Global model-based socio-ecological Assessment of Opportunities and Risks of the Transition to Power-to-X Fuels in the Aviation Sector

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Kurzfassung

Die vorliegende Dissertation verfolgt das Ziel, die techno-ökonomischen und sozio-staatlichen Chancen und Risiken zu identifizieren, die mit dem potenziellen Wandel von fossilen zu synthetischen Kraftstoffen im Luftfahrtsektor global einhergehen könnten. Ein generisches Input-Output-Modell einer Power-to-X-Kraftstoffproduktionsanlage mit einer Photovoltaik- oder einer Windkraftanlage wurde in die sozialen und technischen Bedingungen jedes Landes implementiert, sofern diese in den verwendeten Datenbanken verfügbar waren. Das Resultat der Modellierung ist eine Tabelle, welche die potenziellen Umweltauswirkungen und sozialen Risiken der Produktion von 1 kg Power-to-X-Kraftstoff mit spezifischen Resultaten für jeden untersuchten Standort aufzeigt. Das Modell umfasst mehrere Produktionspfade für biologische und fossile Kraftstoffe an verschiedenen Standorten, welche als Referenzwerte für jeden Indikator dienen. Die Sustainable Development Goals der Vereinten Nationen dienen als normativer Rahmen und Werkzeug zur Identifizierung der relevantesten Nachhaltigkeitskategorien. Die Indikatoren der ökologischen und sozialen Ökobilanz wurden in Anlehnung an die Sustainable Development Goals ausgewählt und entsprechend kategorisiert. Das erste Szenario basiert auf dem aktuellen globalen Energiesystem sowie dem technologischen Status quo. Um die Berücksichtigung eines sich wandelnden Energiesystems sowie technologischer Entwicklungen zu gewährleisten, wurde für das Szenario 2050 ein globales Energiesystemmodell integriert. Das Modell berücksichtigt die globale Energiewende sowie iterative Veränderungen entlang des gesamten Lebenszyklus des Energiesystems bis zum Jahr 2050. Die anschließende Auswertung der Ergebnisse beider Szenarien erfolgte in zwei Schritten. In einem ersten Schritt wurde ein Benchmark für das Treibhausgas-Reduktionspotenzial integriert. Dabei wurden diejenigen Konstellationen mit einem Reduktionspotenzial von weniger als 70 % im Vergleich zum fossilen Vergleichswert aus dem zweiten Bewertungsschritt ausgeschlossen. Im zweiten Schritt wurde jeder ausgewählte Indikator separat analysiert. Hierbei wurde die Anzahl der Power-to-X-Konstellationen, die im Vergleich zu den fossilen und biobasierten Referenzen mit einer geringeren potenziellen Umweltbelastung oder einem geringeren sozialen Risiko verbunden sind, mit der Anzahl der Konstellationen verglichen, die mit einer höheren potenziellen Umweltbelastung oder einem höheren sozialen Risiko verbunden sind. Der Fall, dass die Mehrheit der Konstellationen einen Vorteil gegenüber einer der Referenzen erreicht, wird als Chance für eine nachhaltige Entwicklung betrachtet. Im Falle einer geringen Anzahl an Konstellationen, welche einen Vorteil gegenüber einer Referenz aufweisen, oder gar keiner Konstellation, die einen Vorteil gegenüber einer Referenz aufweist, wird dies als kritische Kategorie bzw. Risiko betrachtet. Zeigt sich lediglich ein Vorteil gegenüber der biobasierten Referenz, jedoch mit höheren potenziellen Umweltauswirkungen oder sozialen Risiken als bei fossilen Kraftstoffen, so ist dies zwar technisch als Vorteil zu werten, jedoch aufgrund des zusätzlichen, einhergehenden Risikos im Vergleich zum Status quo einer genaueren Betrachtung zu unterziehen. In Bezug auf die technisch-ökologischen Aspekte sind insbesondere die Verknappung mineralischer Ressourcen, die Humantoxizität sowie die terrestrische Ökotoxizität als kritische Aspekte zu nennen. Andererseits kann insbesondere eine nachhaltige Entwicklung in den Kategorien terrestrische Versauerung, Wasserverbrauch, Landnutzung, Verknappung fossiler Ressourcen, Feinstaubbildung und marine Eutrophierung erreicht werden. Als kurzfristig größtes sozio-staatliches Risiko entlang der Wertschöpfungskette wurde die Kinderarbeit identifiziert. Bis zum Jahr 2050 können jedoch alle sozio-staatlichen Kategorien als Chance für eine nachhaltige Entwicklung betrachtet werden. Im Rahmen der Untersuchung der techno-ökologischen Indikatoren erfolgte eine detaillierte Analyse der Hauptverursacher potenzieller Umweltauswirkungen. Basierend auf den Erkenntnissen werden mögliche Ansätze zur Verringerung der potenziellen Umweltauswirkungen und sozialen Risiken in verschiedenen Bereichen aufgezeigt. Daraufhin werden die Chancen und Risiken eines Übergangs zu Power-to-X-basierten Kraftstoffen im Luftfahrtsektor zusammengefasst. Die identifizierten Risiken können adressiert und gelöst werden, während die nachhaltigen und technisch umsetzbaren Alternativen für den Klimaschutz im Luftfahrtsektor bisher rar sind.

Abstract

This dissertation seeks to identify the techno-economic and socio-governmental opportunities and risks that could arise globally with the potential transition from fossil to synthetic fuels in the aviation sector. A generic input-output model of a Power-to-X fuel production plant, powered either by a photovoltaic or a wind power plant, was implemented within the social and technical conditions of every country for which data were available in the used databases. The output of this model is a tabular representation of the potential environmental impacts and socio-governmental risks associated with the production of 1 kg of Power-to-X-based fuel, providing specific results for each assessed location. The model includes a number of bio- and fossil-based fuel production pathways at different locations, which provide reference values for each indicator. The United Nations Sustainable Development Goals serve as both a normative framework and a tool for identifying the most relevant sustainability categories. The indicators for the environmental and social life cycle assessments were selected in accordance with the Sustainable Development Goals and classified into corresponding categories. The initial scenario is predicated on the existing global energy system and technological status quo. To account for changes in the global energy system and associated technological developments, a 2050 scenario was integrated into a global energy system model. This model accounts for the global energy transition and the iterative changes potentially occurring throughout the entire life cycle until the year 2050. The results were evaluated in two phases. Firstly, a benchmark for greenhouse gas reduction potential was integrated, with those constellations exhibiting a reduction potential of less than 70% in comparison to the fossil baseline excluded from the second evaluation step. Secondly, each selected indicator was evaluated individually by comparing the number of Power-to-X constellations with a reduced potential environmental impact or social risk in comparison to the fossil- and bio-based references with the number of constellations with an increased potential environmental impact or social risk. If the majority of constellations is able to achieve an advantage over one of the references, this is regarded as an opportunity for sustainable development. In the event that less or no constellations are able to achieve a benefit over one of the references, this is regarded as a critical category or risk. In the event that a benefit against the bio-based reference is achieved, yet the potential environmental impact or social risk is higher than that associated with fossil-based fuels, further analysis is required, as this represents an additional risk in comparison to the status quo. In the context of techno-ecological considerations, the scarcity of minerals, human toxicity, and terrestrial ecotoxicity represent critical issues. Conversely, sustainable development can be achieved within the following categories: Terrestrial acidification, water consumption, land use, fossil resource scarcity, fine particulate matter formation, and marine eutrophication. The issue of child labor represents the most critical socio-governmental aspect in the short-run. Nevertheless, by 2050, all socio-governmental indicators present opportunities for sustainable development. The primary contributors to the potential environmental impacts were identified for the critical techno-ecological indicators, and potential strategies for mitigating the impacts and social risks at various stages are presented. In conclusion, the potential benefits and drawbacks of a shift towards Power-to-X-based fuels in the aviation industry are presented. The identified risks can be addressed and resolved while there is a lack of sustainable and technically feasible alternatives for climate protection in the aviation sector.

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List of Abbreviations

ATJ	Alcohol-to-Jet
ATM	Air Traffic Management
ASTM	American Society for Testing and Materials
BMZ	Federal Ministry for Economic Cooperation and Development
C	Carbon
CAPEX	Capital expenditures
CCU	Carbon capture and utilization
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO	Carbon monoxide
CO_2	Carbon dioxide
COVID-19	Coronavirus Disease 2019
dena	German Energy Agency (Deutsche Energie-Agentur)
DAC	Direct Air Capture
EU	European Union
EU ETS	EU Emission Trading System
FLH	Full load hours
GHG	Greenhouse gas
GPI	Global Peace Index
GWP	Global Warming Potential
H_2	Hydrogen
HDI	Human Development Index
IATA	International Air Tansport Association
ICAO	International Civil Aviation Organization
ITAS	Institute of Technology Assessment and Systems Analysis
ICoS	Integrative Concept of Sustainable Development
IEA	International Energy Agency
ILO	International Labour Organization
KIT	Karlsruhe Instite of Technology
LCA	(Environmental) life cycle assessment
LCC	Life cycle costing
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
LCOE	Levelized cost of electricity
LCSA	Life cycle sustainability assessment
MDGs	Millenium Development Goals
MW	Megawatt
N	Nitrogen
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaic
PtX	Power-to-X
RES	Renewable energy sources
RFNBOs	Renewable fuels of non-biogenic origin
RES	Renewable energy sources
SAF	Sustainable aviation fuel
SDG	Sustainable Development Goal
S-LCA	Social life cycle assessment
SOEC	Solid oxide electrolyzer cell
Syngas	Synthesis gas
TRL	Technology readiness level
TWh	Terrawatthours
UN	United Nations
USD	US Dollar
WiGH	Women in Green Hydrogen

Preface

The initial idea of this dissertation was to identify the environmentally most sustainable locations for the production of PtX-based fuels with the aim of importing them to Germany, optimizing the choice of technologies, the surrounding energy system and the transport distances. During the research and the development of the model, the importance of the social aspects became increasingly evident to me, while my personal interest in the topic increased accordingly. With the intensified research on social aspects, the narrow view on import potentials changed to a broader, global and more holistic view on sustainable development with PtX. This has not only changed the focus of my dissertation, but also my personal perspective and eventually my career.

While a global view is important, it leads to a very complex model. Considering every country in the world, connecting data from various sources to one global model, inevitably leads to uncertainties and a lower level of detail and accuracy. The technologies as well as the social circumstances might change, or even have changed already. The claim of this dissertation is not to perfectly depict the socio-governmental conditions of each country or the technical details of each technology involved. Nevertheless, it does give an overview of the social and environmental opportunities and barriers on a global level and can lead to a better understanding of what could happen, and how the risks could be reduced. Some of the assessed technologies are currently at an early stage of development, making it even more difficult and at the same time important to analyze the risks. Once the technology will be deployed globally, many of the parameters will be less flexible.

1. Introduction

Power-to-X (PtX) is a concept that integrates multiple technologies and is employed to manufacture synthetic products that are traditionally derived from fossil feedstocks. Synthetic products based on PtX are typically derived from green hydrogen (H_2) and contain carbon (C) or nitrogen (N), with energy from renewable energy sources (RES). Green H_2 can facilitate the integration of RES into applications where direct utilization of electricity is challenging. PtX may be used to replace liquid fuels utilized in the transportation sector, chemicals utilized in the industrial sector, or ammonia utilized in the production of fertilizers. A PtX process typically comprises the following elements: a water source, a C or N source (depending on the end product), RES, an electrolyser, a synthesis reactor, and an upgrading/purification step. This series of process steps is employed to generate synthetic fuels and chemicals, which can then be integrated into existing processes, infrastructures, and machinery. This represents a non-fossil-based alternative, either for providing the molecular structure or energy content of the typically fossil-based products in the required form. When the process is powered by RES and the C is obtained from a renewable source as well, the process itself is independent of fossil energy carriers and fossil C. It should be noted that the synthetic hydrocarbon end products still result in the emission of carbon dioxide (CO_2). However, the use of renewable carbon as an input material for the PtX process ensures that the emitted amount of CO_2 is recycled, preventing an increase in the concentration of fossil CO_2 in the atmosphere. This recycling process renders it theoretically carbon-neutral. It is important to note that the provision of materials and construction of plants also result in a carbon footprint and other environmental and social footprints, which must not be overlooked. The objective of this study is to analyze and evaluate the impacts of PtX-based fuels across their entire life cycle, encompassing both techno-ecological and socio-governmental dimensions. This is achieved through a comprehensive global environmental and social life cycle assessment. In order to evaluate these impacts and their severity, it is necessary to have a benchmark system with reference values, as other methods of fuel production also result in environmental and social footprints. This dissertation focuses on the production of jet fuel for the aviation sector, which is frequently identified as one of the most challenging sectors to decarbonize. The potential for PtX-based products to make a meaningful impact in this sector is a key area of investigation. A comparison is made between the opportunities and risks associated with synthetic fuels based on green H_2 (PtX-based fuel) and those associated with the current status quo (fossil-based) or alternative pathways (bio-based) on a global scale. The reference technologies (status quo and potential alternatives) facilitate the evaluation of whether the PtX technology presents an opportunity or risk within each assessed category. The selection and categorization of these opportunities and risks were inspired by the United Nations Sustainable Development Goals (SDGs), ensuring that the most pertinent and urgent sustainability concerns are addressed. In order to facilitate a just and sustainable transition to a global transportation system based on synthetic fuels, the dissertation proposes and discusses a number of potential strategies for addressing the main critical risks. The model provides a comparative analysis at the country level and on a global scale, identifying the primary opportunities and barriers associated with the transition to PtX-based aviation fuels. While the analysis of the results presented in this dissertation is limited to a global perspective, the country-specific results will be utilized in future endeavors. This dissertation addresses the following two-fold research question on a global level:

I. Which environmental and socio-governmental opportunities and risks could arise, if PtX-based fuels replaced fossil- and bio-based fuels in the aviation sector on a global scale in the short- and long-run?

