Energy Research & Social Science 113 (2024) 103574

Contents lists available at ScienceDirect

Energy Research & Social Science

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

Original research article

Rethinking the sustainability of transitions: An illustrative case of burden-shifting and sociotechnical dynamics of aviation fuel in Sweden

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ARTICLE INFO

Keywords:
Sustainability of transitions
Burden-shifting
Life cycle assessment
Multi-system transitions
Collaborative research approach

ABSTRACT

The literature on socio-technical transitions has advanced our understanding of transitions toward sustainability but sometimes overlooks the sustainability consequences of such transitions. A case in point is the burden-shifting phenomenon, a consequence that can occur when efforts to minimize a problem in one context have unintended negative impacts on another. In this article, we adopt a life cycle assessment (LCA) methodology to quantitatively assess the burden-shifting potential of a transition case toward sustainable aviation fuel in Sweden. Our assessment demonstrates how an emerging sustainability transition can result in unintended spatio-temporal impacts, taking into account complex relationships between multiple socio-technical systems. By doing so, we provide an alternative way to study the sustainability *of* transitions, complementing the mainstream transition studies that have mostly studied the transitions *toward* sustainability. In addition, we propose collaborative research approaches, which introduce LCA methodology into transition studies, transcending disciplinary boundaries when engaging questions of environmental sustainability *of* 'sustainability' transitions.

1. Introduction

The young field of sustainability transitions has grown prolifically, contributing to our understanding of system-level transition dynamics *toward* sustainability [1,2]. One of the key characteristics of the field is its explicit interest in environmental sustainability, which makes the field stand out from neighboring fields that have a longer history, such as innovation studies [3] and industrial dynamics [4]. Indeed, the scholarly community of sustainability transitions incorporates the concept of sustainability not only in research practice but also in the very identity of the community. For instance, the community coined the term 'sustainability' transitions, while establishing the ever-growing conference on sustainability transitions (i.e., the International Sustainability Transitions conference) and the high-impact journal Environmental Innovation and Societal Transitions. Also, transition scholars have increasingly published in environmental-sustainability-oriented journals such as Ecological Economics, Nature Sustainability, and Energy Research and Social Science, providing research insights and policy advice on how to accelerate sustainability transitions.

In this fast-growing community, sustainability, as a concept, has been addressed in various ways. Most scholars study transitions *toward* sustainability, typically relying on common assumptions on which innovations are more sustainable, and theorize system-level transition processes toward those innovations [1]. Such innovations are often framed around certain technologies such as solar photovoltaic systems, wind energy, and biofuels, or wider paradigms such as circular economy and nature-based solutions. Few others study the transition *of* sustainability, exploring the performativity of the sustainability concept, i.e., how the meaning of sustainability changes over time and space as well as among actors [5,6]. Suggesting new avenues of research for transition community, a small but growing number of scholars take a more critical stance and debate various issues regarding sustainability *of* transitions, such as de-growth [7], social injustice [8–10], de-colonialism [11], global south [12], reflexive methodology [13] and unsustainabilities [14].

Another critical yet less debated issue concerning the sustainability *of* transitions is the phenomenon of burden-shifting, a consequence that can occur when efforts to minimize a problem in one context (such as reducing emissions in a given spatiotemporal domain) lead to unintended negative impacts in other contexts (such as depleting resources or undermining human well-being in another spatiotemporal domain). We are in times of multi-system transitions in-the-making, spanning

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https://doi.org/10.1016/j.erss.2024.103574
Received 28 December 2023; Received in revised form 26 April 2024; Accepted 30 April 2024

various sectors, such as energy, transportation, mining, agriculture, and food, potentially creating complex relationships between established and emerging value chains [15–17]. Innovations like renewable energy technologies, electric vehicles, hydrogen-based solutions, automation technologies, and biofuels are expected to pave the way for such transitions. Scaling-up of these innovations, though valuable, can be complex and problem-ridden, addressing some aspects of sustainability on the one hand, while creating new challenges on the other. For instance, if transitions toward renewable energy are not managed well, the burden is likely to shift from climate change to social injustice [18], land use, and chemical pollution [19].

In this study, we aim to assess the burden-shifting potential of a sustainability transition in-the-making. We choose a quantitative assessment methodology, namely life cycle assessment (LCA), complementing the previous research that discussed the burden-shifting of sustainability transitions on qualitative [13] and conceptual grounds [19]. Life cycle assessment methodology is known for its sophisticated approach to quantitatively assessing burden-shifting [20] and, therefore, serves well for our purpose. As an illustrative case, we study the ongoing transition toward alternative aviation fuels, i.e., so-called sustainable aviation fuels (SAF), in Sweden. While sustainability transitions literature has previously studied transitions *toward* various kinds of alternative transportation fuels, including SAFs (e.g., [21–23]), less attention has been paid to the sustainability *of* such transitions. Therefore, the ongoing transition toward SAF in Sweden provides us with a relevant and interesting empirical basis for our research aim. Based on an LCA methodology, our findings demonstrate how a potential sustainability transition in a specific place, time, and industry can have unintended negative impacts in another region, time, and sector. As we discuss in the rest of the paper, while SAF may help the Swedish aviation industry meet climate targets (under certain conditions), the creation of new SAF value chains may also result in adverse sustainability impacts that can occur far beyond the Swedish borders. These impacts may not be immediately noticeable, but they could persist for hundreds of thousands of years, leading to long-term cumulative pressures on the environment and society.

Our paper provides a quantitative illustration of how burden-shifting of sustainability transitions might occur, taking account of complex relationships between multiple socio-technical systems in a sustainability transition case-in-the-making. Burden-shifting is not new to scholarly debate and has long been discussed, for instance in the literature on sustainability assessment [20] and global governance [24]. Some scholars have also discussed why potential burden-shifting is important for sustainability transitions, based on a thought experiment [19] and a qualitative methodology [13]. Our study differs from the previous efforts by providing LCA-informed quantitative insights into transition studies. This is a timely contribution given the growing concerns about the sustainability challenges of minerals, metals, and energy infrastructure needed for a low-carbon future [16] as well as the recent calls for pluralistic and alternative ways of conducting sustainability transition research [1,25]. In this vein, van den Bergh [25], in a farewell editorial of Environmental Innovation and Societal Transitions, has already suggested transition scholars consider diversifying their methodological approach and embrace the use of quantitative models, which would create “a more balanced role next to historical, qualitative, and case study research, which have dominated the field so far” [p. 6]. By bridging the LCA research and sustainability transitions field, our paper provides an alternative way to study the sustainability *of* transitions, complementing the mainstream transition studies, which have mostly studied the transitions *toward* sustainability to date. In addition, we, as an interdisciplinary team of LCA and sustainability transitions scholars, draw inspiration from our own experience in this paper and suggest to scholars a collaborative research approach in which LCA can be used as ‘a rehearsing space’, transcending disciplinary boundaries when engaging questions of ‘sustainability’ of sustainability transitions.

