Universität
Augsburg
University

STRATEGIC DESIGN OF ENVIRONMENTALLY AND SOCIALLY SUSTAINABLE SUPPLY NETWORKS

Cumulative Doctoral Dissertation
at the Faculty of Business Administration and Economics
of the University of Augsburg

submitted in partial fulfillment of the requirements for the degree of
Doctor of Economic Sciences (Dr. rer. pol.)

submitted by
Lukas Bastian Meßmann, M.Sc.

Augsburg, Germany, 2022

First reviewer: Prof. Dr. Axel Tuma

Second reviewer: Prof. Dr. Robert Klein

Chairman of the oral exam: Prof. Dr. Marco C. Meier

Date of oral exam: 22 June 2022

CONTENT OF THIS DISSERTATION

LIST OF SCIENTIFIC CONTRIBUTIONS V

1 INTRODUCTION 1

1.1 METHODOLOGICAL BACKGROUND 7

1.2 CONSTITUENT ELEMENTS OF THIS DISSERTATION 13

2 CONTRIBUTIONS 21

CONTRIBUTION A 23

CONTRIBUTION B 25

CONTRIBUTION C 27

CONTRIBUTION D 29

CONTRIBUTION E 31

3 CONCLUSIONS 59

3.1 KEY RESULTS & ADDED VALUE OF THE RESEARCH 60

3.2 OUTLOOK & FUTURE RESEARCH AGENDA 64

REFERENCES 67

LIST OF SCIENTIFIC CONTRIBUTIONS

The following published and submitted scientific contributions are presented within this doctoral dissertation. The articles are sorted following their order of publication. The journal rankings correspond to VHB-JOURQUAL3, published by the German Academic Association for Business Research (VHB).

Contribution A (published in a journal with the ranking **B**)

Messmann, L., Boldoczki, S., Thorenz, A., & Tuma, A. 2019a. *Potentials of preparation for reuse: A case study at collection points in the German state of Bavaria.* Journal of Cleaner Production 211, 1534-1546. doi.org/10.1016/j.jclepro.2018.11.264

Contribution B (published in a journal with the ranking **B**)

Messmann, L., Helbig, C., Thorenz, A., & Tuma, A. 2019b. *Economic and environmental benefits of recovery networks for WEEE in Europe.* Journal of Cleaner Production 222, 655-668. doi.org/10.1016/j.jclepro.2019.02.244

Contribution C (published in a journal with the ranking **B**)

Messmann, L., Zender, V., Thorenz, A., & Tuma, A. 2020. *How to quantify social impacts in strategic supply chain optimization: State of the art.* Journal of Cleaner Production 257, 120459. doi.org/10.1016/j.jclepro.2020.120459

Contribution D (published in a journal with the ranking **A**)

Wietschel, L., Messmann, L., Thorenz, A., & Tuma, A. 2021. *Environmental benefits of large-scale second-generation bioethanol production in the EU: An integrated supply chain network optimization and life cycle assessment approach.* Journal of Industrial Ecology 25(3), 677-692. doi.org/10.1111/jiec.13083

Contribution E (published in a journal with the ranking **A**)

Messmann, L., Wietschel, L., Thorenz, A., & Tuma, A. 2022. *Assessing the social dimension in strategic network optimization for a sustainable development: The case of bioethanol production in the EU.* Journal of Industrial Ecology, Special Issue on Life Cycle Sustainability Assessment for Sustainable Development Goals. doi.org/10.1111/jiec.13324

Important note: At the time of submission of this dissertation, Contribution E was under major revision following the peer reviews. The manuscript printed here represents the version of the manuscript under revision. Until the revision deadline, the manuscript underwent further changes and improvements and was eventually accepted and published. When citing Contribution E, please read first and only refer to the published version: doi.org/10.1111/jiec.13324

1

INTRODUCTION

Human influence causes unprecedented global changes. Unsustainable levels of fishing, water withdrawals, soil degradation, and deforestation cause global crises. Agriculture alone is responsible for 70% of global water withdrawals, 40% of forest losses in tropics and subtropics, and is a major driver of water eutrophication due to nitrogen fertilizer emissions (FAO 2019). Climate change is considered the most significant of the human-induced global crises. The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) stresses the *unequivocal* linkage between human activity and global warming (IPCC 2021). Due to the emission of greenhouse gases, their concentration in the atmosphere, and the subsequently occurring greenhouse effect, global surface temperatures are more than one degree Celsius higher than they were a century ago (IPCC 2021). This is already causing weather extremes, wildland fires, rising sea levels, disturbances in ocean currents, increased temperatures of water bodies, and shifts in climatic zones and seasons, affecting humankind and ecosystems alike. Coastal-specific risks alone will put a billion people at risk, the prevalence of dengue fever is projected to increase significantly, and the already vulnerable access to water and food will further deteriorate for a large portion of the global population until 2040 (IPCC 2022). The IPCC (2022, p. 11) estimates that “3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change”. Global warming also causes a dramatic loss in biodiversity. A sizeable portion of terrestrial species faces extinction even in the optimistic scenario where global warming can be limited to +2 °C until 2100. Currently, land and oceans take up about 56% of CO_2 emissions. This slows the greenhouse effect but increases the oceans’ pH values (acidification) and puts further strains on, among other things, marine biodiversity. The uptake rates and their partially compensational effect in terms of climate change are expected to decrease in the second half of the 21^{st} century (IPCC 2021). The existential risks posed by these global changes are widely acknowledged, but current actions to achieve sustainable and especially climate-neutral societies are not adequate. In 2021, the German Federal Constitutional Court held that the country’s climate change act is partially unconstitutional, as the reduction pathways outlined in it past 2030 are insufficient to protect fundamental freedom rights against the risks posed by climate change (BVerfG 2021a, 2021b).

These global changes can ultimately be traced back to human demand and to the over-consumption of materials, energy, land, and other ecosystem services (Steffen et al. 2015). Human demand is the result of the “pursuit of social and economic goals” (Haberl et al. 2019, p. 1) and the driver of the socioeconomic system (Sinha 2016). The concept of a circular economy is a widely accepted key solution to minimize socio-economically induced environmental and social pressures. It aims at closing material cycles to avoid waste, the loss of finite resources, and the inevitable environmental impacts that socio-economic activities entail (Moreno et al. 2016; Brears 2018). This presumes a sociometabolic perspective, where socio-economic activities and biophysical processes are seen as integrated systems with interconnected biophysical stocks and flows (Haberl et al. 2019). Figure 1 exemplifies the idea of a circular economy and the sociometabolic perspective by embedding the prominent *circular economy systems diagram* of the

Ellen McArthur Foundation (2014, 2015) in a depiction of the scope of sociometabolic research (based on Haberl et al. 2019, p. 2). Ultimately, the goal is decoupling socio-economic well-being from the environmental impacts that biophysical leakages from the socio-economic system exert (Zeug et al. 2021). Since perfect circularity is impossible due to dissipation (Helbig 2018) and for economic, electrochemical, or fundamental thermodynamic reasons (Steinbach and Wellmer 2010), unavoidable leakages should be channeled to safe sinks (Kral et al. 2013) to minimize the environmental externalities.

Socio-economic product and material use can be divided into finite and renewable materials (Ellen MacArthur Foundation 2015). Finite materials are seen as stocks of the socio-economic system and should circulate in technical cycles (Figure 1). In biological cycles, biological nutrients and materials are ultimately circulated back into the biosphere after consumption and contribute to regrowing the previously harvested biomass. This may be the case for, e.g., food byproducts and wastes, which can directly be composted and anaerobically digested, or bio-based products such as wooden furniture or cotton clothes, which have previously been circulated through the technical cycle (Ellen MacArthur Foundation 2019). Here, a key concept is cascade utilization of biomass: for example, wooden biomass can cascade from material use (from the whole wooden product to sawn wooden panels, to strands for paper production) to chemical use (lignocellulose), to energy use (wood as fuel; biogas, biofuels) (Taskhiri et al. 2016).

Similar to biological cycles, finite materials in technical cycles may be considered "technical nutrients" (Ellen MacArthur Foundation 2014). Cascade use is also possible and often referred to as downcycling or retrieval of parts (Krikke 2011). However, Krikke (2011) argues that it is substitution in *closed-loop* supply chains that yields the largest environmental benefits. Substitution occurs when recovered products or materials re-enter the original supply chain and replace a part of the forward supply chain and its associated environmental pressure. The European waste hierarchy (Directive 2008/98/EC) defines the order of recovery options descending by the percentage of value recovered. Waste prevention by maintaining a good's condition and thus prolonging its use phase takes overall priority (Hutner 2017). After a good has passed the waste threshold, i.e., when the owner has disposed of it, preparation for reuse (e.g., inspection, cleaning, repairing) should take place so that the good can be redistributed and thus substitute the upstream part of the forward supply chain. When major refurbishments and parts replacements are necessary, the good re-enters the supply chain at the final manufacturing stage; when only materials recovery (recycling) is possible, only the environmental impacts associated with virgin materials procurement are substituted (Bressanelli et al. 2020). Lastly, the lowest-value recovery option in both biological and technical cycles is thermal recovery, which is only considered a last resort, as it leads to air emissions (i.a., CO_2, fly ash) and wastes (bottom ash) that need to be disposed of (Sabbas et al. 2003).

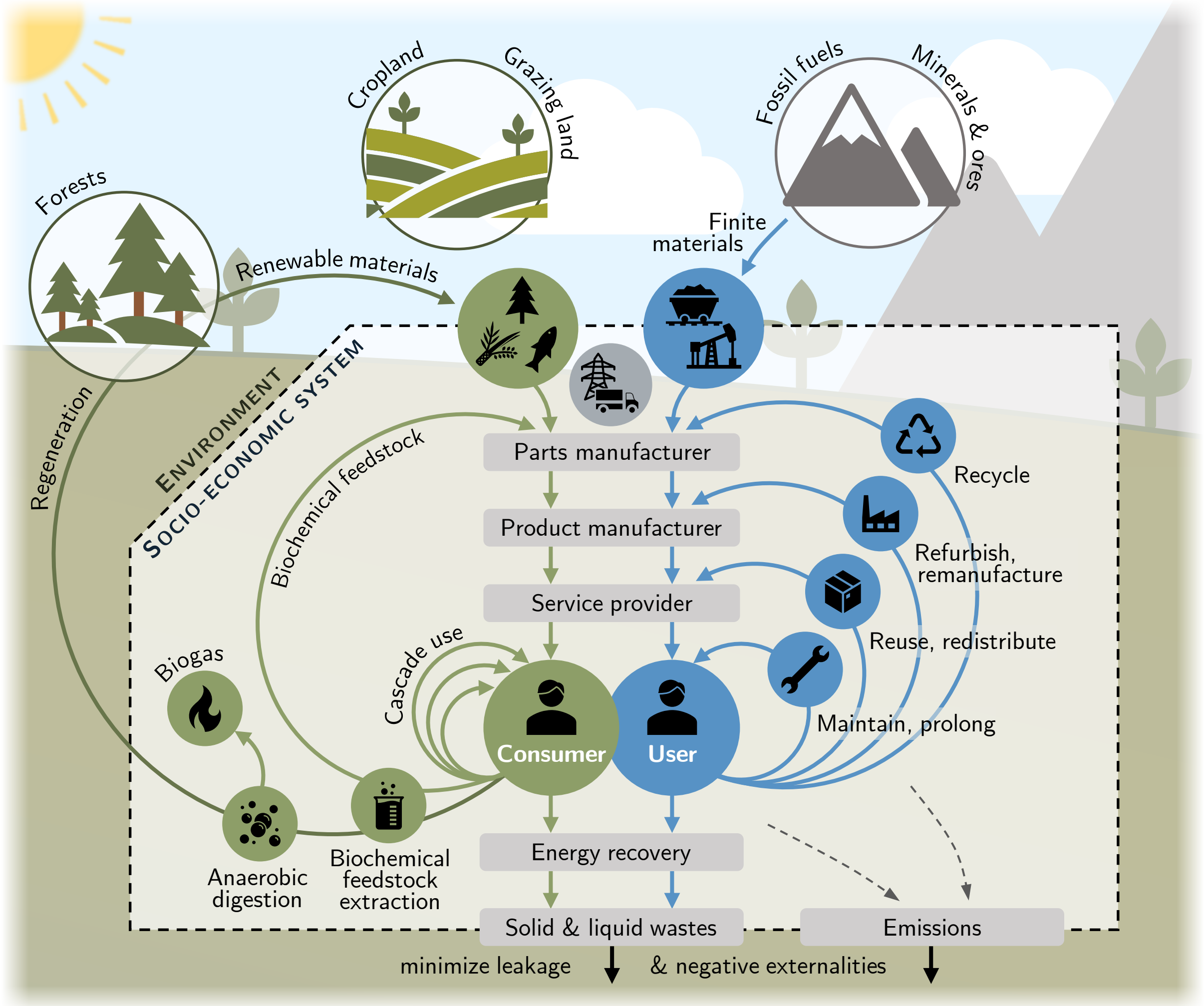


Figure 1. Technical and biological cycles in a circular economy as biophysical flows in a sociometabolic system (own depiction based on the *circular economy systems diagram*, Ellen MacArthur Foundation 2014, 2015, as well as on Haberl et al. 2019, p. 2)

Waste Electric and Electronic Equipment (WEEE) and products of the bioeconomy are two representatives of technical and biological cycles. Both are product categories that have been important subjects of sustainability discussions over the last two decades. WEEE is often cited as a prime example of the exploitative and wasteful nature of anthropogenic handling of earth's resources (Casey et al. 2019) and the detrimental effects of product manufacturing and poor waste management on the environment (Xue et al. 2015). Printed wiring boards account for the largest environmental impacts in the manufacturing stage of forward supply chains (Farrant and Le Guern 2012), and their toxic components require sustainable end-of-life strategies (O'Connor et al. 2016). However, scholars have pointed out that circularity alone does not automatically render reverse processes sustainable. Instead, multiple and possibly conflicting economic and environmental objectives (Quariguasi Frota Neto et al. 2010), strategic network design choices of, e.g., facility locations (Krikke 2011), and, for WEEE in particular, trade-offs between the energy-consuming use phase and primary production (Boldoczki et al. 2021) need to be balanced based on actual environmental impacts (Krikke 2011).

In contrast to the environmentally detrimental example of WEEE, bio-based products are seen as promising examples of environmental advantageousness. Biofuels in particular have the potential to avoid a sizeable portion of the environmental impacts when substituting fossil fuels, the conventional, petrochemical counterpart (Mat Aron et al. 2020). The two most important biofuels in Germany in 2019 were biodiesel and bioethanol (Fachagentur Nachwachsende Rohstoffe 2021). Biodiesel is produced through transesterification from lipid-rich oilseeds, such as rapeseed, and replaces conventional diesel, while bioethanol (alcohol, EtOH) is produced through fermentation of sucrose or starch (Mat Aron et al. 2020). *First-generation* bioethanol (*1G EtOH*) stems from cultivating sugar crops (e.g., sugar beet, sugar cane) and starch crops (e.g., potatoes, maize, other cereal crops) or from energy plants with a high share of cellulose (e.g., switchgrass, miscanthus), which can be converted to sucrose and in turn to ethanol (Bušić et al. 2018). Bioethanol can substitute fossil petrol, e.g., by blending 10 vol.-% ethanol and 90 vol.-% petrol (E10). On the one hand, both biodiesel and bioethanol yield the benefits of carbon sequestration during photosynthesis, where monosaccharides and eventually cellulose and starch are formed (Mahapatra and Kumar 2019; Prasad et al. 2019). The carbon dioxide released during combustion thus corresponds to the airborne CO_2 previously bound within the biomass. This results in significant benefits of biofuels vis-à-vis fossil fuels in terms of climate change (Hjuler and Hansen 2018). On the other hand, the extensive agriculture required to cultivate energy and sugar crops with its negative impacts – acidification, eutrophication, toxicity, water scarcity, and land use changes – is often overlooked (Correa et al. 2017; Mat Aron et al. 2020). Furthermore, it requires areas that could alternatively be used for food production and thus also arguably aggravates global hunger (Muscat et al. 2020). Cellulosic, *second-generation* bioethanol (*2G EtOH*) alleviates the aforementioned issues by only using residues of agricultural food production such as straw and stover (Aditiya et al. 2016). In the EU, 2G EtOH is gaining traction: by 2030, a minimum of 14% of the energy consumed in road and rail transport must be from renewable sources (European Commission 2018), while simultaneously, fuels from cereals, other starch-rich, sugar, or oil crops are limited to 7% (Directive 2015/1513/EU). However, 2G biofuels are only just on the brink between pilot and commercial scale (Hjuler and Hansen 2018).

Both WEEE and EtOH (especially 2G EtOH), despite originating from different environmental domains (lithosphere / biosphere) and different industry sectors (mining sector, manufacturing, semiconductor industry / agriculture, chemical industry), underline that the largest environmental savings potentials lie in a circular economy and closing supply chains. They also demonstrate the interconnectedness between anthropogenic activities and natural ecosystems and show that sustainability issues cannot be solved on the level of individual actors. Closing WEEE cycles necessitates consumers to prolong use phases, to repair instead of replace, to buy second-hand, and to be willing to return used products (Stindt et al. 2017; Georgantzis and van Langen 2021). Policy-makers are required to enact effective framework legislation, municipal authorities to organize and operate functional and accessible collection and recovery systems (Bruno et al. 2021), and producers to conform to take-back responsibility and to close cycles, where possible, at higher tiers than recycling (Leclerc and Badami 2020). Attempts to close bio-based cycles often even lack knowledge about the available feedstock (e.g., amounts of agricultural residues, Thorenz et al. 2018; Wietschel et al. 2019). Furthermore, many biogenic products such as bio-based plastics and bio-based fuels lack economic competitiveness vis-à-vis their fossil-based counterparts (Horvat et al. 2018) and require political subsidies to unlock their environmental potential in terms of categories such as global warming without neglecting possible social or environmental issues in other regards.

On a superordinate level, closing technical and biological cycles supports the achievement of the Sustainable Development Goals (SDGs; cf. section 1.2, Table 3). The SDGs, proclaimed by the United Nations in 2015 (United Nations 2015), set the frame for all of humankind's efforts toward a sustainable future and concern global challenges such as e.g., poverty, hunger, equality, peace, biodiversity, prosperity, and climate change. The SDGs are primarily a political framework. They were adopted on the political level, pertain to all countries worldwide, and the specific 169 targets subordinate to the 17 overarching goals are formulated at government and policy level (Weidema et al. 2020). Nonetheless, the SDGs have also been a "wake-up call" (PwC 2019) for companies, with 72% of surveyed companies mentioning the SDGs in their financial or sustainability reports (PwC 2019). Circular economies and socio-economic activities embedded in the sociometabolic nexus can be viewed in light of the 17 SDGs. The goal of realizing a circular economy with its implied environmental and social benefits is formulated in SDG12 (*responsible consumption and production*). Socio-economic goals are reflected in SDG7 (*affordable and clean energy*), SDG8 (*decent work and economic growth*), and SDG9 (*industry, innovation, and infrastructure*). Explicit and direct externalities linked to anthropogenic activities, which cause global environmental change, are covered by SDG13 (*climate action*), SDG14 (*life below water*), and SDG15 (*life on land*). These externalities can, however, also have adverse social and societal impacts. They may stem from the conflict for arable land between energy and food production (SDG2, *zero hunger*), from human-induced water scarcity (SDG6, *clean water and sanitation*), or from compromised health, e.g., due to pollution (SDG3, *good health and well-being*) (cf. Zeug et al. 2021). In addition, how processes are designed and activities organized *within* the socio-economic system impacts all aspects of human well-being (e.g., poverty, education, equality, peace, justice; SDGs 1, 4, 5, 10, 16).

This dissertation explores and quantifies the potentials of closing technical and biological cycles, exemplary for WEEE and 2G EtOH, as well as the environmental, social, and economic benefits and impacts that this entails. On a superordinate level, this dissertation addresses 16 of the 17 SDGs. While the first contribution is a case study, four of the five contributions (cf. section 1.2) focus on corporate or political decision-making in the context of strategic and sustainable supply network design. Section 1.1 introduces the principal employed methods, and section 1.2 summarizes the five contributions of this dissertation, their particular research questions, and which SDGs they address. Section 2 presents the contributions in full. Lastly, section 3 discusses the added value of the research (section 3.1) and lays out an agenda for future research (section 3.2).

1.1 METHODOLOGICAL BACKGROUND

At the highest level, the methodological foundation of this dissertation lies in the integration of methods, techniques, and hereby obtained results of the field of *Industrial Ecology* into models of the discipline of *Operations Research (OR).* Industrial ecology embraces the afore presented perspective on society-nature metabolisms, interpreting socio-economic activities as part of biophysical ecosystems (Haberl et al. 2019). It is "the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources" (White 1994, p. v). Systems modeling and life cycle thinking are indispensable for informed decision-making and are pivotal principles of Industrial Ecology (Lifset and Graedel 2002). The life cycle perspective requires the evaluation of, e.g., products and services quantitatively as well as vertically, 'from cradle to grave', from the extraction of resources to end-of-life management (Petti et al. 2018), or ideally 'from cradle to cradle' in a circular economy (Dahiya et al. 2020).

Life Cycle Sustainability Assessment (**LCSA**) is the umbrella concept of the *Industrial Ecology* methods employed in this dissertation. LCSA addresses the requirement for life cycle thinking and is the framework for a quantitative, transdisciplinary, and integrated assessment of the environmental, social, and economic pillars of sustainability of a system (UNEP 2011; Goffetti 2020). Its goal is to provide decision support and inform political and corporate decision-makers about the impacts of the system (Valdivia et al. 2021). Analogously to the three sustainability pillars, LCSA comprises the three methods Life Cycle Assessment (LCA), Social Life Cycle Assessment (SLCA), and Life Cycle Costing (LCC), with varying levels of methodological maturity and data availability (Valdivia et al. 2021). LCSA faces several challenges, ranging from lacking methodological consistency and standardization to availability and applicability of indicators and impact assessment methods (cf. Zeug et al. 2021). Applicable and case-specifically relevant quantitative indicators for measuring environmental and especially social sustainability change with scope, context, and regionality of the problem (Petti et al. 2018; Sikdar 2021). In addition, Zeug et al. (2021) state that the most common LCSA approach is an additive approach, where the individual results of LCA, SLCA, and LCC make up the overall LCSA. This creates a particular need for harmonization and synchronization of the results. They and others (e.g., Goffetti 2020) endorse an integrated instead of the additive approach, where social, environmental, and economic aspects are "integrated into a unified assessment and methodological framework", aligned with the aforementioned transdisciplinary, sociometabolic perspective, in which the environmental and socio-economics systems "are not seen as separate entities, but rather facets of one and the same object" (Zeug et al. 2021, p. 3). LCSA ultimately aims to bridge the gap between the transdisciplinary, sociometabolic perspective of Industrial Ecology and the "high-level shared blueprint" (Valdivia et al. 2021, p. 1) of the SDGs. The very first steps to formalize the link between LCSA results and affected SDGs are taken (Wulf et al. 2018; Weidema et al. 2020; Zeug et al. 2021), but the discrepancy between the political and country-level conceptualization of the SDGs and the micro-level and product- or process-focus of LCSA remains a challenge (Wulf et al. 2018).

Together with others, such as Material Flow Analysis (MFA) and environmentally extended input-output analysis, (environmental) **Life Cycle Assessment** (**LCA**) is a central method in Industrial Ecology (Shmelev 2012) and the most mature of the three methods of the LCSA framework. Life Cycle Assessment is used to model the input and output flows of material and energy along the entire life cycle and all stages of the value chain of a product, a service, a process, or a facility (Lifset and Graedel 2002). Figure 2 shows the methodological framework for Life Cycle Assessment. According to the ISO 14040 and 14044 (ISO 2006a, 2006b), an LCA study follows four steps. Step 1 (*goal & scope definition*) defines system boundaries, underlying assumptions, and the functional unit, i.e., a unit of a product, process, service, or facility, to which the further steps refer. In step 2 (*Life Cycle Inventory, LCI*), the functional unit is modeled in terms of the inputs and outputs that occur during its life cycle, often as a composition of a number of sub-processes, which in turn entail their own inputs and outputs. In step 3 (*Life Cycle Impact Assessment, LCIA*), the cumulated input and outputs are characterized to quantify their environmental impacts in various categories (midpoints), which can be aggregated to measure the overall damages to areas of protection (AoP, endpoints). Several existing LCIA methods differ in characterization factors, assumed time horizons, and impact and damage categories, which is not predefined by the ISO standard. Figure 2 presents the characterization exemplary for selected materials and midpoints, and based on the LCIA method ReCiPe 2016 (Huijbregts et al. 2016). ReCiPe 2016 comprises 18 midpoints and the three endpoints, damage to human health, damage to ecosystem quality, and damage to resource availability, which are measured in disability-adjusted life years (DALY), species-years (time-integrated species loss), and USD2013 (surplus costs), respectively. Step 4 represents an iterative evaluation of the three aforementioned steps and of intermediate and final results, as well as the provision of recommendations and conclusions (European Commission 2010).