II. How and at which stage of the life cycle / value chain could the main risks be addressed?

2. State of Research and Motivation

The International Civil Aviation Organization (ICAO) has set an aspirational goal of achieving net-zero CO_2 emissions by 2050. Aviation accounts for 2.5% of global CO_2 emissions, which represents 12% of transport-related emissions. Shipping is responsible for 11% of these emissions, while road transport accounts for 75%. While so far mainly road transport becomes increasingly decarbonized in the transport sector, the areas of long-distance road freight, aviation and shipping will continue to represent a significant source of emissions, according to the International Energy Agency (IEA) Energy Technology Perspectives 2020 report. The current fleet of aircraft and the infrastructure utilized within the aviation sector are predominantly reliant on fossil jet fuel. In addition to the technological challenges associated with developing new aircraft technologies, the long lifespan and the necessity for international operability present significant obstacles to a rapid transition to electric or hydrogen-powered aircraft. As has been posited in numerous publications, it is unlikely that alternative aircraft technologies will be implemented in the near future. [1]–[6]

Additional strategies for reducing emissions in the aviation sector pertain to the improvement of existing aircraft technologies and the optimization of air traffic management (ATM). The Clean Sky EU Joint Technology Initiative, Clean Sky 2, and the German national aviation research program are collectively developing and implementing new aircraft-related technologies with the objective of reducing the ecological footprint of air travel. ATM measures are designed to enhance the efficiency with which airspace and airports are utilized, thereby reducing the ecological footprint and costs associated with air travel. Nevertheless, at the 27th Round Table on Sustainable Development of the Organisation for Economic Co-operation and Development (OECD), it was asserted that these measures would not be enough for achieving the greenhouse gas (GHG) emission reduction objectives. [7], [8]

In addition to the enhancements of aircrafts and the ATM system, sustainable aviation fuels (SAFs) are identified as a pivotal and indispensable component in achieving the GHG reduction objectives outlined in the ICAO State Action Plan for CO2 Emissions Reduction – Germany – of the Ministry of Transport and Digital Infrastructure. Previously, biofuels were predominantly regarded as an alternative fuel source. Despite their status as renewable resources, these fuels are associated with adverse effects on ecological and social sustainability. In light of the classification of bio-based fuels as a subset of SAFs, they can be further categorised into four generations: First-generation biofuels are derived from crop plants, second-generation biofuels are derived from non-food biomass, third-generation biofuels are derived from algal biomass, and fourth-generation biofuels are derived from genetically engineered biofeedstock. While first-generation biofuels have a direct impact on the food supply, second-generation biofuels may still have at least an indirect effect on food availability and prices due to the utilization of resources and land for food production, particularly when animal feed is taken into account. It is therefore possible that an increase in the scale of fuel production of this kind could have an adverse effect on the food supply for an increasing world population. Moreover, the environmental impact on biodiversity and water preservation can be significant for both generations. Third- and fourth-generation biofuels are still in the early stages of development and face significant challenges to large-scale production. [9]–[13]

Given the current limitations in technological possibilities for reducing GHG emissions within the aviation sector, market-based approaches, such as carbon offsetting and the EU Emissions Trading System (EU ETS), are being employed to bridge the gap until emissions can be effectively reduced through technological progress or to provide incentives for such progress. The EU ETS is a cap-and-trade system, wherein the cap represents the total amount of emissions that can be emitted by the covered systems, and the emission allowances within this cap are distributed and traded. As time progresses, the cap is gradually reduced, which creates a scarcity of emission allowances and provides an incentive for emissions to be reduced. The EU ETS encompasses solely intra-European flights within the aviation sector, which is one of the factors that led to the supplementary implementation of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Any excess emissions above the 2019 baseline must be offset through the CORSIA mechanism. The calculation is performed using a growth factor and the operator's annual emissions. The process of offsetting entails the reduction of emissions in a different sector or country that would not have been achieved in the near term otherwise. [13]–[16]

While CO_2 offsetting and emission trading play an important role in the short-term perspective, they do not represent a comprehensive solution for GHG reduction. As Niklas Hagelberg of the United Nations Environment Programme states, "Carbon offsets are not our get-out-of-jail free card." Pearson (2007) demonstrated that these market-based mechanisms provide only economic incentives. Consequently, the most cost-effective methods for obtaining credits for emissions reductions are prioritized, while the socio-ecological impacts are regarded as secondary considerations. A significant proportion of carbon offsetting credits have, in fact, failed to represent genuine savings, according to the Destination 2050 report published by the Royal Netherlands Aerospace Centre and SEO Amsterdam Economics for Airlines for Europe. The aviation manager at Transport & Environment offered the following commentary on the situation with aviation's climate problem: "Airlines paying others so that they can go on polluting is not a solution to aviation’s climate problem. Decades of airlines’ unchecked emissions growth shows governments need to step up and regulate aviation’s climate impact by ending the sector’s tax privileges and mandating clean fuels." The unchecked growth in emissions from the airline industry over decades demonstrates the necessity for governments to regulate the sector's climate impact. This can be achieved by ending the sector's tax privileges and mandating the use of clean fuels. It becomes evident that the market-based measures can be regarded as a means of providing economic incentives for the reduction of emissions. However, they are not an effective means of achieving this reduction. [14], [17]–[19]

In recent years, PtX-based fuels (or e-fuels) have emerged as a promising alternative to market-based mechanisms and fossil- and bio-based fuels. They offer a potential avenue for reducing the GHG footprint of the transport sector and other applicable areas. As stated by the European Commission (2020), PtX-based fuels can be regarded as an effective means of reducing GHG emissions, provided that the H_2 is produced via water electrolysis with electricity derived from RES and the CO_2 is sourced from the atmosphere. At the time of their initial development, the primary motivations for the production of synthetic fuels were not the reduction of CO_2 emissions. As outlined by Stranges (2007), the transition from solid to liquid energy carriers, concerns about the finite nature of petroleum reserves, and the pursuit of energy independence contributed to a growing interest in the Fischer-Tropsch process for the synthesis of liquid fuel. Instead of CO_2 from the atmosphere and green H_2 from water electrolysis, coal was liquefied. [6], [20], [21]

The electrolysis process, which is powered by renewable electricity, results in the splitting of water into H_2 and oxygen (O_2). The carbon component is typically obtained through the reduction of CO_2 to carbon monoxide (CO). The intermediate product is synthesis gas (syngas), which is formed from H_2 and CO. Subsequently, the syngas is catalyzed and upgraded to synthetic hydrocarbons, which can be employed in conventional processes and machines that are typically reliant on fossil-based fuels.

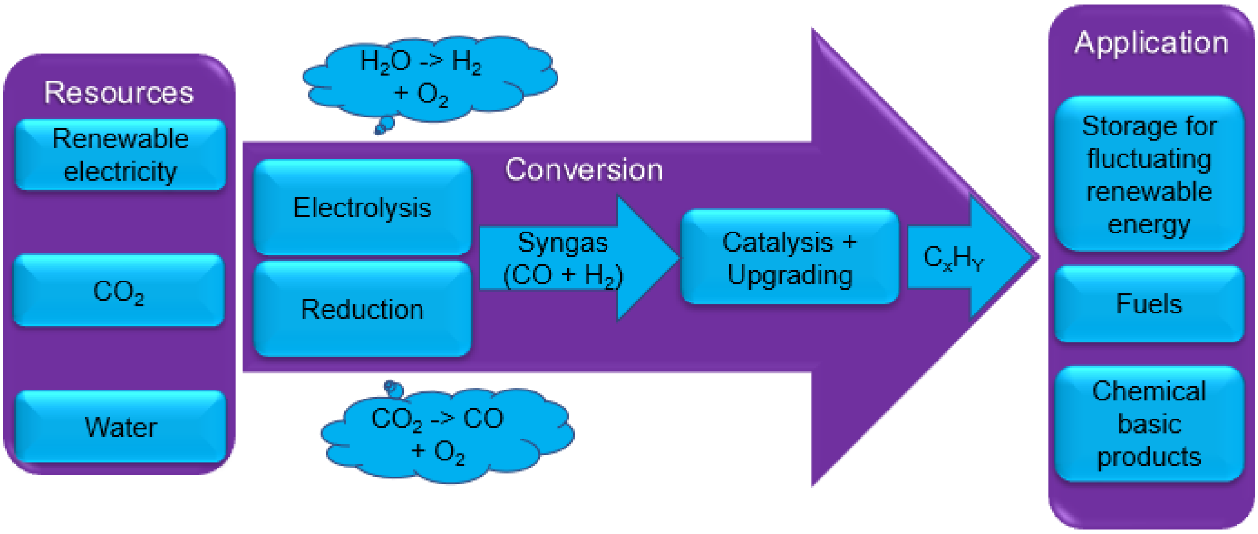

Figure 1: Generic PtX process and products, own illustration based on DECHEMA (2019) [22]

The products depicted in Figure 1 have the potential to replace fossil-based fuels and chemicals in most applications due to their analogous structure and characteristics. Nevertheless, in light of the relatively low energy efficiency of the PtX processes and their sustainability-related implications, it is recommended to prioritize those technologies for which direct electrification or other more efficient alternatives are not anticipated in the near future. The National Hydrogen Strategy of the German government identifies the aviation sector, parts of heavy-duty transport, mobile systems for the defense of Germany and its allies, and shipping as potential applications for PtX. In these applications, direct electrification is currently not feasible or challenging to implement. [23]

The potential for integrating PtX-based fuels into existing infrastructure, vehicles, and engines could have a significant positive impact on the ecological sustainability of the aviation sector. Nevertheless, at current stage the extensive implementation of PtX-based fuels is among other factors constrained by the American Society for Testing and Materials (ASTM) D7566, a directive that enumerates and delineates the approved jet fuel categories. The directive permits the blending of not more than 50% of Fischer-Tropsch synthetic kerosene. Moreover, the costs associated with the production of PtX are currently higher than those associated with the production of fossil-based jet fuel. However, if externalities such as the negative environmental impacts of fossil-based fuels were taken into account, it is possible that the prices of PtX- and fossil-based fuels would converge. It is possible that this price differential may be subject to change in the near future. For example, the European Commission (2020) has proposed the introduction of a climate charge to address the climate-related impacts of fossil fuels. [5], [6], [24] With the restrictions and traffic volume decreasing due to the Coronavirus Disease 2019 (COVID-19) pandemic during the last years, the aviation industry will need some years to recover. The International Air Transport Association (IATA) estimated the growth of revenue passenger kilometers in 2020 with -66.3 %. This presents a potential opportunity for the aviation sector to transition towards a more sustainable model. As recommended by the OECD, this opportunity should be leveraged to facilitate investments in sustainability-related initiatives. [25], [26]

2.1 Sustainability of Power-to-X

Given the objective of GHG emission reduction and the relatively high energy demand of PtX-based fuel production processes, it is clear that PtX fuels should only be produced with electricity derived from RES. The use of fossil-based electricity for the production of PtX fuels would, in aggregate, result in significantly elevated emissions compared to those associated with the current utilization of fossil-based fuels. In the P2X Roadmap 3 of the Kopernikus P2X project, the Global Warming Potential (GWP) of PtX-based fuel production with electricity supplied by the German electricity grid is compared to the GWP of fossil fuel. While the 2030 and 2050 scenarios are modeled with a significant proportion of RES in the grid mix, resulting in a notable advantage in GHG emissions, the utilization of the current grid mix electricity would lead to a higher GHG emission profile than the utilization of fossil-based fuels. [27]

Two methods are currently under consideration for the provision of electricity from RES to a PtX plant:

1) Surplus Electricity from Renewable Energy Sources

The first approach is the utilization of "surplus electricity" from existing RES, which benefits from the low cost and serves as a long-term energy storage solution for the fluctuating electricity supply.

In order to ensure the domestic electricity supply is continuously available, the peak capacity of photovoltaic (PV) or wind power plants must exceed the average demand due to the inherent volatility of the supply. This can result in the generation of excess electricity, which is ultimately wasted energy. In order to prevent any potential harm to the grid, the plants are typically curtailed from the grid. An alternative approach would be to store this excess electricity in the form of PtX-based fuels by powering the PtX plant during periods of lower electricity demand. However, as assessed by Drünert et al. (2019), Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018), as well as Frank Urbansky (2020), the availability of surplus electricity substantially limits the economic feasibility of this approach. The limited availability of electricity reduces the number of operating hours for the electrolyser, resulting in higher specific capital expenditures (CAPEX) per kilogram of product. This approach may become more pertinent in light of an anticipated rise in demand for storage solutions for renewable energy sources and the projected decline in capital expenditure for electrolysers. From an economic standpoint, this would diminish the significance of the number of operating hours. [28]–[30]

2) Additional Renewable Energy Capacities

A second approach to supplying RES electricity to a PtX plant would be to construct and utilize additional capacities that would not have been built without the PtX plant. It is of the utmost importance to adhere to the principle of additionality, as failure to do so would result in an increased utilization rate of fossil-based power plants on the grid, contrary to the initial plan. This is because a portion of the electricity generated from renewable sources would be used for PtX production. This would result in an increase in CO_2 emissions from the grid mix electricity, as the heightened demand for electricity would necessitate the use of fossil-based electricity generation technologies. The potential negative impact of non-additional RES for PtX is illustrated in the third column of Figure 2.

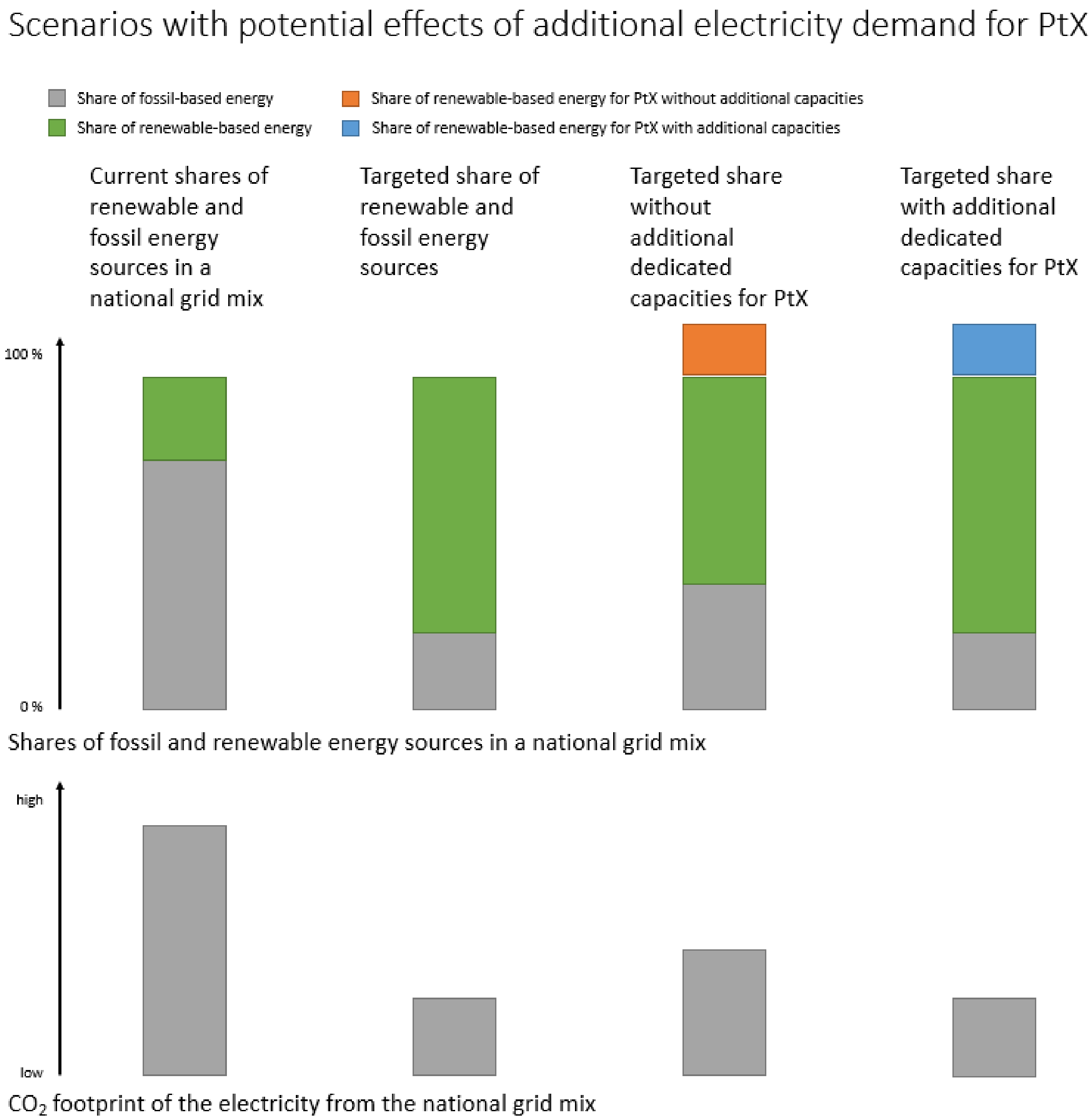

Figure 2: Potential effects of additional electricity demand from PtX production, own illustration based on Kasten and Heinemann (2019) [31]

The provision of the requisite electricity to produce PtX-based fuels in a sustainable manner may be of greater concern in some countries than in others. The following paragraphs present an overview of studies and results on the topic of international supply chains and domestic production of PtX-based fuels, as well as sustainability-related aspects.