2. Burden-shifting

In this section, we briefly revisit the relevant literature on burden-shifting and adjacent phenomena. We begin with LCA literature, which has a knowledge based on quantitative assessment of environmental sustainability impact including burden-shifting, and then move to some relevant discussions in other fields of research, such as regarding ecosystem services trade-offs, eco-dumping, and problem shifting of global governance. Finally, we reflect on what burden-shifting means in the context of sustainability transitions, drawing insights from the relevant debates in transition research. It is worth noting that burden-shifting is neither a fully theorized nor a well-defined phenomenon. It is thus the purpose of this section to provide a working definition of burden-shifting for the context of sustainability transitions.

LCA is built on the premise that man-made objects undergo a life cycle analogous to a biological one, comprising stages of resource extraction, production, use, and disposal [26]. While bearing some resemblance to the stages in value chains terminology (see e.g., [2,27]), life cycle stages also account for the interaction with the environment during the use and disposal stages of the objects, including the ultimate fate of the materials (e.g. to the landfill or incinerator). Burden-shifting occurs when efforts to reduce environmental impacts in one life cycle stage unintentionally lead to negative impacts, either of the same or different types, in other stages [20]. Therefore, a fundamental objective of LCA is to avoid burden-shifting by considering a broad range of environmental issues across all life cycle stages [28].

To exemplify, in the early 2000s, first-generation biofuels were initially considered a climate-neutral alternative for road transport. However, subsequent LCA studies revealed that the overall emissions from fuel production, transport, and natural land clearing for energy crop cultivation[1] outweighed the reduction in tailpipe emissions, highlighting burden-shifting across different stages of the biofuel life cycle. The cultivation of energy crops also contributed to problems such as eutrophication,[2] aquatic toxicity, biodiversity loss, water scarcity, and high food prices, illustrating burden-shifting between different issues [20]. This kind of burden-shifting may impose far-reaching consequences that future generations will be compelled to address. In this example, toxicity impacts [31], eutrophication [32], and over-extraction of water [33] could lead to the long-term accumulation of environmental pressures and resource depletion [34]. In addition, burden-shifting also occurs in spatial and sectoral domains, shifting problems from the point of fuel use to the cultivation of energy crops, and from the road transport sector to the agriculture sector.

Although burden-shifting is predominantly studied by LCA practitioners, similar concepts have also been discussed elsewhere. One such concept is ecosystem services (ES) trade-offs. ES are services provided by the environment, such as regulating, provisioning, cultural, and supporting services like food, water, pollination, soils, and recreation [35]. While ES plays a vital role in human well-being [36], management choices made by humans to maximize the use of certain ES may reduce the provision of other ES, resulting in ES trade-offs [35]. As an example, the management of a forest for timber production may decrease its function as a climate sink, affect the water quality downstream, or reduce the opportunity for human recreation [35]. In general, the decline of ES could lead to environmental degradation [37], poverty, and hunger [38], and affect social well-being, equality, justice, etc. [39].

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[1] Conversion of natural land to cultivated land releases the carbon bound in the natural biomass and the soil as carbon dioxide [20]

[2] Eutrophication is the excessive plant growth as a result of nutrient enrichment by human activity [29]. The discharge of nutrients from soil to water bodies causes nutrient uptake by cyanobacteria and algae, and subsequently suffocating fishes and invertebrates, leading ultimately to the disappearance of species [30].

In a world with limited natural resources, efforts to satisfy diverse value preferences, including social, economic, and human needs, will inevitably lead to ES trade-offs [40]. Although attempts are made to categorize ES trade-offs into spatial, temporal, between beneficiaries, and between ES types [35,41], their dependency on ecosystem characteristics and decision context complicates straightforward analysis. Some studies suggest that understanding the drivers and mechanisms behind the complex dynamics within interdependent socio-ecological-economic systems, through a transdisciplinary approach with stakeholder participation, is essential for mitigating ES trade-offs [36,41]. Yet, others propose proactive measures like nature-based solutions and payment for ecosystem services to conserve ecosystems [36].

The concept of eco-dumping is similar to burden-shifting. Indirectly driven by trade liberalization and the pursuit of cost-competitive products for consumers, eco-dumping transpires when companies operating in nations with stringent environmental regulations import natural resources and commodities from regions with more relaxed standards. This practice effectively shifts the environmental burden associated with production and waste to places where environmental regulations are less rigorous [42,43]. Carbon leakage is an example of eco-dumping. It occurs when polluting industrial plants circumvent stringent climate policy by relocating to jurisdictions with laxer emission constraints [44]. There are several issues associated with eco-dumping. First, it tends to distort the environmental footprint of the importing country due to the omission of upstream effects of consumption [45]. Second, eco-dumping could result in reduced output, employment, and taxable profits at home, along with increased environmental degradation in the regions where the production is relocated [44]. Third, it hinders our understanding of the environmental implications of international trade [45].

To address eco-dumping, scholars proposed the implementation of consumption-based indicators on the national level to account for pollution embodied in trade flows, in addition to territorial emissions [46–48]. Border carbon adjustment measures, such as export rebates, financial compensation for indirect emissions, or the utilization of the best available technologies, are suggested as tools to prevent carbon leakage [49]. Given that eco-dumping has global environmental implications, affecting issues like marine eco-toxicity and climate change, scholars argue that local solutions that target to reduce the impacts of eco-dumping are inadequate. Instead, they emphasize the importance of implementing global measures to avoid eco-dumping, for instance, standardization of global environmental regulations to create an environmental level playing field across diverse jurisdictions [43].

While global regulations may aim at addressing eco-dumping, there are examples of international environmental laws that have led to problem-shifting induced by international environmental treaty regimes, a paradoxical situation in which improving one system's performance degrades another across different environmental domains, spatial, and time scales [24]. Scholars argue that problem-shifting in this context is the result of a reductionist approach used to tackle global environmental problems [24]. This reductionist approach simplifies a complex network of interdependent and indivisible concepts into a single dimension [50]. Although its objective is to achieve a common good, the reductionist approach overlooks the integrated nature of environmental issues, rendering it inadequate in resolving interconnected global challenges [24,51,52]. This concept is aptly illustrated by the implementation of the Montreal Protocol. While this international agreement successfully addressed the immediate problem of ozone depletion by globally phasing out chlorofluorocarbons and hydrochlorofluorocarbons, it inadvertently exacerbated climate change for future generations through the introduction of their replacement - hydrofluorocarbons, a potent greenhouse gas [24].

Scholars in global governance contend that current international environmental laws, with their no-transfer of damage or hazard clauses, primarily address direct and foreseeable problem-shifting while overlooking the potentially substantial consequences of indirect problem-shifting. Similarly, conflict clauses for prioritizing conflicting international laws lack provisions for weighing one global environmental impact against another, raising legitimacy concerns [24]. In contrast, they advocate for a more holistic approach, referred to as the “nexus approach” [51]. This approach envisions an integrated system of international environmental laws that transcends sectors, space, and time, considering the entire Earth system rather than a single environmental aspect [24]. To achieve this, international regulatory regimes and organizations would need to be legally bound by a unifying environmental objective. Such an objective, rooted in overarching environmental standards such as the planetary boundaries [53], can serve as a reference point for legal reasoning and interpretation, ensuring institutional coherence across the Earth's subsystems [24]. For example, to foster a greater understanding of and building knowledge surrounding problem shifting, Rakhyun E. Kim and colleagues have curated a repository that documents “environmental problem shifting cases across different issue areas (e.g., climate, biodiversity, ocean, freshwater, agriculture, and hazardous waste)” from all around the world [54]. These cases focus on problem-shifting induced by international environmental treaty regimes, covering topics such as vertical farming, electrical vehicles, and agroforestry across diverse spatiotemporal contexts.