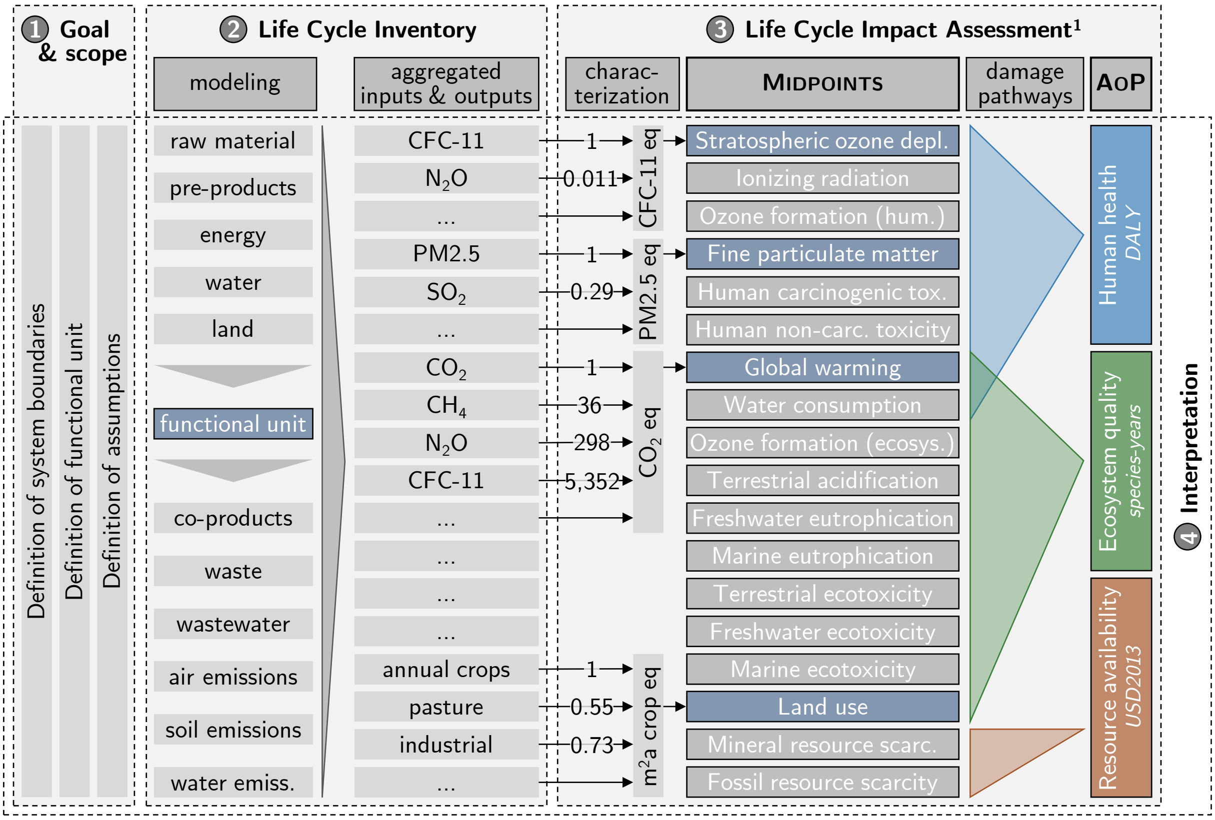


Figure 2. Four steps of Life Cycle Assessment, own depiction according to ISO 14040 and 14044 (ISO 2006a, 2006b). Exemplary cause-effect chains, impact categories (midpoints), and damage on areas of protection (AoP, endpoints). ¹ characterization factors, midpoints, and endpoints are representative for ReCiPe 2016 (Huijbregts et al. 2016).

Such a standardized approach with established impact and damage categories and widely accepted characterization and damage factors does not yet exist for **Social Life Cycle Assessment** (**SLCA**), the newest of the three LCSA methods (Goffetti 2020). In 2009, the Guidelines for Social Life Cycle Assessment (GSLCAP; UNEP/SETAC 2009) were a first attempt to align SLCA with LCA methodologically and to enable the assessment of "the social and socio-economic aspects of products and their positive and negative impacts along their life cycle" (Petti et al. 2018, p. 422). The GSLCAP and the succeeding GSLCAPO (Guidelines for Social Life Cycle Assessment of Products *and Organizations*; UNEP 2021a) define six central socio-economic stakeholders (*local community*, *society*, *workers*, *consumers*, *value chain actors*, *children*), comparable to LCA's areas of protection, and a total of 40 subcategories. In the accompanying Methodological Sheets (UNEP/SETAC 2013; UNEP 2021b), a total of 292 generic as well as site-specific qualitative, semi-quantitative, and quantitative indicators were proposed to measure impacts in terms of these sub-categories (Table 1).

Analogously to LCA, SLCA follows life cycle thinking and attempts "to consider impacts vertically through the supply chain" (Petti et al. 2018, p. 429). This separates SLCA from more company- or site-specific frameworks for CSR (corporate social responsibility), such as ISO 26000 (ISO 2010), the Sustainability Reporting Standards (GRI 2021), AccountAbility 1000 (AccountAbility 1999), or the SA8000 Standard (SAI

1997). The narrower and more horizontal scope of CSR eases its measurement. In contrast, the intricacy of SLCA and of achieving methodological parity with LCA lies in a standardized, guided, and non-arbitrary selection of suitable indicators (Kühnen and Hahn 2017) as well as in measuring a product system based on a functional unit. In LCA, the environmental impacts of the functional unit are "directly linked with physical input/output" flows (Wu et al. 2014, p. 4208) that refer to the functional unit and that can be characterized (cf. Figure 2). SLCA assesses impacts on stakeholders *within* the socio-economic system, and these impacts are "rather related to the behavior of a company instead of the function delivered by a given product" (Wu et al. 2014, p. 4208). For practitioners, this means that a mere CSR assessment of the company or specific sites is more practicable than a life cycle-based, vertical assessment of its and its products' social impacts along the value chain. In academia, the methodological challenges lead to an imbalance in the development of SLCA. Most studies contribute to a "bottom-up" development, i.e., learning about social impacts based on local case studies, while more approaches that develop SLCA "top-down" are needed, or else one risks overlooking cause-effect chains of decisions (Jørgensen 2013, p. 298). Despite the sharp increase in SLCA studies that could be observed after the initial publication of the GSLCAP, SLCA in literature is still deficient despite the advances made. Achieving parity with LCA by fully realizing and standardizing the life cycle idea and the systemic approach of Industrial Ecology remains a research gap in SLCA – especially with regards to functional unit definitions, indicator selection, data availability, and social impact assessment (Kühnen and Hahn 2017; Petti et al. 2018).

Life Cycle Costing (**LCC**) is the third component of LCSA. Its goal is "to capture all costs across the life cycle", complementary to LCA (Swarr et al. 2011, p. 390). In contrast to the mere price of a product, costs occurring from cradle (e.g., R&D) to grave (e.g., end-of-life, via the use phase) are "borne by different actors" (Swarr et al. 2011, p. 390) at different life cycle stages. An LCC thus may incorporate different perspectives, such as the producer's, the consumer's, or society's. Since this dissertation focuses on the environmental and social pillars of sustainability and on the advancement of the application of LCA and SLCA, a holistic and differentiated LCC is not part of this work. Instead, as unlocking available environmental and social potentials (of, e.g., WEEE recovery or 2G EtOH production) needs to be economically feasible, the economic dimension is represented by the associated costs and revenues from a producer's perspective. Extending the existing work by a differentiated LCC should, however, be part of a future research agenda (cf. section 3.2).

Table 1. The six stakeholder categories and 40 subcategories defined in the Guidelines for Social Life Cycle Assessment of Products and Organizations (UNEP 2021a) with numbers of generic and more CSR-focused, site-specific indicators proposed by the accompanying Methodological Sheets (UNEP/SETAC 2013; UNEP 2021b).

Stake-holder category	**Subcategory**	**Proposed indicators**		
		total	*generic*	*site-specific*
Local Community	Delocalization and migration	7	*4*	*3*
	Community engagement	8	*4*	*4*
	Cultural heritage	9	*3*	*6*
	Respect of indigenous rights	9	*4*	*5*
	Local employment	7	*4*	*3*
	Access to immaterial resources	7	*4*	*3*
	Access to material resources	8	*5*	*3*
	Safe and healthy living conditions	7	*4*	*3*
	Secure living conditions	6	*3*	*3*
Society	Public commitment to sustainability issues	8	*3*	*5*
	Prevention and mitigation of conflicts	6	*4*	*2*
	Contribution to economic development	6	*3*	*3*
	Corruption	8	*3*	*5*
	Technology development	6	*3*	*3*
	Ethical treatment of animals	9	*0*	*9*
	Poverty alleviation	4	*1*	*3*
Worker	Freedom of association and collective bargaining	11	*4*	*7*
	Child labour	8	*3*	*5*
	Fair salary	10	*4*	*6*
	Hours of work	7	*2*	*5*
	Forced labour	8	*4*	*4*
	Equal opportunities / discrimination	8	*3*	*5*
	Health and safety	11	*2*	*9*
	Social benefit / social security	6	*3*	*3*
	Employment relationship	4	*1*	*3*
	Sexual harassment	4	*1*	*3*
	Smallholders including farmers	14	*1*	*13*
Consumer	Health and safety	9	*4*	*5*
	Feedback mechanism	6	*3*	*3*
	Consumer privacy	7	*4*	*3*
	Transparency	10	*3*	*7*
	End-of-life responsibility	4	*2*	*2*
Value Chain Actors	Fair competition	9	*5*	*4*
	Respect of intellectual property rights	4	*2*	*2*
	Supplier relationships	4	*0*	*4*
	Promoting social responsibility	7	*2*	*5*
	Wealth distribution	4	*1*	*3*
Children	Education provided in the local community	9	*1*	*8*
	Health issues for children as consumers	5	*1*	*4*
	Children concerns regarding marketing practices	8	*4*	*4*
Six stakeholder categories with 40 subcategories and respective indicators:		292	*112*	*180*

In this dissertation, LCAs and SLCAs are conducted, and their results are integrated into mathematical optimization models to quantify the effects of strategic network design decisions. Strategic network design comprises the long-term planning tasks along both forward and reverse supply chains (Nuss et al. 2015), such as facility locations and capacities, the structure of the distribution system, supplier selection, and strategic sales planning (Meyr et al. 2015). Mathematical modeling of complex real-world decision problems (here: strategic decisions in supply networks) is at the core of the field of *Operations Research* (Domschke et al. 2015, p. 3) and a typical approach to solving network design problems (c.f., Goetschalckx and Fleischmann 2015). Here, (**mixed-integer**) **linear programming** (**MILP**) is an important technique to identify optimal decisions under certain restrictions. Decisions, i.e., degrees of freedom of the decision-maker, are expressed as (partly integer or Boolean type) decision variables (Suhl and Mellouli 2013, p. 6). They are taken according to a defined objective, expressed as an objective function, and are limited by a number of linear constraints, expressed as (in-)equations (Stadtler 2015). Parameters quantify the contribution of a decision variable to the optimization of the objective function, i.e., the minimization of maximization of the objective value, as well as the contribution to the exhaustion of the constraints. In the work at hand, LCA and SLCA results as well as economic data are operationalized and used as input parameters in mathematical optimization models. This allows for determining the effect of strategic network decisions on different environmental and social categories and, by formulating environmental, social, and economic objective functions, for identifying *optimal* decisions for each category.

Dealing with a vast array of different environmental, social, and economic objectives almost necessitates that two or more objectives are mutually conflicting, while others may be mutually complementary or neutral. How conflicting two objectives can be measured by the degree of goal achievement of one objective when optimizing the other, and vice versa. Be z_i^* the objective value of maximized objective i and $z_i(\boldsymbol{x})$ the achieved value of objective i with a solution $\boldsymbol{x}$, then $z_i(\boldsymbol{x})/z_i^*$ is the degree of goal achievement (Domschke and Scholl 2008). When $\boldsymbol{x}_j^*$ is the optimal solution of another objective j and $z_i(\boldsymbol{x}_j^*) < z_i^*$, then i and j are conflicting. In the contributions of this dissertation, the term ‘opportunity costs’ is used to describe the percental detriment of one objective i when maximizing another objective j, i.e., $\left(z_i(\boldsymbol{x}_j^*) - z_i^*\right)/z_i^*$.

Usually, a solution $\boldsymbol{x}$ in a maximization problem is considered a suitable trade-off between two conflicting objectives when it is Pareto-optimal, meaning that there is no other solution $\boldsymbol{x}'$, such that $z_i(\boldsymbol{x}') > z_i(\boldsymbol{x})$ and $z_j(\boldsymbol{x}') \geq z_j(\boldsymbol{x})$ (Chircop and Zammit-Mangion 2013). However, the Pareto-optimal set may comprise several or even an infinite number of non-dominated solutions. This requires a preference on behalf of the decision-maker and a willingness to sacrifice a certain degree of goal achievement in one or each of the objectives. There are several OR methods for multi-criteria (here: bi-objective) optimization problems that are able to identify possible trade-offs. When a meaningful set of weights exist to combine several objectives into one objective function, weighted sum approaches yield the advantage of simplicity and can produce a set of Pareto-optimal solution. However, they cannot identify solutions in non-convex parts of Pareto-optimal frontiers (Chircop and Zammit-Mangion 2013), and determining the weights requires an a-priori preference of the decision-maker, which may bias the balance between the diverse environmental, social, and economic sustainability issues (Finkbeiner et al. 2010). In problems where the objectives can be arranged in meaningful priority order (e.g., $i > j$), lexicographical optimization is a possible method. Here, single-objective optimization of the dominant objective i results in a set of optimal solutions, which constitute the solution space for the secondary objective j. One disadvantage is that this is not feasible with only *one* optimal solution for i and thus optimization of j requires i to be allowed to deviate from *the* optimal solution to some degree (Domschke et al. 2015, p. 62). Furthermore, as this dissertation aims at advancing the environmental and social dimensions in the application of LCSA, a-priori prioritizing would counteract this goal. Two methods that rely on the individual objective values of two objectives, z_i^* and z_j^*, are distance functions (e.g., goal programming) and the ε-constraint method. Distance functions minimize the overall distance (1-norm, 2-norm (Euclidean), or higher) between achieved and desired values (e.g., the objective values). They can, and sometimes need to, include a-priori weighting factors with the aforementioned drawbacks, and relative instead of absolute distances (Domschke et al. 2015, p. 65). The (here: equidistant) ε-constraint method is another way and a standard method to systematically construct an unbiased set of Pareto-optimal solutions, from which a decision-maker can choose a posteriori. Between the two anchor points $z_i(\boldsymbol{x}_i^*)$ and $z_j(\boldsymbol{x}_j^*)$, for both maximization objectives, a set of n values ε_i^k and ε_j^k, with $k = 0, \dots, n+1$, is determined with $\varepsilon_j^k = z_j(\boldsymbol{x}_i^*) + \left(z_j(\boldsymbol{x}_j^*) - z_j(\boldsymbol{x}_i^*)\right) * \frac{k}{n+1}$ (and vice versa for ε_i^k). By solving the single-objective problem

$$\begin{gathered} \max \ z_i(\boldsymbol{x}) \\ \text{s.t.} \ \ z_j(\boldsymbol{x}) \geq \varepsilon_j^k \end{gathered}$$

iteratively for each k and vice versa for $z_i(\boldsymbol{x})$ and ε_i^k, a Pareto-efficient frontier is obtained. This is done in Contributions B, D, and E (section 1.2). The equidistant ε-constraint method yields the benefits of intuitive applicability in a bi-criterion problem (Chircop and Zammit-Mangion 2013) with an unbiased view on the, e.g., environmental, social, or economic, objectives.

1.2 CONSTITUENT ELEMENTS OF THIS DISSERTATION

In this subsection, contributions A, B, D, C, and E (in this order, following the covered sustainability dimensions) are summarized. Table 2 lists the constituent contributions of this dissertation, with their different scopes, perspectives, products, industries, methods, and sustainability categories. While Contributions A & B address technical cycles by the example of (i.a.) business-to-customer (B2C) and business-to-business (B2B) WEEE, respectively, Contributions D & E focus on the European bioeconomy and second-generation bioethanol. Here, Contributions A & D assume a policy perspective on the municipal / regional and EU level, respectively, while Contribution B is conducted from the point of view of an original equipment manufacturer (OEM). Contribution A evaluates reuse potentials from a feasibility perspective and thus follows the implicit sustainability goals of a circular economy, and Contributions B & D & E explicitly assess environmental benefits and impacts of decision-making in their respective application cases. Contributions C & E distinctly address the social pillar of sustainability. Methodologically, Contributions B & D & E are optimization studies and parameterize mixed-integer linear programming models with (S)LCA-based data, while Contribution C explores the state of the art in socially sustainable supply chain optimization by means of a structured literature review.

In detail, **Contribution A** addresses the technical cycle of a circular economy on a regional and municipal level and for B2C products. The study quantifies the potential for preparation for reuse in Bavaria. Reuse is the second priority of the European waste management hierarchy after waste prevention and before lower-value recovery options (Directive 2008/98/EC). The study presents a methodology for the quantitative assessment of potentially reusable wastes, which is carried out for the case of WEEE, used furniture, and used leisure goods at 61 waste collection points (Ger. *Wertstoffhöfe*) in different urban or rural municipalities in the German state of Bavaria. For the aforementioned wastes as well as other bulky products or ones with hazardous or recoverable materials, municipally operated waste collection points and collection containers are the primary disposal sites for consumers and thus are expected to yield the highest reuse potential for B2C products (Parajuly and Wenzel 2017; Curran et al. 2007; WRAP 2011). 3,827 electric and electronic devices, 1,132 pieces of used furniture, and 245 used leisure goods are examined. Each assessed piece is assigned a quality level and, if the piece is damaged, a suspected cause of damage. Based on this assessment, the piece's theoretical potential for reuse is determined. For example, an undamaged piece with high quality could theoretically directly be prepared for reuse, while a piece with low quality is inapt for preparation for reuse and is thus only suited for lower-value recovery options such as recycling. Between these extrema are those cases with medium quality, where the damage has either been inflicted after the waste threshold, i.e., at the collection site, or only before the waste threshold, i.e., during use. Unlocking reuse potentials in these cases would require changes in the handling at collection sites and fundamental political and market changes, respectively. The potentials determined for the assessed sample are extrapolated to the overall waste streams in Bavaria (LfU 2016). Contribution A answers the following research question:

RQ1: What is the quality of different waste streams in different classes of municipalities, and what are the causes of damages?

RQ2: What is the resulting theoretical potential for the preparation for reuse in Bavaria?

RQ3: Which actions recommendations result from the main obstacles to realizing this potential at Bavarian collection points?

Contribution B also addresses the technical cycle, but on EU level and for B2B WEEE. According to the EU directive on WEEE, OEMs and retailers are obliged to take back a large share of end-of-life products (Directive 2012/19/EU). This follows the EU's goal to collect and recycle, by 2019, at least 65% per year of those devices put on the market in the three preceding years (Directive 2008/98/EC). However, only Bulgaria, Croatia, and Poland met this quota in 2019, and 10 member states did not even meet the previous target of 45% (Eurostat 2022). In addition, the vast majority of collected WEEE is recycled instead of being reused, refurbished, or remanufactured. The joint legal framework in the European Union and the importance of this waste stream suggest notable economies of scale for OEM-borne recovery networks on the European scale. Furthermore, as electronic equipment manufacturing is a significant driver of environmental pressure (Quariguasi Frota Neto et al. 2010), higher-value recovery options promise vast environmental benefits. However, collection and recovery is often carried out by third-party logistics providers in lieu of OEMs and devices only recycled, which is partially ascribed to bureaucratic obstacles associated with trans-border registration of hazardous wastes (Nuss et al. 2016). This study thus explores the benefits of optimal configurations of European networks for high-value recovery of WEEE. The network's configuration comprises decisions on the location and technology of collection centers and recovery centers, on regional collection amounts by the OEM and by third-party recyclers, on transportation flows between regions and collection centers, as well as between collection and recovery centers. These decisions are linked with economic (revenues, costs) and environmental (saved impacts of primary production due to recovery, exerted impacts of the network) data. The latter are LCA results in 21 categories (18 midpoints & three endpoints; cf. Figure 2). This includes but is notably not limited to *global warming*. The problem is solved in a model for mixed-integer linear programming (MILP), where each of the economic and 21 environmental categories represents separate objective functions. First, these 22 objective functions are optimized individually to determine optimal decisions and resulting objective values for each category. Subsequently, conflicts and congruencies between the 22 objectives are evaluated based on mutual opportunity costs, and possible trade-offs are derived from Pareto optimization with the ε-constraint method. In detail, Contribution B answers the following research questions:

RQ1: What are optimal configurations of a European WEEE recovery network?

RQ2: What are economic and environmental benefits of network configurations in comparison to third-party recycling?

RQ3: How does the quantity of collectible WEEE affect the results?

In contrast to Contributions A and B, **Contribution D** addresses the biological cycle. In particular, the study assesses the environmental potentials of second-generation bioethanol (2G EtOH) in comparison with first-generation bioethanol (1G EtOH) and fossil petrol in a network optimization study. Instead of taking an OEM perspective, the assessment is carried out on the level of EU policy-making. Decisions of the generic

Greenfield optimization model include feedstock (straw) sourcing and transportation, locations and capacities of biorefineries, distribution of 2G EtOH, and whether to substitute 1G EtOH or petrol. Similar to Contribution B, the model of Contribution D comprises an economic objective and separate 21 environmental objective functions (18 midpoints & three endpoints; cf. Figure 2) with LCA-based parameterization. In addition, as 2G EtOH is only just on the verge of commercialization (Hjuler and Hansen 2018), the study considers five different taxation scenarios to differentiate the economic dimension further and to discuss political levers to support the creation of large-scale production networks for 2G EtOH with the associated realizable environmental benefits. Scenario T1 represents the status quo of bioethanol taxation in each EU member state (European Commission 2020). In scenarios T2 and T3, an excise tax abatement of –50% and –100% is assumed for each country, respectively. Finally, scenarios T4 and T5 assume the introduction of an EU-wide carbon tax of €50 (based on World Bank 2019) and €375 (based on Ricke et al. 2018), respectively. As in Contribution B, the 22 objective functions are first maximized independently, and opportunity costs and Pareto-optimal trade-offs between relevant objectives are calculated, with particular attention to the different taxation scenarios. In detail, Contribution D answers the following research questions:

RQ1: What are the benefits of optimal second-generation ethanol production network configurations to substitute petrol and first-generation ethanol, considering different environmental and economic aspects?

RQ2: Which environmental objectives are congruent, and which are conflicting (considering LCIA midpoints and endpoints)?

RQ3: Which taxation scenario supports the scale-up of a second-generation ethanol production network in the European Union?

