmental sustainability and might even result in significantly higher (aggregated) environmental impacts.

In all scenarios the EUEF is dominated by the indicators mineral and metal resources (average contribution to EUEF: 25% (in 80% scenarios) and 33% (in 95% scenarios), climate change (18% and 12%, respectively), fossil resources (13% and 7%, respectively), and human health (carcinogenic effects) (8% and 11%, respectively). Those four indicators make up between 58% and 69% of the total EUEF for all scenarios.

In order to better understand the results from Fig. 3, the contribution of different technologies to the overall EUEF is analyzed (see Fig. 4) as well as the structure of those scenarios performing worst (SCEN VII, IX, X) and the best 95% scenario (SCEN VI) with respect to the EUEF in the following sections. Note that in Fig. 4 only those technologies are shown which contribute more than 5% to the total European environmental footprint of the scenario in 2050. Thus, the white area stands for all other technologies that contribute with lower shares.

The scenario with the highest EUEF, SCEN IX, is characterized by 100% BEVs in the passenger car segment. Trucks are dominated by gas motors (using synthetic natural gas (SNG)) and FCEVs. The overall demand for P2X is high (almost 2.000 PJ/a), as SNG is also used in the heat sector. This results in an electricity demand of more than 1.500 TWh/a, which is mainly met by 913 GW

of PV systems. The scenario characteristics are reflected in the main contributions to the EUEF (see Fig. 4): construction of PV systems, BEVs, and methanation technologies, which make up ca. two thirds of the total EUEF.

SCEN X has the second highest EUEF of all scenarios. In the passenger car segment, it relies on PHEVs (using synfuels), FCEVs and BEVs, in the truck segment on FCEVs, internal combustion engine (ICE) vehicles (gas motors using mainly SNG), Hybrids and BEVs/trolley trucks. SNG is also used for process heat. Thus, the demand for P2X products is very high (more than 2.500 PJ), ca. 90% of it is imported. This strategy results in an electricity demand of almost 1.700 TWh/a (domestic and abroad), 660 TWh of which are generated nationally (wind onshore, offshore, and PV). Main drivers for the EUEF are the construction of BEVs and FCEVs, but also impacts from electrolysis, methanation, and the construction of concentrated solar power (CSP) plants abroad (see Fig. 4).

The most important contributors to the EUEF in SCEN VII, the scenario with the third highest EUEF, are the construction of FCEVs (LDV), as well as FCEV and BEV passenger cars. Furthermore, construction of geothermal power plants also results in high impacts. This is a result of high shares of FCEVs trucks as well as a dominance of BEVs and FCEVs in road passenger transport. Due to the high H₂ demand in the transport sector, total electricity demand exceeds 1.100 TWh in 2050. It is met by a broad technology mix, which thus avoids very high impacts from the construction of PV as in PV dominated electricity generation scenarios like SCEN IX.

An interesting candidate is also SCEN VI, which achieves a high reduction of (direct) CO₂ emissions at comparably low environmental impacts (lowest EUEF of all 95% scenarios). This scenario is characterized by a comparably restrained electrification strategy of heat and transport: In the building sector, it relies on a relatively high share of district heat, biomass, and solar thermal

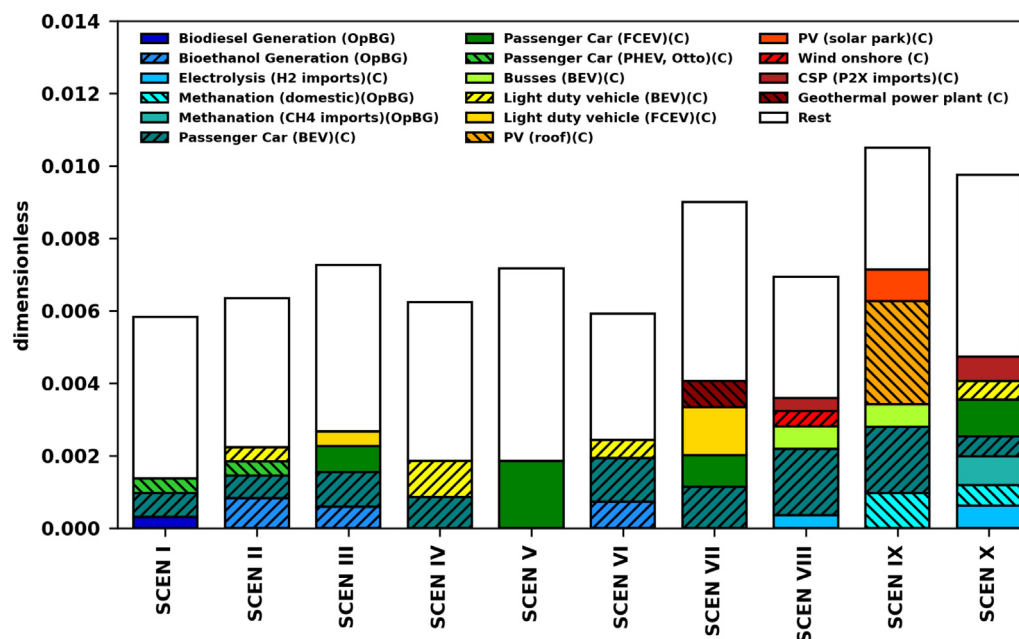


Fig. 4. Main drivers of the Environmental Footprint, i.e. technologies contributing more than 5% to the total EUEF in a scenario in 2050. C: Impacts from construction, OpBG: Impacts from background emissions of operation, BEV: Battery electric vehicle, FCEV: Fuel cell electric vehicle, PHEV, Plug-in hybrid electric vehicle, CSP: Concentrated solar power, P2X: Power to X, PP: Power plant.