Taking Germany as an example, there have been discussions in the past about whether it would be more sustainable to build capacities in Germany for domestic PtX production or to build them in other countries and import the products. One notable example of a project with the objective of importing renewable energy from other countries is Desertec. The Desertec Foundation was established in 2009 with the objective of constructing solar power facilities in the North African desert for the purpose of supplying electricity from RES to Europe. One of the primary concerns with this initiative was that the majority of the generated electricity would be consumed in Europe, thereby failing to provide any tangible benefits to the local communities in North Africa. Additionally, the renewable energy capacities in Germany have already witnessed a significant expansion due to the energy transition, rendering the project less attractive from an investment standpoint. Consequently, the production of green H_2 using electricity from renewable sources and subsequent export to Europe is now being contemplated as a potential successor to the Desertec project. [32], [33]

The E-fuels study conducted by Ludwig-Bölkow-Systemtechnik GmbH and the German Energy Agency (dena) indicates that Germany possesses a considerable technical potential for RES amounting to approximately 1,000 terawatt-hours (TWh) per year. Furthermore, the study highlights that Europe as a whole has sufficient technical RES potential to meet the current and future transport energy demand of the European Union (EU). One example of a domestic production initiative is the planned construction of a 50-megawatt (MW) water electrolysis plant in Germany by BP and Ørsted, which will subsequently be expanded to 150 MW. An expansion to 500 MW is currently under consideration for the production of PtX fuels. The electrolysis plant will be supplied with energy from offshore wind power plants situated in the North Sea. Notwithstanding the theoretical technical potential, the study by Ludwig-Bölkow-Systemtechnik GmbH and dena posits that it would be more economically viable to import PtX-based fuels from other countries. [34], [35]

A similar conclusion is reached in the publication "International aspects of a Power-to-X roadmap," published by Frontier Economics and the World Energy Council. Given the potential for renewable electricity production and the resulting amount of full load hours (FLH) in Germany, the necessary capacity and the implied costs are relatively high in comparison to other countries. It is possible to achieve lower costs through the importation from countries with a greater potential of FLH for RES, as these are a significant factor in the overall cost of PtX. In contrast, the transportation of fuel has a relatively minor impact on costs. Potential international PtX collaborations with Norway, Chile, Morocco, Saudi Arabia, Australia, and China were examined. These countries were selected as representatives of clusters based on their shared political and economic characteristics, as well as their comparable potential for renewable electricity generation. The clusters were developed based on a comprehensive analysis of both hard and soft factors. The hard factors pertain to the FLH, the availability of land, infrastructure, and physical resources for PtX production. The soft factors pertain to political stability, the energy political framework, and trade aspects. The soft factors in the Frontier Economics and World Energy Council study are contingent upon the political context and social circumstances of the respective countries. However, they are primarily utilized as an indicator of the potential risks associated with investments in these contexts. The objective of this study is not to assess whether the development of an international PtX supply chain could potentially have beneficial or detrimental effects on society in these countries. [36]

The study conducted by Agora Verkehrswende et al. (2018) also indicates that cost savings could be achieved through the importation of PtX fuels from other countries. While the study's primary focus is on economic viability, it also addresses qualitative sustainability requirements. These requirements pertain to the necessity of additional RES capacity for the production of PtX fuels, the protection of land resources for the exclusive purpose of food production, the guarantee of RES utilization for PtX production, the provision of supplementary water desalination in arid regions, and the utilization of sustainable carbon sources. [29]

As previously noted by Ekener-Petersen (2014), the EU sustainability criteria on biofuels similarly address social impacts on a small scale. A broader integration of social impacts is relying on voluntary certification schemes, which leaves the standards to the market actors to a large extent. Moreover, the aforementioned sustainability criteria are not applied to fossil-based fuels. This demonstrates the necessity of examining the social impacts of all assessed production pathways, not merely those related to PtX, but also those pertaining to fossil- and bio-based fuels. [37]–[39]

In their impulse paper on the requirements for a climate-friendly and sustainable production of PtX, Kasten and Heinemann (2019) addressed one core question: "What are the requisite conditions for PtX production that will ensure the most favorable sustainability outcomes and minimize adverse effects?" The authors address the social and ecological impacts that could arise through an international PtX supply chain. Similarly, as noted by Agora Verkehrswende et al. (2018), they highlight the necessity for several aspects to be guaranteed and regulated during the development of a sustainable PtX production. Furthermore, the aforementioned additionality of renewable energy capacities, the utilisation of non-fossil CO2, sustainable land use and water consumption must be considered. [29], [31]

The Fraunhofer Institute for Energy Economics and Energy System Technology developed the Global PtX Atlas, which provides a means of evaluating the potential for the production of PtX-based fuels in different regions and countries. A socio-economic analysis is provided, including aspects related to political stability, society, the economy, proximity to Germany, and natural conditions. This analysis can then be used to compare different locations in terms of their socio-economic potential for PtX. Although this is a significant step in evaluating social factors within the context of international PtX supply chains, the emphasis is on comparing different countries and their potential to supply fuels to Germany as an exporting country. Accordingly, this assessment does not provide an overview of potential contributions to global sustainable development, as it is assessed in this dissertation. [40]

The necessity to address the social impacts with other countries involved in the PtX supply chain is briefly mentioned by Siegemund et al. (2017) and Agora Verkehrswende et al. (2018). The use of life-cycle based quantitative indicators and a benchmark allows for the assessment of whether PtX production would be beneficial to ecological and social sustainability in comparison to other jet fuel provision pathways. [29], [36]

The selection of a location has implications beyond mere cost; the varying amount of FLH across the globe similarly affects the level of potential environmental impacts. This is primarily attributable to the ecological footprint of the PV or wind power plant construction, which is comparable to the initial investment costs, and the corresponding yield over the plant's lifetime. A plant with a higher amount of FLH leaves a smaller specific ecological footprint per kWh of electricity, which ultimately results in a smaller specific ecological footprint per kg of PtX fuel. In this work, the model is applied to the sustainability of domestic PtX-based fuel production without further transportation to other countries. However, it could also be used to assess the sustainability of potential international supply chains. In order to obtain a complete picture of the costs and impacts associated with this approach, it would be necessary to include the additional infrastructure and transportation requirements in the analysis. In addition to the financial and environmental considerations, the social risks associated with these developments vary considerably across different countries. A social life cycle assessment (S-LCA) can be employed to evaluate the potential risks to social aspects, such as gender inequality, child labor, or forced labor, that may emerge throughout the life cycle.

In order to account for the potential environmental and social impacts of PtX on a global level, it is imperative to address the entire life cycle at each location. This is due to the fact that the combination of social risks and the potential environmental impacts along the life cycle vary significantly within every constellation. Furthermore, it is essential to develop and integrate a comprehensive reference framework to facilitate a more comprehensive understanding of the sustainability-related advantages and disadvantages, which extend beyond the GHG savings and costs. Given the early stage of global PtX production and development, it is crucial to undertake a comprehensive analysis of the opportunities and risks associated with these fuels in comparison to fossil- or bio-based fuels, with a view to facilitating a sustainable transition. It is therefore crucial to implement a benchmarking system that compares fossil and bio-based fuels quantitatively, allowing for the assessment of the sustainability-related benefits and drawbacks associated with each throughout their life cycles globally.

2.2 Sustainability Benchmarking

While GWP is a crucial factor in assessing the sustainability of fuels or other products, it is not the sole determinant of sustainability. This narrow focus on carbon emissions may inadvertently result in the exacerbation of other environmental and social challenges in the future. In order to account for those aspects currently considered most important, a comprehensive sustainability framework is required. In the context of sustainable development, the SDGs can be regarded as one of the most significant and widely accepted instruments at the global level. The SDGs were devised as a follow-up to the United Nations Millennium Development Goals (MDGs). The development of the SDGs was initiated at the United Nations Conference on Sustainable Development in Rio de Janeiro in 2012 with the objective of addressing environmental, political, and economic issues on a global scale. The SDGs comprise 17 goals and 169 targets, with a focus on five core areas: People, Planet, Prosperity, Peace, and Partnership. The SDGs are defined as global goals and must be implemented with specific national targets domestically. However, they are all interconnected and balance out the three dimensions of sustainability. Furthermore, the transfer of technology, the development of capacity in developing countries, and the raising of public awareness are considered essential elements for enhancing global sustainability. In light of the international scope and multi-dimensional sustainability assessment inherent to this work, the SDGs were selected as the normative framework for this dissertation. [41]–[45]

The International Council for Science and the International Social Science Council undertook a scientific review of the SDGs. Although they are regarded as a significant enhancement of the MDGs, several aspects are subject to criticism. The specific social groups that are necessary to facilitate the progress of the goals, in addition to governmental entities, have not been explicitly identified within the goals themselves. A comprehensive narrative is absent, as there is no discernible depiction of the potential outcomes should the established targets be achieved. A scenario analysis could prove beneficial in this regard. Moreover, the interconnectivity between the various goals is not delineated. While some of the goals may be mutually reinforcing, others may result in trade-offs. For example, it has been proposed that each goal should be linked to a carbon intensity target in order to ensure that the climate or environmentally related goals are not compromised in the pursuit of progress towards another goal. This dissertation primarily addresses this issue, as all categories are linked to the CO_2 benchmark (see section 3.2.1). Other methodological approaches that also sought to connect the SDGs to life-cycle-based indicators can be found in the existing literature. [44]–[50]

In their 2016 study, Maier et al. examined the implementation of an innovative stove system in Bangladesh as a development cooperation project, with a particular focus on its sustainability. The SDGs were employed as impact categories and organized into overarching themes. To account for all dimensions, an environmental LCA was conducted, and an indicator-based approach was employed, which included interviews and literature research. The use of S-LCA and Life Cycle Costing (LCC) was precluded due to their status as evolving methodologies with limited scope. In particular, two limitations of the methodology are of particular relevance in the context of this work. The assessment was conducted ex post, after the stoves had been implemented, thereby enabling an evaluation of social sustainability using interviews. Moreover, the discussion notes that the LCA data is frequently designed for application in developed countries. The incorporation of developing countries into the assessment may necessitate further research and adjustments to the data. In the absence of large-scale industrial PtX supply chains, an alternative approach to ex ante assessment of the social dimension is necessary. Moreover, it is essential to acknowledge the specific circumstances of other countries. [45]

To address the GWP of jet fuels, Cavalett and Cherubini (2018) assessed the potential environmental impacts of two bio-based jet fuels and fossil kerosene, connecting the results with several ecologically focused SDGs. The researchers discovered that bio-based fuels may have a more detrimental impact on the achievement of certain SDGs than fossil kerosene. While the assessments indicate that the impacts on the SDGs by the bio-based FT process can be only slightly decreased by improvements within the technology and supply chain, the impacts of the Alcohol-to-Jet (ATJ) process can be reduced significantly by these improvements, resulting in outcomes that are more favorable than those of fossil kerosene. It is imperative to assess the environmental sustainability of any proposed large-scale production before embarking on such a course of action. This will enable any potential issues, benefits, and avenues for improvement to be identified. The study addressed only ecological indicators, demonstrating that parameters within the assessed technologies and their supply chains can have a significant impact on the potential environmental impact, resulting in outcomes that are more favorable than those of the fossil-based reference. This illustrates the necessity of conducting a comprehensive analysis of the parameters in question. In light of the high sensitivity of PtX to the electricity source, it is imperative to adopt a global perspective that incorporates diverse FLH for a comprehensive ecological assessment. Furthermore, when social and economic indicators are also taken into account, this necessity becomes even more apparent. [51]

In a case study conducted by Wulf et al. (2018), the production of hydrogen through electrolysis in Germany, Austria, and Spain was assessed. The study employed a methodology integrating the SDGs with indicators of Life Cycle Sustainability Assessment (LCSA), a method that integrates ecological, social, and economic LCA indicators. The SDGs were connected at both the aggregated goal-based level and the level of individual indicators. The authors concluded that the indicator sets are often challenging to harmonize due to their disparate scopes. The SDGs primarily address sustainability at the national or regional level, whereas the LCSA focuses on these aspects at the product system level. Nevertheless, aligning the SDG goal-based indicators at the aggregated level and not the individual SDG indicator-based indicator sets with the LCSA indicators is a viable approach for an LCSA study. Furthermore, the three distinct locations, despite their proximity and affiliation with the EU, yielded markedly disparate outcomes across numerous categories. This underscores the necessity of evaluating different locations when assessing potential environmental, economic, and social impacts. [49]

As Eisfeldt and Ciroth (2017) have previously observed, there are numerous direct correlations between the S-LCA and SDG indicators. The S-LCA indicators directly address SDGs 3–6 and 8–12. Similarly, Almanza and Corona (2020) established a link between S-LCA indicators and the SDGs, suggesting that this approach provides a means of evaluating the potential contribution or hindrance of a product to the achievement of SDGs. Nevertheless, it is essential to have a reference point or benchmark for the evaluation of the positive or negative impact. [50], [52]

The concept of benchmarking was also addressed by Fang et al. (2015) in the context of sustainability assessments. The Planetary Boundaries were employed as a normative framework for the benchmarks. Moreover, the project "Linking the UN Sustainable Development Goals to Life Cycle Impact Pathway Frameworks" employs a comparable methodology to that of this dissertation, albeit with a particular emphasis on the context of business. In this regard, the authors utilize the legal framework as a point of reference for the S-LCA aspects and propose a reference product as a benchmark for the environmental LCA. Some links of the SDGs could not be achieved with the S-LCA or LCA indicators. [53], [54]

In evaluating the potential implications of novel technologies on global supply chains, it is imperative to consider the possible impacts on the societies and environments of other countries, as evidenced by numerous instances. The disparate political, societal, and environmental circumstances may yield better or worse outcomes relative to those observed with existing technologies. The implementation of a benchmark and the subsequent analysis of different locations and parameters are introduced in order to ascertain whether any or how many constellations could potentially lead to a more sustainable solution.