By calculating opportunity costs and Pareto-efficient solutions, Contributions B and D demonstrate that the environmental dimension should not be limited to *global warming* (Sikdar 2021) and that decisions with a unilateral focus on one category may lead to unwanted adverse consequences in a whole array of others. While the more holistic approach of LCA is still lacking in many similar articles on strategic network optimization, LCA's applicability in such optimization models has been proven (Eskandarpour et al. 2015). However, the same cannot be said about the social dimension, where indicators are much more complex, subjective, and qualitative and lack theoretical underpinning and often data (Chazara et al. 2017). This is particularly true for positive and negative impacts of strategic decisions in Greenfield optimization models. **Contribution C** explores the state of the art in integrating social aspects and indicators in the field of strategic network design. In a structured literature study, 91 studies are identified and analyzed in detail. This includes, inter alia, whether CSR or SLCA frameworks (such as the GSLCAP; UNEP/SETAC 2009) are cited, whether framework citing leads to more quantitatively applied indicators, which social aspects are addressed in optimization models with which application case, and which quantitative indicators are used. Following this qualitative evaluation, the review analyzes how the social indicators are integrated as parameters in optimization models of the 91 studies. This comprises 85 social objective functions and 14 socially motivated model constraints. Lastly, the objective functions are analyzed for their unit (e.g., ‘jobs’), especially in those few cases where more than one indicator is applied. In detail, Contribution C answers the following research questions:

RQ1: What frameworks for social assessment are referred to, what social aspects are considered, and how is their selection justified?

RQ2: How are social indicators incorporated into quantitative models?

Contribution C finds that indicators are often selected arbitrarily, the number of jobs created is often the only applied indicator, and many studies rely on simplistic weighting methods to assemble social parameters or to aggregate objective function terms with different units. **Contribution E** addresses these research gaps. First, it provides a best-practice approach for a structured selection of a comprehensive set of quantitative and operationalizable social indicators based on existing SLCA frameworks. Second, from the indicators and categories provided by the GSLCAPO (UNEP 2021a), nine applicable SLCA indicators are selected and operationalized for use as MILP model parameters. Based on the case and model of Contribution D, nine social objective functions are formulated and solved individually, alongside the previous economic and 21 environmental objectives. In addition, results from the Social Hotspots Database (SHDB) are used to quantify global social hotspots in additional 25 categories when optimizing different objective functions. Similar to Contribution B and D, but with a particular focus on social optimization and social hotspots, Contribution D answers the following first research question:

RQ1: What are the social benefits, impacts, and hotspots of socially, environmentally, and economically optimal large-scale production networks for second-generation bioethanol in the EU?

The prevalent neglect of the social dimension not only hinders a holistic ex-ante LCSA of strategic supply chain decisions but also leaves decision-makers uninformed about the impacts of their decisions on at least 7 SDGs entirely (cf. Table 3) and a vast array of SDG sub-targets. The social, environmental, and economic categories assessed in Contribution E can be linked with 16 of the 17 SDGs. In this way, the conflicts and congruencies between them also represent the relation between the associated SDGs. This approach enables decision-makers to pay attention to cases where the pursuit of one SDG may potentially have negative consequences on another. This is reflected in the second and final research question of Contribution E:

RQ2: Which SDGs are affected, and what are conflicts and congruencies between them?

Table 2. Contributions A – E and their characteristics at a glance (with title & main or idealized research question)

Contri-bution	**Type of study**	**Methods**	**Sustainability dimension**	**Product / industry**	**Perspective / recipient**
A	Potentials of preparation for reuse: A case study at collection points in the German state of Bavaria *RQ: What is the theoretical potential for preparation for reuse in Bavaria?*				
	empirical	observation	(feasibility)	WEEE (B2C) used furniture leisure goods	municipal / regional policy-makers
B	Economic and environmental benefits of recovery networks for WEEE in Europe *RQ: What is the benefit of optimal configurations of a WEEE recovery network compared to third-party recycling, considering economic and different environmental aspects?*				
	optimization study	MILP model LCA	economic environmental	WEEE (B2B)	OEMs
C	How to quantify social impacts in strategic supply chain optimization: State of the art *RQ: What is the state of the art of integrating social aspects in the field of strategic supply chain optimization?*				
	state of the art review	literature search	social		academia
D	Environmental benefits of large-scale second-generation bioethanol production in the EU: An integrated supply chain network optimization and life cycle assessment approach *RQ: What are the benefits of optimal second-generation ethanol production networks to substitute petrol and first-generation ethanol, considering different environmental and economic aspects?*				
	optimization study	MILP model LCA	economic environmental	2G EtOH	EU policy-makers
E	Assessing the social dimension in strategic network optimization for a sustainable development: The case of bioethanol production in the EU *RQ: What are the social benefits, impacts, and hotspots of socially, environmentally, and economically optimal large-scale second-generation bioethanol production networks in the EU?*				
	optimization study	MILP model LCA SLCA	economic environmental social	2G EtOH	EU policy-makers & OEMs

In one way or another, the five contributions themselves concern different Sustainable Development Goals (SDGs). Table 3 shows which of the assessments made and insights provided in Contributions A, B, D, and E can be linked with the 17 SDGs on the level of the overarching goals, sub-ordinate targets (T), or even single indicators (I) of the SDGs (the literature review of Contribution C not included).

Contribution A, with its narrow focus on the reuse of goods at municipal waste collection points, lays the groundwork for an improvement of Target 6 of SDG11 and especially Target 5 of SDG12 (“By 2030, substantially reduce waste generation through prevention, reduction, recycling, and reuse”) on the municipal or regional level. Detailed knowledge of the potential for reuse enables action recommendations for municipal or regional policy-makers to unlock these potentials (Contribution A; Boldoczki 2022). Furthermore, since product reuse yields significant savings potentials vis-à-vis primary production in many cases (Boldoczki et al. 2020), the potentials presented in Contribution A also serve as an upper bound of the overall achievable environmental savings in various environmental impact categories identified in the follow-up article by Boldoczki et al. (2021).

Contributions B and D provide detailed information on optimal configurations and resulting environmental impacts of WEEE and second-generation bioethanol networks, respectively, on the level of LCIA midpoints and endpoints. This allows for identifying the implications for SDG3[1], SDG6[2], SDG11[3], SDG12[4], SDG13[5], SDG14[6], and SDG15[7]. The economic evaluations of the two contributions are linked with SDG7 and SDG8. Complementing the economically- and environmentally-focused SDGs, the results of Contribution E concern the remaining, socially-focused SDGs (except for SDG17, the targets of which are beyond the system boundaries of this dissertation’s contributions). This is explored in more detail in Contribution E and the accompanying Supporting Information.

---

[1] linked to the endpoint *human health* and the midpoints *stratospheric ozone depletion*, *ionizing radiation*, *ozone formation (human health)*, *fine particulate matter formation*, and *human carcinogenic* and *non-carcinogenic toxicity*

[2] linked to *water consumption*

[3] linked to *fine particulate matter formation* and *land use*

[4] linked to *mineral* and *fossil resource scarcity*

[5] linked to *global warming*

[6] linked to *ecosystem quality*, *marine eutrophication*, and *marine ecotoxicity*

[7] linked to *ecosystem quality*, *ozone formation (terrestrial ecosystems)*, *terrestrial acidification*, *freshwater eutrophication*, *terrestrial ecotoxicity*, and *freshwater ecotoxicity*

Table 3. Matching between Contributions A, B, D, and E and the SDGs, implicitly or explicitly, on the level of the overall goals, their sub-ordinate targets (T), or individual indicators (I).

Sustainable Development Goals		**A**	**B**	**D**	**E**
SDG1	NO POVERTY				■
SDG2	ZERO HUNGER				■
T3	Double the [...] incomes of small-scale food producers [...]				■
SDG3	GOOD HEALTH AND WELL-BEING		■	■	■
T3	End the epidemics of [...] communicable diseases				■
T4	Reduce by one third premature mortality from non-communicable diseases [...]				■
T9	I1 Mortality rate attributed to household and ambient air pollution		■	■	■
Tc	Increase health financing [...] of the health workforce in developing countries [...]				■
SDG4	QUALITY EDUCATION				■
T1	Ensure that all girls and boys complete free, equitable and quality [...] education [...]				■
SDG5	GENDER EQUALITY				■
SDG6	CLEAN WATER AND SANITATION		■	■	■
T1	Achieve universal and equitable access to safe and affordable drinking water for all				■
T2	Achieve access to adequate and equitable sanitation and hygiene for all [...]				■
T4	Increase water-use efficiency [...] & ensure sustainable withdrawals [...] of freshwater [...]		■	■	■
	I2 Level of water stress [...]				■
SDG7	AFFORDABLE AND CLEAN ENERGY			■	■
SDG8	DECENT WORK AND ECONOMIC GROWTH		■	■	■
T1	Sustain per capita economic growth [...]				■
T2	Achieve higher levels of economic productivity [...]		■	■	■
T5	Achieve full and productive employment and decent work for all [...], and equal pay [...]				■
	I1 Average hourly earnings of female and male employees [...]				■
	I2 Unemployment rate [...]				■
T7	Take immediate and effective measures to eradicate forced labour [...]				■
T8	Protect labour rights and promote safe and secure working environments for all [...]				■
	I1 Frequency rates of fatal and non-fatal occupational injuries [...]				■
SDG9	INDUSTRY, INNOVATION AND INFRASTRUCTURE				■
T3	I1 Proportion of small-scale industries in total industry value added				■
SDG10	REDUCED INEQUALITIES				■
T3	Ensure equal opportunity and reduce inequalities of outcome [...]				■
SDG11	SUSTAINABLE CITIES AND COMMUNITIES	■	■	■	■
T3	Enhance [...] capacity for [...] sustainable human settlement planning [...]		■	■	■
T6	Reduce the adverse per capita environmental impact of cities [...]	■	■	■	■
	I2 Levels of fine particulate matter (e.g., PM2.5 & PM10) [...] (population weighted)				■
SDG12	RESPONSIBLE CONSUMPTION AND PRODUCTION	■	■	■	■
T2	Achieve the sustainable management and efficient use of natural resources		■	■	■
T5	Reduce waste generation through prevention, reduction, recycling and reuse	■	■		
SDG13	CLIMATE ACTION		■	■	■
SDG14	LIFE BELOW WATER		■	■	■
T1	[...] reduce marine pollution of all kinds, in particular from land-based activities [...]		■	■	■
SDG15	LIFE ON LAND		■	■	■
T1	Ensure the conservation [...] of terrestrial and inland freshwater ecosystems [...]		■	■	■
SDG16	PEACE, JUSTICE AND STRONG INSTITUTIONS				■
T1	Significantly reduce all forms of violence and related death rates everywhere				■
T3	Promote the rule of law [...] and ensure equal access to justice for all				■
T5	Substantially reduce corruption and bribery in all their forms				■
SDG17	PARTNERSHIPS FOR THE GOALS				

2

CONTRIBUTIONS

CONTRIBUTION A

POTENTIALS OF PREPARATION FOR REUSE: A CASE STUDY AT COLLECTION POINTS IN THE GERMAN STATE OF BAVARIA

Lukas Messmann*, Sandra Boldoczki, Andrea Thorenz & Axel Tuma

Published 2019 in the Journal of Cleaner Production, 211, 1534-1546.

* *Corresponding author*

Available under: https://doi.org/10.1016/j.jclepro.2018.11.264

ABSTRACT

This research addresses the second priority of the waste management hierarchy and the demand for a circular economy. First, we develop a methodology for the quantitative assessment of potentially reusable wastes. Second, based on empirically retrieved primary data following the developed methodology, this study quantifies a theoretical potential for the preparation for reuse of Waste Electric and Electronic Equipment (WEEE), used furniture, and used leisure goods in the German state of Bavaria. We find that between 13% and 16% of these waste streams could immediately be prepared for reuse, depending on the type of waste. A further potential of 13% to 29% could be unlocked through changes to the mode of collection, storage, and the overall treatment of wastes at Bavaria collection points. Most notably, 86% of identifiable damage causes of WEEE are attributed to a lack of sufficient weatherproof roofing. Conclusively, we derive four key action recommendations for unlocking existing potentials.

CONTRIBUTION B

ECONOMIC AND ENVIRONMENTAL BENEFITS OF RECOVERY NETWORKS FOR WEEE IN EUROPE

Lukas Messmann*, Christoph Helbig, Andrea Thorenz & Axel Tuma

Published 2019 in the Journal of Cleaner Production, 222, 655-668.

** Corresponding author*

Available under: https://doi.org/10.1016/j.jclepro.2019.02.244

ABSTRACT

The EU directive on Waste Electrical and Electronic Equipment (WEEE) imposes the obligation to collect a large share of the end-of-life products on electronics manufacturers. Environmental aspects, however, are often considered only rudimentarily. Based on previous research and real-world data, a mixed-integer linear programming (MILP) model of a European reverse network for WEEE is developed, including collection, high-value recovery, or third-party collection and recycling. The results comprise optimal network decisions and corresponding opportunity costs for economic and 21 environmental categories (18 midpoints, three endpoints). The evaluation of the environmental impact is based on data from the ecoinvent database, characterized using the ReCiPe 2016 Life Cycle Impact Assessment (LCIA) method. The results unveil conflicts and congruencies between the objectives. Collection and high-value recovery are preferable in up to six countries for economically optimal networks and in up to 15 countries with optimal benefits for *global warming* and *fossil resource depletion*. Discrepancies in objective values are larger between economic and most of the environmental solutions than in between most of the environmental ones. The dimensions *land use* and *freshwater eutrophication* show the least conflicts with the economic rationale. Solutions for *mineral resource depletion* prefer third-party collection and recycling. Conflicts between solutions are resolved by the ε-constraint method. Sensitivity analyses show the robustness of key findings. This study emphasizes the importance of a broad assessment of environmental impacts as well as mutual economic and environmental opportunity costs in large-scale recovery networks for WEEE.

CONTRIBUTION C

HOW TO QUANTIFY SOCIAL IMPACTS IN STRATEGIC SUPPLY CHAIN OPTIMIZATION: STATE OF THE ART

Lukas Messmann*, Victoria Zender, Andrea Thorenz & Axel Tuma

Published 2020 in the Journal of Cleaner Production, 257, 120459.

* *Corresponding author*

Available under: https://doi.org/10.1016/j.jclepro.2020.120459

ABSTRACT

The development of quantitative social indicators and methods for social impact assessment is not yet on par with their environmental counterparts. This deficit is especially apparent in strategic supply chain optimization. This literature study reviews 91 articles on strategic supply chain optimization to identify the state-of-the-art in this field and to derive a meaningful agenda for future research. First, the review gives an overview on social frameworks, how articles use them to justify the selection of specific social aspects in their studies, and the differences in selected aspects between different kinds of case studies. Second, the social objective functions are compared in detail. This includes social indicators, i.e., how certain aspects are measured, and how they are integrated in optimization models as input parameters. This allows for an analysis of the relations between decision variables (e.g., for facility location or material flows) and attributed social impacts, as well as of the aggregation of social impacts with different units within the same function. Our results show that the number of created jobs is often the only or primary indicator. If more than one indicator is employed in objective functions, a sizable number of studies addresses the problem of aggregation by weighting towards a dimensionless, generic social score. This review sheds light on the need for more sophisticated methods of social impact assessment and social Pareto optimization. It also assists researchers in identifying previously used, feasible parameters in optimization models, in order to contribute to a more comprehensive and more consistently applied set of social indicators.

CONTRIBUTION D

ENVIRONMENTAL BENEFITS OF LARGE-SCALE SECOND-GENERATION BIOETHANOL PRODUCTION IN THE EU:

AN INTEGRATED SUPPLY CHAIN NETWORK OPTIMIZATION AND LIFE CYCLE ASSESSMENT APPROACH

Lars Wietschel*, Lukas Messmann, Andrea Thorenz & Axel Tuma

* *Corresponding author*

Published 2021 in the Journal of Industrial Ecology, 25(3), 677-692. This article met the requirements for a gold-gold JIE data openness badge (http://jie.click/badges).

Available under: https://doi.org/10.1111/jiec.13083
Corrigendum: https://doi.org/10.1111/jiec.13255

ABSTRACT

The use of agricultural residues for the generation of bioethanol has the potential to substitute fuels such as petrol or first-generation bioethanol and thereby generate environmental benefits. Scientific research in this field typically confines the environmental dimension to global warming, disregarding other environmental impact and damage categories. By multi-criteria mixed-integer linear programming, this work examines environmental benefits and economic viability of optimal second-generation bioethanol production network configurations to substitute petrol and/or first-generation bioethanol in the EU. The results comprise environmentally optimal decisions for 18 impact and three damage categories, as well as economically optimal solutions for different excise and carbon tax scenarios. The impact categories global warming potential, particulate matter, and land use are affected the most. Optimal network decisions for different environmental objectives can be clustered into three groups of mutual congruencies, but opportunity costs between the different groups can be very high, indicating conflicting decisions. The decision to substitute petrol or first-generation ethanol has the greatest influence. The results of the multi-dimensional analysis suggest that the damage categories human health and ecosystem quality are suitable to unveil trade-offs between conflicting environmental impacts, e.g., global warming and land use. Taking human health and ecosystem quality as environmental decision criteria, second-generation bioethanol should be used to concurrently substitute first-generation bioethanol and petrol (100% and 18% of today's demand in the EU respectively). However, economic optimization shows that with current taxation, bioethanol is hardly competitive with petrol, and that excise tax abatement or carbon taxes are needed to achieve these volumes.

CONTRIBUTION E

ASSESSING THE SOCIAL DIMENSION IN STRATEGIC NETWORK OPTIMIZATION FOR A SUSTAINABLE DEVELOPMENT: THE CASE OF BIOETHANOL PRODUCTION IN THE EU

Lukas Messmann*, Lars Wietschel, Andrea Thorenz & Axel Tuma

* *Corresponding author*

This article met the requirements for a gold-gold JIE data openness badge (http://jie.click/badges).

The manuscript printed here represents the version of Contribution E under revision. Until publication the manuscript underwent further changes and was eventually accepted and published. When citing Contribution E, please read first and only refer to the version published online 2022 in the Journal of Industrial Ecology.

Available under: https://doi.org/10.1111/jiec.13324

ABSTRACT

The complexity of social indicators and their subjective and often qualitative nature render their inclusion into quantitative optimization models for network design and strategic decision-making challenging. The social dimension is thus often implemented only rudimentarily, thwarting a holistic sustainability assessment and neglecting many of the social issues addressed in the Sustainable Development Goals (SDGs). This work presents a structured process for including a comprehensive set of social aspects by selecting applicable quantitative and regionalized social indicators. This approach is applied to the case of second-generation bioethanol production in the EU. Based on inter alia the Guidelines for Social Life Cycle Assessment of Products and Organizations, the Social Hotspots Database, state-of-the-art literature, as well as previous work, we compile 9 social objective functions and 25 functions for social hotspot identification. They are evaluated alongside one economic and 21 environmental LCA-based objective functions in a mixed-integer linear programming (MILP) model. Key results show that social optimization either leads to large, labor-intensive or regionally focused, indicator-driven networks. *Injuries and fatalities* in the feedstock sectors of Central and Eastern European countries is the primary social hotspot. On the level of the overarching SDGs, SDG13 is most congruent with other goals, while SDG7 is hindered by pursuing other goals. This study's approach is novel in strategic network design and the European bioeconomy, and, by operationalizing the social dimension, enables a more holistic life cycle sustainability assessment and the consideration of the SDGs.

1 INTRODUCTION

For decades, most companies oriented their strategic supply chain design solely towards economic performance. To address the challenges of our time, the United Nations formulated the Sustainable Development Goals (SDGs; United Nations, 2015) to provide a common ground for peace, prosperity, health and education, reduced inequality, while tackling climate change and biodiversity loss. In 2019, 72% of over 1,000 globally acting companies mentioned the SDGs in their reporting, although only 1% measured their actual performance (PwC, 2019). Companies are hence aware of their role in achieving sustainable development, but not of their actual impact. Incorporating operationalized environmental, economic, and social indicators as early as in strategic decision-making is the basis of aligning with the 17 SDGs.

While the SDGs are the "high-level shared blueprint" (Valdivia et al., 2021, p. 1), the Life Cycle Sustainability Assessment (LCSA) framework (UNEP, 2011) divides sustainability into three pillars. For the environmental pillar, Life Cycle Assessment (LCA) is a formally defined concept (ISO, 2006) that copes with both the product and the strategic, more aggregated level. Unlike product-specific or site-specific assessments, sustainable decision-making on a strategic and multi-regional scale, by nature, relies heavily on aggregated and often generic data. In the field of strategic supply network design, many studies have addressed both LCA-based environmental impacts and economic feasibility in mathematical optimization models (Eskandarpour et al., 2015). The case of social sustainability is more intricate: While taking or not taking a decision has quantifiable repercussions in the economic and environmental dimensions, the social implications of the decision are not always clear ex-ante. The complexity of social indicators, their subjective and often qualitative nature, and a lack of data (Valdivia et al., 2021) render their inclusion into quantitative decision-making models complex. Existing social frameworks, such as the ISO 26000 (ISO, 2011) or the Sustainability Reporting Standards (GRI, 2021), focus on ex-post evaluations, which allow for site- or product-specific assessments (e.g., Kolotzek et al., 2018, Ren et al., 2015). In contrast, strategic network design is located on a more generic level of aggregation and includes Greenfield problems, where social considerations and their interconnectedness with environmental and economic criteria (Valdivia et al., 2021) need to be quantifiable before strategic decisions are taken.

Although general interest in the inclusion of social issues is observed in the literature (Mujkic et al., 2018), the state-of-the-art implementation of the social dimension is far from being on par with the economic and environmental dimensions (Barbosa-Póvoa et al., 2018). Recently, Messmann et al. (2020) reviewed 91 articles with social objective functions for strategic network design and concluded: 1) most of the reviewed articles (74%) do not cite any existing social framework, and only 14% use frameworks specifically for identifying relevant social issues or quantifiable indicators (Ghaderi et al., 2018; Mota et al., 2015b; Soleimani et al., 2017). Those articles that rely on frameworks tend to cover more social issues, but the reasoning behind the selection is often not transparent, and there is no "best practice" process to build upon. 2) There is only a small number of consistently applied indicators, and only a few studies include several at once (Anvari & Turkay, 2017; Pishvaee et al., 2014; Zhu & Hu, 2017). Job creation is the only issue that is reliably found in the majority (69%) of relevant literature, mainly expressed by the total number of jobs created (Lin et al., 2019; Miret et al., 2016; Mousavi Ahranjani et al., 2018; Roni et al., 2017). 3) There are hardly any attempts of impact assessment or multi-dimensional analyzes, e.g., multi-criteria optimization. Studies instead weight and aggregate the aspects by applying, e.g., the AHP method (Jakhar, 2015; Sahebjamnia et al., 2018; Shokouhyar & Aalirezaei, 2017). More quantitative approaches, such as the Social Hotspots Database (Benoît-Norris et al., 2018) or the Product Social Impact Life Cycle Assessment database (Ciroth & Eisfeldt, 2016), have not yet been applied in this field. Against this background, this work sets out to accomplish the following research goal:

- ***Research Goal:*** Provide a best-practice approach for a structured and transparent selection of a comprehensive set of quantitative and operationalizable social indicators based on existing frameworks.

Since the selection of suitable indicators and their application are case-specific, we present our approach in a case study in the context of the European bioeconomy. Agriculture claims the largest share of anthropogenically used land, which is why the use of renewable raw materials is subject to several tensions (Eurostat, 2021e; Hennig et al., 2016; Thorenz et al., 2018). Anthropogenic land use is associated with high environmental impacts in its current state (Lewandowski, 2015). Utilizing starch, protein, oil-based, or other dedicated energy crops as a source for renewable energy and materials (first-generation) as substitutes for fossil-based counterparts competes for land with food security. These conflicts can partly be avoided by using harvesting residues (second-generation). The bioeconomy thus represents a challenging application case for multi-criteria strategic network planning and is linked to multiple SDGs. Ultimately, we investigate the following research questions, which are addressed in sections 2 and 3:

- ***RQ1:*** What are the social benefits, impacts, and hotspots of socially, environmentally, and economically optimal large-scale production networks for second-generation bioethanol in the EU?
- ***RQ2:*** Which SDGs are affected, and what are interlinkages between them?

2 METHODS

Subsection 2.1 first motivates and describes the case study. This is necessary, as the focal supply chain, the geographical and system boundaries, and the level of aggregation influence the outcome of the indicator selection, which is described in subsection 2.2. Subsections 2.3 and 2.4 then select social indicators and integrate them into the problem by formulating social objective functions and functions for social hotspot identification.