While burden-shifting, ES trade-offs, eco-dumping, and problem-shifting exhibit subtle differences, they share a common ground, stemming from (often unintended) consequences arising from intended human activities aimed at achieving specific environmental, social, or economic goals. These phenomena emerge within complex systems, necessitating the need to understand their origins and the dynamics of the systems in which they manifest. Such insights can facilitate the development of strategies for avoidance or mitigation of burden-shifting.

We define the burden-shifting of sustainability transitions as *new problem creation by an intended sustainability transition.* Such a phenomenon can occur when intentions to minimize a problem in one transition context result in unintended (or, rarely, intended) negative impacts on another context. Although burden-shifting is not explicitly discussed in sustainability transitions literature, Köhler et al. [1], in their agenda-setting paper for sustainability transitions research asked how transition scholars can address sustainability in a more nuanced manner, and work with inherent complexity and contestation given that “*… we tend to take sustainability for granted by looking at one dimension at a time, by not pausing to unpack it in various contexts, thereby missing potential conflicts and trade-offs (e.g. greenhouse gas emissions vs. biodiversity and land use in the case of biofuels).*” [p. 21–22]. Nonetheless, some transition studies, from a critical and reflexive perspective, touch upon concepts resembling burden-shifting (see, for example, [13,18,19]). These scholars argue that sustainability is often narrowly operationalized in sustainability transitions, overlooking potential trade-offs between social, economic, and environmental aspects [13]. For instance, while low-carbon energy transitions may mitigate climate change, they may also exacerbate social injustices or come at the expense of exporting embodied emissions overseas [18]. Furthermore, the diffusion of low-carbon technology may inadvertently lead to environmental problem-shifting due to uncertainties and gaps in our knowledge of complex ecological systems [19]. However, such negative impacts extending beyond the immediate spatial and temporal boundaries of the case are often overlooked, despite being incurred by the transitions under study [13].

While there is no one-size-fits-all solution to avoid the burden-shifting of sustainability transitions, some recommend adopting a reflexive perspective to reflect on the choice of case studies, the sources of unsustainability, potential trade-offs, and system boundaries [13]. Such suggestions resonate well with ongoing debates concerning the geography of sustainability transitions and transition justice. Feola [7], for example, problematizes the sustainability of sustainability transitions, and raises the question of “*when does the attempt of capital to spatio-temporally ‘fix’ environmental crises result in their displacement, rather* *than the mitigation or eradication of environmental impacts?*" [p. 247]. In the context of multi-system transitions, Kanger et al. [17] argue there is a growing challenge of navigating transitions at multiple scales and time horizons, which lead to "damned if you do, damned if you don't" policy dilemma. One such dilemma presented is the energy-mobility connection: "*Continuing support to fossil fuel based energy production and transport would only exacerbate existing inequalities, e.g. uneven access to clean environment or uneven distribution of health impacts. Cutting support for fossil fuels, on the other hand, will create other problems such as the loss of income and structural unemployment for entire regions dependent on incumbent systems*" [p. 53]. Also, citing Sovacool et al. [55], they furthermore argue *"a shift to renewable energy production balanced by vehicle-to-grid, will likely intensify inequalities elsewhere, e.g. the negative impacts of increasing global cobalt demand on the miners in Congo"* [17].

Other suggestions include applying multidisciplinary knowledge and fostering interdisciplinary collaboration in transition research [19,25]. In this paper, we bridge the LCA research and sustainability transitions field, providing an alternative way to study the sustainability *of* transitions, more specifically to study the burden-shifting of sustainability transitions. As we present in the remainder of this paper, we use LCA to quantitatively analyze transitions in-the-making to gain information on whether burden-shifting will emerge in a transition and if so, what are the drivers of such potential burden-shifting.

3. Research design

LCA is a quantitative decision support tool that facilitates the systematic evaluation of resource use and potential environmental impacts of a product or service throughout its life cycle, from raw material acquisition to disposal [26,56]. The application of LCA typically involves four iterative phases [57]. The first phase is the description of the goal and scope, which defines the purpose of the study, the evaluation and/or comparison unit (referred to as the functional unit), the system boundaries, the choice of system modeling, and the assumptions made. In the second phase, inventory analysis, input (resources), and output (emissions) data from each process in the life cycle are collected and aggregated over the life cycle. In the third phase, life cycle impact assessment, the collected resources and emissions are linked to environmental impact categories and converted into common impact units. In the last phase, the results of the inventory and impact assessment are interpreted to respond to the goal of the study [57]. This is the phase where burden-shifting can be identified, offering insights into how impacts may potentially shift throughout the life cycle. These four phases are applied to our case study and their implementation is illustrated in the remainder of Section 3 and Section 4.

3.1. Case background

In the past few decades, the global air transport industry has grown exponentially, with revenue passenger kilometers surging over 75-fold from 1960 to 2018 [58]. This upward trend is expected to continue [59]. While aviation has positive impacts on the global economy and mobility [60], it is also held responsible for contributing to climate change [58]. As a hard-to-abate industry [61], aviation is currently heavily reliant on fossil fuels [62], and is accountable for about 5 % of anthropogenic global greenhouse gas emissions [60]. Despite this, there is no evidence of a decline in global air traffic [63], leading many scholars to argue that the industry must undergo a radical transformation.

While some scholars assert that emerging technologies such as hydrogen-powered or electric aircraft are as yet mature enough to significantly reduce aviation emissions in the immediate future [64], others believe that SAF could be a low-carbon substitute for fossil aviation fuels [61,65], having the potential to save life cycle greenhouse gas emissions by up to 90 % per megajoule of energy compared to fossil aviation fuel[3] [66].

Our case study centers on Sweden, a country committed to achieving net-zero greenhouse gas emissions in all sectors by 2045 [67]. In addition to this national target, the Swedish aviation industry has set an even more ambitious goal of zero fossil fuel use on domestic flights by 2030 [68]. To encourage low-carbon aviation and foster a market for alternative fuels, the Swedish government enacted a law in 2021 that mandates blending SAF with fossil aviation fuels. The target is to achieve a scale of 30 % volume blending of SAF by 2030 [69]. Despite the considerable expectations [70], there remains little understanding of whether, and under what circumstances, the transition from fossil aviation fuels to SAF within established and emerging value chains can deliver the anticipated environmental sustainability outcomes. This case serves as a representative example, illustrating how the burden-shifting of transition toward a normatively 'greener' technology can be analyzed and understood.

3.2. LCA goal and scope definition

The goal of our LCA is to identify and understand the potential burden-shifting that may arise from the transition toward using SAF in domestic air travel in Sweden. To achieve this, we conduct a comparative analysis of the potential life cycle environmental impacts associated with air travel powered by conventional fossil aviation fuel and Swedish SAFs. Considering that bio-based feedstock supports the functioning of multiple sectors in Sweden such as road transport, heat, and power, paper and pulp, etc., we account for its potentially limited availability [71]. Consequently, we examine two distinct SAF pathways: one derived from forest residues and the other involving renewable electricity & biogenic carbon dioxide, within the context of the year 2030.