The International PtX Hub has published a scoping paper on the sustainability of PtX. Similarly, it addresses sustainability concerns from a variety of perspectives and offers recommendations for addressing these concerns. The document offers a synthesis of the findings from a range of other studies on this subject, providing a comprehensive overview of the key issues and measures. [55]

2.3 Methodological Distinction

As the basic idea of this work´s sustainability assessment methodology is related to the integrative Concept of Sustainable Development (ICoS), developed at the Institute for Technology Assessment and Systems Analysis (ITAS) of the Karlsruhe Institute of Technology (KIT) between 1999 and 2002, the ICoS is described and distinguished from the applied approach here. The ICoS methodology combines a science-based normative top-down approach with a problem-related bottom-up process. The top-down process commences with the three fundamental elements of sustainability, as delineated in the Brundtland report. The postulate of inter- and intragenerational justice, a global perspective, and an anthropocentric approach are fundamental tenets of the concept. Subsequently, these elements are articulated as three sustainable development goals:

1. Securing human existence
2. Maintaining society´s productive potential
3. Preserving society´s options for development and action

Ultimately, the sustainable development goals are operationalized through the implementation of 25 substantial and instrumental sustainability rules, which are then contextualized with specific indicators contingent on the intended application. [56], [57]

While specific sustainability rules at the local level would be suitable for assessment in this context, their application is not feasible. Given the necessity of assessing a non-existing plant in each country worldwide, particularly the integration of local stakeholders into the assessment, which is typically a bottom-up process included in the application of ICoS (Rösch et al., 2018; Fuss et al., 2018; Nayono et al., 2016), it is not a viable approach in this case. In lieu of this, the potential impacts and risks associated with the entire life cycle are evaluated with the assistance of databases. Moreover, the three dimensions of sustainability (ecology, society, and economy) are more appropriate for this study. The model generates the quantitative results for the three dimensions through the methods of LCA, S-LCA, and, to a limited extent, LCC. The SDGs are employed to balance and connect the dimensions. [58]–[60]

The methodological distinction between the PtX Atlas and other works in the field can be drawn in a number of different ways. This work is focused on global sustainable development and the general implementation of PtX production processes for either domestic use or export in almost any country. The PtX Atlas is primarily concerned with the formation of collaborative relationships with Germany and the identification of potential export markets for PtX products to Germany. Moreover, the PtX Atlas compares the potential of different countries in relation to one another, but does not yet include a comparison to fossil or biogenic benchmarks or an assessment of the transition itself.

2.4 Summary

A review of the existing literature reveals the following conclusions regarding the current state of research:

1. While PtX is gaining increasing political and industrial traction, there are still barriers to a global scale-up.

2. The production of PtX-based products in conjunction with RES is a necessary step towards achieving sustainability. This necessitates the development of additional capacity or the utilisation of surplus electricity.

3. In the context of international supply chains for PtX-based products, it is imperative that considerations of social and ecological sustainability are not compromised in pursuit of lower prices. This necessitates the establishment of standards, benchmarks, and a comprehensive assessment of associated risks.

4. Some sustainability requirements for PtX have already been established, as evidenced by the implementation of additionality and renewability criteria for RES.

5. The SDGs provide a global framework for a sustainability assessment that balances the social, ecological, and economic dimensions of sustainability. While they can be utilized for sustainability benchmarking, their application remains limited.

6. The sustainability of PtX is a topic that has been addressed in numerous projects and publications. Nevertheless, the social dimension is seldom considered.

A quantitative model of the socio-governmental and ecological opportunities and risks associated with the global transition from fossil- and bio-based fuels to PtX fuels in combination with the SDGs has yet to be developed. This model offers significant potential for the early identification of sustainability concerns and the implementation of appropriate mitigation strategies.

3. Methodology

This dissertation is comprised of multiple parts. A generic ecological and social sustainability assessment model that is connected to the average technical potential and cost for the generation of wind- and solar-based power generation in every country; a global energy system model for potential developments until 2050; and a benchmarking system to analyze the main sustainability-related opportunities and risks of a transition to PtX-based fuels. This section is intended to provide an overview of the methods employed, with particular attention to their relevance within the context of this work. Klöpffer and Grahl (2009) constituted the principal source for the section. [61]

3.1 Introduction to Sustainability Assessment

The sustainability assessment is conducted with life-cycle based methods for potential environmental, economic, and social impacts, which are subsequently delineated in the following subsections. As elucidated by Mazzi (2020), life-cycle thinking is indispensable for the evaluation of sustainability concerns, as the actual burden can frequently be hidden at or shifted to other stages of the life cycle. One illustrative example is the mining of lithium for the production of batteries, which has increased markedly with the gradual electrification of the transport sector, as discussed by Wanger (2011). The extraction of lithium, which is predominantly conducted in South America, has resulted in significant environmental and human health impacts on the local population. It is not possible to address or identify these issues when the system boundary of the assessment is limited to the production facility of an electric car. The life cycle of a product typically commences with the design phase, followed by the extraction of resources, which are then processed and manufactured into a product and eventually discarded or recycled. During the use-phase, the product is utilized and maintained. A comprehensive assessment of a product's sustainability can only be achieved by considering the entire life cycle. This approach allows for the identification of potential areas for improvement. [62], [63]

3.1.1 Environmental Life Cycle Assessment

In accordance with the aforementioned life cycle approach, environmental life cycle assessment (LCA) was devised for the purpose of evaluating the prospective environmental impacts of a product system "from cradle to grave." The first LCAs were developed around 1970 with the name Resource and

Environmental Profile Analysis at the Midwest Research Institute in the USA. The primary focus of early LCAs was the packaging of products, as exemplified by the initial LCA conducted in Germany. In a study conducted by Oberbacher et al. (1996), the potential environmental impacts and costs associated with packaging materials for liquids were assessed. Subsequently, numerous workshops and research initiatives have contributed to the advancement of LCA methodology and the establishment of standardized procedures. [64]

As outlined in ISO 14040, the framework is comprised of four principal stages, which are delineated in Figure 3. The following section will provide a detailed examination of these stages. [65]

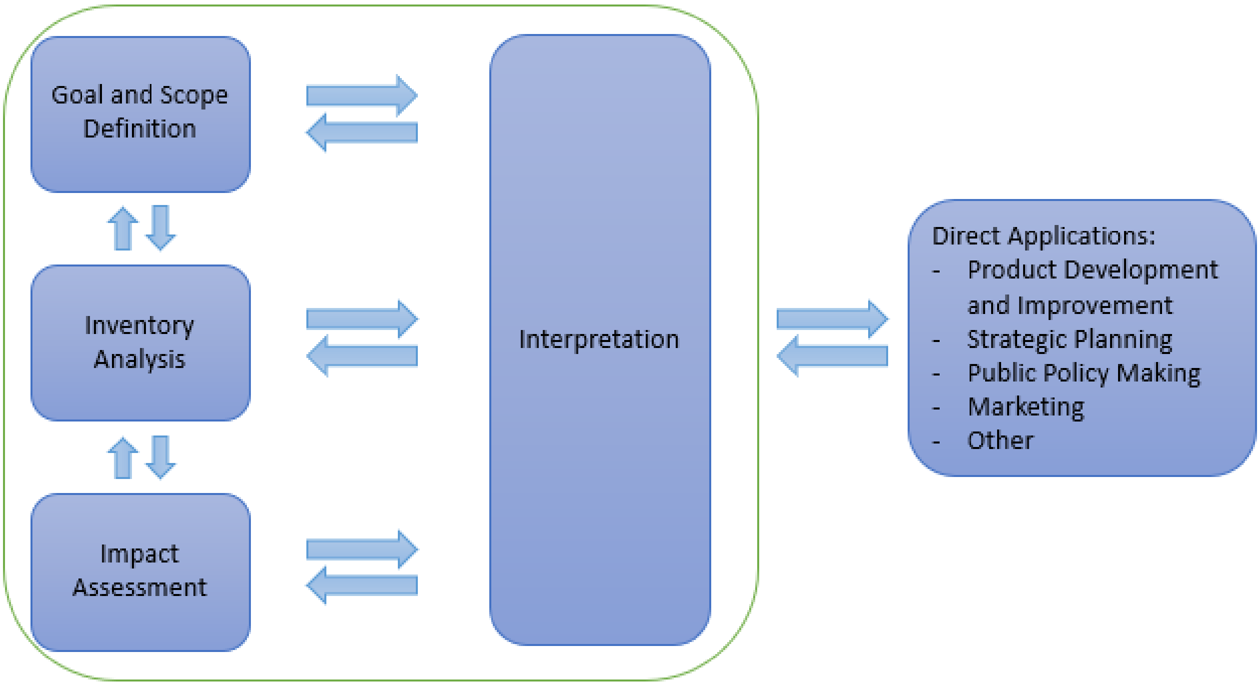

Figure 3: Own illustration of the iterative steps of LCA based on Klöpffer (1997) [66]

Goal and Scope Definition

The goal and scope section delineates the objective and subject matter of the study, as well as the boundaries and functional unit of the assessed product system. Moreover, this stage entails the delineation of overarching principles, the selection of an impact assessment and evaluation methodology, the identification of the intended audience as well as peer reviews. It is foreseen that these elements will enhance the transparency of the LCA. [66]

The product system, comprising a functional unit, represents the entirety of the process steps and life cycle phases of the product, which end up in the fulfilment of a specific function. In the case of an aircraft, for instance, the provision of all materials for its manufacture and all associated manufacturing and maintenance activities until the eventual recycling and disposal of the aircraft itself could be included. Additionally, the provision and combustion of the jet fuel and the utilisation of airport infrastructure would also need to be considered. All of these steps serve the function of transportation. In the case of passenger aircraft, the functional unit of passenger kilometers could be used to operationalize them.

In the context of product system comparison, the exclusion of life cycle phases from the system boundaries is a viable approach when utilizing the LCA methodology. This approach is predicated on the assumption that the excluded life cycle phase would be identical for all product systems, and thus would not contribute to any different results when assessing and comparing them. Furthermore, portions of the product system that result in an insignificant contribution may also be disregarded. A common approach is to exclude parts that contribute less than 1% to the mass, energy demand, or potential environmental impact of the product system. Nevertheless, it is still necessary to ascertain whether the excluded component has been identified as a significant contributor to environmental impact in other studies, as materials with a minimal mass fraction within a product system can nevertheless exert a considerable influence on the overall potential environmental impact.

Life Cycle Inventory

The Life Cycle Inventory (LCI) encompasses all material and energy inputs and outputs, which must be balanced at each stage of the life cycle. Two categories of data are distinguished: The background data, which is predominantly comprised of information related to energy, transportation, commodities, and chemicals, is likely to be sourced from the background database and existing literature. In contrast, the primary, more specific foreground data is typically obtained from manufacturers and suppliers within the context of research projects.

Life Cycle Impact Assessment

A Life Cycle Impact Assessment (LCIA) is a method of evaluating the potential environmental impacts of a given product system. It should be noted that the results presented are potential impacts, rather than actual. In order to ascertain the actual impacts, it would be necessary to consider additional factors, such as the corresponding concentrations at the place of exposure and the more detailed characteristics of the substances in question.

Figure 4 illustrates an exemplary main process with precursors and successors, with each process connected to specific emissions and resource use. The final product of this process is deemed to be 5 kg of a generic end product. The characterization factors provide an indication of the potential environmental impacts associated with each process and functional unit. Although the assessed processes are part of the technosphere, the resources are drawn from and the emissions are ending up in the biosphere.

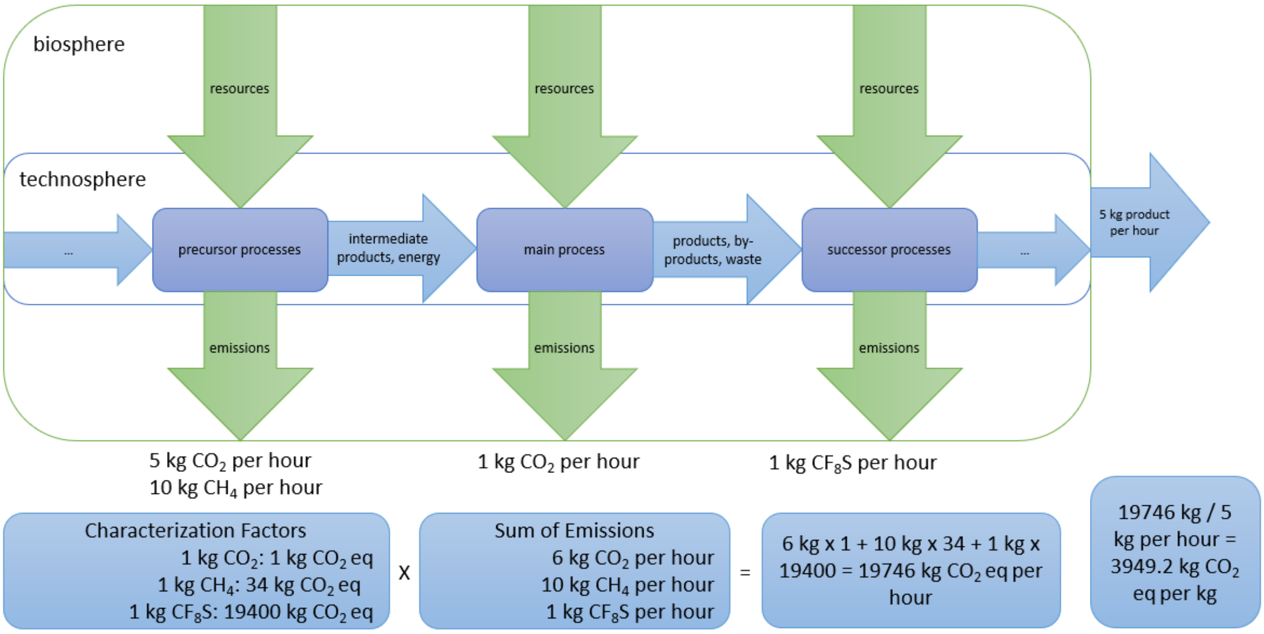

Figure 4: Example of an LCA model with GWP results

The potential environmental impacts are typically expressed with midpoint indicators, which focus on specific environmental concerns, such as climate change or ecotoxicity. The aggregation of midpoint indicators facilitates the communication of results and enhances the utility of LCA as a decision-making support tool by enabling the calculation of endpoint impacts. The three endpoint areas are human health, ecosystem, and resource availability. Nevertheless, the aggregation of impacts is associated with methodological challenges, as the direct correlation between specific environmental impacts and a particular degree of damage to ecosystems or human health is often difficult to quantify. The methodology presented here differs from the existing approaches in its application to a similar objective.