2.1 Problem description

The case study is based on and extends the model presented by Wietschel et al. (2021; Supporting Information S1, section 1). They use multi-criteria mixed-integer linear programming (MILP; modeled with IBM ILOG CPLEX 20.1.0.0) to investigate environmental benefits and economic viability of optimal second-generation (2G) bioethanol (EtOH) production networks for petrol and first-generation (1G) EtOH substitution in the EU. 2G bioethanol is based on lignocellulosic harvesting residues (here: wheat, maize, barley, and rapeseed straw). No environmental impacts are allocated for the growth phase; however, impacts of additional N-P-K fertilization to compensate for nutrient losses through straw evacuation are considered (Wietschel et al., 2021). From an LCA perspective, this work approximates the environmental consequences of optimal decisions by predominantly consequential modelling in the foreground system (e.g., avoided burdens), while using attributional background databases (ecoinvent 3.5, accessed with SimaPro 9) with average processes (cf. Schaubroeck et al., 2021) due to a lack of marginal process data (Supporting Information S1, Table S17, gives detailed information on key modelling characteristics).

Figure E1 illustrates the value chain of 2G EtOH and the problem description with sets and variables. The superstructure comprises the 91 NUTS-1 regions of the EU27, in which all decisions are taken. They include feedstock sourcing (inter- or intra-regional) to biorefineries, biorefinery locations and capacities, and bioethanol production and distribution to substitute petrol or first-generation bioethanol. These decisions are taken so as to maximize an economic or 21 environmental objective functions. The environmental dimension comprises 18 impact and three damage categories of the LCIA method ReCiPe 2016. The economic dimension is represented by profit maximization in five tax scenarios. Scenario T1 represents the current country-specific taxation of bioethanol. In scenarios T2 and T3, the excise tax is reduced by 50% and 100%, respectively. Finally, scenarios T4 and T5 assume EU-wide carbon taxes of €50 and €375, respectively.

Fertile land is used to meet a wide variety of human needs, and growing global population aggravates the pressure on the limited land. This leads to the socio-economic “food, energy and environment” trilemma (Lewandowski, 2015, p.37), making the inclusion of the social dimension particularly relevant in the given application case. The environmental and economic objectives applied by Wietschel et al. (2021) cover nine of the 17 SDGs (Supporting Information S2, Details 3). Consequentially, seven socially-focused goals and many subordinate social targets of all SDGs are not represented. The approach presented in this section sets out to select and operationalize social indicators to fill the existing gaps and promote all SDGs. The model is then solved for each objective, trade-offs between different social, environmental, and economic categories are analyzed through multi-objective optimization, and social hotspots are evaluated. Lastly, the objectives are matched to 16 of the 17 SDGs (SDG17 is excluded since it rather targets political cooperation to facilitate sustainable development worldwide than explicitly socio-economic or environmental goals), and potentially positive and negative impacts on the attainment of the SDGs are investigated.

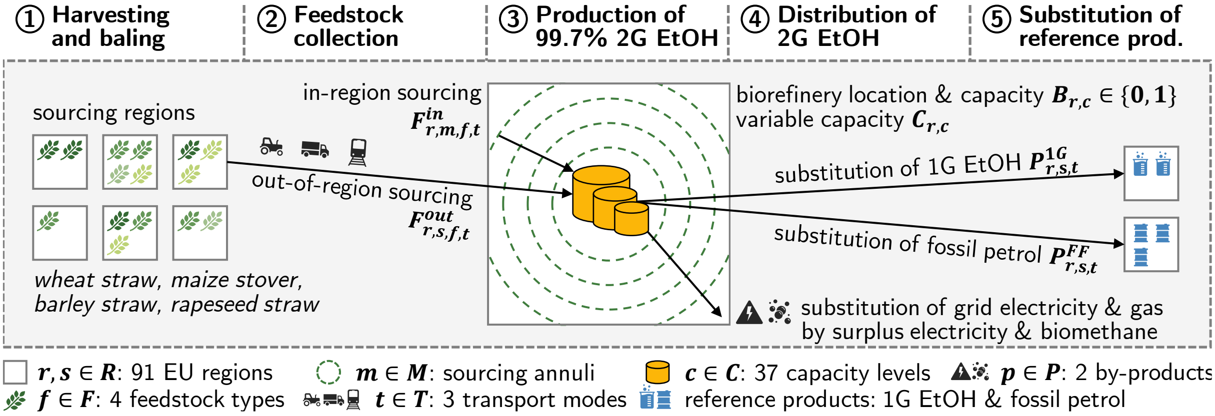


Figure E1. Value chain of 2G EtOH and visual problem description, including sets and variables of the MILP model (cf. Supporting Information S1, section 1)

2.2 Selection of issues and indicators

This work presents a structured three-step selection approach (Figure E2) to identify the relevant and quantifiable social issues in the given context. This ensures that the social dimension is not exclusively represented by a single and arbitrarily chosen issue and indicator but covers as many aspects associated with network decisions as possible. In step 1 of the approach, suitable social assessment frameworks are selected. In step 2, relevant and quantifiable social issues are identified, and the irrelevant ones are excluded. Readily (case-specifically) applicable indicators proposed by the selected framework are directly adopted, and suitable operationalized indicators are developed for the remaining issues. In step 3, the indicators are operationalized and integrated in the MILP model. Here, we differentiate between optimizable social objective functions (SOF), where decisions exert distinctly positive or negative impacts, and social hotspot functions (SHF), which provide ex-post insights on a plethora of potential social issues along the global value chains. The realization of steps 1 to 3 is detailed in sections 2.3 (for the path towards the SOFs) and 2.4 (for the SHFs).

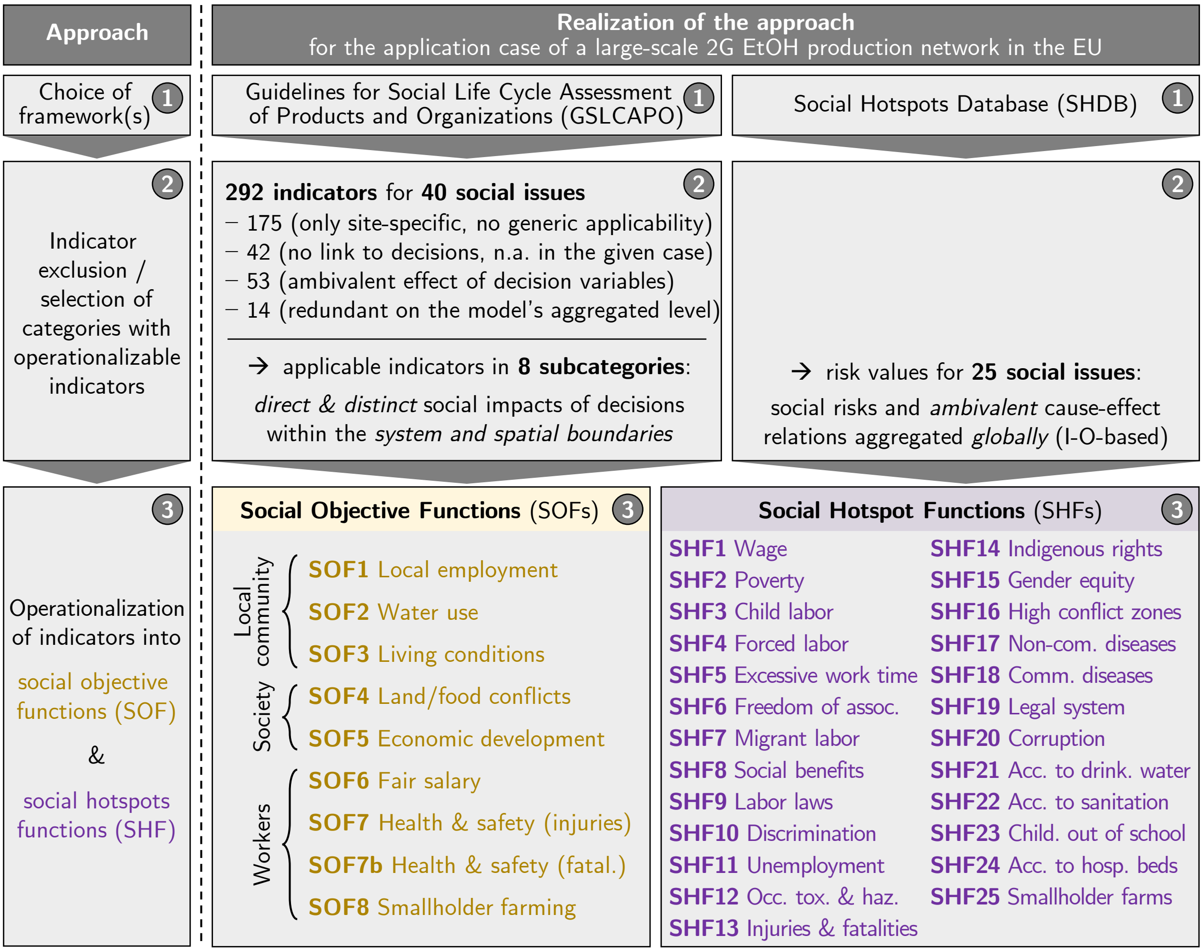


Figure E2. Approach for issue and indicator selection, operationalization and definition of indicators, and the formulation of social objective functions and social hotspot functions.

2.3 Social objective functions

Step 1 (framework selection): While the SDGs are the overarching and globally accepted framework, their subordinate targets and indicators are not precisely designed to measure the impacts of specific supply chain decisions but rather to evaluate the progress of municipalities, countries, and humankind towards sustainable development. On the other end of the spectrum, there is a vast array of frameworks for evaluating social aspects in specific value chains and for certifying companies. Norms and standards such as the Sustainability Reporting Standards (GRI, 2021), the SA8000 (SAI, 1997), and the ISO 26000 (ISO, 2011) are among the most frequently cited frameworks in network design studies (Messmann et al., 2020), but are often rather designed for site-specific assessments or auditing suppliers and companies' existing supply chains. While the Guidelines for Social Life Cycle Assessment of Products and Organizations (GSLCAPO; UNEP, 2020) and their methodological sheets (UNEP, 2021; UNEP SETAC, 2013) also feature mostly site-specific and qualitative indicators, they explicitly focus on decision-making processes and are more product-focused through their kinship with environmental LCA. For the case of a bioethanol production network, the GSLCAPO with its indicators for 40 social issues (subcategories)[8] are viewed as a suitable foundation for quantifying distinctly positive or negative social impacts.

Step 2 (indicator exclusion/selection): We successively reduce the given set of 40 social issues by excluding those of the 292 indicators that cannot be operationalized in this case study for different reasons: 175 indicators are only site-specific with no generic applicability in this aggregated Greenfield problem (e.g., the indicator measures social impacts that heavily depend on the actual location of a facility or how an existing facility is operating). 42 indicators are not affected by any model decision or do not apply to the case of bioethanol production (e.g., the indicator refers to unrelated products or regions, or model decisions are assumed to not impact the aspects measured by the indicator). For 53, the effect of decisions on this indicator is ambivalent (when the indicator measures impacts that may be associated with the decision, e.g., political circumstances, but the decision's impact cannot be classified as distinctly positive or negative), and 14 indicators are redundant (e.g., when several indicators are proposed that measure the same aspect, e.g., poverty) on the aggregated level of the model (detailed selection and exclusion process in Supporting Information S2, Details 1). This leaves eight social issues, which are the basis for developing social objective functions (SOF). For some, the GSLCAPO provide readily applicable indicators in this application case; for others, their operationalization and use as parameters in mathematical objective functions is based on existing approaches in this field (Kühnen & Hahn, 2017; Messmann et al., 2020), GSLCAPO's data source suggestions, and own developments (Tables E1 & E2).

---

[8] The methodological sheets of 2013 proposed 189 generic and specific indicators for the 31 social issues (subcategories) in five stakeholder categories of the 2009 edition of the Guidelines for Social Life Cycle Assessment of Products (GSLCAP). The new 2020 GSLCAPO add nine social issues (subcategories) and a sixth stakeholder category (children). An according new version of the methodological sheets with complementing new indicators was released in 2021. It adopts a 107 of the previously existing indicators and adds 103 new, mostly site-specific ones (new generic indicators are often only given in terms of possible data sources, which we count as one). This results in a combined set of 292 indicators (see Supporting Information S2, Details 1).

Table E1. Selected social issues and their indicators, as presented in the GSLCAPO and the methodological sheets

Social issue (subcategory)	**Indicator proposed by the methodological sheets**	**Social objective function (SOF)**	**Operationalized indicator(s) for the case of 2G EtOH production in the EU**	**Data sources**
Local employment	Unemployment statistics by country	SOF1 *Local employment*	Unemployment rate by region	Eurostat (2021h), (World Bank, 2021f)
Access to material resources	Levels of industrial water use	SOF2 *Water use*	Water use in the network; water stress level by country	FAO (2021)
Safe and healthy living conditions	Pollution levels by country	SOF3 *Living conditions*	Air emissions in the network; excess mortality from air pollution by region; population density by region	Anderson et al. (2004), EEA (2021), WHO (2021), Eurostat (2021g), Health Effects Institute (2020), WHO (2018), World Bank (2021d, 2021e)
Prevention and mitigation of conflicts	Is the organization doing business in a sector that features linkages to conflicts?	SOF4 *Land-food conflict*	Land occupation in the network; agricultural caloric yield by region	Eurostat (2021b), Lee et al. (2016), World Bank (2021a)
Contribution to economic development	Economic situation of the country/region (GDP, [...])	SOF5 *Economic development*	GDP per capita by region	Eurostat (2021d), IMF, (2021), World Bank (2021c)
Fair salary	Non-poverty wage by country	SOF6 *Fair salary*	Wages by country and sector; poverty threshold by country	Catherine Benoît-Norris et al. (2018), World Bank (2021b)
Health and safety	Number/percentage of injuries or fatal accidents in the organization [...]	SOF7a *Workers' health & safety*	Number of non-fatal accidents by days lost, country, and sector; number of employees by country and sector	Eurostat (2021a, 2021f), ILO (2021a, 2021b)
		SOF7b *Workers' health & safety*	Number of fatal accidents by country and sector; number of employees by country and sector	Eurostat (2021a, 2021f), ILO (2021a, 2021b)
Smallholders including farmers	*(new subcategory since 2020, no indicators available yet)*	SOF8 *Smallholder farming*	Area share of small agricultural holdings by region	Eurostat (2021c), FAO (2000, 2010, 2020)

Step 3 (objective function formulation): The social objective functions represent social fields of action, where strategic network decisions exert distinctly positive or negative impacts. Table E2 lists the SOFs with a verbal description and their generic calculation scheme. The SOFs are formulated as maximization functions as they consider the impacts and benefits of both the network itself and of substituting the two reference products. The specific parameter calculations and objective function formulations are provided in detail in Supporting Information S1 (sections 2.1 and 2.2).

Table E2. Social objective functions. DV_r generically represents all decision variables (detailed in Supporting Information S1, section 1), broken down by region r, to illustrate the relation between network decisions and the various social parameters. DV_r thus may stand for feedstock provision and transportation, biorefinery construction, 2G bioethanol production and transportation, and substitution of 1G bioethanol or petrol. The complete mathematical formulation of the SOFs, including substitution, and the calculation and sources of the model parameters are provided in Supporting Information S1.

Social objective functions
SOF1 (*Local employment*) weights the number of jobs created by the network decisions with a parameter for the regional unemployment rate relative to the EU27 average. In this way, jobs created in regions with higher unemployment rates are favored (cf. Mota et al., 2015a; Zahiri et al., 2017; Zhalechian et al., 2016). $\text{maximize: } DV_r * job\ factor_r * \frac{unemployment\ rate_r}{unemployment\ rate_{EU27}}$
SOF2 (*Water use*) weights the water used in the network with country-specific water stress levels, which is also the indicator of SDG6.4 (FAO, 2021) $\text{maximize: } DV_r * water\ use * \frac{water\ stress\ level_r}{water\ stress\ level_{Europe}}$
SOF3 (*Living conditions*) weights network-induced air emissions with regional population density and the calculatory marginal excess mortality per pollutant of each region. $\text{maximize: } DV_r * air\ emissions * \frac{excess\ mortality_r * population\ density_r}{excess\ mortality_{EU27} * population\ density_{EU27}}$
SOF4 (*Land/food conflict*) weights the potential loss in agricultural production by the network's land occupation by the regional caloric grain yields. This is contrasted with the potential gain in cultivation areas through the substitution of the references (e.g., the substitution of 1G EtOH would free up land that would instead be available for food production). $\text{maximize: } DV_r * land\ occupation * yield_r * caloric\ value\ of\ wheat$
SOF5 (*Economic development*) weights the created economic value added by network decisions with a parameter for the regional GDP per capita (calculated as an input-output-based (Aguiar et al., 2016), sector-specific weighted average) relative to the EU27 average. The regional GDP is one of the indicators proposed by the methodological sheets and used as an indicator by the EU in its cohesion reports (European Commission, 2017). The economic value of network activities is assumed to mirror the elements of the economic objective function, i.e., higher costs contribute positively to SOF5. This assumption neglects induced values that, e.g., a newly built facility may add to a local economy but ensures quantifiability (e.g., Govindan et al., 2016a; Zhu & Hu, 2017). $\text{maximize: } DV_r * economic\ value_r * \frac{GDP\ per\ capita_{EU27}}{GDP\ per\ capita_r\ (global\ I\text{-}O\text{-}based\ weighted\ average)}$
SOF6 (*Fair salary*) weights regionally created jobs with the compound fraction between the average sector wage in a country, the country's poverty line, and the wage-poverty ratio on an EU27 average. Therefore, regions with high relative sector wages and a low relative poverty threshold are favored. $\text{maximize: } DV_r * job\ factor_r * \frac{daily\ wage_r}{daily\ wage_{EU27}} * \frac{poverty\ line_{EU27}}{poverty\ line_r}$
SOF7a and SOF7b (*Workers' health and safety*) use 10-year averages of lost employee-years and fatalities, respectively, per employee due to work accidents by country and sector to determine the number of employee-years and lives, respectively, that can be expected to be lost through network decisions or to be saved through substitution. $\text{maximize: } DV_r * job\ factor_r * avg.\ employee\text{-}years\ lost_r$ $\text{maximize: } DV_r * job\ factor_r * avg.\ lives\ lost_r$
SOF8 (*Smallholder farming*) focuses on the economic value of feedstock regionally sourced in the network. The value is multiplied with the input-output-based, sector-specific weighted average over the area share of smallholder farms (≤ 2 ha) as well as the fraction of economic value channeled to agriculture. $\text{maximize: } DV_r^{feedst.} * economic\ value_r^{agri.} * area\ fraction\ of\ smallholdings_{r\ (global\ I\text{-}O\text{-}based\ weighted\ average)}$

2.4 Social hotspot functions

Step 1 (framework selection): The social objective functions are network-centered in their goal and scope, as global implications are mostly beyond the system boundaries of the decision-making process. However, regional decisions in a globalized economic system may also entail global implications. Therefore, and similar to Fürtner et al. (2021), the network-centered social objective functions are complemented by results from the Social Hotspots Database V4 (2019) (Benoît-Norris et al., 2018), accessed via SimaPro 9.2.0.1. It provides country- and sector-specific social risks as well as an impact assessment method and is methodologically based on the GSLCAPO. The SHDB uses 160 indicators, data on labor intensity, and the underlying input-output model of the Global Trade Analysis Project (GTAP 9) (Aguiar et al., 2016) to accumulate social risk values along global value chains (so-called social hotspot indices; Benoît-Norris et al., 2018) for 140 countries and 57 sectors in 5 impact categories with 25 subcategories (cf. Supporting Information S2, Details 2). Risk values are expressed in medium risk hour equivalents (mrheq) per USD2011.

Step 3 (hotspot function formulation): The social risk values highlight existing social issues along global value chains in 25 subcategories. They are used to compile 25 social hotspot functions (SHFs; Supporting Information S1, section 2.3) by composing a product/process system from the twelve different GTAP sectors that the network activities (i.e., decision variables) comprise (Supporting Information S1, Figure S1). The SHDB-based risk entailed in a process is proportional to its economic value, mirroring the economic objective function. Thus, the risk value of a sector (converted to mrheq/EUR2020) in a country is multiplied by the economic value (in EUR2020) associated with decisions (e.g., biorefinery construction costs). For substituted products (e.g., petrol), the economic value can be interpreted as saved costs. The result is an absolute hotspot value (in mrheq), i.e., the aggregate of all risks entailed by all decisions taken in the production network. Therefore, production networks of different sizes are hardly comparable in absolute risk values, but the risk accumulated (or saved) per ton of 2G EtOH is more meaningful.

The social risks in different sectors or countries are explicitly *not* provided to induce divestment incentives from regions with high risks but instead aim to shed light on social issues to facilitate a positive development. This may imply that the greatest opportunities for improving social issues can be found in regions with high social risks (Benoit-Norris & Norris, 2015). Due to ambiguous cause-effect relations and the uncertainty, whether activities, expressed by the model's decision variables, are levers for the better or reinforce adverse circumstances, the social hotspot values are not optimized. This contrasts with the social (and economic and environmental) objective functions, where one unit of a decision variable has distinctly positive or negative effects on the respective social indicator. Instead, the 25 hotspot functions are quantified by co-calculation when optimizing other objective functions. This implies that the awareness of risks for e.g., questionable labor practices in a supply chain, enables a positive social development and due diligence of the respective operating companies.

3 RESULTS

Subsections 3.1 to 3.3 corresponds to step 4 of the presented approach. 3.1 presents the socially, environmentally, and economically optimal production networks, 3.2 discusses the results of Pareto optimization between different pairs of objectives, and 3.3 provides the results of the social hotspot assessment. Subsection 3.4 corresponds to step 5 and presents the impact of the objective functions on the SDGs semi-quantitatively.

3.1 Sustainable network planning

Since the production of 2G EtOH is more expensive than 1G EtOH and petrol (Padella et al., 2019), with current country-specific taxation, 2G EtOH can only be sold economically in countries with an excise tax reduction, leading to very small production networks (see Supporting Information S1, Figure S4). In the following, the economic dimension is represented by tax scenario T3 since an excise tax reduction of 100% in all EU member states offers the most clear-cut economic-environmental trade-offs. Figure E3 presents production networks for selected objective functions of the three sustainability pillars. The economic optimization leads to a production network of primarily high-capacity biorefineries and is concentrated in countries of Central and Eastern Europe (CEE), with additional biorefineries in the EU's "breadbasket" in central France. Both are characterized by an abundant feedstock supply, and CEE countries additionally yield the economic advantage of below-average costs. The 26 biorefineries can valorize about 47% of the total feedstock potential to produce 11 Mt of second-generation bioethanol, which could substitute 10.8% of the total current petrol demand. The objective value of €1.55 billion (i.e., the profit) is relatively small compared to the network costs of €11.25 billion, which hints at a higher sensitivity towards model parameters. The environmental dimension is represented by the objectives *global warming* and *land use*, which are two relevant (cf. Supporting Information S1, section 3.2) and conflicting (cf. Supporting Information S1, section 3.7.1) environmental impact categories. While optimization of *global warming* leads to 100% utilization of the available feedstock to substitute as much petrol as possible, the objective *land use* exclusively substitutes first-generation ethanol, utilizing 20% of the available feedstock. Optimizing *global warming* results in a total benefit of 58.3 billion tons of CO_2 saved, while optimizing *land use* would only save 7.5 billion tons. Since the entire demand for 1G bioethanol is substituted with *land use* optimization, over 11.3 billion m^2 annual cropland eq. could be saved, which would then be free for alternative uses such as additional food production or ecosystem restoration (the implications of this change are beyond the scope of this work). In contrast, the optimization of *global warming* would increase the land use impact of the network by 1.9 billion m^2 annual cropland eq. Apart from minor differences due to slightly adjusted parameters (cf. Supporting Information S1, Appendix 6), the results align with Wietschel et al. (2021).