heat. The process heat sector is characterized by a high share of biomass, direct electrification, and district/CHP heat. SCEN VI does not use H_2 or SNG in the industry or buildings sector. In the road passenger segment, PHEVs make up approx. 30% of the total car fleet, the rest are mainly BEVs. A few ICEs remain in the vehicle fleet in 2050. No FCEVs enter the passenger car market in this scenario. Trucks are mainly PHEVs, with only a small share of BEVs/trolley trucks and no FCEVs. These strategies result in a relatively low demand for syngas (for the PHEVs and remaining ICE in the transport sector), but again no H_2 or SNG is required. As a consequence, electricity demand (924 TWh/a) and installed capacities (549 GW) are lower in SCEN VI than in the other 95% scenarios. The restrained electrification strategy in SCEN VI thus avoids at least partly the environmental impacts of the construction of BEV and FCEVs, as well as very large installations of PV, resulting in the lowest EUEF of all 95% scenarios, despite relatively large impacts from bioethanol generation.

In the 80% scenarios, those technologies that are often responsible for the high EUEF in the 95% scenarios (BEVs, FCEVs, PV, ...) are generally deployed to a lesser extent. Instead, in the 80% scenarios, higher environmental impacts result from the operation of plants and vehicles that still use fossil fuels. However, the EUEF of the 80% scenarios generally remains below that of the 95% scenarios, as the additional impacts from fossil fuels in the 80% scenarios are not offset by the additional impacts from the construction of “new” technologies in the 95% scenarios.

4. Discussion

This paper presents for the first time a multi-scenario environmental impact assessment for the complete German energy system. Its approach integrates high quality LCA data (including some most recent LCIs for energy and transport technologies) with a broad scenario comparison. Transformation strategies for the German energy system developed by a variety of institutions and models have successfully been adapted to allow a normalized scenario comparison and to identify key sectors for future environmental impacts, namely the transport sector and the production of synthetic fuels. Even though this approach

provides a (more) comprehensive picture of the German energy scenario landscape, the methodology is still under development and significant aspects need more attention in the future, as discussed in the following sections.

4.1. Uncertainties and limitations of the analysis

Like any study, the analysis here has its uncertainties and limitations, many of which have been already identified in previous similar studies (e.g. Volkart et al., 2017; Blanco et al., 2020; Junne et al., 2020b; Astudillo et al., 2017; Fernández et al., 2019; Vandepaer and Gibon, 2018):

Although there are many LCA studies on energy and transportation technologies, one of the major challenges is the availability of current, high quality LCI data for all technologies represented in the energy system model. While a range of relevant LCI data is available in databases such as ecoinvent, those data are frequently outdated. Furthermore, ambitious climate mitigation strategies often assume the deployment of technologies that are under development today (or have yet to be developed), which are often not (yet) considered in LCI databases. One option is to consider published LCI data from other sources. However, quality and consistency assurance of these additional data is often not possible. The mapping of the technologies in the LCI database to the technologies represented in the ESM is not an easy task. ESM generally represent “reference technologies” that reflect typical characteristics of the technologies considered. It is not guaranteed that the – often very specific – technologies for which LCI data are available are representative for the ESMs’ reference technologies. This can lead to an over- or underestimation of certain impacts.

Another challenge arises from the requirement to make statements about environmental impacts of systems that lie far in the future. This challenge of a prospective assessment concerns both, the detailed models and specifications of energy and transport technologies, and also all the processes for the production of materials, components and entire plants, the extraction of raw materials, generation of fuels, etc. derived from LCI databases. While assumed efficiency improvements of the foreground technologies are taken into account in FRITS, material requirements

are assumed to remain constant, which neglects possible improvements in material efficiency (see e.g. Harvey, 2018; Öko Institut, 2011; Gerboni et al., 2008; Marscheider-Weidemann et al., 2016; ISI, 2012 for the construction of cars). Furthermore, aspects like the re-use of components, recycling of materials is not explicitly included in the analysis. However, a better representation of circular economy could have a significant impact on the results, but has to remain a task for future studies. Especially the case of batteries for transport shows that aspects like re-use and recycling might have significant impacts on the results and a better representation of this aspect should be taken into account in future studies. The assumption of constant shares of secondary material and material efficiency imply, despite others factors, that e.g. the “mineral and metal resources” indicator in particular in the transport sector is probably overestimated.

In the background database, the electricity mix is adjusted to consider an ongoing decarbonization of the electricity sector. However, other expected changes like the energy carrier/technology mix for process heat and freight transport, new production routes in particular for bulk materials such as steel and cement, energy and material efficiency of production processes etc. have not been considered in the present study. Thanks to ongoing and completed collaborative development work, prospective adjustments in the background database will become more and more standard in the future (Sacchi et al., 2022b).