The integration of LCA and S-LCA indicators with the SDGs demonstrates the potential implications for internationally recognized sustainability categories, while maintaining the reliability of the quantitative midpoint-based results.

Interpretation

In accordance with the guidelines set forth by the Joint Research Centre of the European Commission for the interpretation of LCA results, the interpretation phase can be divided into three principal steps.

1. The first step is the identification of significant issues, which is based on the results of the LCI and LCIA phases. This phase comprises the analysis and structuring of the LCIA results for the purpose of identifying the main contributing life cycle stages, processes, and elementary flows. By this, the most relevant impact categories are identified.

2. An evaluation of the results is conducted, taking into account factors such as completeness, sensitivity, and consistency. This step represents a final examination of the consistency and reliability of the applied assumptions, methods, and data, thus enabling the formulation of definitive conclusions.

3. The final stage of the process is the formulation of conclusions, limitations, and recommendations. In light of the preceding steps, the final interpretation is undertaken. This comprises a conclusion, a discussion of the limitations of the study, and a recommendation for future research. [67]

3.1.2 Life Cycle Costing

Life Cycle Costing (LCC) is used to assess the total cost of a product system along the entire life cycle, which goes beyond the initial capital investment costs. Similar to the boundaries of LCA, the entire life cycle of products is assessed with this method. Among others, this can include the operation and maintenance and the end-of-life. This shall facilitate the economic comparison of different alternatives in a more effective and comprehensive way, as stated in Sesana and Salvalai (2013). [68]

3.1.3 Social Life Cycle Assessment

S-LCA is similarly designed to collect and communicate impacts that may arise throughout the entire life cycle of a product system, in a manner analogous to that of LCA. The majority of tools utilized in the context of social responsibility are based on management information and may address the impacts at a specific facility, as well as potentially the initial tier of their supply chain. However, as elucidated by Benoît et al. (2010), S-LCA is oriented towards the examination of social risks and opportunities throughout the entirety of the product system's life cycle. [69]

The PSILCA v.3 database is employed for the S-LCA of this dissertation. It is based on the multi-regional input/output database Eora, which provides a comprehensive overview of the global economy, including inter-industrial sector flows. Connected to the international and domestic monetary flows between the industrial sectors, PSILCA provides a social risk per US dollar (USD) for several indicators. The following description is based on the PSILCA v.3 documentation (Maister et al., 2020). [70]

Risk assessment

The social risks are classified into different levels, which are then used as indicator values for the risk assessment. For example, the range of 0–7.5 fatal accidents per 100,000 employees is translated into a very low risk level, indicating that workers are unlikely to suffer fatal accidents. The range of 7.5–15 represents a low risk, 15–25 a medium risk, 25–40 a high risk, and more than 40 a very high risk. The social risks assessed for industrial sectors are based on data from a number of international organizations, including the World Bank, the International Labour Organization (ILO), the World Health Organization, and the UN.

Characterization

The aforementioned risk levels are characterized with a factor that harmonizes all results into medium risk hours for the purpose of facilitating comparison. The term "risk hours" refers to the number of worker hours that are exposed to a specific social risk throughout the product's life cycle. In this instance, a very low risk is equivalent to 0.01 medium risk hours, whereas a very high risk hour is equivalent to 100 medium risk hours. A low-risk hour is equivalent to 0.1 medium-risk hours, while a high-risk hour is equivalent to 10 medium-risk hours.

The social risks pertain to a number of stakeholder groups, including workers, local communities, value chain actors, society at large, and consumers. This distinction is relevant to this work, as it is important to understand whether a transition to a different fuel supply chain could potentially affect the social impact directly (for example, with regard to the typical salary along the supply chain in this industry) or indirectly (for example, with regard to government spending for education in an assessed country). [70]

As Finkbeiner et al. (2010) have observed, a significant number of social indicators are not contingent on a single product or process. These indicators are frequently geographically oriented and focus on the present status of factors such as the Human Development Index (HDI), the country's infrastructure, and its health and social systems. Consequently, the relation to the assessed product system has to be elaborated with additional assumptions. [71]

3.2 Goal and Scope of this Sustainability Assessment

The objective of the sustainability assessment within this dissertation is twofold. While the impetus behind the production of synthetic fuel in the early 20th century was rooted in the desire for independence from oil-related imports and the scarcity of oil, the focus has since shifted to the reduction of GHG emissions through the production of CO_2-neutral fuels. The initial objective is to ascertain which PtX configurations can make a substantial contribution to GHG emission reduction, as described in section 3.2.1. Concurrently, it is imperative not to overlook the other potential environmental and societal implications. Consequently, the second objective is to evaluate the potential social and environmental implications of a transition from fossil- or bio-based fuels to PtX-based fuels. This second part is conducted with a benchmark system comprising categories inspired by the UN Sustainable Development Goals, which are described in section 3.2.2.

The intended audience of this work is the general public, technology providers, non-governmental organizations (NGOs), academic institutions, and any other stakeholders that may be affected by the development of PtX plants and supply chains in any country worldwide.

3.2.1 CO_2-Goal Setting

Given the global scope of this work, it is not feasible to consider specific national goals for CO_2 emission reduction in detail. Instead, a more generic approach is taken, with some elements based on the delegated regulation of the European Commission. In accordance with the delegated regulation on the union methodology for renewable fuels of non-biogenic origin (RFNBOs), a 70% reduction of greenhouse gas (GHG) emissions in comparison to a fossil baseline of 94 g CO_2eq/MJ is required for RFNBOs. This value of 70% serves as a benchmark for the CO_2-goal setting for the PtX constellations at each location within the model presented in this dissertation. Those constellations that do not reach the 70% reduction threshold are excluded from the subsequent benchmark assessment. Only the aforementioned threshold value of 70% is applied in this instance; the remaining scope and methodological aspects of the aforementioned delegated regulation are not applied. In contrast to the aforementioned delegated regulation, the scope of the method applied here considers the construction of all main process steps and equipment, including wind and PV power plants. [72]

3.2.2 Benchmark Categorization inspired by the UN Sustainable Development Goals

“Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.” The definition from the Brundtland report, "Our Common Future," is arguably the most widely used when discussing sustainable development. The intergenerational and intragenerational dimensions of sustainability are of particular significance in this dissertation, as they are addressed in different categories. It is imperative that climate change measures be implemented to ensure intergenerational sustainability, as climate change will have a significantly greater impact on future generations than it has on the current ones. Nevertheless, the transition of traffic to alternative and renewable modes of transport must not be borne by today's society alone. The impact on society is particularly noteworthy when viewed from a global perspective, as it is in this context that a variety of social risks emerge in different countries and regions. [73], [74]

There are numerous instances where the resources of certain countries are utilized for the provision of transportation services in other countries, resulting in significant adverse effects on local communities and ecosystems.

The extraction of oil in Nigeria by Shell has resulted in a multitude of environmental and social harms. Osai Ojigho of Amnesty International Nigeria stated, “The discovery of oil in Ogoniland has brought huge suffering for its people. Over many years, we have documented how Shell has failed to clean up contamination from spills and it’s a scandal that this has not yet happened. The pollution is leading to serious human rights impacts - on people’s health and ability to access food and clean water.” Moreover, the Malabu scandal has demonstrated not only the ecological impacts of oil extraction and fossil-based fuels, but also the socio-governmental negative impacts, including allegations of bribery of government officials and executions of protesters in Nigeria. [75], [76]

Olson et al. (2016) cite a report on an oil pipeline that makes a number of claims regarding human rights abuses. These include violations of labor laws, inadequate or lack of compensation for appropriated lands, repression of dissent, corruption, falsification of documents, silencing of the press, destruction of the environment and infrastructure, and paramilitary coercion. [77]

While the production of fossil-based fuels undoubtedly has a detrimental impact on society, bio-based fuels also present a potential threat to local stakeholders. The question of whether it is justifiable to use potential food resources from another country to propel an aircraft in other countries serves as an illustrative example. Renzaho et al. addressed the impact of biofuels on the Sustainable Development Goals. The production of first-generation biofuels (1G) has a direct impact on food availability and food prices. Second-generation biofuels (2G) also have an indirect impact, as they utilize potential resources for food production. The production of bio-based fuels can result in land use change and indirect land use change, which can have an impact on the climate, biodiversity, and other categories. Moreover, the application of fertilizers, pesticides, and water is a significant factor. [78]

Concurrently, the transition towards an electric transport system also has significant environmental and societal implications. The extraction of lithium has a significant water footprint, with a water demand of nearly 2 million liters per ton of lithium. This is particularly pertinent in arid regions such as South America. Other methods exist that require less water, but the use of chemicals inevitably results in contamination of the soil, water, and air. In addition to lithium, the production of batteries also requires cobalt and nickel. Cobalt is almost exclusively available in the Democratic Republic of Congo, where it is often extracted without the use of heavy machinery. This has significant social implications, as it gives rise to concerns about the prevalence of child labor in the absence of adequate safety measures. [79]

These examples illustrate the necessity of conducting a comprehensive sustainability assessment at the outset, in order to identify and address potential negative impacts and prevent them, to the extent possible. While the primary objective is to reduce CO_2 emissions, it is imperative that the impact on society and other ecological aspects is not exacerbated, and may even be enhanced. In order to embed the potentially affected sustainability aspects into a normative framework, a suitable concept for sustainable development needs to be integrated.

The Sustainable Development Goals (SDGs) provide an overview of the critical topics that must be addressed in order to achieve global sustainable development. The indicators derived from the LCA and S-LCA results are employed here to address the categories outlined by the Sustainable Development Goals (SDGs). The data utilized to represent the Sustainable Development Goals (SDGs) have been sourced from the United Nations website. [41], [80]

It is not assumed that PtX-based fuels could achieve any of the Sustainable Development Goals in their entirety. In this context, the SDGs serve as an overview of relevant topics of sustainability on a global scale. This indicates that the SDGs are not directly addressed in this context; rather, they represent the categories of sustainability concerns addressed through the use of LCA and S-LCA indicators. This analysis aims to ascertain whether PtX-based fuels could have a positive or negative impact on these sustainability concerns, with fossil- and bio-based fuel production serving as benchmarks within each category. As several quantitative indicators from the LCA and S-LCA may impact the same SDG, it is essential to exercise caution when selecting indicators and establishing their link to the relevant SDG.

The data pertaining to the various indicators within the specified categories were obtained from Frischknecht et al. (2019), Maister et al. (2020), and Ciroth and Eisfeldt (2020). The aforementioned sources are no longer explicitly referenced in this section; additional sources are quoted accordingly. [70], [81], [82]

1. No poverty

“End poverty in all its forms everywhere.”

Although this is a clearly defined objective, poverty is a multifaceted phenomenon. The SDG indicators address several key areas

- the proportion of people living in poverty (according to international and national standards)
- the coverage of social protection
- the living standards
- the effects of and protection from disasters
- financial efforts to fight poverty

It is important to note that while some countries have gained significant wealth through the exploitation of fossil energy resources, this does not necessarily indicate that the population has benefited from this growth and that poverty has been effectively addressed. As Olson and Lenzmann (2016) have observed, the benefits are typically concentrated among a few individuals, while the remaining population experiences adverse effects at the social and economic levels. [77]

One aspect that merits consideration is the remuneration provided to compensate for the work performed. A low salary can have a direct impact on an individual's poverty. The potential risks associated with this low salary are evaluated using the S-LCA indicator for fair salary. In order to define a "fair salary," three different standards are considered:

- the minimum wage required by law
- the local ´prevailing industry wage´
- The ´living wage´ (after the UNEP/SETAC definition), which is measured with three different indicators:
    - Living wage, per month
    - Minimum wage, per month
    - Sector average wage, per month

The mean salary of the assessed sector is then put into relation with the living wage of the respective country. In the absence of data on the country's living wage, the prevailing minimum wage is used as a reference point. In the absence of minimum wage data for a specific country, the mean living wage across country groups is used as a reference point. It is important to note that the living wage is based on the cost of living in the cheapest region within the respective country.

2. Zero hunger

“End hunger, achieve food security and improved nutrition and promote sustainable agriculture.”

The zero hunger-goal addresses

- Hunger and malnutrition
- Agricultural productivity
- Genetic diversity of seeds, plants and animals
- Economic aspects.

When alternative fuels, specifically bio-based fuels, are discussed, the food vs. fuel debate is often addressed. Although it is accurate to conclude that at least the initial generation of biofuels relies on food crops, a more comprehensive perspective is essential in this context. The view of feedstocks used for the production of bio-based fuels is often limited to a narrow perspective due to a lack of consideration of their multi-functionality and by-products. Moreover, the feedstocks utilized for bio-based fuels can be intermediate products or by-products within the agricultural sector that would frequently not be identified as food. It is therefore recommended that a broader range of indicators than simply food availability or biomass utilization be considered when attempting to establish a link between fuel production and global hunger. [83]

In lieu of examining the quantity of biomass or agricultural resources employed in fuel production, this analysis addresses the potential for adverse effects on agricultural and other land. The phenomenon of acidification has the potential to impede agricultural productivity over the long term, thereby placing the future of food production at risk. This, in turn, could contribute to an increase in hunger worldwide. In order to assess the potential environmental impact along the life cycle, the LCA indicator terrestrial acidification is employed here.

3. Good health and well-being

“Ensure healthy lives and promote well-being for all at all ages.”

The objective of promoting good health and well-being is to implement measures that protect individuals from disease and mortality, while also enhancing the quality and accessibility of healthcare systems and services globally.

The global health crisis precipitated by the SARS-CoV-2 virus has demonstrated that the world's health systems were ill-prepared to respond to such a challenge. While certain aspects of this category, such as life expectancy, maternal and child mortality, demonstrated improvement over recent years prior to the pandemic, the focus has shifted and the rate of progress has slowed down as a result of the pandemic. It became evident that augmented financial investment is imperative to attain enhanced development within this category and to fortify preparedness for future crises, as postulated by Khetrapal and Bhatia (2020). It should be noted that the S-LCA indicator of health expenditures is not directly connected to the production of fuels. It demonstrates the potential vulnerability associated with a relatively low proportion of the national gross domestic product (GDP) being allocated to health services. Moreover, this indicator is not capable of providing a definitive assessment of the functionality of a national health system. However, it can serve as a preliminary risk evaluation. In particular, when contemplating international collaborative efforts pertaining to PtX production or development cooperation, this category must not be overlooked. [84]

The LCA indicators of human carcinogenic toxicity and human non-carcinogenic toxicity are employed as direct impact indicators for this category, as they assess the potential impacts on human health throughout the life cycle of the assessed processes. The potential impact is quantified in kilograms of 1,4-dichlorobenzene-equivalents (1,4DCB-eq) for both non-carcinogenic and carcinogenic human toxicity. The indicator 1,4DCB-eq represents the release of chemicals with deleterious effects on human health that people are exposed to at various stages of the life cycle. The indicator is typically employed for the assessment of the elevated risk of non-cancer and cancer disease incidences.