The analysis encompasses both the established (involving conventional fossil aviation fuel) and emerging value chains (involving SAF) (see Fig. 1), spanning from feedstock extraction and conversion to fuel production to consumption during a typical flight.[4] We assume that the established value chain involves the oil industry and air transportation sector while the emerging value chain is likely to involve a variety of sectors such as forestry, renewable energy, and air transportation. The unit of assessment in this study is one megajoule of fuel. Our modeling follows the attributional approach, whereby environmental impacts are ascribed to product systems based on the mapping of product emissions and resource flows throughout their life cycles [72].

The two SAF production pathways: Fisher-Tropsch synthesis of synthetic gas from forest residues (FR-SAF) and renewable electricity & biogenic carbon dioxide (RE-SAF) are based on several key assumptions:

- FR-SAF pathway: In 2030, the availability of local forest residue as a feedstock may be limited due to competing demands spanning across multiple socio-technical systems, which provide societal functions such as transport, pulp and paper, and energy. To meet the SAF production requirements, we assume that the reduced output of certain entities reliant on forest residue feedstock, such as electricity production from local combined heat and power (CHP) plants, can be compensated for by electricity production elsewhere. For the current analysis, we assume the compensating electricity will come from the

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[3] Life cycle greenhouse gas emission savings of SAF vary depending on feedstock, production pathways and assumptions made.

[4] A typical flight in this case study is represented by a twin engine single aisle aircraft averaging 600 km per flight. A flight cycle includes takeoff, climb, cruise, descent, approach and landing phases. The type of aircraft and the distance traveled are specified, since the types and amount of gases and particles emitted are different for each specification.

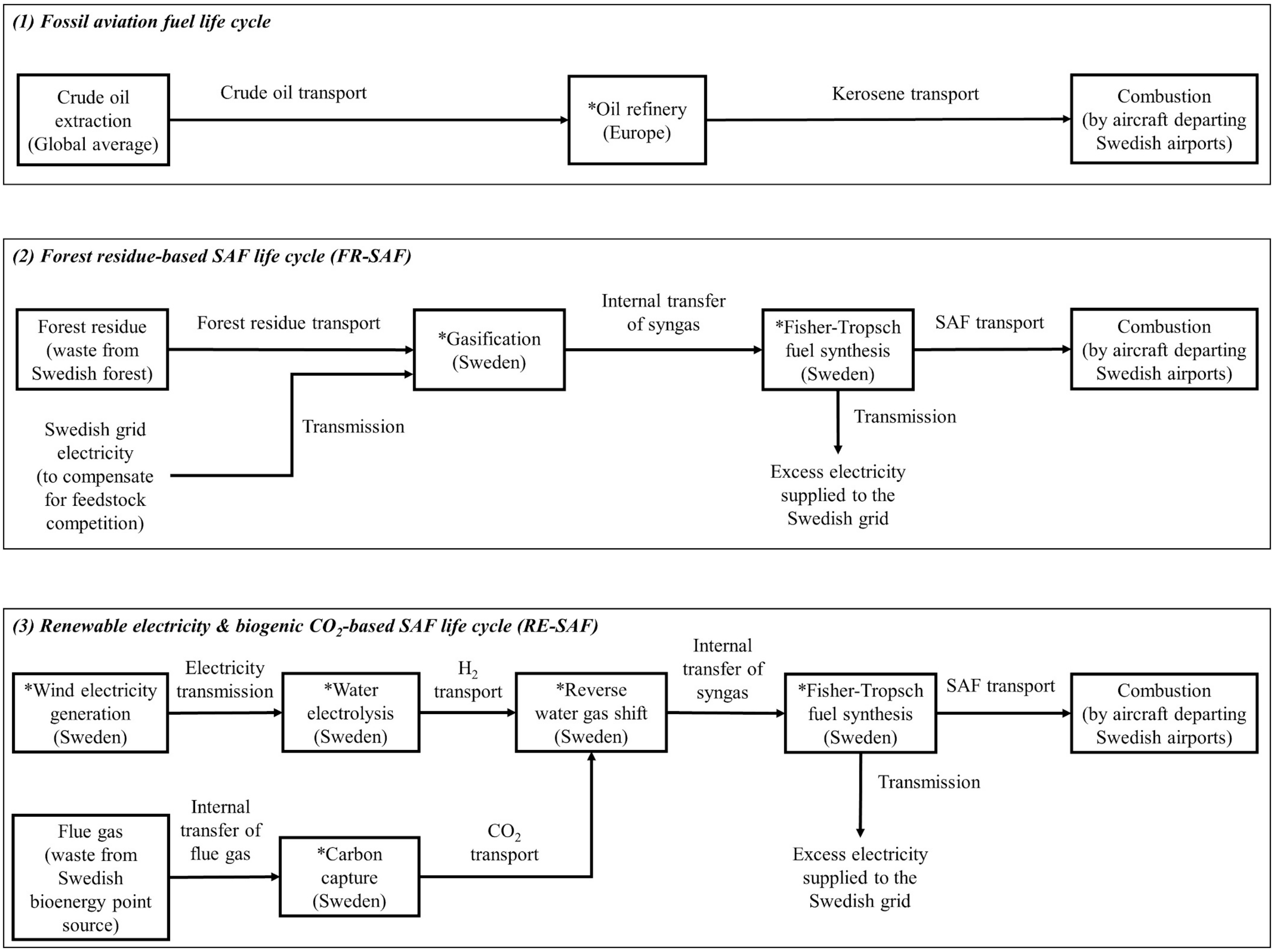

Fig. 1. The system boundary of the case study depicts the life cycles of 1) fossil aviation fuels, 2) SAF based on forest residue, and 3) SAF based on renewable electricity & biogenic carbon dioxide in 2030. The blocks (i.e., foreground system in LCA terminology) include processes specific to the product or service under study, such as feedstock extraction, feedstock processing, fuel synthesis, and combustion. Meanwhile, shared processes (i.e., background systems in LCA terminology) such as transportation are shown as arrows, energy supply is partly shown as arrows, and waste management is not shown. * indicate local operations with global material supply for facility establishments.

national grid, proportionally supplied by hydro, wind, nuclear, CHP, and solar sources.

- RE-SAF pathway: Renewable electricity for the production of green hydrogen will be exclusively generated from dedicated onshore wind turbines. This assumption is in line with the expectation that the largest Swedish onshore wind farm will support the green industrial revolution, including the so-called green hydrogen production, in Sweden's north [73].
- For both pathways: Any excess electricity generated as a by-product during the fuel synthesis process may be integrated into the national electricity grid.

To facilitate the identification of potential burden-shifting, this case study considers multiple environmental issues, including climate change, freshwater use, land use and conversion, eutrophication, depletion of non-renewable resources, toxic impacts on human health, and eco-toxic impacts from metals and synthetic organic chemicals (see Appendix A for details). While these issues primarily pertain to the environment, they also have some implications for social sustainability. For instance, the consideration of human and eco-toxicity accounts for the adverse effects of chemicals on human health and the ecosystem, as the analysis includes the entire chain of events from chemical emissions into the environment to their accumulation in food chains, uptake by humans and species, and the subsequent impact on human health and the ecosystem [74].