The SOFs and their results can be divided into results for those SOFs where the network itself yields benefits (SOF1, SOF5, SOF6, SOF8), and SOFs where benefits are generated through substitution (SOF2, SOF3, SOF4, SOF7). Results for the former are mainly comparable to the results of the *global warming* optimization. While also suggesting about 100% feedstock sourcing, the substitution decision is less determined by the effects of the substitution itself. Instead, the social objectives aim to exploit opportunities, e.g., to create additional jobs or economic value where possible, and subsequently, substitute demand within the model's constraints (cf. Supporting Information S1, section 2.4). Even though optimization of SOF5 (*economic development*) results in the substitution of 93% of the 1G EtOH demand (compared 1.2% for SOF1 and 1.9% for SOF6), the values of SOF1 (*local employment*) and SOF6 (*fair salary*) deteriorate by only 19%, when SOF5 is optimized (cf. Supporting Information S1, Figure S21). These social objectives lead to distinctly negative economic objective values in every tax scenario, especially with SOF5 (T1: −€19.6 billion, T2: −€14.5 billion, T3: −€11.0 billion, T4: −€17.8 billion, T5: −€8.4 billion). The other group of social objectives is more diverse in terms of feedstock sourced (ranging from 1%, SOF7b, to 97%, SOF3), and depend more on the regional characteristics of their parameters. For example, 2G EtOH production for SOF2 only takes place in countries with a low water stress level and also needs the benefits of substituting water-intensive 1G EtOH to operate viably. Lastly, the total risk value displayed in Figure E3 (in mrheq per ton EtOH) reflects global social hotspots connected to the respective solution. A concentration on CEE countries (e.g., SOF2) or a focus on less developed regions (e.g., SOF5) entails significantly higher social risks than networks with large production capacities in Western European countries (cf. section 3.3).

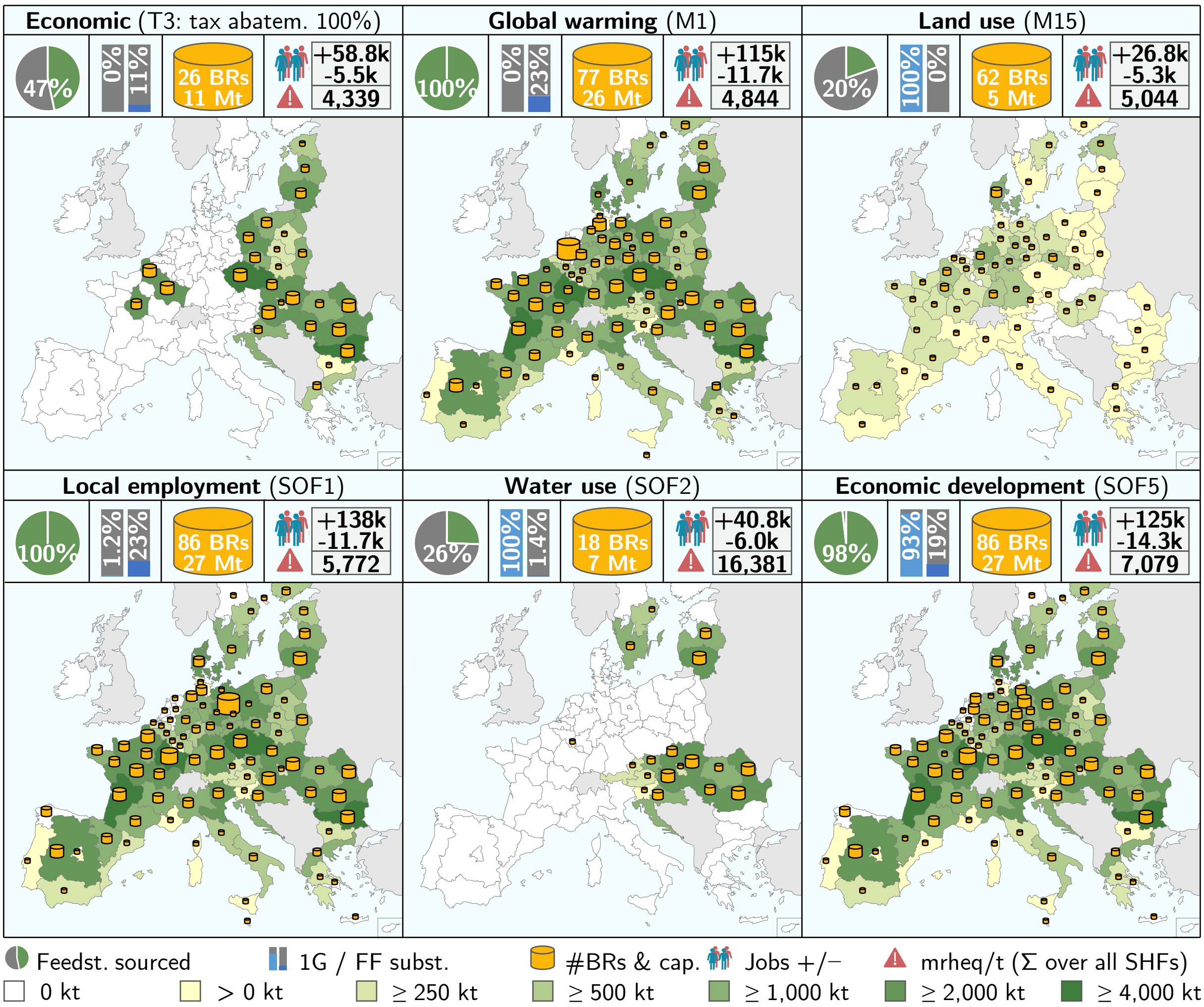


Figure E3. Optimal biorefinery locations and capacities (the size of cylinders corresponds to the capacity) and regional amounts of feedstock sourced (green shades, in metric kilotons) for six objectives. The legend also includes respective percentages of total feedstock collected (pie chart), the percentages of 1G demand and fossil petrol demand substituted (bar charts), the total number and total capacity of biorefineries (BRs & cap.), the number of jobs created and lost, as well as the total risk increase over all SHFs (in mrheq per ton). Figures S4-S15 in Supporting Information S1 display analogous information for the economic objective in four tax scenarios, four environmental objectives (E2, M1, M5, M15), and eight SOFs, and in terms of amounts of feedstock sourced, jobs created, and hotspot values accumulated.

3.2 Pareto optimization

Pareto optimization reveals the leverage of the different social parameters on the regional distribution of the activities. Regional differences are only discernible in nuances once 100% of the available feedstock potential is sourced (cf. Figure E3). If the social dimension were not forced into a tight corset of constraints (Supporting Information S1, section 2.4), the complete production would occur in the region with the highest social parameter value (e.g., the highest unemployment rate). When an economic constraint is introduced in Pareto optimization (applying the equidistant ε-constraint method), and less than 100% of the feedstock is sourced, regional social aspects emerge more clearly.

Figure E4 displays Pareto-optimal frontiers between the economic objective (in tax scenario T3) and SOF1, SOF5, SOF6, and SOF2, visualizing network configurations at three points along the frontier in terms of created jobs.

The single-criteria economic optimization leads to 58,805 additional jobs, mainly in CEE countries and northern France (cf. Figure E3), while 5,457 jobs are assumed to be lost due to the substitution of petrol. This net job creation of 53,348 already corresponds to 42,1% of the value when maximizing SOF1 (*local employment*, 126,697). Once SOF1 is introduced as an additional objective, the network starts to shift to regions with high unemployment rates in Spain and Italy (point a). Greece hardly benefits from SOF1 due to its scarce feedstock supply. When sacrificing 11% profit, the pure number of jobs created increases by 30% (from 53,348 to 69,365), but the objective value of SOF1 (in unemployment-weighted job equivalents) improves by more than 49% (from 43,378 to 64,781). These effects become more pronounced with increasing preference for SOF1 (point b). Beyond point (c), where almost all feedstock is sourced, the gradient of the Pareto frontier becomes steeper, meaning that marginal social gains are disproportionately more expensive. Here, only a few regions with a combination of high costs and low unemployment rates are exempted (e.g., Southern Germany, Austria, the Netherlands).

Multi-criteria optimization between the economic objective and SOF5 (*economic development*) discriminates economically strong metropolitan regions such as most capital regions and economically strong countries and favors regions in CEE countries and northern France (a and b). Even though regions of central and western Spain also have favorable model parameters due to a comparably low GDP per capita, these regions are not selected. The preference for CEE countries can be explained by the benefits in profitability *and* GDP, while costs indices in Spain hamper profitability. Notably, with a further preference for SOF5 (c), the network is only slightly larger than for (a) and (b), since additional gains for SOF5 are mostly realized by shifts in sourcing and transportation decisions. When higher SOF5 values are obtained, profit drops disproportionately to its lowest value in any of the curves with over −€10 billion.

SOF6 (*fair salary*) favors regions with high sector wages relative to the poverty threshold. Regional differences in Pareto optimization are slightly more pronounced than with the other SOFs. Italy, in particular, profits from SOF6 but also selected regions in France, Spain, and Germany. The Pareto-optimal frontier has, at first, only a small gradient, meaning that SOF6's objective value can be tripled while remaining profitable (point c). After that point, the value again drops disproportionately.

Unlike the afore shown SOFs, benefits for SOF2 (*water use*) are generated through substitution and not by the network. As the economically preferential regions are coincidentally also, in large parts, regions with a lower water stress level (mostly CEE countries), the network structure does not change much along the Pareto frontier. Trade-offs concern almost only the substitution decision, and positive objective values can be realized for both objectives, as long as petrol is neither exclusively substituted (as left of point a) nor substituted too little (as right of point c).

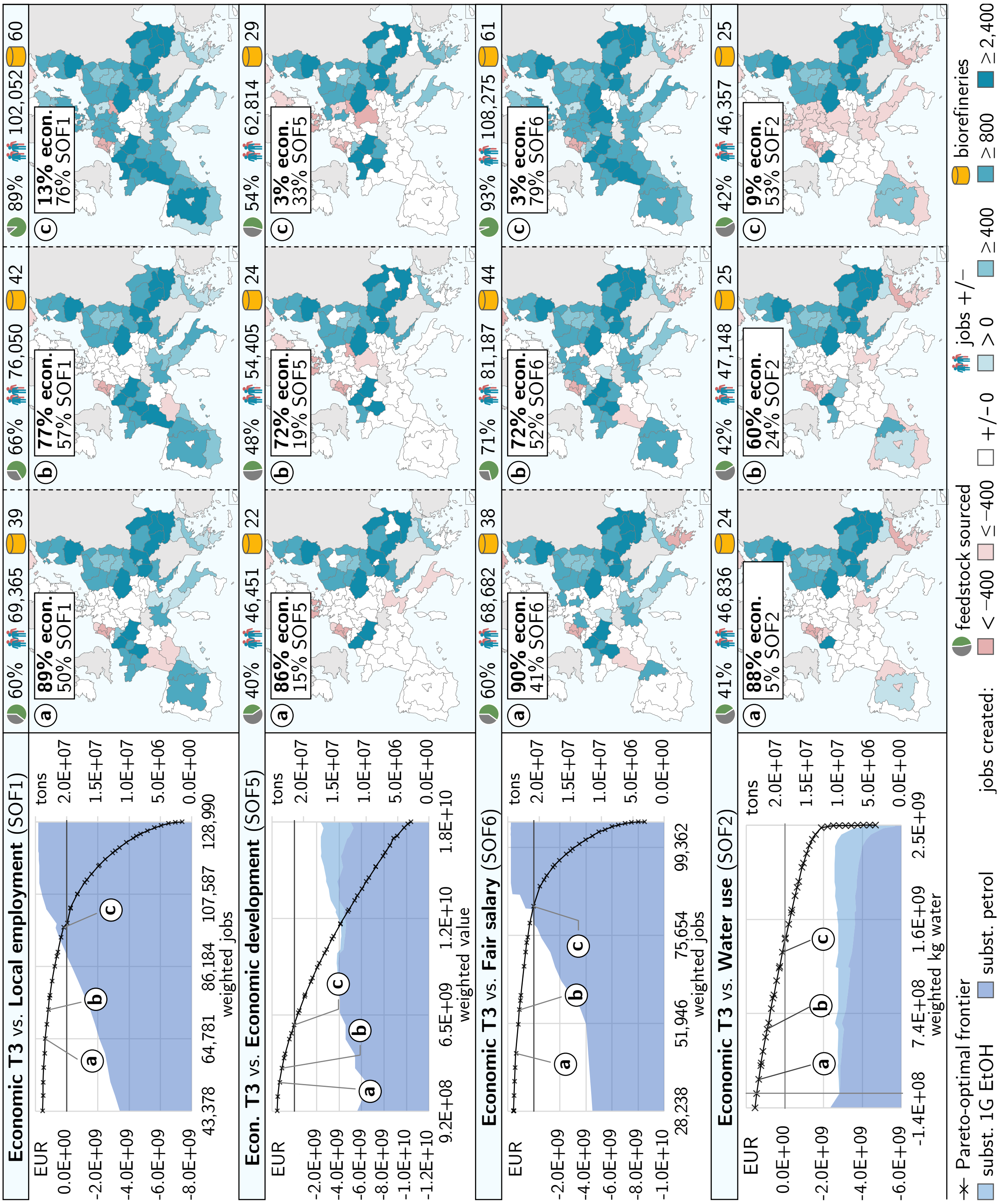


Figure E4. Selected Pareto-optimal frontiers between different social objective functions and the economic objective in tax scenario T3. The graphs include the substituted reference products on the secondary axes as stacked area plots. For three Pareto-optimal points, the optimal network design is displayed as maps that visualize the net number of regionally created jobs as blue/red shades. (a) corresponds to the Pareto point closest to 90% of the optimal economic objective value, (b) represents a numerical "compromise point" (i.e., with the shortest Euclidean distance to the two optima), and (c) is the last point with an economic profit. The legend also includes respective percentages of total feedstock collected, the total number of biorefineries, and the net number of jobs created and lost. Figure S17 in Supporting Information S1 displays analogous Pareto curves for pairs of different objectives (economic, E2, SOF1) and the effect on the respective third category.

3.3 Social hotspots

Figure E5 shows social hotspots in networks of selected objective functions. Over all objective functions, SHF6 (*freedom of association, collective bargaining, and right to strike*) is the most relevant hotspot, followed by SHF4 (*forced labor*), SHF12 (*toxics and hazards*), and SHF13 (*injuries & fatalities*) (cf. Supporting Information S2; Figure S3). Significant risks in a country-sector are either due to high specific risk values or stem from a high share of network activities, which is why the feedstock sector with its high percentage in the overall production costs has by far the most prominent social hotspots, regardless of SHF.

The economic objective entails the most distinct hotspots and is exposed to 33% higher risk than *global warming* (12,960 compared to 9,739 mrheq/t). The relatively high risks can be explained by a focus of activities on CEE countries, which, on average, have higher social hotspot values. The feedstock sector in Romania has the highest contribution in most of the hotspot functions, contributing up to 27% to the total *injuries & fatalities* risks. This is mainly attributed to Romania's feedstock sector inherently and the contributing chemicals sector (fertilizer provision). Likewise afflicted with high social risks are Romania's transportation and construction sectors and Hungary's feedstock sector. Networks based on the objectives *global warming* and *land use* are less critical due to networks that are more widely distributed over all countries. Here, Germany and France are also significant hotspots. This is primarily explained by their large share in the value chain (cf. Figure E3) and secondarily (e.g., for SHF16) by above-average indicator values in the SHDB (e.g., in Germany due to violent xenophobic incidents combined with a comparably large proportion of immigrants; Benoît-Norris et al., 2018; HIIK, 2021; UNHCR, 2021). Comparing *land use* with *global warming*, the construction sector is more critical due to smaller biorefineries and resulting lower scale effects. The network of *local employment* optimization slightly emphasizes countries with higher unemployment rates like France or Spain, wherefore they appear among the high-risk countries. *Economic development* favors economically weaker regions. Since this objective in particular benefits from long-distance transportation of EtOH, this sector is also subject to significant risks, especially in terms of SHF4, SHF6, SHF20, SHF10 and SHF23.

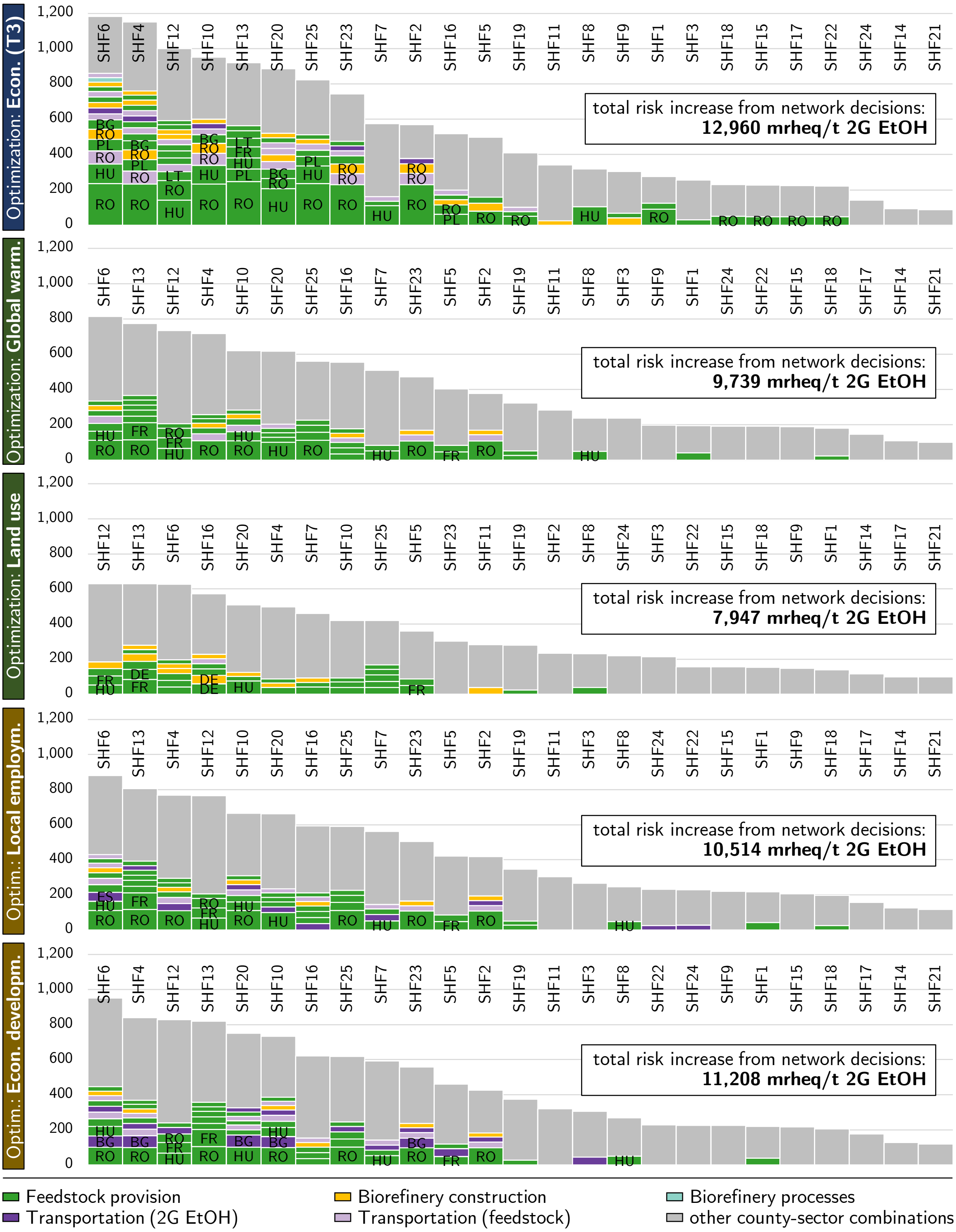
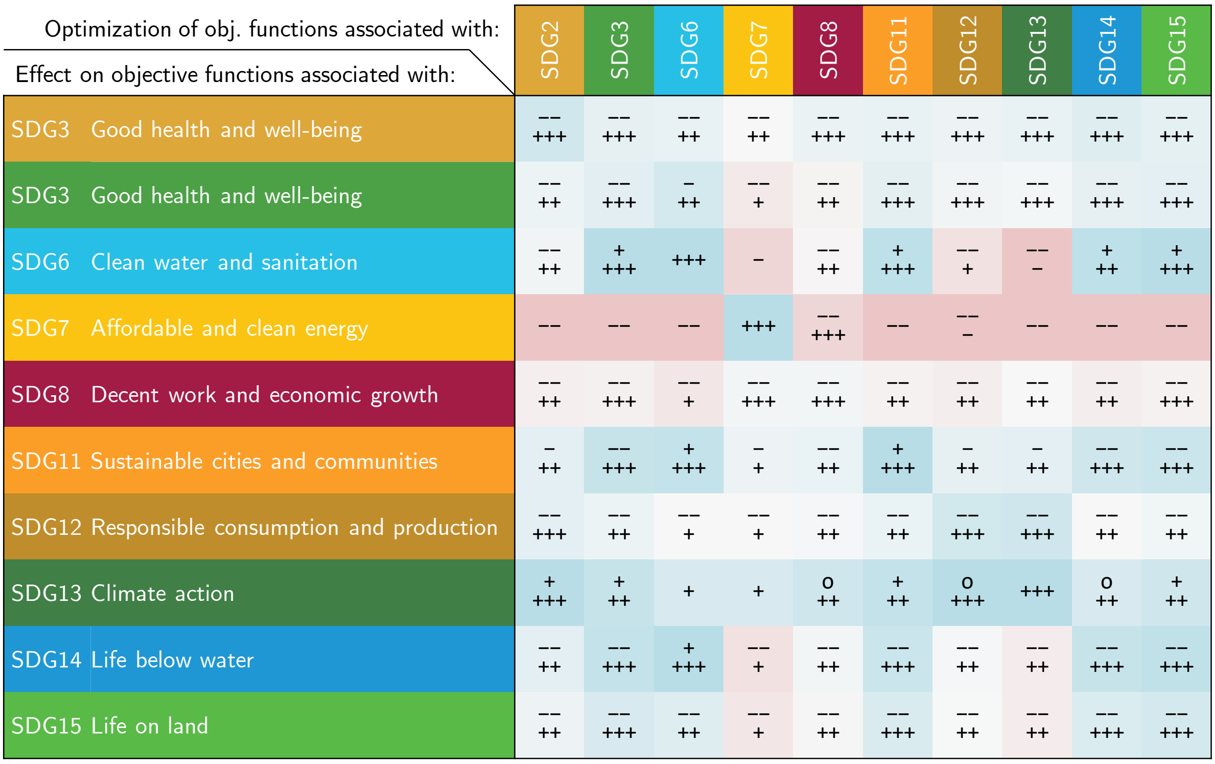


Figure E5. Relative contributions of country- and sector-specific social risks to the SHFs, in mrheq / ton 2G EtOH, co-calculated for different objective functions. Each diagram provides the country-sector hotspots with the highest contribution to the respective SHF, not accounting for reduced risks due to substitution. To ensure legibility, single country-sector combinations with risk ≥2% (approx. 23 mrheq/t) of the height of the largest column (SHF6 for economic optimization) and country tags with ≥4% are displayed. Figures S18-S20 in Supporting Information S1 evaluate the category-wise, regional, and process-wise aspects (including substitution) of the hotspot analysis separately.

3.4 Impact on SDGs

Together with the environmental and economic categories, the SOFs and SHFs cover a broad range of the SDGs. Supporting Information S1 (Table S18) and S2 (Details 3) show the matching of SOFs, SHFs, environmental and economic objective functions to individual goals, targets, and indicators of the SDGs. By calculating pair-wise opportunity costs (i.e., the percental detriment in one category when optimizing the other; cf. Figure S21), conflicts and congruencies between the different optimizable objective functions, and in turn, the interlinkages between the SDGs associated with these functions, are evaluated (Figure E6). Figure S23 in Supporting Information S1 displays the same interlinkages but for affected SDGs associated with the non-optimized SHFs. For insights on the relationships on the level of individual categories, see Figures S24 and S25.