Double counting of impacts is generally an issue for the coupling of ESMs and LCA, as e.g. impacts of the construction of technologies within the geographical boundaries of the system assessed may be counted twice—once in the foreground system (e.g. as part of the impacts from the industry sector) and a second time in the background systems (e.g. as impacts of the construction phase of a technology). In this study, this issue is tackled for electricity supply at the level of the electricity markets in the ecoinvent database (see also methods section and Junne et al., 2020b). However, double counting could not be avoided for the heat and transport sectors in the present study. In few other studies, this issue is addressed (see e.g. Fernández et al., 2019; Vandepaer et al., 2020). However, a conclusive valid method does not yet exist (Vandepaer et al., 2021).

The regionalization of the LCI data is very coarse. A better representation of international trade of plants and plant components and regionally differentiated flows could be operationalized integrating information from Input–Output tables in process based LCI databases (such approaches are called “hybrid LCA”), as e.g. done by Hertwich et al. (2015), Wang et al. (2020), Wolfram and Wiedmann (2017). However, the development of an LCI database with a higher geographical resolution was beyond the scope of this study.

This study has shown that the transport sector is responsible for a large share of the environmental impacts. However, the representation of the transport sector in the scenarios is comparatively coarse and should be improved in future studies. For example, it should be differentiated between different passenger car and truck sizes. Moreover, better data for annual mileage, drive cycles, lifetime, re-use and retrofitting (e.g. of batteries) etc. should be integrated in future modeling approaches. On the LCA side, it would be beneficial to integrate tools for a systematic assessment of the environmental impacts of transportation, as e.g. developed by Sacchi et al. (2022a), Bauer et al., into FRITS.

This study focused on the assessment of environmental impacts of different supply side strategies for the decarbonization of the energy system, as demand is identical in all scenarios. However, demand side strategies (e.g. more efficient electric appliances, energetic refurbishment of the building stock, sufficiency) represent key elements of a successful energy transition and might not come without additional environmental costs (or

benefits). For example, it can be expected that a higher level of ambition in climate protection will be accompanied by a more consistent energy refurbishment of the building stock, which then can be expected to go along with additional environmental impacts.

An energy system model is always a strongly simplified representation of the real system. This concerns technological granularity and diversity with regard to relevant technologies required for a stable and secure system operation. Simplifications are also made with regard to regional aspects when addressing national strategies such as underlying assumptions on costs, renewable potentials and grid expansions. With respect to the scenarios used in our analysis, a second level of uncertainty is introduced by the harmonized re-modeling of the transformation strategies, which relies on assumptions which are different from those of the original studies.

The scenarios considered here examine strategies for reducing CO₂ emissions between 80% and 95%, the target corridor applicable at the beginning of the study in 2017. Germany's energy policy targets have been systematically tightened in recent years. Currently, Germany is aiming to become greenhouse gas neutral by 2045. The stricter targets require new strategies which not only represent a more consistent and faster implementation of those technologies already envisioned in older scenarios, but in addition probably require the use of new technologies such as Carbon Dioxide Removal (CDR), Bioenergy Carbon Capture and Storage (BECCS), new production routes in the industry sector (for example use of H₂ as reduction matter for steel production in order to avoid process related emissions), etc., which are not (yet) included in the FRITS framework.

The analysis presented here provides only a preliminary assessment of potential hotspots and strategies for a reduction of the environmental footprint of existing energy system transformation strategies. For a more robust assessment of strategies, a study is needed that systematically examines the environmental impact of defossilization strategies in individual sectors and their consequences on the overall system.

4.2. Comparison of results with other studies

For all these reasons discussed above, details of the results of this study must be interpreted with due caution, although it can be assumed that the broad results are qualitatively robust. In this section, those broad results are compared with results from other studies which also couple energy system models with LCA. However, due to different geographical scope, different degrees of GHG emission reduction in the scenarios considered, different methodological approaches, different system boundaries, indicators, technological granularity etc., the comparison can only be qualitative.

Many studies have estimated co-benefits and adverse side effects of the transformation of *electricity systems* alone. Ref. Berrill et al. (2016) have found that electricity systems based largely on variable renewable energy sources reduce climate change impacts compared to conventional electricity supply systems, but result in larger mineral resource depletion and greater land use. These results are similar to those found for the electricity sector in this study, although impact assessment methods differ. In our analysis, we also find that there is a risk of increasing threat of ecosystem quality (freshwater and terrestrial acidification, freshwater ecotoxicity) and human health (carcinogenic and non-carcinogenic effects, respiratory effects) in the highly ambitious scenarios mainly arising from the construction of PV systems and wind power plants. Of these indicators, only freshwater ecotoxicity (albeit with different LCIA method) is also considered by Berrill et al. (2016), who do not find increasing impacts.

Hertwich et al. (2015) analyzed impacts from business-as-usual (BAU) and moderately ambitious (2 °C–3 °C, GHG reduction ca. 50%) global scenarios and concluded that the decarbonization of electricity supply with wind, PV, and CSP may reduce GHG emissions, freshwater ecotoxicity, eutrophication, and particulate-matter emissions, findings which are consistent with the results for the moderately ambitious scenarios here.