3.3. Life cycle inventory analysis and impact assessment

For the future foreground systems (shown as the blocks in Fig. 1), we use data from Lai et al. [71] as a basis and adjust them to account for the assumptions concerning competition for forest residue supply, green hydrogen production, and handling of fuel synthesis by-product (Section 3.2). These datasets, representing emerging SAF technologies like gasification and water electrolysis, are projected from pilot plant to industrial scales using simulations, linear scaling, or a learning curve approach.

As for the background system (partly shown as arrows in Fig. 1), we combine four data sources to create plausible future scenarios: 1) the Ecoinvent 3.7.1 cutoff database - a commercially available data libraries of human activities, documenting natural and man-made inputs into these activities and their associated emissions released to water, soil and air [75]; 2) the SSP2 pathway in which our shared socio-economic system will take on the 'middle of the road' path - developed in the Integrated Assessment Models [76]; 3) the IPCC under 2 °C scenario [77]; and 4) the projected Swedish electricity mix in 2030 from Energimyndigheten [78] electrification scenario. For more information on the datasets used and modified in this study, refer to Supplementary Data in Appendix C.

To evaluate the potential life cycle environmental impacts of the fuels, we utilize the ReCiPe midpoint method from a hierarchist perspective [74]. This method transforms the life cycle inventory results into a limited number of environmental impact categories such as climate change and mineral depletion (see Appendix A). To account for the impact of aviation non-CO_2 emissions [58], we extract the flight phase emission data from Elgowainy et al. [79] and Lee et al. [58] and utilize emission indices for water vapor, soot, and sulfur provided by Lee et al. [58] to calculate the potential climate impact of the combustion phase of the fuel life cycles. LCA software Activity Browser [80] is used to facilitate this assessment. For a detailed description of ReCiPe, the midpoint impact pathway, and the hierarchist perspective, refer to Appendix C.

4. Case results

The potential life cycle environmental impacts of SAFs are presented in Fig. 2, normalized to European fossil aviation fuel (represented by value one in Fig. 2). The full non-normalized results can be found in Appendix C, while a detailed explanation of each environmental impact category can be found in Appendix A.

Our LCA shows that all SAF types could have better environmental

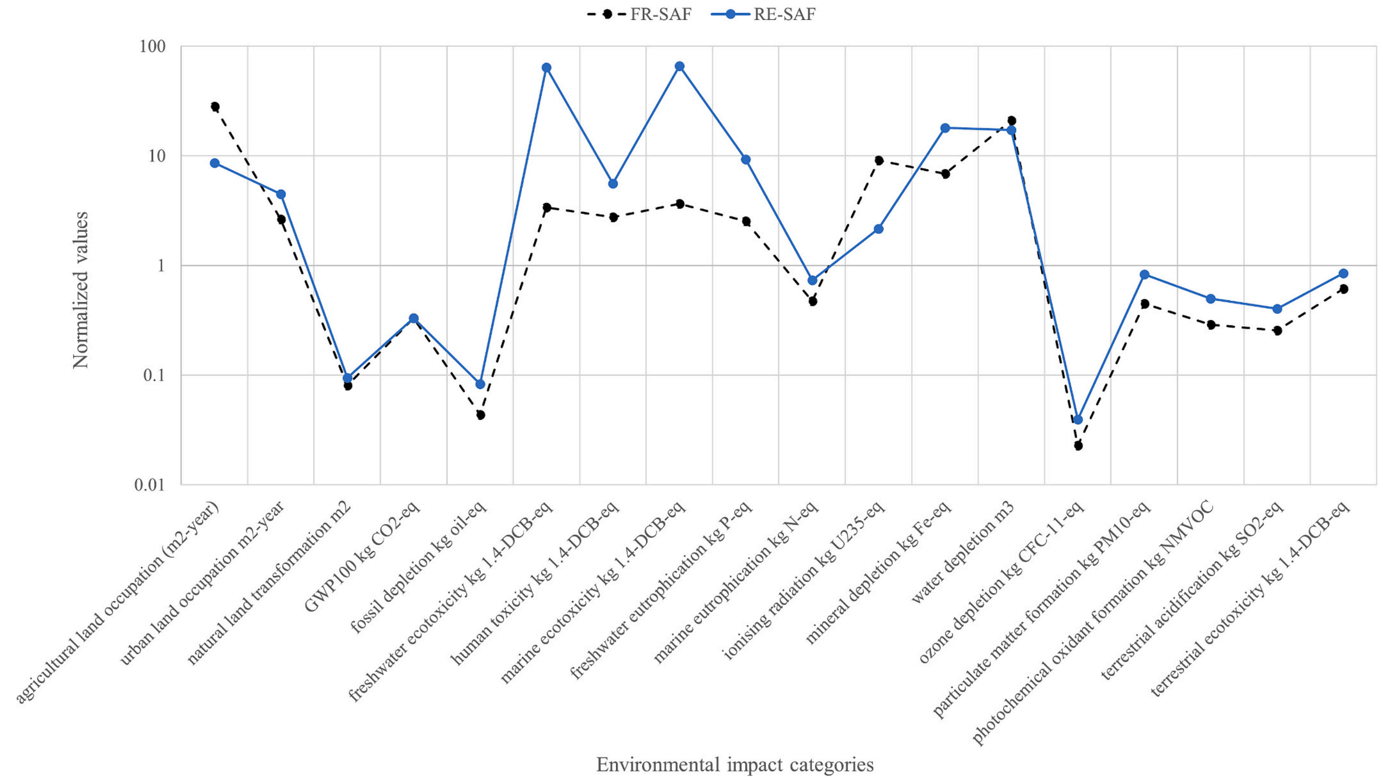

Fig. 2. Potential life cycle environmental impacts of SAFs normalized to European fossil aviation fuel. Value one represents European aviation fuel.

performance than fossil aviation fuel in the categories of natural land transformation, climate change, fossil resource depletion, marine eutrophication, ozone depletion, photochemical ozone formation, particulate matter formation, terrestrial ecotoxicity, and terrestrial acidification. However, burden-shifting may arise between other environmental impact types. For instance, SAF produced from renewable electricity & biogenic carbon (RE-SAF) exhibits the highest impact scores in six impact categories, with its most noteworthy impacts observed in freshwater and marine ecotoxicity, as well as mineral resource depletion. While SAF derived from forest residue (FR-SAF) outperforms fossil aviation fuels in nine impact categories, it does come with significantly higher impacts concerning agricultural land occupation, ionizing radiation, and water depletion.

4.1. *Analysis of potential burden-shifting*

Our case study operates on the premise that SAF can serve as a low-carbon alternative to fossil aviation fuel and contribute to the sustainability transition of the Swedish aviation sector. While our LCA results in Fig. 2 show that all SAF types have the potential to outperform fossil aviation fuel in terms of climate change impacts, they may fall short in other environmental impact categories, indicating the potential for burden-shifting. While reducing emissions can help the Swedish aviation industry meet climate targets, the creation of new SAF value chains may also result in adverse environmental and social impacts that can occur far beyond Sweden's borders. These negative impacts may not be immediately noticeable, but they could persist for hundreds of thousands of years, leading to long-term cumulative pressures on the environment and society. In the following subsections, we examine burden-shifting that could arise from transitioning to FR-SAF and RE-SAF, demonstrating how burden-shifting can potentially occur across different problem types, spatial and time scales, and industrial sectors. We describe the impact categories with the highest scores for the two fuel alternatives, as shown in Fig. 2. A full analysis of all the impact categories with values of more than one is provided in Appendix C Table S-4.