Optimization of obj. functions associated with: Effect on objective functions associated with:	SDG2	SDG3	SDG6	SDG7	SDG8	SDG11	SDG12	SDG13	SDG14	SDG15
SDG3 Good health and well-being	−− +++	−− +++	−− ++	−− ++	−− +++	−− +++	−− +++	−− +++	−− +++	−− +++
SDG3 Good health and well-being	−− ++	−− +++	− ++	−− +	−− ++	−− +++	−− +++	−− +++	−− +++	−− +++
SDG6 Clean water and sanitation	−− ++	+ +++	+++	−	−− ++	+ +++	−− +	−− −	+ ++	+ +++
SDG7 Affordable and clean energy	−−	−−	−−	+++	−− +++	−−	−− −	−−	−−	−−
SDG8 Decent work and economic growth	−− ++	−− +++	−− +	−− +++	−− +++	−− ++	−− ++	−− ++	−− ++	−− +++
SDG11 Sustainable cities and communities	− ++	−− +++	+ +++	− +	−− ++	+ +++	− ++	− ++	−− +++	−− +++
SDG12 Responsible consumption and production	−− +++	−− ++	−− +	−− +	−− ++	−− ++	−− +++	−− +++	−− ++	−− ++
SDG13 Climate action	+ +++	+ ++	+	+	o ++	+ ++	o +++	+++	o ++	+ ++
SDG14 Life below water	−− ++	−− +++	+ +++	−− +	−− ++	−− +++	−− ++	−− ++	−− +++	−− +++
SDG15 Life on land	−− ++	−− +++	−− ++	−− +	−− ++	−− +++	−− ++	−− ++	−− +++	−− +++

Figure E6. Interlinkages between social, environmental, and economic objective functions on the level of their associated SDGs, based on opportunity cost calculation (percental detriment in one category compared to its optimal value when optimizing another). SDGs with optimized objective functions are displayed on top, affected ones to the left. Categories are assumed to be fully congruent with a detriment of less than −5% (+++), congruent between −5% and −50% (++), slightly congruent between −50% and −95% (+), either neutral or unrelated between −95% and −105% (o), conflicting between −105% and −150% (−), and strongly conflicting with a detriment of more than −150% (−−). Two indications are given for each pair of SDGs, representing the range between the most conflicting and the most congruent relationship between two objective functions of the associated SDGs. The colored shades indicate whether conflicts (red) or congruencies (blue) prevail qualitatively.

As with conflicts and congruencies on the level of different objective functions, the achievement of SDGs may be hindered or promoted by pursuing different goals. For example, in terms of **SDG13**, networks optimal for all other goals range from slightly to strongly co-beneficial, yielding the more benefits, the more petrol is substituted. In the case of bioethanol, a large portion of conflicts between environmentally-oriented SDGs stems from opposing substitution decisions, wherefore affected SDGs behave ambiguously towards the others. This is the case for **SDG2**, **SDG3**, **SDG11**, **SDG14**, **SDG15**, and, with the most pronounced tendencies, **SDG6**. Here, a production network optimal in terms of M1 (*global warming*, SDG13) entails no co-benefits and even jeopardizes the achievement of SDG6. In contrast, the optimization of objective functions of SDG3 always leads to at least small co-benefits for SDG6 (e.g., E1 & SOF3) and even comprises fully congruent objectives (e.g., M14 & M4).

Furthermore, there are conflicts between the three pillars of sustainability, such as with **SDG7** (linked with the economic objective). Here, an optimal network entails minor benefits and some detriments for the other SDGs but pursuing any other goals compromises SDG7 strongly. Divides may also run between different targets within one SDG, depending on the perspective and the sustainability dimension, or even within one target, depending on the context. For example, **SDG8** can be divided into two groups: The (corporate and profit-focused) economic objective (target 8.2) together with health & safety issues (target 8.8.1), and (the societal and GDP-focused) SOF5 (target 8.1) together with employment (SOF1; target 8.5.2) and remuneration issues (SOF6; target 8.5.1). The first group is highly conflicting with the second group and all other SDGs, while the second group co-benefits from the others. Similarly, **SDG12** with target 12.2 (natural resources) is divided into E3 (*resource availability*) & M17 (*fossil resource scarcity*), and M16 (*mineral resource scarcity*). The former generally benefit from any bioethanol network, particularly from the substitution of petrol, while the latter is impacted by the material requirements of the network itself, with only minor substitution benefits.

4 DISCUSSION AND CONCLUSION

This study provides a best-practice approach for a structured and transparent inclusion of a comprehensive set of social aspects. This is done by selecting applicable quantitative and operationalizable social indicators from the Guidelines for Social Life Cycle Assessment of Products and Organizations and the Social Hotspots Database. The approach is applied in a network optimization model for second-generation bioethanol in the EU. The complete set of categories encompasses economic, 21 environmental, and 34 social functions. The model thereby addresses 16 of the 17 SDGs and extends existing work, especially by operationalizing the social dimension. The results allow for identifying socially optimal decisions (social objective functions) and evaluating possible social hotspots in global value chains (social hotspot functions).

The different objective functions lead to four fundamentally different network structures, some of which are closely related to the substitution decision. First, economically optimal networks concentrate on lower-cost CEE countries to be competitive with petrol prices in more expensive countries (especially in scenarios T1–T3). The higher the subsidization (excise tax abatement or carbon taxation), the more competitive bioethanol becomes, leading to more extensive production networks. Second, several environmental objectives suggest an exclusive substitution of 1G bioethanol with widely dispersed but capacity-wise small production networks (e.g., *land use*). The third group is similar to the second group in terms of exclusive 1G EtOH substitution, but the networks are small to medium-sized and concentrated on regions most favorable in terms of the respective regional social parameters. This is the case for SOF2, SOF4, and SOF7. The fourth principal network structure comprises environmentally optimal solutions that fully exploit the feedstock potential in large production networks. Depending on the environmental objective, 2G bioethanol should either substitute 1G bioethanol *and* petrol (e.g., *ecosystem quality*) or petrol exclusively (e.g., *global warming*). Those social objective functions where the benefits (in e.g. employment and regional development) stem from the network itself, as well as SOF3, fall into this group. Here, the effects of substitution are less decisive than the size of the network itself.

The feedstock sector of Romania constitutes the most significant social hotspot, to which *injuries & fatalities* and *freedom of association* contribute the most. Therefore, when a bioethanol producer decides to invest in these countries, due diligence and supplier auditions are necessary to ensure safe working conditions. In addition, construction and transportation sectors also entail notable risks that would, in practice, need to be assessed in detail. This work takes only an ex-post and aggregated look at the co-calculated (not optimized) social hotspot functions, since the risk scores from the SHDB are designed to shed light on potential social grievances without inducing divestment incentives from regions with high risks (Benoit-Norris & Norris, 2015). The approach provides a valuable basis for decision-makers in strategic supply chain design by pointing at hotspots. Subsequent analyses would be necessary in practice to elucidate the circumstances behind each indicator, country, and sector value.

The analysis of interlinkages between SDGs supports the notion that sustainability of strategic decisions is not universal but rather case-specific and varies between a plethora of interlinked social, environmental, and economic criteria. Given the diversity of the different goals, pursuing a specific goal will necessitate concessions in others. SDG8 and SDG12 are prime examples for why one action can benefit or harm not only different sustainability goals differently but also targets and indicators within the same goal. On a more thematic level, particularly the bioeconomy is at the center of tensions between different stakeholders. European policy-makers could use the lever of taxation (cf. Wietschel et al., 2021) to improve the competitiveness of 1G and 2G bioethanol vis-à-vis fossil fuels to foster the achievement of inter alia SDG13 while simultaneously realizing significant benefits in terms of, inter alia, employment (SDG8.5) and regional development (SDG8.1). At the same time, this step could strengthen the energy self-sufficiency of the EU and significantly reduce dependencies on energy imports from countries with a questionable human rights record. This decision needs, however, to be taken consciously. The labor intensity of residue harvesting and transportation and the hereby accumulated risk for adverse social circumstances along the global upstream value chains could create new hotspots that must be monitored. The decision would also put further stress on land, water, mineral resources, and food security, especially in the case of 1G ethanol. The discontinuation of subsiding 1G bioethanol alleviates some of the latter tensions but prevents the full climate, employment, and regional development potential from being unlocked. Especially corporate decision-makers need to be aware of the likely hotspots in their specific value chains (section 3.3), but also of the potential for environmental and social benefits that adjustments of strategic decisions yield, which could be unlocked with sacrifices in profits (section 3.2).

It needs to be emphasized that this work does not present a full LCSA, lacking a comprehensive LCC. The study rather aims at advancing the application of SLCA in the field of strategic network design, at presenting results of social and LCA-based environmental optimization on the same level, and at discussing the economic feasibility of these results. Further research should complement this with a comprehensive LCC including different stakeholders (Schaubroeck et al., 2019) and also evaluate a possible aggregation of the results. In this study, we focused on the heterogeneous nature of the various social and environmental categories to inform about the consequences of decisions and possible undesired repercussions. While simple aggregated LCSA "scores" facilitate decision-making by reducing complexity, aggregation also bears the risk of obscuring critical information and requires more elaborate and well-communicated aggregation schemes (e.g., Zeug et al., 2021). It also bears mentioning that, while aspects of 16 of 17 SDGs are covered, this study cannot address the interrelationships between all SDGs, as the objective functions only relate to individual subordinate targets or to the goals only ideationally. Furthermore, the most readily applicable indicators are not necessarily those that society and academia should keep relying on in the medium term. While the GDP is a commonly applied indicator in similar studies and European cohesion policy (European Commission, 2017) with undoubted advantages, the measurement of the well-being of the various societal stakeholders should arguably go beyond this metric (Costanza, 2015; Hoekstra, 2019); instead, metrics such as QALY (quality-adjusted life years) have been proposed (Weidema, 2006) and the importance of impact pathways between different area of protection is emphasized (Schaubroeck & Rugani, 2017). Lastly, the selected set of indicators is mainly limited by the focus of this study on strategic Greenfield decisions in the European second-generation bioeconomy. Other authors may select or exclude indicators for similar reasons as in the work at hand but compile a different or extended set of indicators when adjusting the application case or scope.

This work illustrates that decision-makers, be it on a corporate level and following one or more business objective functions, or on a political level and using the SDGs as a framework, need to be aware of reciprocities between the various criteria. Subjective experience, socio-cultural conditions, personal values, or attitudes of decision-makers play important roles particularly in environmentally and socially oriented decision-making. This work provides an approach that allows decision-makers to also consider a large number of different quantitatively assessed sustainability aspects and trade-offs between them, thus supporting the rationalization of social and environmental criteria. With evidence-based decision-making under consideration of socio-cultural preconditions, second-generation bioethanol production has the potential to contribute to a socially, environmentally, and economically sustainable development.

ACKNOWLEDGEMENTS

The authors would like to thank Sabrina Linsmaier for her valuable and high-quality input.

When citing Contribution E, please read first and only refer to the version published online 2022 in the Journal of Industrial Ecology. doi.org/10.1111/jiec.13324.

REFERENCES

Aguiar, A., Narayanan, B., & McDougall, R. (2016). An Overview of the GTAP 9 Data Base. Journal of Global Economic Analysis, 1(1), 181–208. https://doi.org/10.21642/JGEA.010103AF

Anderson, H., Atkinson, R., Peacock, J., Marston, L., & Konstantinou, K. (2004). Meta-analysis of time-series studies and panel studies of particulate matter (PM) and ozone (O3) : report of a WHO task group. In Report of a WHO Task group. https://apps.who.int/iris/handle/10665/107557

Anvari, S., & Turkay, M. (2017). The facility location problem from the perspective of triple bottom line accounting of sustainability. International Journal of Production Research, 55(21), 6266–6287. https://doi.org/10.1080/00207543.2017.1341064

Barbosa-Póvoa, A. P., da Silva, C., & Carvalho, A. (2018). Opportunities and challenges in sustainable supply chain: An operations research perspective. European Journal of Operational Research, 268(2), 399–431. https://doi.org/10.1016/j.ejor.2017.10.036

Benoit-Norris, C., & Norris, G. A. (2015). Chapter 8 : The Social Hotspots Database. The Sustainability Practitioner's Guide to Social Analysis and Assessment, November, 52–73. https://www.researchgate.net/publication/287215286_Chapter_8_The_Social_Hotspots_Database_Context_of_the_SHDB

Benoît-Norris, Catherine, Bennema, M., & Norris, G. (2018). The Social Hotspots Database: Supporting documentation Update 2019.

Brandão, M., Heijungs, R., & Cowie, A. L. (2022). On quantifying sources of uncertainty in the carbon footprint of biofuels : crop / feedstock , LCA modelling approach , land-use change , and GHG metrics. 34, 1608–1616. https://doi.org/10.18331/BRJ2022.9.2.2

Chen, Z., & Andresen, S. (2014). A Multiobjective Optimization Model of Production-Sourcing for Sustainable Supply Chain with Consideration of Social, Environmental, and Economic Factors. Mathematical Problems in Engineering, 2014, 1–11. https://doi.org/10.1155/2014/616107

Ciroth, A., & Eisfeldt, F. (2016). PSILCA – A Product Social Impact Life Cycle Assessment database. Database version 1.0. Documentation. http://www.openlca.org/documents/14826/6d439d91-ddf5-480f-9155-e4787eaa0b6b

Costanza, R. (2015). Time to leave GDP behind.: EBSCOhost. Nature, 505, 283–285. http://web.a.ebscohost.com.ezproxy.royalroads.ca/ehost/pdfviewer/pdfviewer?vid=1&sid=c3a79af4-c748-4a1a-87e5-a158f249ca45%40sessionmgr4008

Devika, K., Jafarian, A., & Nourbakhsh, V. (2014). Designing a sustainable closed-loop supply chain network based on triple bottom line approach: A comparison of metaheuristics hybridization techniques. European Journal of Operational Research, 235(3), 594–615. https://doi.org/10.1016/j.ejor.2013.12.032

EEA. (2021). Air quality statistics calculated by the EEA (F). http://aidef.apps.eea.europa.eu/?source=%7B%22query%22%3A%7B%22match_all%22%3A%7B%7D%7D%2C%22display_type%22%3A%22tabular%22%7D

Eskandarpour, M., Dejax, P., Miemczyk, J., & Péton, O. (2015). Sustainable supply chain network design: An optimization-oriented review. Omega (United Kingdom), 54, 11–32. https://doi.org/10.1016/j.omega.2015.01.006

European Commission. (2017). My Region, My Europe, Our Future. Seventh report on economic, social and territorial cohesion. In JRC Technical Report. https://doi.org/10.2776/5244

Eurostat. (2021a). Accidents at work by days lost and NACE Rev. 2 activity. [Hsw_n2_04]. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_n2_04&lang=en

Eurostat. (2021b). Crop production in national humidity by NUTS 2 regions [apro_cpnhr]. https://ec.europa.eu/eurostat/product?code=agr_r_acs&mode=view&language=en

Eurostat. (2021c). Farm indicators by agricultural area, type of farm, standard output, legal form and NUTS 2 regions [ef_m_farmleg]. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ef_m_farmleg&lang=en

Eurostat. (2021d). Gross domestic product (GDP) at current market prices by NUTS 2 regions. [Nama_10r_2gdp]. http://appsso.eurostat.ec.europa.eu/nui/show.do?lang=en&dataset=nama_10r_2gdp

Eurostat. (2021e). Land cover overview by NUTS 2 regions. [Land_lcv_ovw]. https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

Eurostat. (2021f). Non-fatal accidents at work by NACE Rev. 2 activity and sex. [Hsw_n2_01]. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_n2_01&lang=en

Eurostat. (2021g). Population density by NUTS 3 region [demo_r_d3dens]. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=demo_r_d3dens&lang=en

Eurostat. (2021h). Unemployment rate by sex and age and NUTS2 regions (%). http://appsso.eurostat.ec.europa.eu/nui/show.do?lang=en&dataset=lfst_r_lfu3rt

FAO. (2000). World Programme for the Census of Agriculture 2000. https://www.fao.org/world-census-agriculture/wcarounds/wca2000/en/

FAO. (2010). World Programme for the Census of Agriculture 2010. https://www.fao.org/world-census-agriculture/wcarounds/wca2010/en/

FAO. (2020). World Census of Agriculture 2020 - Country information. https://www.fao.org/world-census-agriculture/wcarounds/wca2020/countries2020/en/

FAO. (2021). FAO's Global Information System on Water and Agriculture. AQUASTAT. http://www.fao.org/aquastat/en/databases/

Fathollahi-Fard, A. M., Hajiaghaei-Keshteli, M., & Mirjalili, S. (2018). Multi-objective stochastic closed-loop supply chain network design with social considerations. Applied Soft Computing, 71, 505–525. https://doi.org/10.1016/j.asoc.2018.07.025

Fürtner, D., Ranacher, L., Perdomo Echenique, E. A., Schwarzbauer, P., & Hesser, F. (2021). Locating Hotspots for the Social Life Cycle Assessment of Bio-Based Products from Short Rotation Coppice. Bioenergy Research, 14(2), 510–533. https://doi.org/10.1007/s12155-021-10261-9

Ghaderi, H., Moini, A., & Pishvaee, M. S. (2018). A multi-objective robust possibilistic programming approach to sustainable switchgrass-based bioethanol supply chain network design. Journal of Cleaner Production, 179, 368–406. https://doi.org/10.1016/j.jclepro.2017.12.218

Govindan, K., Jha, P. C., & Garg, K. (2016a). Product recovery optimization in closed-loop supply chain to improve sustainability in manufacturing. International Journal of Production Research, 54(5), 1463–1486. https://doi.org/10.1080/00207543.2015.1083625

Govindan, K., Paam, P., & Abtahi, A.-R. (2016b). A fuzzy multi-objective optimization model for sustainable reverse logistics network design. Ecological Indicators, 67, 753–768. https://doi.org/10.1016/j.ecolind.2016.03.017

GRI. (2021). Global Reporting Standards. https://www.globalreporting.org/standards/

Health Effects Institute. (2020). State of Global Air 2020. https://www.stateofglobalair.org/data/#/air/table

Hennig, C., Brosowski, A., & Majer, S. (2016). Sustainable feedstock potential – a limitation for the bio-based economy? Journal of Cleaner Production, 123(August), 200–202. https://doi.org/10.1016/j.jclepro.2015.06.130

HIIK. (2021). Conflict Barometer 2020. Heidelberg Institute for International Conflict Research.

Hoekstra, R. (2019). Replacing GDP by 2030. Cambridge University Press. https://doi.org/10.1017/9781108608558

ILO. (2021a). Days lost due to cases of occupational injury with temporary incapacity for work by economic activity - Annual. https://www.ilo.org/shinyapps/bulkexplorer41/?lang=en&segment=indicator&id=INJ_DAYS_ECO_NB_A

ILO. (2021b). Employees by sex and economic activity (thousands). https://www.ilo.org/shinyapps/bulkexplorer41/?lang=en&segment=indicator&id=EES_TEES_SEX_ECO_NB_A

IMF. (2021). World Economic Outlook Update, January 2021. https://www.imf.org/en/Publications/WEO/weo-database/2020/October/

ISO. (2006). ISO 14040 (2006) Environmental management – life cycle assessment – principles and framework. https://www.iso.org/standard/37456.html

ISO. (2011). ISO 26000 Social Responsibility. https://www.iso.org/iso-26000-social-responsibility.html

Jakhar, S. K. (2015). Performance evaluation and a flow allocation decision model for a sustainable supply chain of an apparel industry. Journal of Cleaner Production, 87, 391–413. https://doi.org/10.1016/j.jclepro.2014.09.089

Kolotzek, C., Helbig, C., Thorenz, A., Reller, A., & Tuma, A. (2018). A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications. Journal of Cleaner Production, 176, 566–580. https://doi.org/10.1016/j.jclepro.2017.12.162

Kühnen, M., & Hahn, R. (2017). Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience. Journal of Industrial Ecology, 21(6), 1547–1565. https://doi.org/10.1111/jiec.12663

Lee, J., Nam, D. S., & Kong, C. (2016). Variability in nutrient composition of cereal grains from different origins. SpringerPlus, 5(1), 419. https://doi.org/10.1186/s40064-016-2046-3

Lewandowski, I. (2015). Securing a sustainable biomass supply in a growing bioeconomy. Global Food Security, 6, 34–42. https://doi.org/10.1016/j.gfs.2015.10.001

Lin, C.-C., Liu, W.-Y., & Huang, G.-L. (2019). Fuzzy Multi-objective Forest Biomass-to-biofuel Facility Location Problem with Social Consideration. Energy Procedia, 158, 4067–4072. https://doi.org/10.1016/j.egypro.2019.01.830

Messmann, L., Zender, V., Thorenz, A., & Tuma, A. (2020). How to quantify social impacts in strategic supply chain optimization: State of the art. Journal of Cleaner Production, 257, 120459. https://doi.org/10.1016/j.jclepro.2020.120459

Miret, C., Chazara, P., Montastruc, L., Negny, S., & Domenech, S. (2016). Design of bioethanol green supply chain: Comparison between first and second generation biomass concerning economic, environmental and social criteria. Computers and Chemical Engineering, 85, 16–35. https://doi.org/10.1016/j.compchemeng.2015.10.008

Mirmohammadi, S. H., & Sahraeian, R. (2018). A Novel Sustainable Closed-loop Supply Chain Network Design by Considering Routing and Quality of Products. International Journal of Engineering, 31(11). https://doi.org/10.5829/ije.2018.31.11b.16

Mota, B., Gomes, M. I., Carvalho, A., & Barbosa-Povoa, A. P. (2015a). Supply chain design and planning accounting for the Triple Bottom Line (pp. 1841–1846). https://doi.org/10.1016/B978-0-444-63576-1.50001-7

Mota, B., Gomes, M. I., Carvalho, A., & Barbosa-Povoa, A. P. (2015b). Towards supply chain sustainability: economic, environmental and social design and planning. Journal of Cleaner Production, 105, 14–27. https://doi.org/10.1016/j.jclepro.2014.07.052

Mousavi Ahranjani, P., Ghaderi, S. F., Azadeh, A., & Babazadeh, R. (2018). Hybrid Multiobjective Robust Possibilistic Programming Approach to a Sustainable Bioethanol Supply Chain Network Design. Industrial and Engineering Chemistry Research, 57(44), 15066–15083. https://doi.org/10.1021/acs.iecr.8b02869

Mujkic, Z., Qorri, A., & Kraslawski, A. (2018). Sustainability and Optimization of Supply Chains: a Literature Review. Operations and Supply Chain Management: An International Journal, 186–199. https://doi.org/10.31387/oscm0350213

Padella, M., O'Connell, A., & Prussi, M. (2019). What is still limiting the deployment of cellulosic ethanol? Analysis of the current status of the sector. Applied Sciences (Switzerland), 9(21). https://doi.org/10.3390/app9214523

Pishvaee, M. S., Razmi, J., & Torabi, S. A. (2014). An accelerated Benders decomposition algorithm for sustainable supply chain network design under uncertainty: A case study of medical needle and syringe supply chain. Transportation Research Part E: Logistics and Transportation Review, 67, 14–38. https://doi.org/10.1016/j.tre.2014.04.001

PwC. (2019). Creating a strategy for a better world. How the Sustainable Development Goals can provide the framework for business do deliver progress on our global challenges. https://www.pwc.com/gx/en/sustainability/SDG/sdg-2019.pdf

Rahimi, M., & Ghezavati, V. (2018). Sustainable multi-period reverse logistics network design and planning under uncertainty utilizing conditional value at risk (CVaR) for recycling construction and demolition waste. Journal of Cleaner Production, 172, 1567–1581. https://doi.org/10.1016/j.jclepro.2017.10.240

Rahimi, M., Ghezavati, V., & Asadi, F. (2019). A stochastic risk-averse sustainable supply chain network design problem with quantity discount considering multiple sources of uncertainty. Computers & Industrial Engineering, 130, 430–449. https://doi.org/10.1016/j.cie.2019.02.037

Ramos, M. J., Sousa Fragoso, R. M. de, & Feiden, A. (2019). A Multi-objective Approach for Supply Chain Network Design: Tilapia Pisciculture in Paraná State - Brazil. Journal of Agricultural & Food Industrial Organization, 17(1). https://doi.org/10.1515/jafio-2018-0003

Ren, J., Manzardo, A., Mazzi, A., Zuliani, F., & Scipioni, A. (2015). Prioritization of bioethanol production pathways in China based on life cycle sustainability assessment and multicriteria decision-making. The International Journal of Life Cycle Assessment, 20(6), 842–853. https://doi.org/10.1007/s11367-015-0877-8