Luderer et al. (2019) have shown that the 2 °C scenarios analyzed there lead to reduced human health impacts, but a shift of the resource demand from fossil to mineral resources, which is in line with the results for the 80% scenarios here, although human health impacts might increase compared to 2020 in some of our 95% scenarios. (Luderer et al., 2019) further conclude that the scale of co-benefits and adverse side effects depends strongly on the particular choice of technologies, a conclusion which is supported by the results here. (Xu et al., 2020) found that the decarbonization of the European electricity system can be expected to be accompanied with an increase in metal demand and land use, which again is in line with our results.

Many studies address the environmental impacts of current and future transport technologies (Cox et al., 2020, 2018; Ueckerdt et al., 2021; Sternberg et al., 2019; Sacchi et al., 2021; Bekel and Pauliuk, 2019; Petruskiene et al., 2021; Blat Belmonte et al., 2020; Hill et al., 2020; Sun et al., 2020; von Drachenfels et al., 2021). However, it is a methodological challenge to consistently compare results from different studies at different system levels with the results here. As mentioned above, it would be helpful to integrate LCI data from very systematic tools for the assessment of environmental impacts of transport technologies such as Sacchi et al. (2022a) and Bauer et al. in FRITS. However, this was beyond the scope of this study and could be tackled in the future.

On the level of the whole energy system for Switzerland, Vandepaer et al. (2020) found many co-benefits of greenhouse gas reduction of 95%, but adverse side effects with respect to metal resource depletion and human toxicity due to the construction of PV panels and electric vehicles. However, due to different impact assessment methods (ReCiPe Goedkoop et al. (2008) in Vandepaer et al. (2020), ILCD/Environmental Footprint Fazio et al. (2018) here), the results here cannot be compared directly with results from Vandepaer et al. (2020). The transport sector in their study also contributes significantly to the total impacts, although to a lesser extent than in this study. However, for a more detailed comparison additional detailed data on the development of the car and truck fleet is necessary, which was not documented in the publication.

Volkart et al. (2017) also used Switzerland as a case study for an ex-post impact assessment of scenarios for the whole energy system. They found out that climate-friendly energy systems (CO₂ emission reduction: 60%) also perform better than a reference case in terms of fossil energy depletion, GHG emissions, but worse with respect to metal depletion, ecosystem damages and human health. With a differing LCIA method, and a much lower emission reduction their results are difficult to be directly compared with our results, although they are qualitatively similar.

Blanco et al. (2020) analyze scenarios for the whole energy system in Europe which achieve a GHG emission reduction of 80%–95%. Their analysis focusses on impacts from P2X technologies. Due to different indicator definitions (they use LCIA methods from ReCiPe (Goedkoop et al., 2008)), their result cannot be directly compared with results here. However, in qualitative agreement with this study here, they found that indirect CO₂ emissions can be of similar magnitude as direct CO₂ emissions, and that impacts in most categories they consider decrease with stricter GHG emission reduction. However, they also found that toxicity related impacts may increase. A comparison of their results for the transport sector is difficult due to different methodology and different ways of displaying the results.

The study from Volkart et al. (2018) has a focus on moderately ambitious global energy system transformation strategies (up to ca. 50% GHG emission reduction). Even though they use different LCIA methods than in this paper, they also show that climate change scenarios have co-benefits with respect to environmental and human health impacts, but adverse side effects with respect to water and land use, which is broadly consistent with our results here.

The “mineral and metal resources” indicator used here is a highly aggregated indicator which does not allow to draw conclusions e.g. on possible resource bottlenecks. To achieve this, it is necessary to analyze the demand for specific resources at the level of individual technologies, which has been done e.g. in Junne et al. (2020a). Here, too, it can be seen that the transport sector is the driving force in the demand for resources such as neodymium, dysprosium for electric motors of electric vehicles as well as lithium and cobalt for batteries.

Thus, it can be concluded here that the results of the present study are largely consistent with results of other studies. However, a more detailed, quantitative comparison is often difficult due to different LCIA approaches, different system boundaries and sectoral aggregation, different degrees of CO₂ emission reduction etc.

5. Summary, conclusions, and outlook

The study presents the first systematic assessment of life cycle-based environmental impacts of different technical strategies to reduce energy-related CO₂ emissions of the German energy system by approximately 80% or by 95%. With respect to the research questions formulated in the introduction, it could be shown that

- The long-term transformation of the energy system in order to reduce energy-related direct CO₂ emissions is usually accompanied by reductions in other environmental impacts as well. However, exceptions occur with regard to the demand for mineral resources, land use and certain human health aspects (carcinogenic and non-carcinogenic effects), which might increase in the future—depending on the transformation pathway.
- Ideas on how the German energy system needs to be transformed in order to reduce CO₂ emissions by 80% (or by 95%) differ widely in the literature. The differences in the environmental impacts resulting from the various scenarios are correspondingly large. In particular, different strategies with respect to the defossilization of the transport sector, the use of P2X and the power generation mix significantly influence the environmental impacts.
- The comparison of transformation strategies which achieve an 80% reduction of direct CO₂ emissions with those who reduce emissions by 95% shows that there is a clear risk of higher environmental impacts in more ambitious climate protection scenarios in most impact categories. The main reasons for this are a higher number of BEVs and FCEVs, as well as higher installed capacities for electricity production, which can be accompanied by comparably high impacts. However, the results also show that ambitious climate protection does not necessarily imply higher environmental impacts in other categories. This indicates that there is not necessarily a conflict of goals between climate protection and a broader environmental protection.
- The transport sector is responsible for the largest share of environmental impacts with respect to almost all indicators and across all scenarios. Drivers are primarily the construction of new BEVs and FCEVs, but also – depending on the scenario – the generation of biofuels.