4.1.1. *Transitioning to FR-SAF*

Fig. 2 illustrates the significant environmental impact of the FR-SAF life cycle, particularly in agriculture land occupation, ionizing radiation, and water depletion. This shift in environmental concerns from climate change highlights issues such as biodiversity loss, human exposure to radiation, water scarcity, and the survival of plant and fish species. These elevated impacts result from attributing emissions to grid electricity, which we assume can compensate for the reduced electricity production in CHP due to feedstock competition (Section 3.2). Since the projected Swedish electricity mix in 2030 is mainly composed of hydro, wind, nuclear, CHP, and solar sources [78], we can trace the burden-shifting of FR-SAF transitions back to these energy sources.

To be used for electricity production in CHP, forest residue is primarily sourced from production forests. While many of these forests adhere to sustainable management practices, incorporating concepts like ecosystem services and landscapes and ecological connectivity, the current emphasis on increasing wood production to mitigate climate change and boost bio-economy conflicts with biodiversity conservation goals [81]. Even when managed sustainably, Felton et al. [82] report that over 2000 forest-related species in Sweden are threatened by activities like forest felling. Given that biodiversity significantly affects ecosystem functions and services critical for human society over time [83], its conservation has increasingly gained public attention. Burden-shifting, from climate change to agricultural land occupation, in this case, has effectively shifted the focus from aviation to the forestry industry.

The high ionizing radiation potential is attributed to the use of nuclear electricity, which forms part of the potential Swedish electricity grid for 2030 [78]. The treatment of tailings in uranium mills and nuclear power plant operations releases radionuclides, thus subjecting workers and communities to chronic radiation exposure that can lead to serious health effects, including cancer and genetic mutation [30,84]. The increasing demand for nuclear fuel in Sweden is likely to subject uranium miners and processing workers in regions such as North America, Australia, Canada, Namibia, or Nigeria[5] to long-term radiation exposure and increase the risk of hereditary diseases in their descendants. A large amount of decarbonized water is required to cool down the nuclear power plant during operations, which could lead to water scarcity for future generations and threaten the marine species' survival [33]. Here, the focus is shifted from the aviation industry to the nuclear energy sector, given the significant environmental and health concerns associated with the latter.

4.1.2. *Transitioning to RE-SAF*

As shown in Fig. 2, the adoption of RE-SAF has the potential to mitigate climate change while increasing pressure on urban land occupation, freshwater and marine ecotoxicity, human toxicity, freshwater eutrophication, and mineral depletion. This potential burden-shifting is primarily attributed to the deployment of dedicated onshore wind turbines for renewable electricity production. Currently, over 70 % of the wind turbines installed worldwide are electromagnetic rotor types made from copper coils [85]. The use of virgin copper in these turbines can result in ecotoxicity, human toxicity, and eutrophication. The disposal of sulfidic tailings from copper mines and copper scraps to landfills can transform urban land into dump sites, where the infiltration of nutrients from sulfidic tailings treatment and metal leaching into the ocean and freshwater can occur, leading to toxic effects and adverse impacts on human health, freshwater bodies, and the ocean [30,86]. Such phenomenon can be particularly pronounced in copper-rich countries like Chile, Peru, or Zambia.

The extraction of virgin copper and iron to support wind turbine construction can potentially cause mineral resource depletion. Mineral depletion occurs when enriched but non-renewable deposits are overmined [87]. The remaining minerals are often of inferior quality, with an even greater amount of mining residue per kilogram of mineral excavated [86], making them more technologically challenging to access and higher in cost to extract [87]. Mineral depletion, declining quality, and difficult access could potentially lead to severe economic consequences as well as limitations on minerals-dependent innovation for future generations [87]. This example highlights how efforts to mitigate climate change have shifted the burden from the aviation industry to the extractive industries.

5. Discussion

Our life cycle assessment shows quantitatively how a potential sustainability transition in a specific place (i.e. Sweden), time (i.e. the year 2030), and industry (i.e. aviation) can have unintended negative impacts (e.g. ionizing radiation, ecotoxicity) in another space (e.g. Chile, Nigeria), time (e.g. future generations) and sector (e.g. energy, extractive industries). Some can interpret these findings as “damned if you do, damned if you don't” transition paradox while others can see this as an optimization or policy issue at the macro level. We, instead, ask ourselves what transition scholars can learn from the insights gained in our case study on burden-shifting and how they can go about studying the question of the sustainability of transitions in the future.

A growing number of transition scholars emphasize the importance

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[5] The countries engaged in uranium and copper minings (see also Section 4.1.2) are identified based on the extraction datasets provided by Ecoinvent 3.7.1 cutoff database. The claim of negative impacts in these other jurisdictions are based on the casue-and-effect chains for emissions to the environment, or impact pathways, utilized by the ReCiPe method to calculate the potential life cycle impacts (see Section 3.3).

of understanding complex relationships between established and emerging value chains in multi-system transitions, spanning various sectors, such as energy, transportation, mining, agriculture, and food [15–17]. While multi-system transitions are argued to be necessary, there are also ongoing debates on the challenge of navigating transitions at multiple scales and time horizons [17] as well as concerns about the sustainability challenges of minerals, metals, and energy infrastructure needed for a low-carbon future [16]. However, recognizing that multi-system transitions can provide an expanded understanding of transitions [88], incorporating these concerns into the scope of multi-system analysis can be an alternative approach for future transition studies.

Our LCA of the FR-SAF pathway in Sweden takes into account competing demands spanning across multiple socio-technical systems, which provide societal functions such as transport, pulp and paper, and energy. While FR-SAF potentially contributes less to climate change compared to fossil aviation fuel, to label it as a more 'sustainable' transition option would require a deeper understanding of the potential burden-shifting. Our findings show that feedstock competition is the primary factor underlying the burden-shifting. This unsustainability stems from the assumption that multiple sectors rely heavily on forest-based feedstock as a means to shift away from fossil fuel dependence. In the context of fierce competition for forest-based feedstock, even countries like Sweden, with vast forested land areas, could face resource scarcity over time.

Similarly to the FR-SAF pathway, the life cycle global warming potential of RE-SAF may appear lower than that of fossil aviation fuel. However, our findings show that SAF produced from renewable electricity and biogenic carbon falls short in overall environmental performance, identifying virgin copper used in the wind turbine as one of the primary drivers of burden-shifting. This case exemplifies how employing LCA unveils global value chains and complex connections between seemingly disparate systems and industrial sectors, often overlooked by transition studies. For instance, our analysis identifies the co-dependency between RE-SAF production in Sweden and copper mining in Chile. Without a careful context-specific assessment, these findings may not be generalized to other transition cases with different spatiotemporal settings. However, we argue that unintended burden-shifting remains a probable and significant phenomenon that deserves further attention in the community of sustainability transitions research.