Rezaei, S., & Kheirkhah, A. (2018). A comprehensive approach in designing a sustainable closed-loop supply chain network using cross-docking operations. Computational and Mathematical Organization Theory, 24(1), 51–98. https://doi.org/10.1007/s10588-017-9247-3

Roni, M. S., Eksioglu, S. D., Cafferty, K. G., & Jacobson, J. J. (2017). A multi-objective, hub-and-spoke model to design and manage biofuel supply chains. Annals of Operations Research, 249(1–2), 351–380. https://doi.org/10.1007/s10479-015-2102-3

Sahebjamnia, N., Fathollahi-Fard, A. M., & Hajiaghaei-Keshteli, M. (2018). Sustainable tire closed-loop supply chain network design: Hybrid metaheuristic algorithms for large-scale networks. Journal of Cleaner Production, 196, 273–296. https://doi.org/10.1016/j.jclepro.2018.05.245

SAI. (1997). SA8000® Standard. https://sa-intl.org/programs/sa8000/

Samadi, A., Mehranfar, N., Fathollahi Fard, A. M., & Hajiaghaei-Keshteli, M. (2018). Heuristic-based metaheuristics to address a sustainable supply chain network design problem. Journal of Industrial and Production Engineering, 35(2), 102–117. https://doi.org/10.1080/21681015.2017.1422039

Schaubroeck, T., Petucco, C., & Benetto, E. (2019). Evaluate impact also per stakeholder in sustainability assessment, especially for financial analysis of circular economy initiatives. Resources, Conservation and Recycling, 150, 104411. https://doi.org/10.1016/j.resconrec.2019.104411

Schaubroeck, T., & Rugani, B. (2017). A Revision of What Life Cycle Sustainability Assessment Should Entail: Towards Modeling the Net Impact on Human Well-Being. Journal of Industrial Ecology, 21(6), 1464–1477. https://doi.org/10.1111/jiec.12653

Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., & Benetto, E. (2021). Attributional & consequential life cycle assessment: Definitions, conceptual characteristics and modelling restrictions. Sustainability (Switzerland), 13(13), 1–47. https://doi.org/10.3390/su13137386

Shokouhyar, S., & Aalirezaei, A. (2017). Designing a sustainable recovery network for waste from electrical and electronic equipment using a genetic algorithm. International Journal of Environment and Sustainable Development, 16(1), 60. https://doi.org/10.1504/IJESD.2017.080851

Soleimani, H., Govindan, K., Saghafi, H., & Jafari, H. (2017). Fuzzy multi-objective sustainable and green closed-loop supply chain network design. Computers & Industrial Engineering, 109, 191–203. https://doi.org/10.1016/j.cie.2017.04.038

Sonnemann, G., & Vigon, B. (2011). Global Guidance principles for life cycle assessment databases. A Basis for Greener Processes and Products. https://lca-net.com/publications/show/global-guidance-principles-life-cycle-assessment-databases

Thorenz, A., Wietschel, L., Stindt, D., & Tuma, A. (2018). Assessment of agroforestry residue potentials for the bioeconomy in the European Union. Journal of Cleaner Production, 176(December), 348–359. https://doi.org/10.1016/j.jclepro.2017.12.143

Tsao, Y.-C., Thanh, V.-V., Lu, J.-C., & Yu, V. (2018). Designing sustainable supply chain networks under uncertain environments: Fuzzy multi-objective programming. Journal of Cleaner Production, 174, 1550–1565. https://doi.org/10.1016/j.jclepro.2017.10.272

UNEP. (2011). Towards a Life Cycle Sustainability Assessment. https://doi.org/DTI/1412/PA

UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020. https://www.lifecycleinitiative.org/library/guidelines-for-social-life-cycle-assessment-of-products-and-organisations-2020

UNEP. (2021). Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021. https://www.lifecycleinitiative.org/library/methodological-sheets-for-subcategories-in-social-life-cycle-assessment-s-lca-2021

UNEP SETAC. (2013). The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA). https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf

UNHCR. (2021). Figures at a Glance. https://www.unhcr.org/en-us/figures-at-a-glance.html

United Nations. (2015). Sustainable Development Goals. https://sdgs.un.org/goals

Valdivia, S., Backes, J. G., Traverso, M., Sonnemann, G., Cucurachi, S., Guinée, J. B., Schaubroeck, T., Finkbeiner, M., Leroy-Parmentier, N., Ugaya, C., Peña, C., Zamagni, A., Inaba, A., Amaral, M., Berger, M., Dvarioniene, J., Vakhitova, T., Benoit-Norris, C., Prox, M., ... Goedkoop, M. (2021).

Principles for the application of life cycle sustainability assessment. The International Journal of Life Cycle Assessment, 26(9), 1900–1905. https://doi.org/10.1007/s11367-021-01958-2

Weidema, B. P. (2006). The Integration of Economic and Social Aspects in Life Cycle Impact Assessment. The International Journal of Life Cycle Assessment, 11(S1), 89–96. https://doi.org/10.1065/lca2006.04.016

WHO. (2018). Ambient (outdoor) air quality database 2018. https://www.who.int/data/gho/data/themes/air-pollution/who-air-quality-database/2018

WHO. (2021). AirQ+: software tool for health risk assessment of air pollution. https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/airq-software-tool-for-health-risk-assessment-of-air-pollution

Wietschel, L., Messmann, L., Thorenz, A., & Tuma, A. (2021). Environmental benefits of large-scale second-generation bioethanol production in the EU: An integrated supply chain network optimization and life cycle assessment approach. Journal of Industrial Ecology, 25(3), 677–692. https://doi.org/10.1111/jiec.13083

World Bank. (2021a). Cereal yield (kg per hectare). https://data.worldbank.org/indicator/AG.YLD.CREL.KG

World Bank. (2021b). Employing Workers. https://www.worldbank.org/en/research/employing-workers/data/working-hours

World Bank. (2021c). GDP, PPP (current international $). https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.CD

World Bank. (2021d). PM2.5 air pollution, mean annual exposure (micrograms per cubic meter). https://data.worldbank.org/indicator/EN.ATM.PM25.MC.M3

World Bank. (2021e). Population density (people per sq. km of land area). https://data.worldbank.org/indicator/EN.POP.DNST

World Bank. (2021f). Unemployment, total (% of total labor force). https://data.worldbank.org/indicator/SL.UEM.TOTL.ZS?name_desc=false

Zahiri, B., Zhuang, J., & Mohammadi, M. (2017). Toward an integrated sustainable-resilient supply chain: A pharmaceutical case study. Transportation Research Part E: Logistics and Transportation Review, 103, 109–142. https://doi.org/10.1016/j.tre.2017.04.009

Zeug, W., Bezama, A., & Thrän, D. (2021). A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy. International Journal of Life Cycle Assessment, 26(10), 1998–2023. https://doi.org/10.1007/s11367-021-01983-1

Zhalechian, M., Tavakkoli-Moghaddam, R., Zahiri, B., & Mohammadi, M. (2016). Sustainable design of a closed-loop location-routing-inventory supply chain network under mixed uncertainty. Transportation Research Part E: Logistics and Transportation Review, 89, 182–214. https://doi.org/10.1016/j.tre.2016.02.011

Zhu, L., & Hu, D. (2017). Sustainable Logistics Network Modeling for Enterprise Supply Chain. Mathematical Problems in Engineering, 2017, 1–11. https://doi.org/10.1155/2017/98978

3

CONCLUSIONS

3.1 KEY RESULTS & ADDED VALUE OF THE RESEARCH

Subsection 3.1 summarizes the results of the five contributions and discusses the value they add to their respective field of research.

Contribution A[9] quantifies the potential for preparation for reuse at Bavarian waste collection points. Results show that about 14% (16,361 t annually) of electric and electronic devices, 13% of used furniture (142,710 t annually), and 16% of used leisure goods could theoretically directly be prepared for reuse. This shows the large gap between the goals of a circular economy and the status quo of reuse (with reuse quotas of 0.5% and 6% for WEEE and furniture, respectively). It also underlines the need for distinct reuse quotas of, e.g., 5% (Johnson et al. 2015; Queiruga and Queiruga-Dios 2015; Esenduran et al. 2016) next to the already existing recovery quota of 65% (Directive 2008/98/EC), which is foremost attributable to recycling. Furthermore, a significant fraction of goods disposed at Bavarian collection points are damaged at the collection point, e.g., from being exposed to weather (particularly WEEE) or from being handled in large collection containers. Based on the gathered results, four distinct action recommendations for municipal and regional (Bavarian) policy-makers with the respective unlockable potential for reuse are formulated.

The study was conducted as part of a research project titled ‘Potentialabschätzung ausgewählter Abfallströme für die Vorbereitung zur Wiederverwendung’ (*Estimation of the potential of selected waste streams for the Preparation for Reuse*), which was funded by the Bavarian State Ministry of the Environment and Consumer Protection. Based on the results of Contribution A and the succeeding study by Boldoczki et al. (2020), and in collaboration with the ministry, a practical guideline was compiled and distributed to municipalities, waste management authorities, recycling companies, collection point operators, and other stakeholders to foster an improvement in the reusable volumes at Bavarian collection points (StMUV 2019). Academically, the quantified potentials were subsequently used in the studies by Boldoczki et al. (2020, 2021), who assess the environmental savings potential from increased preparation-for-reuse quotas in an integrated LCA and MFA approach. The formulation of action recommendations was picked up and extended by Boldoczki 2022. Lastly, the results were also appreciated on the European level when the study was included in ‘Science for Environmental Policy’, the European Commission’s scientific news alert service (European Commission 2019).

---

[9] *RQ1*: What is the quality of different waste streams in different classes of municipalities and what are the causes of damages? *RQ2*: What is the resulting theoretical potential for the preparation for reuse in Bavaria? *RQ3*: Which actions recommendations result from the main obstacles to realizing this potential at Bavarian collection points?

Contribution B[10] and **Contribution D**[11] stress the need for closing technical and biological cycles to reduce the environmental pressures exerted by the socio-economic system. Environmental benefits, 'avoided burdens', are achieved through substitution of parts of the forward supply chain when recovering WEEE (Contribution B) or of different product systems, in this case, fossil-based fuels or first-generation bioethanol (1G EtOH), by second-generation bioethanol (2G EtOH, Contribution D). Both studies also underline the need for an ex-ante, quantitative consideration of environmental aspects ideally based on a holistic Life Cycle Assessment with a differentiated analysis of the entire set of environmental categories.

Contributions B and D develop network optimization models for WEEE recovery network and for 2G EtOH production, respectively. The studies present optimal network decisions for 22 different economic and LCA-based environmental objectives, assess conflicts and congruencies between objectives, and identify Pareto-efficient trade-offs. In both studies, the results differ vastly between the different objectives, most notably between economic and environmental ones, but also between different environmental categories. Conflicts are often either due to the overall network size and layout or, in the case of bioethanol, conflicting substitution decisions. Economically optimal networks are often smaller. They are concentrated on Central and Eastern European countries with lower labor costs. Economically optimal networks yield notable environmental benefits in a number of environmental categories (e.g., *global warming*), but most environmentally optimal networks are economically infeasible. Only in scenario T5 of Contribution D (with a carbon tax of €375) do the economic and most environmental objectives show a high degree of congruency, which would enable a large production network for 2G EtOH and profitably substituting a fifth of the petrol demand in the EU. However, economically and some environmentally optimal solutions (e.g., *global warming*) can also be harmful in other categories, underlining that other environmental issues besides *global warming* should not be ignored (Sikdar 2021). For example, for any network for high-value WEEE recovery, network impacts in terms of *mineral resource scarcity* outweigh the benefits from avoided burdens, which is why WEEE collection should exclusively be carried out by third-party recyclers for this objective. Similarly, substitution of fossil petrol yields

---

[10] What is the benefit of optimal configurations of a WEEE recovery network from an OEM perspective compared to third-party recycling, considering economic and different environmental (LCIA endpoint and midpoint) aspects? *RQ1*: What are optimal configurations of a European WEEE recovery network? *RQ2*: What are economic and environmental benefits of network configurations in comparison to third-party recycling? *RQ3*: How does the quantity of collectible WEEE affect the results?

[11] *RQ1*: What are the benefits of optimal second-generation ethanol production network configurations to substitute petrol and first-generation ethanol, considering different environmental and economic aspects? *RQ2*: Which environmental objectives are congruent, and which are conflicting (considering LCIA midpoints and endpoints)? *RQ3*: Which taxation scenario supports the scale-up of a second-generation ethanol production network in the European Union?

much smaller benefits in *land use* than the impacts that a network necessary to realize these benefits would cause.

Contributions B and D add to existing research on strategic supply chain optimization by their differentiated view on the level of environmental and LCA-based impact and damage categories, which was hitherto neglected in lieu of greenhouse gas emission alone or purely economic assessments. In addition, Contribution D adds to bioeconomic research by taking an EU perspective and providing European policy-makers with a differentiated decision support on how a scale-up of the European bioeconomy for second-generation bioethanol can be achieved and which environmental benefits can be realized. The results of Contribution D, in particular, underline the importance of political guidance if unlocking the full environmental potential is politically desired.

Contribution C[12] presents a comprehensive and structured review of articles on strategic supply chain optimization that include explicit social objective functions. The results show that in many articles, social indicators are chosen arbitrarily. The number of jobs created is the primary and often the only objective that is maximized. Other objective functions use unitless, weighted social 'scores', aggregated a priori from, e.g., expert interviews with the Analytic Hierarchy Process (AHP) method. In those cases where a study's model does incorporate more than one social indicator in their objective function, studies rely on weighted sums with predetermined weighting factors, where the unit of and thus the relationship between the different social aspects remains hidden. Among the observed studies, neither more advanced multi-criteria optimization approaches *between* the social aspects, nor attempts of a social impact assessment are observed. Contribution C illustrates the intricacy of and the subsequent clear research gap that exists in integrating social aspects quantitatively into strategic planning. The current state of the art at this intersection between Operations Research and Industrial Ecology is nowhere near an appropriate representation of the diverse and complex nature of the social aspects of strategic decisions.

Contribution E[13] addresses the research gap identified by Contribution C by providing a best-practice approach for the inclusion of applicable social indicators into strategic network design, applied to the case of 2G EtOH of Contribution D. The results of nine social objective functions show that social objectives, just as environmental ones, are heterogenous and may conflict with each other and with economic and environmental goals in, e.g., overall network capacity, facility locations, and

---

[12] What is the state of the art of integrating social aspects in the field of strategic supply chain optimization? *RQ1*: What frameworks for social assessment are referred to, what social aspects are considered, and how is their selection justified? *RQ2*: How are social indicators incorporated into quantitative models?

[13] *Research Goal*: Provide a best-practice approach for a structured and transparent selection of a comprehensive set of quantitative and operationalizable social indicators based on existing frameworks. *RQ1*: What are the social benefits, impacts, and hotspots of socially, environmentally, and economically optimal large-scale production networks for second-generation bioethanol in the EU? *RQ2*: Which SDGs are affected, and what are interlinkages between them?

substitution decisions. This heterogeneity partially stems from specific parameter values (as is the case for environmental objectives, e.g., which substitution decision yields higher benefits?), and partially from fundamental differences in how decisions contribute to social benefits, i.e., whether substitution (avoided adverse social circumstances) or the network itself (e.g., employment) yields the benefits. For example, on the one hand, the objectives *local employment* and *economic development* both favor as large networks as possible and have a high degree of mutual congruency, while the network optimal in terms of *water use* is concentrated on a few favorable countries with a low water stress level and can only beneficially be operated due to substitution of the water-wise much more harmful 1G EtOH. On the other hand, *water use* and *economic development* are rather congruent, while *water use* and *local employment* are conflicting due to parameter-wise correlations between low water stress levels and under-average economic development figures in Central and Eastern European countries, and high water stresses and above-average unemployment rates in southern European countries. In addition to operationalizing social indicators for social objective functions, Contribution E also quantifies social hotspots, i.e., the risk for socially adverse situations along global value chains, in 25 categories from the Social Hotspots Database. This allows decision-makers to anticipate those social effects that may have no apparent and direct connection with their decision. For example, many economic, environmentally, and socially optimal networks aggregate high social risks in terms of *freedom of association, collective bargaining, and right to strike*, especially from agricultural network activities in Romania. Therefore, due diligence in local supplier selection is necessary to avoid a realization of these risks in practice.

Contribution E adds to the field of strategic network design by integrating a significantly more diverse set of social indicators into social objective functions than hitherto state of the art. In addition, the identification of potential social hotspots arising from strategic decisions is an informative tool for decision-makers. In particular, this contribution demonstrates the need and presents a best-practice approach for the consideration of all *three* dimensions of sustainability, as well as for how both corporate and political decision-making can contribute to (or possibly hinder) the achievement of the Sustainable Development Goals. Furthermore, by (1) evaluating results, conflicts, congruencies, and Pareto-efficient solutions on the level of individual environmental midpoints and social subcategories instead of presenting three monolithic LCA, SLCA, and economic results, as well as by (2) evaluating the results on the level of the overarching SDGs, Contribution E follows a more integrative approach to LCSA, similar to and as advocated by, e.g., Zeug et al. (2021) and Goffetti (2020).

3.2 OUTLOOK & FUTURE RESEARCH AGENDA

Subsection 3.2 identifies and motivates methodological and thematic pathways of future research. Ensuing from this dissertation's contributions, several different research pathways lie ahead. They entail (1) methodological enhancements in the application of the holistic LCSA approach, namely in terms of LCC, (2) an extension of the tripartite sustainability pillars by climate resilience as an inherent goal and desired feature of supply networks in view of global warming, (3) advancement in the sophistication of the existing models, namely the introduction of stochastic programming, which the aforementioned extension necessitates, and (4) the transfer of the proven approach of integrating LCSA results into OR models to other thematic areas, namely the European hydrogen strategy.

Of the three methodologies that make up Life Cycle Sustainability Assessment (Life Cycle Assessment, LCA, Social Life Cycle Assessment, SLCA, and Life Cycle Costing, LCC), LCC and thus the economic pillar of sustainability has been explored the least in the contributions of this dissertation. Contribution B, Contribution D, and Contribution E do include economic objective functions, which represent profit maximization. While this was suited for these studies to evaluate trade-offs between economic feasibility and environmental potentials, a holistic LCC, besides assuming the same cradle-to-grave and cradle-to-cradle perspective as in LCA, may include more angles than just the corporate and may include more components than product costs and revenues. While upstream costs in a product's life cycle, such as R&D, may be included in corporate controlling, downstream costs associated with its end-of-life or occurring during the use phase at the consumer are also part of a differentiated LCC (Rebitzer et al. 2003). From society's perspective, an LCC may also assume the polluter-pays principle and internalize the costs that arise from the environmental externalities during a product's life, which are currently borne by society (Swarr et al. 2011). This includes restoration costs (e.g., health care costs due to environmental pollution, ecosystem restoration, water treatment), compensation or damage costs (e.g., the value of lost health), or abatement costs (e.g., climate change) (CE Delft 2018; True Price Foundation 2020).

With the severe challenges that humankind and ecosystems alike will face even in the most optimistic scenarios of climate change mitigation (IPCC 2021), environmentally, economically, and socially sustainable production and consumption will not suffice to alleviate the serious risks posed by global warming and other human-induced global crises. Climate change adaption (IPCC 2022) or, in a broader sense, climate resilience becomes a necessity and should be considered alongside the three pillars of sustainability. Resilience is a system's ability "to maintain [...] or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems" (Meerow et al. 2016, p. 39) and thus entails both absorptive and adaptive capacities (Folke et al. 2002). From the perspective of supply chain planners and managers, extreme weather events induced by global warming pose the threat of disrupting global supply chains (IPCC 2022) by causing direct damage to facilities, decreasing process water availability, increasing price volatility, and exposing employees to increased disease risks (Langholtz et al. 2014). Agriculture and, with it, the here assessed bioeconomy are particularly vulnerable to supply disruptions. In the short term, weather extremes threaten crop harvests and increase yield variability (Ray et al. 2015), and in the long term, less suitable conditions may lead to a decline in average yields (Zampieri et al. 2019; Langholtz et al. 2014). Consequently, climate resilience should arguably be included in supply chain planning, especially in the context of bioproducts. Future research will provide an overview of resilience metrics in various fields, explore the incorporation of resilience metrics in network optimization models, and show which planning decisions support the creation of *resilient* second-generation bioethanol networks in the EU.

As the rapidity in which a system is able to recover from a disturbance is one characteristic of the system's resilience, Meerow et al. (2016) emphasize the importance of temporal scales in resilience thinking. In addition to disturbing events, the disturbing *trend* of global warming supports this notion (Wardekker et al. 2010). The incorporation of a 'resilience dimension' into the case study presented in Contributions D and E requires the static optimization model of those studies (i.e., no temporal scale; all decisions and parameters refer to one year) to be converted into a dynamic model with a sufficient temporal scale. *Stochastic linear programming* is a common method to account for the stochasticity of disruption events in optimization models (e.g., Li and Grossmann 2021, Ahranjani et al. 2018, Torabi et al. 2015). This is often done with a two-stage approach, where first-stage decisions are taken a priori, "here and now", based on known uncertainty parameters, while second-stage decisions represent "wait and see", and are taken depending on the manifestation of the stochastic elements along the time horizon (Li and Grossmann 2021, p. 4). In the case of second-generation bioethanol production networks, first-stage decisions comprise location and capacity decisions, while second-stage decisions are dependent on inter alia stochastic supply disruption scenarios and may comprise sourcing and transportation decisions. Preliminary experiments with a converted dynamic stochastic programming model based on the MILP model presented in Contributions D and E show that solvability with the afore employed CPLEX solver is stretched to its limits. Therefore, future research will explore the suitability of more sophisticated simulation-optimization algorithms (cf. Amaran et al. 2014) for this application case.

Further potential for future research presents itself also on a thematic level. Both the European as well as the strategic and policy-maker-focused perspective of the optimization approach of Contribution D also apply to other promising, environmentally beneficial products. Similar to second-generation bioethanol, green hydrogen is considered one of the cornerstones of a decarbonized economy and in need of a rapid up-scaling of technologies and production volumes (IEA 2019; IRENA 2020). While hydrogen faces strong competition with battery electric vehicles in private transportation, green hydrogen is projected to yield the largest environmental benefits in aviation and shipping, as well as for industrial processes such as steel production

(Rystad Energy 2021). ‘Green’ hydrogen is produced via hydrolysis and, given that the required electricity is generated renewably, is the most sustainable production pathway of hydrogen. However, it needs to pass technological learning curves (Noussan et al. 2020) and currently requires governmental support (Nazir et al. 2020) for market penetration. Since the potential for green electricity varies strongly within the EU and in neighboring regions, importing green hydrogen (e.g., from North Africa; Wang et al. 2020) may be both viable and necessary (Wietschel et al. 2020). However, due to its low volumetric energy density, long-distance hydrogen transportation by lorry, rail, or ship is expensive, but refitting methane pipelines and newly constructing distinct hydrogen pipelines likewise entails high costs and requires elaborate planning effort (Nationaler Wasserstoffrat 2021). Therefore, European policy faces a combined network planning and allocation problem. Future research will address this by informing European policy-makers about the environmental potential of optimal green hydrogen production and transportation networks as well as the levers to unlock this potential by optimally allocating produced green hydrogen to hydrogen demanding industries in the EU. This will, presumably, confirm the suitability of strategic network optimization approaches not only from a corporate, but also and especially from the perspective of political decision-makers on the level of the European Union.

REFERENCES

AccountAbility. 1999. *AccountAbility 1000 (AA1000) framework: standards, guidelines and professional qualification.* 10.1080/0969160x.1999.9651618.

Aditiya, H.B., T.M.I. Mahlia, W.T. Chong, H. Nur, & A.H. Sebayang. 2016. Second generation bioethanol production: A critical review. *Renewable and Sustainable Energy Reviews* 66: 631–653. 10.1016/j.rser.2016.07.015.

Ahranjani, P.M., S.F. Ghaderi, A. Azadeh, & R. Babazadeh. 2018. A Hybrid Multiobjective Robust Possibilistic Programming Approach to a Sustainable Bioethanol Supply Chain Network Design. *Industrial and Engineering Chemistry Research* 57(44): 15066–15083. 10.1021/acs.iecr.8b02869.