4. Quality education

"Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all."

Access to quality education is a fundamental human right. Education should be inclusive and equitable, and opportunities for lifelong learning should be widely available.

In addition to the accessibility and caliber of fundamental education, this objective encompasses the essential competencies and understanding requisite for sustainable development, gender- and disability-sensitive pedagogical practices, secure educational infrastructure, scholarships for developing countries, and the qualifications of educators.

The global pandemic of 2020 resulted in over 1.6 billion students being unable to attend their educational institutions, according to the World Bank Group (2021). There is a significant risk that some of these students may never resume their studies. Children from low-income households often lacked the resources to adapt to the new forms of learning that were introduced during the pandemic. The absence of quality education could have significant consequences if the learning losses are not addressed in a timely manner, concurrently with the recovery of the global education system. It may be reasonably assumed that an increase in expenditure on education as a percentage of GDP would result in a more comprehensive and widespread coverage of the topic of sustainability. This, in turn, could result in more effective integration of sustainability considerations at all stages. It is evident that the education system necessitates financial resources to recuperate and to have an opportunity for sustainable development. In this context, the S-LCA indicator employs public expenditure on education for this category. [85]–[87]

It should be noted, however, that the S-LCA indicator public expenditure on education can only identify a potential area of concern in this case. A high risk in this category does not necessarily indicate that fuel production has a negative impact. Rather, it suggests that there is a possibility that spending on education may be insufficient in certain areas throughout the life cycle of the fuel, which is unlikely to change in the near future due to a transition to alternative fuel production pathways. Consequently, it serves as an indicator of the current status quo in the respective countries and as a measure of where improvements may be necessary for an inclusive and fully sustainable transition.

5. Gender equality

"Achieve gender equality and empower all women and girls."

This objective addresses all forms of discrimination, violence, harmful practices, and deficiencies in access to social services and healthcare for women.

As previously noted by ActionAid Australia (2018) in their report, "Undermining Women's Rights – Australia's Global Fossil Fuel Footprint," the extraction of fossil fuels has been identified as a significant contributor to adverse impacts on women's health, safety, and income. A number of factors contribute to this negative impact. A substantial number of male workers are typically deployed to extraction projects, which can result in elevated rates of gender-based violence, HIV prevalence, and the demand for paid sexual services in those locations. Moreover, the governments' revenues, which are crucial for funding essential public services such as education and healthcare, as well as for compensating for the unpaid labor of women, are frequently diminished by the practice of tax evasion within the fossil fuel industry. Concurrently, the gender wage gap in the energy sector is markedly higher than in non-energy sectors. [88], [89]

The potential impact of PtX-based fuels on gender equality is evaluated using the S-LCA indicator gender wage gap, which directly addresses the wage gap within the assessed life cycle of the product systems. This indicator is employed to evaluate the potential for wage-related gender inequality across the entirety of the life cycle of the various fuel production pathways, with consideration of the involvement of different industries. This allows for an evaluation of whether alternative fuels could potentially increase or decrease the risk of gender inequality. It must be acknowledged that this would not address the fundamental issue of gender inequality. However, the substitution of fossil- or bio-based fuels with PtX-based fuels could still have an impact on the issue. The data utilized for the risk assessment of a gender wage gap do not account for discrepancies in qualifications, job roles, or working hours. [82]

6. Clean water and sanitation

"Ensure availability and sustainable management of water and sanitation for all."

The clean water and sanitation goal is concerned with the availability and quality of water on a global scale, as well as the means of addressing these issues.

The production of alternative fuels has the effect of increasing the demand for water. The production of both bio- and PtX-based fuels requires water at different stages of the life cycle. For instance, irrigation is necessary for bio-based fuels, while the water electrolysis used to produce green H_2 is a key step in the PtX-based fuel process. A transition from fossil fuels to biofuels would place significant strain on global water resources, largely due to the high water demand associated with feedstock cultivation. This could potentially contribute to an increase in water shortages. [90]

PtX-based fuels also result in an increased specific water demand per kilogram of fuel in comparison to fossil-based fuels. However, it should be noted that the demand is generally lower than that of bio-based fuels. Nevertheless, the domestic fuel production would serve as an additional water sink for each country, necessitating its consideration. The provision of water for drinking purposes should never be compromised as a result of fuel production.

The World Resources Institute has published a world map indicating the countries that are expected to experience water stress by the year 2040. It is notable that several countries with high or extremely high water stress, as indicated on the map, are currently regarded as having significant potential for PtX. [91]

The quantity of water utilized for the provision of various fuel types is quantified through the LCA indicator of water consumption. This indicator is not contingent upon the local availability or scarcity of water at each location. To account for the aspect of scarcity as well, the S-LCA indicator "industrial water depletion" is included. It demonstrates the current status of water consumption by the industrial sector in relation to the total water withdrawal and the available water resources. This indicates the potential risk of the assessed industry exceeding sustainable water consumption. Firstly, the proportion of water consumption by the industrial sector in relation to the total volume of water withdrawal is calculated. Secondly, the amount of total water withdrawal in relation to the total renewable water resources available is indicated. Although the PtX industry is not yet fully established, it can demonstrate the extent to which the energy sector in the assessed countries is already exerting pressure on local water resources. Furthermore, it demonstrates the associated risk in comparison to the bio-based and fossil-based fuel production pathway.

It should be noted that the model presented in this dissertation does not account for the specific impacts of water desalination and provision processes within each country. Therefore, it is important to conduct a separate analysis at the country and project level when planning the construction of fuel production facilities.

7. Affordable and clean energy

“Ensure access to affordable, reliable, sustainable and modern energy for all.”

Access to affordable, reliable, sustainable, and modern energy for all is a fundamental human right.

The objective of affordable and clean energy is to guarantee access to energy and to increase the proportion of renewable energy, while also fostering international collaboration and expanding the prospects and investments in clean energy in developing countries.

As the global transition towards renewable energy progresses, the land required for the construction of wind and solar power plants has emerged as a significant point of discussion. This is particularly relevant when considering that PtX necessitates the deployment of additional renewable energy capacities beyond those utilized for national electricity consumption.

McKinsey has identified the scarcity of "top-quality land" as a significant challenge to the transition to renewable energy sources. In their article, "Renewable-energy development in a net-zero world," the authors analyze this problem with the example of Germany. The land use model indicates that 51% of Germany's land could potentially be utilized for onshore wind power. However, when considering the numerous constraints associated with the construction of these facilities, including technical, environmental, and regulatory factors, only 9% of the land in question would be suitable for the installation of wind power plants. In light of Germany's stated objectives, the development process would be subject to considerable pressure, with the requirement for 4-6% of the feasible land area. [92]

The development of international supply chains for the provision of PtX fuels facilitates the construction of renewable energy capacities in other countries. While this does result in an overall increase in renewable energy capacity in this country, it is important to note that the energy produced may ultimately be utilized for fuels or other PtX-based products and potentially exported, rather than for the common electricity generation in the country. Furthermore, the situation could potentially deteriorate, as the high economic and ecological sensitivity to FLH may result in the most favorable locations for RES plants being utilized by PtX plants, thereby hindering the transition of the domestic energy system to RES. This issue is directly connected to the land use that is associated with the production of PtX-based (or bio-based) fuels. Accordingly, the LCA indicator "land use" has been incorporated as an indicator for this category. This indicator measures the total area of land occupied over the entire life cycle of the product or system being assessed, expressed in area of land occupied multiplied by the number of years it is in use.

The indicator also accounts for land that would not be suitable for the construction of renewable energy facilities. Furthermore, it does not consider the amount of available land in each country. Consequently, it is only a proxy for this risk. A more detailed assessment could be conducted by identifying the exact locations that offer a high amount of FLH for wind or solar energy. However, the detailed assessment of region-specific FLH within the countries is beyond the scope of this work.

8. Decent work and economic growth

"Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all."

The objective of decent work and economic growth encompasses not only GDP growth and employment rates, but also material footprints, wages, education, child labor, work-related injuries, labor rights, sustainable tourism, bank service utilization, and aid for trade.

The issue of child labor remains a significant concern in many parts of the world. In light of the considerable resources required for the development of renewable energy and PtX, it is imperative not to overlook the risk of child labor. Similarly, in the context of biofuels, labor laws and standards in the agricultural sector are often inadequate, which can result in an elevated incidence of child labor and occupational injuries. The generation of electricity from renewable sources and PtX-based fuel production, particularly the extraction of raw materials, is associated with a significant risk of child labor. As reported by the ILO (2018), 218 million children were engaged in employment, of whom 152 million were subjected to child labor, with 73 million of these children working in hazardous conditions during the period covered by the report. Although there has been a reduction over the past few decades, it is evident that significant efforts are still required to eradicate child labor on a global scale. It is imperative that the production of PtX-based fuels does not impede this progress. [93]–[95]

In order to assess the risk of child labor throughout the life cycle of the product systems, the S-LCA indicator "child labor, total (female and male)" is employed. The indicator is directly influenced by the supply chains. The degree of risk is determined by the proportion of children engaged in employment within the industries under assessment at each stage of the product life cycle.

9. Industry, innovation and infrastructure

“Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.”

The objective of the industry, innovation, and infrastructure category is to facilitate the development, expansion, and modernization of sustainable infrastructure, industry, and research. It addresses the necessity for a just transition to sustainable industries and infrastructure through the implementation of innovative sustainable technologies.

As indicated in The Production Gap Report 2021, governments globally are still aiming to produce more than 200% of the amount of GHG that would be consistent with the 1.5°C goals by 2030. It is anticipated that gas production will continue to increase, at least up to 2040. Furthermore, the production of coal is expected to remain at a considerably higher level than is environmentally sustainable. In order to be consistent with the Paris Agreement Goals, a rapid decline is necessary. [96]

In addition to the reduction of fossil CO_2 emissions, the scarcity of fossil resources is addressed through a transition to renewable fuels. The reduction of fossil resource utilization throughout the life cycle is typically accompanied by a corresponding decline in the emission of fossil CO_2. Although there are no direct fossil CO_2 emissions or fossil resource use in the PtX plant (which utilises a non-fossil carbon source), fossil resources are still employed throughout the life cycle. In this context, the LCA indicator "fossil resource scarcity" is employed to assess the category in question. A reduction in the dependence on and extraction of fossil resources may be regarded as a positive step towards the implementation of innovative sustainable infrastructure and industry. A reduction in the potential impact on fossil resource scarcity would also result in a decrease in the CO_2 emission level of the industry. The scarcity of fossil resources is indicated by kg oil-eq, which is measured by the upper heating value. This indicator addresses the utilization of all fossil resources along the life cycle by their upper heating value, which then leads to a potential increase in scarcity.

10. Reduced inequalities

“Reduce inequality within and among countries.”

The objective of reducing inequalities is to achieve national equality with regard to economic growth and income disparities between the poorest and the median income group. It also entails the inclusion of all individuals, equal opportunities, and the reduction of inequalities in international comparisons. While SDG 10 is closely associated with emigration and refugees, it also addresses the issue of discrimination. Therefore, it is important to consider the rights of indigenous peoples in connection to the exploitation of areas for fuel production. The potential for fuel production to infringe upon the rights of indigenous peoples is heightened when new areas are exploited.

In this category, the S-LCA indicator for respect of indigenous rights is employed. The indicator demonstrates the potential for human rights to be violated throughout the life cycle of a project. Initially, the presence of indigenous populations in a country is a key factor in the assessment. Secondly, the legal framework within a country is considered. This is measured by the extent to which a country's efforts, ratifications, and declarations align with the rights of indigenous peoples.

11. Sustainable cities and communities

“Make cities and human settlements inclusive, safe, resilient and sustainable.”

This category addresses the issue of access to safe and affordable living space, basic supplies, and sustainable transportation. Another aspect of the sustainable cities and communities goal is the planning process of cities and rural areas in the context of green areas, sustainability, disaster protection, and pollution. The issue of pollution is addressed in this work with the LCA indicator fine particulate matter. This can be directly attributed to SDG indicator 11.6.2, which addresses the level of fine particulate matter. The measurement of fine particulate matter is expressed in emitted mass [kg] of PM2.5 equivalents. In contrast to GWP, this has a relatively local impact on human health. For example, the fine particulate matter emitted through the combustion of liquid fuels can have a direct impact on human health after being inhaled. The impact of fuel combustion in aircrafts is not within the scope of this study.

12. Responsible consumption and production

"Ensure sustainable consumption and production patterns."

SDG number 12 encompasses a number of aspects pertaining to sustainable consumption and production. The material footprint, food waste, waste treatment, recycling, and the integration of sustainability policies and measures in companies and countries are discussed. In light of the necessity for minerals to facilitate the transition to renewable energy sources and the elevated risk of scarcity for certain minerals, it is imperative to ensure efficient utilization. As stated in the report "Minerals for Climate Action," As indicated in the report, "The Mineral Intensity of the Clean Energy Transition," an increase in demand for certain minerals of up to 500% is anticipated in order to achieve the goals set forth in the Paris Agreement. It seems inevitable that a significant increase will occur, regardless of the technological pathway prioritized for alternative fuels, as all of them are, to some extent, connected to renewable electricity generation, which in turn requires certain minerals throughout the entire life cycle. SDG indicator 12.2.1 addresses material footprints in the context of efficient material use. In light of the aforementioned considerations, the LCA indicator mineral resource scarcity is employed in this analysis to evaluate the potential environmental impacts of the various fuel production pathways in terms of their efficient utilization of mineral resources.

13. Climate Change

"Take urgent action to combat climate change and its impacts."

The objective of climate action is to enhance awareness and adaptation to climate change, and to implement climate change measures at the national and global levels in order to facilitate unified efforts against climate change.

As reported by the IEA (2021), the GHG emissions of the transport sector exhibited a decline during the initial year of the pandemic due to the implementation of lockdown measures, which resulted in a reduction in mobility across numerous countries. However, a resurgence in emissions was observed in 2021. In order to achieve climate neutrality and the requisite reduction in CO_2 emissions from this sector, it is necessary to implement specific policies that are tailored to the mode of transport in question. [97]

The use of bio- and PtX-based fuels is relevant in reducing CO_2 emissions from the transport sector, particularly in the context of sustainable aviation fuels, given the current infeasibility of direct electrification in the aviation sector. The production of renewable energy and bio- or PtX-based fuels is frequently regarded as a climate-neutral process. However, when the entire life cycle is taken into account, the global warming potential (GWP) of renewables, bio- and PtX-based fuels is not equal to zero. In the case of electricity derived from renewable sources, whether as product or as a feedstock, the specific technology and the quantity of FLH are of significant consequence. An increase in the amount of FLH and the utilization factor of the plant results in a reduction in the GWP. Furthermore, the electricity grid mix utilized to construct the plants also exerts a considerable influence. An increase in the proportion of renewable energy sources within the grid mix will result in a reduction in the GWP of the produced plant. The GWP is expressed in kg CO_2 eq and is directly correlated with the SDG indicator 13.2.2 Total GHG emissions per year.