We suggest that in the future, scholars expand the scope of their analysis to understand the implications of transformative changes in multiple socio-technical systems (e.g., road transport, paper and pulp, and energy systems) necessitated by the adoption of so-called sustainable innovations (e.g., SAF). Given the potential for significant macro-level impacts resulting from the co-evolution of multiple socio-technical systems, there will be more need for understanding the dynamics of competition for natural resources. We echo the recent advice for transition scholars to incorporate changes in connected systems alongside the focal system shift in their studies [17,88]. These interconnections, also known as telecoupled [7], connecting systems [17], or sector coupling [89] call for new approaches to study cross-sector dynamics, co-dependencies, and ways to establish sustainable couplings between systems [17], both locally and globally. Such approaches can entail, among others, examining the existing functional (e.g. shared supply chain) and structural (e.g. shared infrastructure) couplings between systems of interest, modifying study system boundaries, identifying new interaction points that further connect the new and existing systems, and exploring interaction patterns among systems (e.g. competitive, symbiotic, complementing) [88].

In future transition studies, scholars of sustainability transitions can benefit from insights generated by LCA applied in multi-disciplinary settings. Identifying potential burden-shifting of a sustainability transition can provide a useful rehearsal space for exploration, enabling the examination of plausible options and quantification of potential environmental impacts [90], and aiding in selecting cases for transition studies. For instance, to investigate whether (and under which conditions) using recycled copper in wind turbine construction would make the transition case toward RE-SAF in Sweden more sustainable than using virgin copper, we (as a team of transition and LCA scholars) replace virgin copper dataset with recycled copper dataset in wind turbine production in our LCA model. This modeling experiment demonstrates that the incorporation of recycled copper can mitigate potential impacts on freshwater and marine ecotoxicity, and mineral and water depletion of the RE-SAF pathway (see Appendix B). This demonstration, however, does not imply that the utilization of recycled copper equates to an inherently more sustainable pathway. Our analysis with dataset replacement focuses solely on the value chain dimension of the potential RE-SAF transition. The broader roles of users, policy, culture, and transnational environment [91] in transitioning the copper recycling industry remain unexplored and warrant further studies. What the LCA analysis suggests is that recycled copper could be an alternative material with lower environmental impacts for future turbine constructions, opening up new and previously not considered avenues for scholars studying the transition toward renewable energy or RE-SAF, allowing for the expansion of system boundaries to explore the role of recycled copper in the transition processes.

In this paper, we empirically analyze a transition case toward SAF in Sweden to illustrate the relevance of the burden-shifting phenomenon for sustainability transitions. Our focus centers on elucidating burden-shifting while using empirical data from an aviation case for an 'illustrative' purpose to convince the reader that our argumentation is plausible [92]. By grounding our analysis on the burden-shifting phenomenon in the relevant literature, we attempt to build a robust foundation for our argument. Furthermore, we complement our effort with an LCA of the empirical case, providing "additional (not sole) justification for our argument" [92][p.23]. Such a research journey has been characterized by some level of interdisciplinarity and creativity. On the one hand, we bridge between transition literature and LCA research, two fields that have operated in relative isolation. On the other hand, we combine the qualitative depth of an illustrative case study with the quantitative rigor of LCA.

Although our case study demonstrates that burden-shifting of sustainability transitions can arise in multiple dimensions and that LCA can serve as a sophisticated tool to identify and uncover some of the deeper reasons for burden-shifting, we are aware that LCA methodology can be value-laden and performative, as it "*has been shaped by many kinds of social and cultural concerns, and it in turn shapes, funnels and specifies these concerns*" [93][p.434]. We echo that "[even] *the most extensive life cycle study in the world could not conclusively encompass all environmental burdens related to a product, and the broader the chains of influence are extended, the greater the indeterminacies and uncertainties grow*" [93][p.434]. Despite we acknowledge that modeling transitions involve utilizing highly uncertain assumptions, scenarios, datasets, and parameters for the future [94], quantification or statistical evaluation of uncertainties of future unknowns is often infeasible [71]. Therefore, model uncertainties should be studied and communicated transparently [94], for instance, by applying sensitivity analysis (e.g. recycled copper in our case study) to understand the effects of uncertainty [95], or by developing scenario ranges (e.g. multiple SAF production pathways) to test the robustness of the LCA results [96]. In addition, van der Giesen et al. [94] suggest that the practice of responsive evaluation, i.e. involvement of experts, in every step of the LCA could lower the qualitative and quantitative uncertainties associated with the assessment. It is this suggestion of Giesen et al. and our strong desire to transfer research experience that motivates us to propose two collaborative research approaches. These approaches engage both LCA methodology and transition theory for addressing questions of environmental sustainability *of* transitions and minimizing potential burden-shifting of sustainability transitions.

These two approaches explained below, entail using LCA as 'a rehearsing space' to identify potential burden-shifting of plausible sustainability transition pathways (e.g. FR-SAF and RE-SAF), understanding their underlying causes (e.g. feedstock competitions and virgin copper), experimenting with alternative scenarios by adjusting model parameters (e.g. recycled copper incorporation), and refining research designs by expanding system boundaries, and/or altering case selections. The approaches have a heavy emphasis on collaboration between transition scholars and LCA researchers, fostering knowledge and ideas exchange.

The first approach involves a collaborative and sequential process in which the LCA researcher plays a supporting role in designing the transition research. Here, the LCA researcher models the existing transition pathway, identifies the potential burden-shifting phenomena, changes and tests alternative parameters, and provides information to transition scholars. This contributes to laying the groundwork for the design of transition studies. The second approach is an interdisciplinary process in which the LCA researcher plays a participatory role in the transition research design process. While the LCA researcher conducts customized LCAs to identify the burden-shifting of the specific potential transition pathways, researchers from both fields interpret the results collaboratively, reflecting on the broader implications of burden-shifting and collectively deciding which scenarios or model parameters to test. Subsequently, transition scholars refine transition research designs, taking into account factors like system expansion or multi-system interactions, aiming to develop a more robust and perhaps more environmentally sustainable case for study. While the former process is comparatively less tedious and resource-intensive, the latter is customizable to serve the purpose of the transition studies.

In this current endeavor, the SAF production pathways were developed, and model parameters were tested based on the interdisciplinary process, while the LCA modeling and interpretation of results were done in a manner closer to the collaborative and sequential process. Nevertheless, we find the collaboration meaningful and educational. As researchers from different disciplines and onto-epistemological backgrounds, the interdisciplinary setting encourages us to be open-minded and receptive to new ideas and perspectives, leading to new insights and knowledge generation. These approaches are useful but are by no means the only workable ones. Researchers from both fields are encouraged to contribute their ideas on alternative ways of working together and exploring how best the identification of burden-shifting can add value to transition research.

6. Conclusion

This paper aimed to provide an alternative and quantitative way to study the sustainability *of* transitions, complementing the mainstream studies of transitions *toward* sustainability. We addressed this through an illustrative case on the sustainability of a SAF transition, utilizing LCA to assess the burden-shifting potential of a sustainability transition in-the-making.

Our case study showed that burden-shifting of sustainability transitions can arise between environmental impacts, space, time, and sectors and that LCA can serve as a sophisticated tool to identify and uncover some of the deeper reasons for burden-shifting. In our specific case of potential transition toward SAF, the reasons underlying burden-shifting unveiled connections between the focal system, global value chains, and industrial sectors, enhancing our understanding of complex relationships between established and emerging value chains in future multi-system transitions.