All in all, it can be concluded that the magnitude of the environmental impact of the overall energy system clearly depends on the technology choice and decarbonization strategies in each sector. However, the results suggest that the following strategies may be (amongst many others) worth considering for significantly reducing the environmental footprint of transformation strategies:

- Reducing the *amount* and *size* of BEVs (in particular the batteries) and FCEVs, as impacts from the passenger transport mainly arise from the construction phase of the cars. A reduction of the individual road traffic and the corresponding vehicle stock could be achieved through intelligent car-sharing and public transport concepts. The use of PHEVs (with lower battery capacities than BEVs) plus synfuels (for the few long-distance rides or off-grid rides of trolley trucks) could be a purposeful compromise. However, this conclusion should be supported by further analyses, which could not be carried out within the scope of this study.
- Reducing environmental impacts of the construction stage of BEVs and FCEVs.
- Avoiding H_2 and especially SNG in the building and process heat sector if direct electrification or use of solar heat and (renewable) district heat is possible.
- In the electricity sector, a balanced mix of wind onshore, offshore and PV could decrease impacts compared with a strategy focusing on a massive investment in PV alone, in particular at a high level of (indirect) electrification and a resulting high electricity demand.
- Electrification should be as moderate as possible and as far as possible based on direct electrification, in order to avoid conversion losses during the generation of H_2 or SNG, as conversion losses are always associated with additional electricity generation capacities leading to additional environmental impacts.

However, future research is required to further support the conclusions presented here. As discussed above, the availability, representativeness and quality of LCI data for relevant energy and transport technologies must be improved (in particular when assessing impacts for even more ambitious transformation strategies as those analyzed here). Prospective LCA and a systematic and consistent harmonization of foreground scenarios and prospective adjustments in the background LCI database is still a challenge. On the scenario side, a better representation of the transport sector in the models is required. Furthermore, a systematic assessment of decarbonization strategies for individual sectors (including their consequences of the sector level strategies on entire system) could help to identify and combine those sector strategies which would allow minimizing the overall impacts of the system. Our study paves the way for such a systematic assessment in the future. Furthermore, more research is needed to determine the most environmentally friendly level of direct or indirect electrification of heat and transport. And finally, research should aim to include environmental impacts directly in scenario development, in addition to reductions in direct CO_2 emissions and system costs (which are often the focus), in order to make a significant contribution to the development of transformation strategies for an energy system which is not only climate *but overall* environmentally friendly. Finally, it should be emphasized that the feasibility and speed of energy system transitions also and especially depends on energy and material efficiency strategies outside the energy sector. Dematerialization and energy efficiency efforts in the construction industry, the chemical industry and in many other sectors entail considerable resource and thus energy savings. This reduces the demand of

the entire energy system and thus accelerates and smoothes its transition.

List of acronyms:

- BAU: Business-as-usual
- BECCS: Bioenergy carbon capture and storage
- BEV: Battery electric vehicle
- CHP: Combined heat and power
- CSP: Concentrated solar power
- ESM: Energy system model
- EUEF: European environmental footprint
- FCEV: Fuel cell electric vehicle
- FRITS: Framework for the assessment of environmental impacts of transformation scenarios
- GHG: Greenhouse gas
- IAM: Integrated assessment model
- ICE: Internal combustion engine
- LCA: Life cycle assessment
- LCI: Life cycle inventory
- LCIA: Life cycle impact assessment
- LDV: Light duty vehicle
- P2X: Power-to-X (synthetic fuels and gases, such as H_2 , synthetic CH_4 and synthetic liquid hydrocarbons)
- PC: Passenger car
- PHEV: Plug-in hybrid electric vehicle
- PP: Power plant
- PtM: Power-to-methane
- PV: Photovoltaics
- pkm: Passenger kilometer
- SNG: Synthetic natural gas
- tkm: ton kilometer

CRedit authorship contribution statement

T. Naegler: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **J. Buchgeister:** Investigation, Writing – review & editing. **H. Hottenroth:** Validation, Investigation, Writing – original draft. **S. Simon:** Formal analysis, Writing – review & editing. **I. Tietze:** Writing – review & editing. **T. Viere:** Writing – review & editing. **T. Junne:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Acknowledgments

The authors wish to acknowledge Claudia Sutardio and Anke Weidlich (INATECH Freiburg) who provided the results from the flexABLE model as input for the scenarios which form the basis of this analysis. Furthermore, we are grateful to Steffen Lewerenz (INEC Pforzheim) who supported the modeling of life cycle inventory data.

Funding

This study has been funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) under the project number 03ET4058 as part of the project InNOSys.

Appendix A. Supplementary data

Supplementary material related to this article (supplementary information on the methodology and overview over used LCI data sets and data manipulations) can be found online at <https://doi.org/10.1016/j.egy.2022.03.143>.