This category is evaluated prior to all others, as it is the primary indicator of this study. It serves as a crucial point of reference for the evaluated PtX configurations. Only those PtX constellations that achieve a 70% reduction in GWP, as outlined in section 3.2.1, are subjected to the subsequent benchmark assessment.

14. Life below water

“Conserve and sustainably use the oceans, seas and marine resources for sustainable development.”

The Life below Water goal encompasses two distinct aspects. The issue of water overuse can be divided into two distinct categories: the overuse of water as a sink and the overuse of water as a source. The sink aspect is used to describe the contamination of water sources, for example through acidification and eutrophication of these ecosystems, as well as through an increase in plastic debris. The source aspect for example pertains to fishing activities that result in an imbalance within the marine ecosystem. In order to assess this category, the LCA indicator marine eutrophication is employed.

The increase in waterborne emissions of N compounds is used as a measure of marine eutrophication, which is the accumulation of N in the water. The elevated concentration of N in the water results in an increase in planktonic biomass, which subsequently reduces the available concentration of dissolved O_2 for any life forms in the water.

15. Life on land

“Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.”

The objective of the "Life on Land" goal is to ensure the sustainable utilization and recovery of ecosystems, with a particular focus on forests, mountains, desertification, and biodiversity.

This work addresses the specific issue of the toxic impacts that fuel production can have on terrestrial ecosystems throughout the life cycle of the fuel in question. In light of the considerable increase in demand for minerals associated with the transition to renewable energy sources, it is imperative not to overlook the ecotoxic impacts of mining, waste disposal, and other activities throughout the life cycle. Bicer and Dincer (2018) demonstrated that electric vehicles or vehicles powered by ammonia have a considerably greater potential for environmental impact on terrestrial ecotoxicity than cars fueled by fossil-based gasoline or diesel. The utilization of copper and steel throughout the life cycle has a considerable impact on this matter. The LCA indicator of terrestrial ecotoxicity is integrated for the assessment of this category. Similarly to the indicators for human toxicity, it is expressed in 1,4DCB-eq. [98], [94]

16. Peace, justice and strong institutions

“Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.”

The prevalence of conflicts worldwide, along with the pervasiveness of corruption, bribery, and limited access to justice, collectively impede the realization of sustainable development on a global scale. The objective of the category of peace, justice, and strong institutions is to address numerous issues where individuals are subjected to hardship, whether due to conflict or a dearth of reliable institutions that can uphold the rule of law.

In general, the extraction of resources, and thus the energy sector, is prone to significant corruption risks. This is an example of the paradox of plenty. In countries situated in regions endowed with natural resources, the revenues derived from these resources are frequently diverted from their intended purpose of fostering economic growth and social welfare due to the prevalence of corruption. Consequently, the theoretical advantage of possessing high-demand resources becomes a disadvantage for the country's development. It is not uncommon for substantial financial commitments to be associated with energy-related initiatives, which in turn increases the likelihood of corruption. Once a project has commenced and financial resources have been committed, it is challenging to halt the project, even when corrupt practices become necessary to maintain its progress.

As the United Nations has shown in its report "Global Impact of War in Ukraine: Energy crisis", the war has precipitated a global energy crisis, with ramifications extending beyond mere energy prices to encompass energy and food scarcity. In the context of the global energy crisis, countries around the world are compelled to implement new strategies for their energy supply in a time-sensitive manner. This has resulted in an increased reliance on high-emission technologies, such as coal plants in Germany. [99], [100]

Two distinct indicators are employed for this category. The involvement of corruption and bribery throughout the life cycle is addressed by the S-LCA indicator, which measures the active involvement of enterprises in corruption and bribery. The indicator is employed here to assess the extent to which the sectors engaged in the evaluated supply chains are implicated in instances of corruption and bribery. This is directly connected to the SDG indicator 16.5.2. The proportion of businesses that had at least one contact with a public official and that paid a bribe to a public official, or were asked for a bribe by those public officials, during the previous 12 months. As a second indicator, the risk of conflicts are evaluated within in this category. The Global Peace Index (GPI) serves as the basis for this indicator, which assesses three key dimensions: societal safety and security, the prevalence of ongoing domestic and international conflict, and the degree of militarization.

17. Partnership for the goals

“Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development.”

The Partnership for the goals is divided into the following aspects:

- Finance: International budgets and investments
- Technology: The global access to environmentally sound technologies and the internet
- Capacity-building; Financial and technical assistance on an international level
- Trade: Tariffs and export
- Systemic issues: Policy and institutional coherence; Data monitoring and accountability

While international partnerships also present certain risks, as evidenced in category 16, it is imperative to underscore the potential benefits they offer. The formation of robust international partnerships has the potential to enhance the implementation of the other Sustainable Development Goals (SDGs). In a 2022 study, Filho et al. explored the significance of partnerships in achieving the other SDGs and concluded that greater emphasis should be placed on this aspect and that strategic alliances are essential for sustainable development. [101]

This category is not associated with a quantitative indicator utilized in the assessment. This category is analyzed qualitatively to discuss the opportunities and risks of international cooperation in the field of PtX, considering all stages from capacity building to production and international trade.

Summary

In summary, each of the SDGs could be connected to the production of fuels at some stage of the life cycle, with implications for socio-governmental and techno-ecological aspects. The transition to PtX-based fuels may have beneficial or detrimental effects on various sustainable development aspects. It is crucial to address these issues in order to prevent the sacrifice of other sustainable development aspects when reducing the CO_2 emissions of the aviation sector or other sectors that could utilize PtX. It is imperative to avoid what has been termed the "carbon tunnel vision," which is the tendency to consider only greenhouse gas emissions in isolation.

It is not the intention of this work or model to suggest that any of the SDGs will be reached or failed due to fuels alone. The SDGs serve as a framework, yet they are not integrated as actual indicators. The categories assessed are named in accordance with the SDGs, but not all of the indicators evaluated are, in fact, indicators of the SDGs. The nature of the connections is, in some cases, based on subjective relevance, given the limited availability of quantitative indicators. The interrelationships between the indicators and categories are presented in tabular form below:

Table 1: Connections of categories to the indicators

CATEGORY	Indicators
1. **NO POVERTY**	Fair salary (S-LCA)
2. ZERO HUNGER	Terrestrial acidification (LCA)
3. GOOD HEALTH AND WELL-BEING	Human carcinogenic toxicity (LCA), Human non-carcinogenic toxicity (LCA), Health expenditure (S-LCA)
4. QUALITY EDUCATION	Public expenditure on education (S-LCA)
5. GENDER EQUALITY	Gender wage gap (S-LCA)
6. CLEAN WATER AND SANITATION	Water consumption (LCA), Industrial water depletion (S-LCA)
7. AFFORDABLE AND CLEAN ENERGY	Land use (LCA)
8. DECENT WORK AND ECONOMIC GROWTH	Child labour (S-LCA)
9. INDUSTRY, INNOVATION AND INFRASTRUCTURE	Fossil resource scarcity (LCA)
10. REDUCED INEQUALITIES	Indigenous rights (S-LCA)
11. SUSTAINABLE CITIES AND COMMUNITIES	Fine particulate matter (LCA)
12. RESPONSIBLE CONSUMPTION AND PRODUCTION	Mineral resource scarcity (LCA)
13. CLIMATE ACTION	Global Warming Potential (LCA)
14. LIFE BELOW WATER	Marine eutrophication (LCA)
15. LIFE ON LAND	Terrestrial ecotoxicity (LCA)
16. PEACE, JUSTICE AND STRONG INSTITUTIONS	Risk of conflicts (S-LCA), Active involvement of enterprises in corruption and bribery (S-LCA)
17. PARTNERSHIP FOR THE GOALS	Opportunities and challenges of international cooperation (qualitative)

3.2.3 Scope

The scope of the LCA model is defined as "well-to-gate," which signifies its starting point at the resource provision stage for fuel production and plant construction, and concluding point at the gate of the plant/refinery with regard to the produced fuel. The inclusion of catalysts was not feasible due to the limited availability of data and the minimal impact on the results. The geographical scope of the model encompasses all countries included in the PSILCA v3 database. The integration of capacity factors for wind and PV for each country is based on average values for the entire country, without consideration of specific locations that may offer more favorable conditions.

In the case of the S-LCA model, the scope is restricted to the primary feedstock provision and its precursors. This phase of the value chain provides a basis for comparison between fossil, bio, and PtX-based fuels. The data availability for the other parts of the value chains is rather limited, and it would be challenging to achieve comparability between the different types of fuels. The use phase of the fuels is excluded from both social and environmental LCAs on the assumption that the impacts are similar for all assessed alternatives. Moreover, the model does not incorporate the globally or locally required or potentially produced amount of fuels. Nevertheless, the quantity of fuel could be upscaled within the model. The model employs a functional unit of 1 kg of fuel produced.

3.3 Life Cycle Inventory

The life cycle inventory (LCI) of this study is constructed in a manner that allows for the model to be utilized for a generic assessment on a global scale. Consequently, the social risks and potential environmental impacts of fuel production can be evaluated for all locations worldwide. The assessed PtX fuel production facilities do not currently exist in the assessed locations at the specified scale. Consequently, the focus is on potential global developments.

The environmental LCA's foreground system is comprised of the assessed PtX processes (and reference technologies), including the generation, construction, and operation of the plants with 1 kg of fuel as the functional unit. In the context of the LCC and S-LCA, the scope is limited to the electricity generation (or other feedstock provision for the reference technologies).

The time horizon is set at two different points in time. The baseline scenario is set to the year 2022, while the future scenario is set to the year 2050. The future scenario is modelled using a dynamic LCA approach. A single scenario incorporates a range of potential developments, including fluctuations in prices, shifts in electricity mixes, advancements in technology, and changes in recycling rates. This approach employs an iterative methodology. A detailed description of the energy system model employed in this scenario can be found in Section 4.

3.3.1 LCI of the PtX Process

The PtX fuel production process is modeled on the basis of the Fischer-Tropsch synthesis with product upgrading and a high-temperature Solid oxide electrolyzer cell (SOEC) co-electrolysis. The model is based on the values presented in the third Kopernikus P2X roadmap. Synthetic jet fuel is regarded as the end product. The primary process steps that are the focus of the model are the energy source, the carbon source, the water source, the co-electrolysis, the synthesis, and the upgrading. [27]

Carbon Source

CO_2 is a main resource for PtX processes, serving as the carbon component of synthetic hydrocarbons. Although CO is a necessary component for the production of syngas, it is typically not available in this form. Consequently, CO_2 is captured and transformed into a carbon feedstock through a reduction process. Carbon dioxide can be obtained from a variety of sources and through the use of different technologies. Industrial processes such as the production of cement, steel, ammonia, and fossil-based hydrogen or the conditioning of natural gas currently result in a considerable amount of CO_2 emissions. These emissions could be captured and utilized through the Carbon Capture and Utilization (CCU) approach. Moreover, biogenic sources, including biogas plants, bioethanol production, and combined power and heat plants based on biomass, also emit CO_2, which could be utilized for PtX. A third option is direct air capture (DAC), which involves the adsorption of CO_2 from the atmosphere. This approach allows for the utilization of CO_2 without the geographical limitations inherent to industrial or biogenic CO_2 sources. As detailed in the dena e-fuels study, the potential of biomass-derived CO_2 is for example relatively limited in the MENA region. Consequently, renewable CO_2 would have to be extracted from the atmosphere for large-scale PtX production. Given the global scope of the model and the absence of consideration for existing biogenic or fossil CO_2 sources, DAC is chosen as the carbon source. The model incorporates the construction and operation of the DAC facility. The data regarding construction and sorbent materials are derived from Deutz and Bardow (2021). The energy demand associated with the operation of the DAC is incorporated into the overall energy demand of the process. [36], [102]–[104]

Water Source

The electrolysis of the PtX process necessitates the input of water, which is split into H_2 and O_2 by the process. Within the model, the provision of water is implemented in a generic manner via the ecoinvent process market for deionized water. It should be noted that the technical model does not include specific processes and transportation, particularly in the context of landlocked countries. Nevertheless, the issue of water scarcity is acknowledged and evaluated within the S-LCA. The indicator of industrial water depletion is employed to assess the water stress within the country and the impact of the industrial energy sector on this stress.

Co-Electrolysis

The co-electrolysis is a process that combines two steps of the PtX method into one. In contrast to the conventional process of water electrolysis, which splits water into O_2 and H_2, the co-electrolysis simultaneously reduces CO_2 to CO, thereby converting water and CO_2 directly into syngas. The technology is currently at a relatively low technology readiness level (TRL), but it has the potential to achieve greater energy efficiency than other alternatives. The construction of the electrolyser is modelled using data from Schreiber et al. (2020). The utilization rate of the electrolysis is equivalent to the utilization rate of the electricity-generating technology associated with each constellation. The model does not consider storage technologies for hydrogen or syngas. [105]

Fischer-Tropsch Synthesis and Upgrading

The Fischer-Tropsch (FT) synthesis is a process through which syngas is converted into a range of gaseous, liquid, and solid hydrocarbons through a catalyzed reaction. In the initial phase, the CO is dissociated on the catalyst surface, either directly or with the assistance of H_2. In conjunction with supplementary hydrogen, the dissociated carbon atoms form intermediate hydrocarbons (C_xH_y) as monomers for polymerization. The presence of hydrogen also results in the formation of water. Subsequently, the C_xH_y monomers are coupled to a wide variety of products, as delineated by the Anderson-Schulz-Flory distribution model. The probability of chain growth, α, determines the product fractions that are formed. As α increases, the length of the C-chains of the products also increases. It is typical to desire a high fraction of middle distillate fuels (e.g., diesel and kerosene) in the final product. The value of α is dependent upon the temperature and the ratio of the syngas feed. The feed from the

FT reactor is subjected to further processing through upgrading, namely hydrocracking and hydrotreatment, in order to produce the desired synthetic fuel, in this case jet fuel. [106]–[109]

The construction of the plants is modeled with the ecoinvent chemical factory, organics, dataset. The dataset represents the typical material composition of a chemical factory for organic chemicals. The same dataset is employed for the purposes of modelling bio-based fuel production processes. In comparing the material composition of different synthesis processes, it is evident that modular, decentralized plants exhibit notable differences from monolithic, centralized ones. The ecoinvent dataset is more accurately described as a monolithic, centralized plant, which is the status quo within the fossil-based industry. Nevertheless, the integration of renewable energy sources may necessitate the adoption of more flexible strategies. Although this is a significant factor, it is not further examined in this study due to limitations in the available data.