The insights gained from our study contribute to the ongoing discussions of the transition community on methodological diversity, multi-system transitions, and reflexivity from a quantitative perspective. Our collaborative research approaches introduce LCA methodology into transition studies, transcending disciplinary boundaries when engaging questions of environmental sustainability *of* 'sustainability' transitions. Albeit left unexplored in our study, we also envision that research engaging in the burden-shifting of sustainability transitions can enrich future conversations on the transition of sustainability, justice in transitions, unsustainabilities, and de-growth. It thus falls on the transition scholars to engage and explore in what other ways LCA, and assessing burden-shifting, can best offer value to their research endeavors.

Funding

This work is part of the SETA project, which is supported by the Swedish Energy Agency (Grant No. 50332-1).

CRediT authorship contribution statement

Yat Yin Lai: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emrah Karakaya:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

I have shared my data in Appendix C - Supplementary Data

Appendix A

Explanation of the environmental impact categories assessed by this study based on the midpoint characterization factors used by the ReCiPe assessment method [74].

Environmental Impact categories	Indicator at midpoint	Explanation
Land use	Potentially disappearance of a fraction of species	Expresses relative species loss caused by land use or land transformation, proportionate to relative species loss caused by average annual crop production.
		Land occupation involves a change in land cover, where the land is no longer suitable for the original habitats. The transformation of natural land for human activities discourages the dwelling of species.
Climate change	Global warming potential	Expresses the amount of additional radiative forcing integrated over time caused by the emission of 1 kg of greenhouse gas relative to the additional radiative forcing integrated over that same time horizon caused by the release of 1 kg of carbon dioxide.

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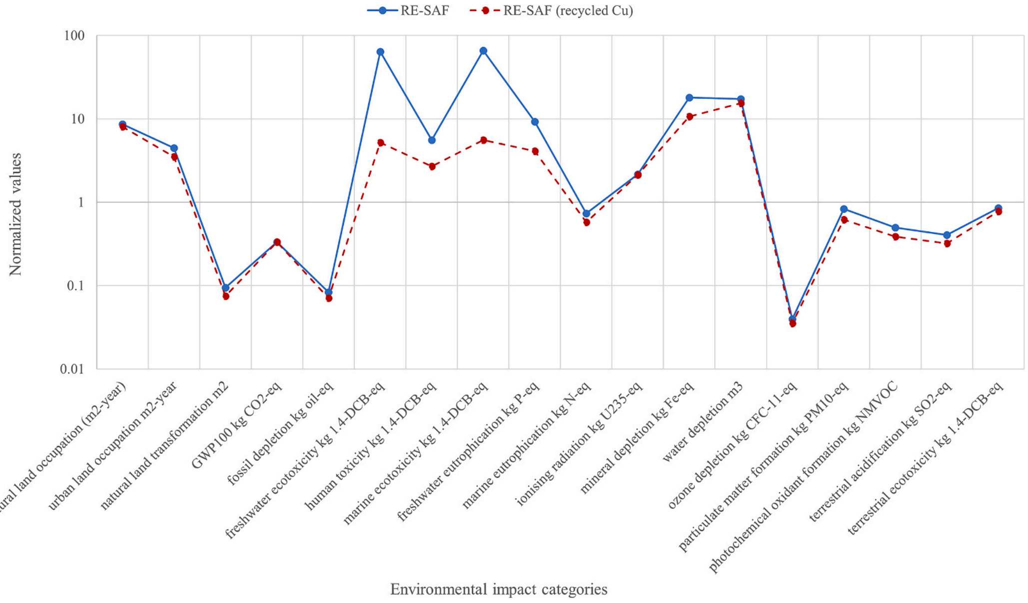
(*continued*)

Environmental Impact categories	Indicator at midpoint	Explanation
		An increase in global mean temperature will result in damage to human health and ecosystems.
Toxicity	Toxicity potential	Calculated by dividing the toxic potential of a chemical by the potential impact of the chemical 1.4-dichlorobenzene emitted to urban air for human toxicity, to freshwater for freshwater ecotoxicity, to seawater for marine ecotoxicity, and industrial soil for terrestrial ecotoxicity.
		Chemical emissions to the environment can cause increased mortality, reduced growth, reduced mobility, mutations, behavior changes, etc., to natural organisms.
		Human exposure to chemicals can result in a wide range of non-cancer diseases and an increase in cancer risk.
Aquatic eutrophication	Eutrophication potential	Measures the residence time of a substance emitted to freshwater/seawater relative to the world average residence time of phosphorus (or nitrogen) emitted to freshwater (or seawater).
		The discharge of phosphorus from soil to freshwater, and of nitrogen from the soil to seawater cause nutrient uptake by cyanobacteria and algae, and subsequently by fish and invertebrates, leading ultimately to the disappearance of species.
Stratospheric ozone depletion	Ozone depletion potential	Quantifies the amount of ozone a substance (in chemicals) can deplete relative to CFC-11 for a defined time horizon.
		Ozone depletion can cause a larger amount of UVB radiation to reach the earth, thus increasing the incidence of skin cancer and cataracts.
Ionizing radiation	Ionizing radiation potential	Expresses the collective exposure dose caused by the emission of a radionuclide relative to the emission of Uranium-235 into the air. A collective exposure dose is the total average exposure (per kg body weight) multiplied by the global population integrated over time.
		Exposure to radionuclides can lead to death or severe heredity effects.
Fossil depletion	Fossil fuel potential	Measures the ratio between the energy content of a specific fossil resource and the energy content of crude oil.
		Due to fossil material scarcity, future extraction will involve more remote locations and more advanced and expensive techniques.
Mineral depletion	Surplus ore potential	Expresses the average extra amount of ore to be produced in the future for the extraction of 1 kg of a specific mineral counting in all future production of the mineral, relative to the extra amount of ore to be produced in the future for the extraction of 1 kg of iron counting in all future production of iron.
		The more mineral resources that are extracted today, the higher risk the grade of the ore will decrease in the future, resulting in an increase in ore produced per kilogram of mineral resource extracted.
Water use	Water depletion potential	Measures as the amount of water consumed divided by the amount of water extracted from surface water bodies or aquifers.
		Reduction in freshwater availability can reduce drinking water, food production, plant diversity, and fish species.
Particulate matter formation	Particulate matter formation potential	Measures the intake of fine particulate matter from the emissions in a specific region relative to particulate matter 10 (PM10) intake from the average world emissions.
		Intake of fine particulate matter can cause damage to human health.
Photochemical ozone formation	Ozone formation potential	Measures the intake of ozone formed from the emissions of NOx or NMVOCs in a specific region relative to the ozone intake from the average world emissions.
		Human intake of atmospheric ozone can cause respiratory disease and uptake of ozone by vegetation can reduce growth and seed production.
Terrestrial acidification	Acidification potential	Expresses the environmental persistence of an acidifying substance emitted in a specific region relative to the average environmental persistence of sulfates emitted in the world.
		Atmospheric deposition of sulfates, nitrates, and phosphates causes a change in acidity in the soil and deteriorates the growth environment for plant species.

Appendix B

Potential environmental impact of RE-SAF, derived electricity generated from virgin copper-based and recycled copper-based wind turbines, normalized to European fossil aviation fuel. Value one represents European aviation fuel.



Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2024.103574.

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