References

- Arden, F., 2017. Ökobilanzieller Vergleich zweier unterschiedlicher solarthermischer Kollektoren mit Behälterspeicher innerhalb eines Nahwärmeversorgungssystems. (Master Thesis). Pforzheim University of Applied Sciences, Pforzheim, Germany.
- Arvesen, A., et al., 2014. Life cycle assessment of an offshore grid interconnecting wind farms and customers across the north sea. *Int. J. Life Cycle Assess.* 19 (4), 826–837.
- Astudillo, M.F., et al., 2017. Life cycle inventories of electricity supply through the lens of data quality: exploring challenges and opportunities. *Int. J. Life Cycle Assess.* 22 (3), 374–386.
- Bauer, C., et al., Carculator - an open-source, comprehensive and transparent life cycle assessment tool for passenger cars, Available from: <https://calculator.psi.ch/>.
- Bekel, K., Pauliuk, S., 2019. Prospective cost and environmental impact assessment of battery and fuel cell electric vehicles in Germany. *Int. J. Life Cycle Assess.* 24 (12), 2220–2237.
- Benitez, A., et al., 2021. Ecological assessment of fuel cell electric vehicles with special focus on type IV carbon fiber hydrogen tank. *J. Cleaner Prod.* 278, 123277.
- Berrill, P., et al., 2016. Environmental impacts of high penetration renewable energy scenarios for Europe. *Environ. Res. Lett.* 11 (1), 014012.
- Blanco, H., et al., 2020. Life cycle assessment integration into energy system models: An application for power-to-methane in the EU. *Appl. Energy* 259, 114160.
- Blat Belmonte, B., et al., 2020. Identification of the optimal passenger car vehicle fleet transition for mitigating the cumulative life-cycle greenhouse gas emissions until 2050, 2 (1). pp. 75–99.
- Bouman, E.A., Øberg, M.M., Hertwich, E.G., 2016. Environmental impacts of balancing offshore wind power with compressed air energy storage (CAES). *Energy* 95, 91–98.
- Breemersch, T., et al., 2010. In: E. Commission (Ed.), Update and further development of the transport model TREMOVE. Transport & Mobility Leuven (TML), Emisia, ifeu, Brussels.
- Bründlinger, T., et al., 2018. dena-Leitstudie Integrierte Energiewende. ewi Energy Research and Scenarios gGmbH.
- Cox, B., 2018. Mobility and the energy transition: A life cycle assessment of swiss passenger transport technologies including developments until 2050. Zürich (Switzerland, ETH Zürich (Switzerland).
- Cox, B., et al., 2018. Uncertain environmental footprint of current and future battery electric vehicles. *Environ. Sci. Technol.* 52 (8), 4989–4995.
- Cox, B., et al., 2020. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. *Appl. Energy* 269, 115021.
- Crenna, E., et al., 2019. Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA. *Int. J. Life Cycle Assess.* 24 (10), 1851–1877.
- European Commission, 2018. European platform on life cycle assessment. Developer environmental footprint (EF): EF reference package 2.0 (pilot phase) (last update 2018). available from <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml>.
- Fazio, S., et al., 2018. Supporting information to the characterisation factors of the recommended EF Life Cycle Impact Assessment method - new models and differences with ILCD. JRC Technical Reports, JRC.
- Fernández, Astudillo M., et al., 2019. Human health and ecosystem impacts of deep decarbonization of the energy system. *Environ. Sci. Technol.* 53 (23), 14054–14062.
- García-Gusano, D., Garraín, D., Dufour, J., 2017. Prospective life cycle assessment of the spanish electricity production. *Renew. Sustain. Energy Rev.* 75, 21–34.
- García-Gusano, D., et al., 2016. Integration of life-cycle indicators into energy optimisation models: the case study of power generation in Norway. *J. Cleaner Prod.* 112, 2693–2696.
- Gargiulo, A., Carvalho, M.L., Girardi, P., 2020. Life cycle assessment of Italian electricity scenarios to 2030, 13 (15). p. 3852.
- Gerboni, R., et al., 2008. NEEDS - Deliverable No °9.2-RS1a Final Report on Technical Data, Costs Life Cycle Inventories of Fuel Cells. European Commission.
- Goedkoop, M., et al., 2008. ReCIPE 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level.
- Greening, B., Azapagic, A., 2012. Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK. *Energy* 39 (1), 205–217.
- Günther, J., et al., 2017. Den Weg zu einem treibhausgasneutralen Deutschland ressourcenschonend gestalten. German Environment Agency (Umweltbundesamt - UBA).