Amaran, S., N. V. Sahinidis, B. Sharda, & S.J. Bury. 2014. Simulation optimization: a review of algorithms and applications. *4OR* 12(4): 301–333. 10.1007/s10288-014-0275-2.

Boldoczki, S. 2022. How to unlock potentials of preparation for reuse: barriers and action recommendations. *Die Unternehmung - Swiss Journal of Business Research and Practice* 76(2).

Boldoczki, S., A. Thorenz, & A. Tuma. 2020. The environmental impacts of preparation for reuse: A case study of WEEE reuse in Germany. *Journal of Cleaner Production* 252: 119736. 10.1016/j.jclepro.2019.119736.

Boldoczki, S., A. Thorenz, & A. Tuma. 2021. Does increased circularity lead to environmental sustainability?: The case of washing machine reuse in Germany. *Journal of Industrial Ecology* 25(4): 864–876. 10.1111/jiec.13104.

Brears, R.C. 2018. The Circular Economy. In *Natural Resource Management and the Circular Economy*, 1–30. Cham: Springer International Publishing. 10.1007/978-3-319-71888-0.

Bressanelli, G., N. Saccani, M. Perona, & I. Baccanelli. 2020. Towards circular economy in the household appliance industry: An overview of cases. *Resources* 9(11): 1–23. 10.3390/resources9110128.

Bruno, G., A. Diglio, R. Passaro, C. Piccolo, & I. Quinto. 2021. Measuring spatial access to the recovery networks for WEEE: An in-depth analysis of the Italian case. *International Journal of Production Economics* 240: 108210. 10.1016/j.ijpe.2021.108210.

Bušić, A., N. Mardetko, S. Kundas, G. Morzak, H. Belskaya, M.I. Šantek, D. Komes, S. Novak, & B. Šantek. 2018. Bioethanol production from renewable raw materials and its separation and purification: A review. *Food Technology and Biotechnology.* 10.17113/ftb.56.03.18.5546.

BVerfG. 2021a. Beschluss des Ersten Senats vom 24. März 2021 - 1 BvR 2656/18 -, Rn. 1-270.

BVerfG. 2021b. Constitutional complaints against the Federal Climate Change Act partially successful. Accessed March 27, 2022.

Casey, K., M. Lichrou, & C. Fitzpatrick. 2019. Treasured trash? A consumer perspective on small Waste Electrical and Electronic Equipment (WEEE) divestment in Ireland. *Resources, Conservation and Recycling* 145(February): 179–189. 10.1016/j.resconrec.2019.02.015.

CE Delft. 2018. *Environmental Prices Handbook EU28 version.*

Chazara, P., S. Negny, & L. Montastruc. 2017. Quantitative method to assess the number of jobs created by production systems: Application to multi-criteria decision analysis for sustainable biomass supply chain. *Sustainable Production and Consumption* 12: 134–154. 10.1016/j.spc.2017.07.002.

Chircop, K. & D. Zammit-Mangion. 2013. On ε-Constraint Based Methods for the Generation of Pareto Frontiers. *Journal of Mechanics Engineering and Automation* 3: 279–289.

Correa, D.F., H.L. Beyer, H.P. Possingham, S.R. Thomas-Hall, & P.M. Schenk. 2017. Biodiversity impacts of bioenergy production: Microalgae vs. first generation biofuels. *Renewable and Sustainable Energy Reviews* 74: 1131–1146. 10.1016/j.rser.2017.02.068.

Curran, A., I.D. Williams, & S. Heaven. 2007. Management of household bulky waste in England. *Resources, Conservation and Recycling* 51: 78–92. 10.1016/j.resconrec.2006.08.003.

Dahiya, S., R. Katakojwala, S. Ramakrishna, & S.V. Mohan. 2020. Biobased Products and Life Cycle Assessment in the Context of Circular Economy and Sustainability. *Materials Circular Economy* 2(1). 10.1007/s42824-020-00007-x.

Directive 2008/98/EC. of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives.

Directive 2012/19/EU. of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE). 10.5040/9781782258674.0030.

Directive 2015/1513/EU. of the European Parliament and of the Council amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources.

Domschke, W., A. Drexl, R. Klein, & A. Scholl. 2015. *Einführung in Operations Research.* 9th ed. Springer-Lehrbuch. Springer Berlin Heidelberg. 10.1007/978-3-662-48216-2.

Domschke, W. & A. Scholl. 2008. *Grundlagen der Betriebswirtschaftslehre.* 4th ed. Springer-Verlag Berlin Heidelberg.

Ellen MacArthur Foundation. 2014. *Towards the Circular Economy Vol. 3:*

Accelerating the scale-up across global supply chains.

Ellen MacArthur Foundation. 2015. *Towards a Circular Economy: Business Rationale for an Accelerated Transition.*

Ellen MacArthur Foundation. 2019. Circulate products and materials. Accessed March 7, 2022.

Esenduran, G., E. Kemahlıoğlu-Ziya, & J.M. Swaminathan. 2016. Take-Back Legislation: Consequences for Remanufacturing and Environment. *Decision Sciences* 47(2): 219–256. 10.1111/deci.12174.

Eskandarpour, M., P. Dejax, J. Miemczyk, & O. Péton. 2015. Sustainable supply chain network design: An optimization-oriented review. *Omega* 54: 11–32. 10.1016/j.omega.2015.01.006.

European Commission. 2010. *International Reference Life Cycle Data System (ILCD) Handbook - General Guide for Life Cycle Assessment - Detailed Guidance.* 1st ed. Luxembourg: Publications Office of the European Union. 10.2788/38479.

European Commission. 2018. Renewable Energy – Recast to 2030 (RED II).

European Commission. 2019. *Waste potential: more of our refuse electronics, furniture and leisure goods could be re-used, suggests German study.*

European Commission. 2020. Weekly Oil Bulletin. Accessed March 14, 2022.

Eurostat. 2022. Waste statistics - electrical and electronic equipment. Accessed March 4, 2022.

Fachagentur Nachwachsende Rohstoffe. 2021. Aktuelle Marktsituation. Kraftstoffabsatz in Deutschland.

FAO. 2019. *The State of the World's Biodiversity for Food and Agriculture. The State of the World's Biodiversity for Food and Agriculture.* 10.4060/ca3129en.

Farrant, L. & Y. Le Guern. 2012. Which environmental impacts for ICT? - LCA case study on electronic mail. In *2012 Electronics Goes Green 2012+*, 1–5.

Finkbeiner, M., E.M. Schau, A. Lehmann, & M. Traverso. 2010. Towards Life Cycle Sustainability Assessment. *Sustainability* 2(10): 3309–3322. 10.3390/su2103309.

Folke, C., S. Carpenter, T. Elmqvist, L. Gunderson, C.S. Holling, & B. Walker. 2002. Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations. *AMBIO: A Journal of the Human Environment* 31(5): 437–440. 10.1579/0044-7447-31.5.437.

Georgantzis, G.D. & S.K. van Langen. 2021. Urban Mining of e-Waste and the Role of Consumers. In *Current Topics in Recycling*, ed. by Dimitris S. Achilias. IntechOpen, October 19. 10.5772/intechopen.100363.

Goetschalckx, M. & B. Fleischmann. 2015. Strategic Network Design. In *Supply Chain Management and Advanced Planning*, ed. by Hartmut Stadtler, Christoph Kilger, and Herbert Meyr, 107–124. 5th ed. Heidelberg, New York, Dordrecht, London: Springer. 10.1007/978-3-642-55309-7.

Goffetti, G. 2020. *The Life Cycle Sustainability Assessment framework through the lens of the systemic approach.*

GRI. 2021. Global Reporting Standards.

Haberl, H., D. Wiedenhofer, S. Pauliuk, F. Krausmann, D.B. Müller, & M. Fischer-Kowalski. 2019. Contributions of sociometabolic research to sustainability science. *Nature Sustainability* 2(3): 173–184. 10.1038/s41893-019-0225-2.

Helbig, C. 2018. *Metalle im Spannungsfeld technoökonomischen Handelns: Eine Bewertung der Versorgungsrisiken mit Methoden der Industrial Ecology.*

Hjuler, S.V. & S.B. Hansen. 2018. LCA of Biofuels and Biomaterials. In *Life Cycle Assessment: Theory and Practice*, ed. by Michael Z. Hauschild, Ralph K. Rosenbaum, and Stig Irving Olsen, 755–782. 10.1007/978-3-319-56475-3_30.

Horvat, D., S. Wydra, & C.M. Lerch. 2018. Modelling and Simulating the Dynamics of the European Demand for Bio-Based Plastics. *International Journal of Simulation Modelling* 17(3): 419–430. 10.2507/IJSIMM17(3)435.

Huijbregts, M., Z.J.N. Steinmann, P.M.F.M. Elshout, G. Stam, F. Verones, M.D.M. Vieira, M. Zijp, & R. van Zelm. 2016. ReCiPe 2016 - A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. *National Institute for Public Health and the Environment*: 194.

Hutner, P. 2017. *Transdisziplinärer Ansatz zur Förderung einer Circular Economy durch nachhaltiges Ressourcenmanagement.* Hamburg: Verlag Dr. Kovač GmbH.

IEA. 2019. *The Future of Hydrogen: Seizing today's opportunities.*

IPCC. 2021. *Climate Change 2021 - The Physical Science Basis.* 10.3724/sp.j.7103161536.

IPCC. 2022. *Climate Change 2022 - Impacts, Adaption and Vulnerability: Summary for Policymakers.*

IRENA. 2020. *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5 °C climate goal.*

ISO. 2006a. ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework.

ISO. 2006b. ISO 14044:2006. Environmental management — Life cycle assessment — Requirements and guidelines.

ISO. 2010. ISO 26000:2010. Guidance on Social Responsibility.

Johnson, M., K. Mcmahon, & C. Fitzpatrick. 2015. *Research of Upcycling Supports to Increase Re-use, with a Focus on Waste Electrical and Electronic Equipment (UpWEEE).* Accessed March 4, 2022.

Jørgensen, A. 2013. Social LCA - A way ahead? *International Journal of Life Cycle Assessment* 18(2): 296–299. 10.1007/s11367-012-0517-5.

Kral, U., K. Kellner, & P.H. Brunner. 2013. Sustainable resource use requires "clean cycles" and safe "final sinks." *Science of the Total Environment* 461–462: 819–822. 10.1016/j.scitotenv.2012.08.094.

Krikke, H. 2011. Impact of closed-loop network configurations on carbon footprints: A case study in copiers. *Resources, Conservation and Recycling* 55: 1196–1205. 10.1016/j.resconrec.2011.07.001.

Kühnen, M. & R. Hahn. 2017. Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience. *Journal of Industrial Ecology* 21(6): 1547–1565. 10.1111/jiec.12663.

Langholtz, M., E. Webb, B.L. Preston, A. Turhollow, N. Breuer, L. Eaton, A.W. King, S. Sokhansanj, S.S. Nair, & M. Downing. 2014. Climate risk management for the U.S. cellulosic biofuels supply chain. *Climate Risk Management* 3: 96–115. 10.1016/j.crm.2014.05.001.

Leclerc, S.H. & M.G. Badami. 2020. Extended producer responsibility for E-waste management: Policy drivers and challenges. *Journal of Cleaner Production* 251. 10.1016/j.jclepro.2019.119657.

LfU. 2016. *Hausmüll in Bayern. Bilanzen 2015.* Accessed March 4, 2022.

Li, C. & I.E. Grossmann. 2021. A Review of Stochastic Programming Methods for Optimization of Process Systems Under Uncertainty. *Frontiers in Chemical Engineering* 2(January): 1–20. 10.3389/fceng.2020.622241.

Lifset, R. & T.E. Graedel. 2002. Industrial ecology: goals and definitions. *A Handbook of Industrial Ecology.* 10.4337/9781843765479.00009.

Mahapatra, M.K. & A. Kumar. 2019. Fermentation of Oil Extraction: Bioethanol, Acetone and Butanol Production. In *Prospects of Renewable Bioprocessing in Future Energy Systems*, ed. by Ali Ashgar Rastegari, Ajar Nath Yadav, and Arti Gupta, 219–249. 10.1007/978-3-030-14463-0_8.

Mat Aron, N.S., K.S. Khoo, K.W. Chew, P.L. Show, W.H. Chen, & T.H.P. Nguyen. 2020. Sustainability of the four generations of biofuels – A review. *International Journal of Energy Research* 44(12): 9266–9282. 10.1002/er.5557.

Meerow, S., J.P. Newell, & M. Stults. 2016. Defining urban resilience: A review. *Landscape and Urban Planning* 147: 38–49. 10.1016/j.landurbplan.2015.11.011.

Meyr, H., M. Wagner, & J. Rohde. 2015. Structure of Advanced Planning Systems. In *Supply Chain Management and Advanced Planning*, ed. by Hartmut Stadtler, Christoph Kilger, and Herbert Meyr, 99–106. 5th ed. Heidelberg, New York, Dordrecht, London: Springer. 10.1007/978-3-642-55309-7.

Moreno, M., C. De los Rios, Z. Rowe, & F. Charnley. 2016. A Conceptual Framework for Circular Design. *Sustainability* 8(9): 937. 10.3390/su8090937.

Muscat, A., E.M. de Olde, I.J.M. de Boer, & R. Ripoll-Bosch. 2020. The battle for biomass: A systematic review of food-feed-fuel competition. *Global Food Security* 25: 100330. 10.1016/j.gfs.2019.100330.

Nationaler Wasserstoffrat. 2021. *Wasserstofftransport.*

Nazir, H., C. Louis, S. Jose, J. Prakash, N. Muthuswamy, M.E.M. Buan, C. Flox, et al. 2020. Is the H2 economy realizable in the foreseeable future? Part I: H2 production methods. *International Journal of Hydrogen Energy* 45(27): 13777–13788. 10.1016/j.ijhydene.2020.03.092.

Noussan, M., P.P. Raimondi, R. Scita, & M. Hafner. 2020. The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective. *Sustainability* 13(1): 298. 10.3390/su13010298.

Nuss, C., R. Sahamie, & D. Stindt. 2015. The Reverse Supply Chain Planning Matrix: A Classification Scheme for Planning Problems in Reverse Logistics. *International Journal of Management Reviews* 17: 413–436. 10.1111/ijmr.12046.

Nuss, C., D. Stindt, R. Sahamie, & A. Tuma. 2016. Eine quantitative Analyse europäischer Richtlinien und Verordnungen zur Abfall- und Kreislaufwirtschaft am Beispiel der Elektro- und Elektronikindustrie. *Zeitschrift Für Umweltpolitik & Umweltrecht* 39(1): 37–69.

O'Connor, M.P., J.B. Zimmerman, P.T. Anastas, & D.L. Plata. 2016. A strategy for material supply chain sustainability: Enabling a circular economy in the electronics industry through green engineering. *ACS Sustainable Chemistry and Engineering* 4(11): 5879–5888. 10.1021/acssuschemeng.6b01954.

Parajuly, K. & H. Wenzel. 2017. Potential for circular economy in household WEEE management. *Journal of Cleaner Production* 151: 272–285. 10.1016/j.jclepro.2017.03.045.

Petti, L., M. Serreli, & S. Di Cesare. 2018. Systematic literature review in social life cycle assessment. *International Journal of Life Cycle Assessment* 23(3): 422–431. 10.1007/s11367-016-1135-4.

Prasad, S., K.R. Sheetal, P.S. Renjith, A. Kumar, & S. Kumar. 2019. Sweet Sorghum: An Excellent Crop for Renewable Fuels Production. In *Prospects of Renewable Bioprocessing in Future Energy Systems*, ed. by Ali Ashgar Rastegari, Ajar Nath Yadav, and Arti Gupta, 291–314. 10.1007/978-3-030-14463-0_11.

PwC. 2019. *Creating a strategy for a better world. How the Sustainable Development Goals can provide the framework for business do deliver progess on our global challenges.*

Quariguasi Frota Neto, J., G. Walther, J. Bloemhof, J. Van Nunen, & T. Spengler. 2010. From closed-loop to sustainable supply chains: The WEEE case.

International Journal of Production Research 48(15): 4463–4481. 10.1080/00207540902906151.

Queiruga, D. & A. Queiruga-Dios. 2015. The Reuse of Waste Electrical and Electronic Equipment (WEEE). A Bibliometric Analysis. *International Journal of Waste Resources* 5. 10.4172/2252-5211.1000177.

Ray, D.K., J.S. Gerber, G.K. MacDonald, & P.C. West. 2015. Climate variation explains a third of global crop yield variability. *Nature Communications* 6(1): 5989. 10.1038/ncomms6989.

Rebitzer, G., D. Hunkeler, & O. Jolliet. 2003. LCC-The economic pillar of sustainability: Methodology and application to wastewater treatment. *Environmental Progress* 22(4): 241–249. 10.1002/ep.670220412.

Ricke, K., L. Drouet, K. Caldeira, & M. Tavoni. 2018. Country-level social cost of carbon. *Nature Climate Change* 8(10): 895–900. 10.1038/s41558-018-0282-y.

Rystad Energy. 2021. *The Rystad Energy Transition Report*.

Sabbas, T., A. Polettini, R. Pomi, T. Astrup, O. Hjelmar, P. Mostbauer, G. Cappai, et al. 2003. Management of municipal solid waste incineration residues. *Waste Management* 23(1): 61–88. 10.1016/S0956-053X(02)00161-7.

SAI. 1997. SA8000® Standard.

Shmelev, S.E. 2012. Industrial Ecology: Material and Energy Flows, Life Cycle Analysis. In *Ecological Economics: Sustainability in Practice*, 19–34. Dordrecht: Springer Netherlands. 10.1007/978-94-007-1972-9_2.

Sikdar, S. 2021. Quo vadis quantitative sustainability assessment?—a personal statement. *Clean Technologies and Environmental Policy* 23(7): 1929–1930. 10.1007/s10098-021-02190-0.

Sinha, R. 2016. *Systems Modeling Approaches to Physical Resource Management: An Industrial Ecology Perspective.*

Stadtler, H. 2015. Linear and Mixed Integer Programming. In *Supply Chain Management and Advanced Planning*, ed. by Hartmut Stadtler, Christoph Kilger, and Herbert Meyr, 525–536. 5th ed. Heidelberg, New York, Dordrecht, London: Springer. 10.1007/978-3-642-55309-7.

Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney, & C. Ludwig. 2015. The trajectory of the anthropocene: The great acceleration. *Anthropocene Review* 2(1): 81–98. 10.1177/2053019614564785.

Steinbach, V. & F.W. Wellmer. 2010. Consumption and use of non-renewable mineral and energy raw materials from an economic geology point of view. *Sustainability* 2(5): 1408–1430. 10.3390/su2051408.

Stindt, D., J. Quariguasi Frota Neto, C. Nuss, M. Dirr, M. Jakowczyk, A. Gibson, & A. Tuma. 2017. On the Attractiveness of Product Recovery: The Forces that Shape

Reverse Markets. *Journal of Industrial Ecology* 21(4): 980–994. 10.1111/jiec.12473.

StMUV. 2019. Leitfaden für die Vorbereitung zur Wiederverwendung. Accessed March 17, 2022.

Suhl, L. & T. Mellouli. 2013. *Optimierungssysteme*. Springer-Lehrbuch. Berlin, Heidelberg: Springer Berlin Heidelberg. 10.1007/978-3-642-38937-5.

Swarr, T.E., D. Hunkeler, W. Klöpffer, H.L. Pesonen, A. Ciroth, A.C. Brent, & R. Pagan. 2011. Environmental life-cycle costing: A code of practice. *International Journal of Life Cycle Assessment* 16(5): 389–391. 10.1007/s11367-011-0287-5.

Taskhiri, M.S., M. Garbs, & J. Geldermann. 2016. Sustainable logistics network for wood flow considering cascade utilisation. *Journal of Cleaner Production* 110: 25–39. 10.1016/j.jclepro.2015.09.098.

Thorenz, A., L. Wietschel, D. Stindt, & A. Tuma. 2018. Assessment of agroforestry residue potentials for the bioeconomy in the European Union. *Journal of Cleaner Production* 176: 348–359. 10.1016/j.jclepro.2017.12.143.

Torabi, S.A., M. Baghersad, & S.A. Mansouri. 2015. Resilient supplier selection and order allocation under operational and disruption risks. *Transportation Research Part E: Logistics and Transportation Review* 79: 22–48. 10.1016/j.tre.2015.03.005.

True Price Foundation. 2020. *MONETISATION FACTORS FOR TRUE PRICING*.

UNEP/SETAC. 2009. *Guidelines for social life cycle assessment of products*.

UNEP/SETAC. 2013. *The methodological sheets for sub-categories in social life cycle assessment (S-LCA)*. 10.1007/978-1-4419-8825-6.

UNEP. 2011. *Towards a Life Cycle Sustainability Assessment*. DTI/1412/PA.

UNEP. 2021a. *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020*.

UNEP. 2021b. *Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021*.

United Nations. 2015. Sustainable Development Goals.

Valdivia, S., J.G. Backes, M. Traverso, G. Sonnemann, S. Cucurachi, J.B. Guinée, T. Schaubroeck, et al. 2021. Principles for the application of life cycle sustainability assessment. *International Journal of Life Cycle Assessment* 26(9): 1900–1905. 10.1007/s11367-021-01958-2.

Wang, A., K. Van der Leun, D. Peters, & M. Buseman. 2020. *European Hydrogen Backbone: How a dedicated hydrogen infrastructure can be created*.

Wardekker, J.A., A. de Jong, J.M. Knoop, & J.P. van der Sluijs. 2010. Operationalising a resilience approach to adapting an urban delta to uncertain climate changes. *Technological Forecasting and Social Change* 77(6): 987–998. 10.1016/j.techfore.2009.11.005.

Weidema, B., M. Goedkoop, E. Meijer, & R. Harmens. 2020. *LCA-based assessment of the Sustainable Development Goals. Development update and preliminary findings of the Project "Linking the UN Sustainable Development Goals to life cycle impact pathway frameworks."*

White, R.M. 1994. Preface. In *The Greening of Industrial Ecosystems*, ed. by Braden R. Allenby and Deanna J. Richards, v–vi. Washington, D.C.: National Academies Press, January. 10.17226/2129.

Wietschel, L., A. Thorenz, & A. Tuma. 2019. Spatially explicit forecast of feedstock potentials for second generation bioconversion industry from the EU agricultural sector until the year 2030. *Journal of Cleaner Production* 209: 1533–1544. 10.1016/j.jclepro.2018.11.072.

Wietschel, M., A. Bekk, B. Breitschopf, I. Boie, J. Edler, W. Eichhammer, M. Klobasa, et al. 2020. *Chancen und Herausforderungen beim Import von grünem Wasserstoff und Syntheseprodukten.*

World Bank. 2019. *State and Trends of Carbon Pricing 2019.* Washington, DC: World Bank, June. 10.1596/978-1-4648-1435-8.

WRAP. 2011. *Realising the Reuse Value of Household WEEE.* Accessed March 27, 2022.

Wu, R., D. Yang, & J. Chen. 2014. Social Life Cycle Assessment Revisited. *Sustainability* 6(7): 4200–4226. 10.3390/su6074200.

Wulf, C., J. Werker, P. Zapp, A. Schreiber, H. Schlör, & W. Kuckshinrichs. 2018. Sustainable Development Goals as a Guideline for Indicator Selection in Life Cycle Sustainability Assessment. *Procedia CIRP* 69: 59–65. 10.1016/j.procir.2017.11.144.

Xue, M., A. Kendall, Z. Xu, & J.M. Schoenung. 2015. Waste management of printed wiring boards: A life cycle assessment of the metals recycling chain from liberation through refining. *Environmental Science and Technology* 49(2): 940–947. 10.1021/es504750q.

Zampieri, M., A. Ceglar, F. Dentener, A. Dosio, G. Naumann, M. Berg, & A. Toreti. 2019. When Will Current Climate Extremes Affecting Maize Production Become the Norm? *Earth's Future* 7(2): 113–122. 10.1029/2018EF000995.

Zeug, W., A. Bezama, & D. Thrän. 2021. A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy. *International Journal of Life Cycle Assessment* 26(10): 1998–2023. 10.1007/s11367-021-01983-1.