- Haase, M., Rösch, C., 2019. Sustainability assessment of innovative energy technologies - integrated biomass-based production of fuel, electricity and heat. In: 27th European Biomass Conference and Exhibition. Lisbon, Portugal.
- Harvey, L.D.D., 2018. Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060. *Appl. Energy* 212, 663–679.
- Hauschild, M.Z., 2018. Introduction to LCA methodology. In: Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds.), *Life Cycle Assessment: Theory and Practice*. Springer International Publishing, Cham, pp. 59–66.
- Hellweg, S., Milà i Canals, L., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* 344 (6188), 1109–1113.
- Henning, H.-M., Palzer, A., 2015. Was kostet die energiewende? In: Was kostet die Energiewende? - Wege zur Transformation des deutschen Energiesystems bis 2050. FhG ISE.
- Hertwich, E.G., et al., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *PNAS* 112 (20), 6277–6282.
- Hill, N., et al., 2020. Determining the Environmental Impacts of Conventional and Alternatively Fuelled Vehicles Through LCA - Final Report for the European Commission, DG Climate Action. Ricardo Energy & Environment; ifeu; E4tech; Brussels.
- Immendoerfer, A., et al., 2017. Life-cycle impacts of pumped hydropower storage and battery storage. *Int. J. Energy Environ. Eng.* 8 (3), 231–245.
- ISI, 2012. Gesamt-Roadmap Energiespeicher für die Elektromobilität 2030. Fraunhofer ISI.
- Jorge, R.S., Hawkins, T.R., Hertwich, E.G., 2012. Life cycle assessment of electricity transmission and distribution—part 1: power lines and cables. *Int. J. Life Cycle Assess.* 17 (1), 9–15.
- Junne, T., et al., 2020a. Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt. *Energy* 211, 118532.
- Junne, T., et al., 2020b. Environmental sustainability assessment of multi-sectoral energy transformation pathways: Methodological approach and case study for Germany. *Sustainability* 12 (19), 8225.
- Klein, S., et al., 2017. Erneuerbare Gase - ein Systemupdate der Energiewende. Enervis Energy Advisors GmbH, Initiative Erdgasspeicher E.V. (INES), Bundesverband Windenergie e.V. (BWE).
- Koj, J.C., et al., 2017. Site-dependent environmental impacts of industrial hydrogen production by alkaline water electrolysis. *Energies* 10 (7), 860.
- Lamb, W.F., et al., 2021. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* 16 (7), 073005.
- Liebich, A., et al., 2021. In: Umweltbundesamt, F.E.A. (Ed.), System comparison of storable energy carriers from renewable energies. ifeu - Institut für Energie- und Umweltforschung gGmbH, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Joanneum Research Forschungsgesellschaft mbH; Dessau-Roßlau.
- Luderer, G., et al., 2019. Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Commun.* 10 (1), 5229.
- Lutz, C., et al., 2018. Gesamtwirtschaftliche Effekte der Energiewende. GWS, DLR, Osnabrück, Germany, Prognos, DIW Berlin.
- Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L., Tercero, Espinoza L., Angerer, G., Marwede, M., Benecke, S., 2016. Rohstoffe für Zukunftstechnologien 2016. In: DERA Rohstoffinformationen 28. Deutsche Rohstoffagentur (DERA, Berlin, p. 353.
- Miotti, M., Hofer, J., Bauer, C., 2017. Integrated environmental and economic assessment of current and future fuel cell vehicles. *Int. J. Life Cycle Assess.* 22 (1), 94–110.
- Mottschall, M., Bergmann, T., 2013. In: U. German Environmental Agency (Umweltbundesamt) (Ed.), *Treibhausgas-Emissionen durch Infrastruktur und Fahrzeuge des Straßen-, Schienen- und Luftverkehrs sowie der Binnenschifffahrt in Deutschland*. Öko-Institut, Roßlau-Dessau.
- Naegler, T., et al., 2021. Integrated multidimensional sustainability assessment of energy system transformation pathways. *Sustainability* 13 (9), 5217ff.
- Nitsch, J., 2014. GROKO II - Szenarien der deutschen Energieversorgung auf der Basis des EEG-Gesetzentwurfs - insbesondere Auswirkungen auf den Wärmesektor. Bundesverband Erneuerbare Energie E.V. (BEE).
- Nitsch, J., et al., 2012. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. DLR, FhG IWES, IFNE.
- Öko Institut, 2011. Ressourceneffizienz und ressourcenpolitische Aspekte des Systems Elektromobilität - Arbeitspaket 7 des Forschungsvorhabens OPTUM: Optimierung der Umweltentlastungspotenziale von Elektrofahrzeugen. Öko-Institut e.V., Darmstadt.
- Pauliuk, S., et al., 2017. Industrial ecology in integrated assessment models. *Nature Clim. Change* 7, 13.

- Pehl, M., et al., 2017. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nat. Energy* 2 (12), 939–945.
- Petrauskienė, K., et al., 2021. Comparative environmental life cycle and cost assessment of electric, hybrid, and conventional vehicles in Lithuania. *Sustainability* 13 (2), 957.
- Pflüger, B., et al., 2017. Langfristszenarien Für Die Transformation Des Energiesystems in Deutschland. FhG ISI, Consentec, ifeu.
- Qussous, R., Künzel, T., Weidlich, A., 2019. Effects of a coal phase-out on market dynamics: Results from a simulation model for Germany. In: International Conference on the European Energy Market (EEM). Ljubljana, Slovenia.
- Raugei, M., Kamran, M., Hutchinson, A., 2020. A prospective net energy and environmental life-cycle assessment of the UK electricity grid. *Energies* 13 (9), 2207.
- Rauner, S., Budzinski, M., 2017. Holistic energy system modeling combining multi-objective optimization and life cycle assessment. *Environ. Res. Lett.* 12 (12), 124005.
- Repenning, J., et al., 2015. Klimaschutzszenario 2050 - 2. Endbericht. Öko-Institut, FhG ISI, Hans-Joachim Ziesing, Berlin, Karlsruhe.
- Sacchi, R., Bauer, C., Cox, B.L., 2021. Does size matter? The influence of size, load factor, range autonomy, and application type on the life cycle assessment of current and future medium- and heavy-duty vehicles. *Environ. Sci. Technol.* 55 (8), 5224–5235.
- Sacchi, R., et al., 2022a. Carculator: an open-source tool for prospective environmental and economic life cycle assessment of vehicles. *Renew. Sustain. Energy Rev.* (submitted for publication).
- Sacchi, R., et al., 2022b. Prospective Environmental impact assessment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renew. Sustain. Energy Rev.* 160, 112311. <http://dx.doi.org/10.1016/j.rser.2022.112311>.
- Sala, S., Cerutti, A., Pant, R., 2017. In: Union, P.O.o.t.E. (Ed.), Development of a Weighting Approach for the Environmental Footprint. Joint Research Center (JRC), Luxembourg.
- Schebek, L., et al., 2013. BioEnergieDat - die OpenSource datenplattform für BioEnergie in deutschland.
- Schlenzig, C., 1999. Energy planning and environmental management with the information and decision support system MESAP. *Int. J. Glob. Energy Issues* 12.
- Shmelev, S.E., van den Bergh, J.C.J.M., 2016. Optimal diversity of renewable energy alternatives under multiple criteria: An application to the UK. *Renew. Sustain. Energy Rev.* 60, 679–691.
- Simons, A., Bauer, C., 2015. A life-cycle perspective on automotive fuel cells. *Appl. Energy* 157, 884–896.
- Sokka, L., et al., 2016. Environmental impacts of the national renewable energy targets - A case study from Finland. *Renew. Sustain. Energy Rev.* 59, 1599–1610.
- Spanos, C., Turney, D.E., Fthenakis, V., 2015. Life-cycle analysis of flow-assisted nickel zinc-, manganese dioxide-, and valve-regulated lead-acid batteries designed for demand-charge reduction. *Renew. Sustain. Energy Rev.* 43, 478–494.
- Sternberg, A., Hank, C., Hebling, C., 2019. Greenhouse gas emissions for battery electric and fuel cell electric vehicles with ranges over 300 kilometers. Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany.
- Sun, X., et al., 2020. Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. *J. Cleaner Prod.* 273, 123006.
- Teske, S., et al., 2019. Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios to achieve the Paris Agreement Goals with non-energy GHG pathways for 1.5°C and 2°C. Springer: Springer International Publishing, Cham, Switzerland.
- Teske, S., et al., 2021. It is still possible to achieve the Paris climate agreement: Regional, sectoral, and land-use pathways. *Energies* 14 (8), 2103.
- Tietze, I., et al., 2017. Comparing pumped hydropower storage and battery storage-applicability and impacts. *Euro - Asian J. Sustain. Energy Dev. Policy* 5, 15–29.
- Ueckerdt, F., et al., 2021. Potential and risks of hydrogen-based e-fuels in climate change mitigation. *Nature Clim. Change* 11 (5), 384–393.
- UVEK, 2018. UVEK LCI Data 2018. Bundesamt für Umwelt BAFU, Switzerland, <https://nexus.openlca.org/database/UVEK%20LCI%20Data>.
- van Oers, L., Guinée, J.B., Heijungs, R., 2020. Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. *Int. J. Life Cycle Assess.* 25 (2), 294–308.
- Vandepaer, L., Gibon, T., 2018. The integration of energy scenarios into LCA: LCM2017 conference workshop, Luxembourg, September 5, 2017. *Int. J. Life Cycle Assess.* 23 (4), 970–977.
- Vandepaer, L., et al., 2020. Energy system pathways with low environmental impacts and limited costs: Minimizing climate change impacts produces environmental cobenefits and challenges in toxicity and metal depletion categories. *Environ. Sci. Technol.* 54 (8), 5081–5092. <http://dx.doi.org/10.1021/acs.est.9b06484>.
- Vandepaer, L., et al., 2021. The integration of life cycle assessment into energy system models: best practices, current challenges and aim for the next decade. *Int. J. Life Cycle Assess.* (submitted for publication).
- Volkart, K., Mutel, C.L., Panos, E., 2018. Integrating life cycle assessment and energy system modelling: Methodology and application to the world energy scenarios. *Sustain. Prod. Consump.* 16, 121–133.
- Volkart, K., et al., 2017. Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland. *Energy Policy* 106, 155–168.
- von Drachenfels, N., et al., 2021. Scale-up of pilot line battery cell manufacturing life cycle inventory models for life cycle assessment. In: *Procedia CIRP*, vol. 98, pp. 13–18.
- Wang, C., et al., 2020. The social, economic, and environmental implications of biomass ethanol production in China: A multi-regional input-output-based hybrid LCA model. *J. Cleaner Prod.* 249, 119326.
- Weber, S., et al., 2018. Life cycle assessment of a vanadium redox flow battery. *Environ. Sci. Technol.* 52 (18), 10864–10873.
- Wernet, G., et al., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21 (9), 1218–1230.
- Wolfram, P., Wiedmann, T., 2017. Electrifying Australian transport: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity. *Appl. Energy* 206, 531–540.
- Wulf, C., et al., 2018. Life cycle assessment of hydrogen transport and distribution options. *J. Cleaner Prod.* 199, 431–443.
- Xu, L., et al., 2020. An environmental assessment framework for energy system analysis (EAFESA): The method and its application to the European energy system transformation. *J. Cleaner Prod.* 243, 118614.