3.3.2 Life Cycle Inventory of the Renewable Energy Source

While the deployment of bioenergy, hydropower, and geothermal power plants is typically constrained by the location and local capacities, solar and wind energy, in particular, have the potential to be deployed anywhere and contribute to the growth of a renewable energy system, as described by Fasihi and Breyer (2020). Consequently, PV and wind power are selected as prospective renewable energy sources for PtX, as they can be utilized in any location and do not necessitate additional feedstocks or capacities, unlike biomass, for instance. It should be noted, however, that other sources may also be relevant. They are not assessed here due to the presence of additional constraints and the heightened complexity involved in their implementation within the model. [110]

Photovoltaic Power Plants

The PV power plants in this model are based on the ecoinvent-process electricity production, photovoltaic, 570kWp open ground installation, multi-Si. This is currently the only available open ground installation of a PV plant in the ecoinvent database. The required capacity of the PV plant is linearly scaled to the energy demand of the PtX plant.

The modification of the ecoinvent dataset was conducted in line with the initially available datasets of different locations:

1. The annual yield per kWp [kWh/kWp] of the assessed regions worldwide was derived from the online tool renewables.ninja, which is based on the publications of Pfenninger and Staffel (2016) and Staffel and Pfenninger (2016). The input values for the online tool are based on a generic PV plant without tracking, as no further information is provided within the assessed ecoinvent process. [111], [112]
2. With an assumed plant lifetime of 30 years, a capacity of 570 kWp, and 8% losses, the electricity production over the plant lifetime was calculated.
3. The inverse of this value equals the utilized plant per kWh output.
4. The cleaning water-related inputs and outputs were adjusted accordingly.

Wind Power Plants

Due to the assessment of every country, of which several ones are landlocked, offshore wind power plants are excluded from the model. The model of onshore wind power plants is based on the ecoinvent-process *electricity production, wind, >3MW turbine, onshore.* The yield and resulting utilization per kWh of the onshore wind power plants were integrated in a slightly different way than with the PV plants:

1. Similarly to the approach taken with the PV plants, the capacity factor of wind power plants was obtained from the online tool renewables.ninja. The input values are based on the Enercon E-112 turbine, which serves as the reference technology for the ecoinvent-process.
2. The capacity factor was multiplied by 8760 hours per year, the capacity of the wind power plant, and the assumed lifetime of 20 years to obtain the electricity production over the lifetime.
3. The inverse of this value was used to calculate the utilized plant per kWh output.
4. The lubricating oil-related inputs and outputs were adjusted accordingly.

3.3.3 Levelized Cost of Electricity as Feedstock Costs for the Power-to-X Process

Although it was previously addressed in the initial German LCA by Oberbacher et al. (1996) [64], the economic assessment is not a fundamental component of the LCA methodology. Similarly, the economic aspects are regarded as a connecting parameter between the technical and social aspects in this model. This work is primarily concerned with the social and ecological implications of fuel production, rather than with the economic aspects, which are typically already considered in many assessments. This approach was inspired by Giegrich et al. (2003), who divided sustainable development into two spheres: The human society, with its fundamental requirements, and the environment, with its capacity to accommodate impacts, are the two core elements. The economic aspect is regarded as a connecting element in this framework, a perspective that is also reflected in this dissertation. [113]

The levelized cost of electricity (LCOE) is calculated and employed as an input factor in the S-LCA, given that it is based on monetary values. It should be noted, however, that the study does not assess the full costs of fuel production at any given location.

The LCOE was calculated for two distinct electricity-generating technologies utilized for PtX: PV and wind, onshore. In this generic LCC model for electricity generation, both the capital expenditure (CAPEX) and the operational expenditure (OPEX) are considered in conjunction with the weighted average cost of capital (WACC). The default values for CAPEX and OPEX are assumed to be equal for every location, which does not reflect the reality of the situation but is not feasible to provide more detailed information for every assessed region within the scope of this work. The modeled LCOE is contingent upon the available FLH, which were integrated in accordance with the methodology delineated in section 3.3.2. Although the data do not reflect the actual prices due to the absence of labor costs and other specific parameters, the derived LCOE data can be used as a proxy for the technical potential of renewable energy provision and as an input variable for the S-LCA.

The values for both technologies were derived from a number of published sources. The objective of this model is not to calculate the actual prices or to forecast prices for the year 2050. The objective is to provide values for each assessed region that reflect the influence of the respective amount of FLH. [114]–[117]

Photovoltaic Power Plant

The LCOE of the modeled generic PV power plant is based on several key factors, including the CAPEX, OPEX, location-specific yield, WACC, degradation, and the lifetime of the plant. The following values have been integrated into the model for the 2022 and 2050 scenarios:

Table 2: Cost parameters for the PV power plant model

		2022	**2050**
CAPEX	€ / kWp	431	164
OPEX	€ / kWp / a	8.8	4.2
WACC$_{\text{NOMINAL}}$	%	5.7	5.7
WACC$_{\text{REAL}}$	%	2.5	2.5
DEGRADATION	% / a	0.25	0.25
LIFETIME	a	30	30

Wind Power Plant, onshore

The LCOE of the modeled generic wind onshore power plant is similarly based on CAPEX, OPEX, location-specific yield, WACC and lifetime of the plant. Degradation is not considered here. The following values are integrated into the model for 2020 and the 2050 scenario:

Table 3: Cost parameters for the wind power plant model

		2022	**2050**
CAPEX	€ / kWp	1700	825
OPEX	€ / kWp / a	39	6.5
WACC$_{\text{NOMINAL}}$	%	6.2	6.2
WACC$_{\text{REAL}}$	%	4.1	4.1
LIFETIME	a	20	20

Social Life Cycle Inventory of the Power-to-X Process

The data availability of social risks along the value chain is severely limited, and thus, the assessment is not conducted separately for different types of electricity-generating technologies, with the exception of Great Britain. It is reasonable to argue that the social risks associated with a coal power plant and a PV power plant may vary in practice. Among other factors this is due to the fact that differing materials from different regions in the world are required for construction, the varying job skills needed at various life cycle stages and the disparate working conditions associated with operating the different plant types. Nevertheless, all technologies are considered within each sector, and thus the actual contributions of PV and wind power plants remain part of the data sets, aggregated with the other technologies. The calculated monetary value for each location is then used to model the connection to the social risks associated with the life cycle of the technology.

3.3.4 Life Cycle Inventory and Social Life Cycle Inventory of the Reference Technologies

The benchmark technologies are integrated into harmonized models for the LCA and S-LCA. As the results of the S-LCA are largely contingent upon the location and the industries involved throughout the life cycle, the LCA outcomes are primarily influenced by the fuel production process and the associated feedstock and material provision. For a unified assessment of social risks and potential environmental impacts, it is essential to align both locations and processes. The bio-based fuel production processes that are the subject of this modelling exercise are intended to represent a prospective scenario. Rather than representing detailed expectations or plans for biofuel production, the modelling is intended to contribute to a range of alternative social risks and potential environmental impacts in relation to fossil kerosene. The ten countries with the highest biofuel production in the world in 2020 were selected based on the statistical review of world energy 2021 by BP [118]: United States, Brazil, Indonesia, Germany, China, Thailand, France, Netherlands, Spain and Argentina. The corresponding feedstocks and fuel production processes were selected based on a synthesis of diverse sources, including other models, estimates, national strategies, and the availability of feedstocks pertinent to the production of biofuels. It should be noted that these scenarios do not reflect the actual bio-kerosene production in any of the selected countries. Rather, they are intended to illustrate different technological and geographical configurations with various feedstocks. It is possible that some of the selected pathways may already be obsolete or have been superseded. Nevertheless, they can serve as a point of reference. The selected processes from both databases (S-LCA and LCA) are not entirely consistent due to the reliance on available datasets. The datasets were selected based on their potential connections and the availability of the data, as outlined in Table 4.

Table 4: Biogenic fuel production constellations

COUNTRY	TECHNOLOGY	FEEDSTOCK	S-LCA SECTOR	LCA FEEDSTOCK	REFERENCES
ARGENTINA	HEFA	Soy oil	Oils and animal fats and vegetable	soybean meal and crude oil production | soybean oil, crude | Cutoff, U | RoW	[119]
BRAZIL	ATJ	Sugarcane	Agriculture and forestry	market for sugarcane | sugarcane | Cutoff. U | BR (w/o transport)	[120] - [121]
CHINA	HEFA	Palm oil	Vegetable oil and forage	Palm oil	[122]
FRANCE	GFT	Agricultural residues	Products of agriculture, hunting and related services	wheat production | straw, organic | Cutoff, U | CH	[123]
GERMANY	GFT	Agricultural residues	Agriculture and hunting	wheat production | straw, organic | Cutoff, U | CH	[123]
INDONESIA	HEFA	Palm oil	Food crops	palm oil mill operation | palm oil, crude | Cutoff, U | RoW	[124]
NETHERLANDS	GFT	Agricultural residues	Products of agriculture, hunting and related services	wheat production | straw, organic | Cutoff, U | CH	[123]
SPAIN	GFT	Agricultural residues	Agricultural and livestock services	wheat production | straw, organic | Cutoff, U | CH	[123]

THAI-LAND	HEFA	Palm oil	Oil Palm	palm oil mill operation | palm oil, crude | Cutoff, U | RoW	[125]
UNITED STATES	GFT	Rape seed	Oilseed farming	Rape seed production | rape seed | Cut-off, U | US	[126]

In order to connect the feedstocks to the social risks from the database, that arise through the provision of the feedstocks, a monetary value is assigned. The costs associated with the feedstocks are derived from the International Council on Clean Transportation (ICCT) working paper on the financial implications of supporting alternative jet fuels in the EU. [127]

The fossil benchmark is modeled using the ecoinvent dataset for kerosene production and a petroleum refinery operation in the “Rest of World”. This is, in fact, a replication of the dataset for Europe, excluding Switzerland, and is regarded as a proxy for the global average. For further details, please refer to the ecoinvent documentation. A production volume-weighted average incorporating the regional activities accessible in ecoinvent v3.6 (BR, CH, CO, Europe without Switzerland, IN, PE, ZA) would result in an overestimation of the proportion of refinery complexity type IV within the global petroleum refinery sector. Accordingly, the blend of refinery complexity types utilized for the European activity was determined to be a better proxy for this global dataset. The costs associated with social risks were derived from the Energy Information Administration (EIA) energy outlook. Given the considerable volatility in the prices of fossil fuels, they are included in the sensitivity analysis. [128], [129]

3.4 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) method ReCiPe 2016 (hierarchist) was chosen for the impact categories and characterization factors of potential environmental impacts within this work. The social LCIA is conducted with the social impacts weighing method of the PSILCA database. Both assessment methods are used for the 2022 and the 2050 scenario.

Firstly, all considered PtX constellations that are unable to achieve the requisite CO_2 emission reduction of 70% are excluded. Secondly, all constellations that are linked to incomplete datasets from the PSILCA database are excluded from the assessment of those impact categories for which the datasets are incomplete. The remaining constellations are then compared to the fossil- and bio-based benchmarks and counted. In the event that either the fossil- or bio-based benchmark can be reached by a constellation, it is assumed that this constellation can contribute to positive sustainable development within the given impact category, given that the potential environmental impact or social risk is lower. The number of constellations that can contribute to positive sustainable development is then compared to the number of constellations that cannot. This ratio indicates whether the risks or opportunities are more prevalent within the assessed impact category.

3.5 Interpretation

The interpretation step in this work is conducted with a further analysis of the technical reasons for and potential measures to address the critical risks. It has to be emphasized that even if the majority of PtX constellations can reach one benchmark, it does not necessarily mean that there is no risk involved. It simply means that the risk is not higher than with either the current status quo of fossil-based fuel production or the currently discussed alternatives of bio-based fuels according to the model.

The potential risks and opportunities inherent to each category are explored through the lens of two distinct scenarios. The 2050 scenario accounts for potential developments in costs and the global energy system. As a consequence of a greater proportion of PtX constellations achieving the CO_2 benchmark, the number of constellations subjected to assessment is correspondingly increased. The PtX technologies are currently more expensive than their alternatives, resulting in a higher number of worker hours and an inherent increase in risk per kilogram of fuel due to the elevated labor requirements. Those countries that have already reached the socio-governmental benchmarks in the current scenario are typically countries with a higher technical potential and a relatively low risk within the assessed category. From a social perspective, the 2050 scenario demonstrates whether the risk would remain elevated among the assessed constellations, even when the number of worker hours is more comparable and the range of involved countries is broader. This includes countries with comparatively lower technical potential. From a techno-ecological perspective, the 2050 scenario provides an opportunity to assess the potential situation in which the different technologies are further developed and the global electricity mix is predominantly based on renewable sources. These factors result in a shift in the potential environmental impacts associated with the upstream phase of production. This results in a different ecological footprint for each process phase, thereby modifying the overall impact throughout the life cycle.

4. Energy System Model

This section and the described model were developed in collaboration with Mr. Dominik Poncette and Mr. Philipp Rentschler. The author of this dissertation mainly worked on the scenario integration, wind power and recycling aspects.

This section presents a global energy system model that serves as the background system for the 2050 scenario. This section outlines the development and LCA outcomes of the global energy system model.

The development of energy provision over the coming decades is of paramount importance for the achievement of the goals set out in the Paris Agreement. As indicated by the International Renewable Energy Agency (IRENA, 2018), the growth of renewable energy sources would need to occur at a rate six times faster than that observed thus far to meet the aforementioned targets. Moreover, the expansion must occur across all sectors. The transport sector is of significant importance, particularly in light of the growing electrification of transportation systems and the prospective deployment of electricity from renewable sources (RES) to generate fuels through PtX technology. The increasing share of renewables has implications for not only ecological perspectives but also economic and social ones. For instance, the number of jobs in the energy sector could increase from approximately 40 million to a range of 64.8 to 76.5 million by 2050. While the number of jobs in the fossil fuel sector would decline, new employment opportunities would emerge in the renewable energy sector, as well as in energy efficiency and grid enhancement. Furthermore, the reduction in health impacts from air pollution and global investments that could lead to improved education worldwide may also have positive societal implications. [130]

As the assessed PtX plants are all connected with their own additional electricity source, the purpose of the integrated dynamic global energy system is twofold: firstly, to account for the utilization of electricity by the reference technologies of bio-based or fossil fuel production processes; secondly, to account for the change of the entire background system. This is significant because it affects the potential environmental impacts of all precursors throughout the product life cycle, including the production of the plants and equipment. It is common practice to integrate an energy scenario only for the foreground system, thereby neglecting the impact of the energy scenario on all precursors. Accordingly, a new power plant and its intermediary components in 2050 in the model would still be produced with the original electricity mix from the database, rather than with the adjusted, integrated electricity mix of 2050. In particular, when the electricity mix is undergoing a transition towards an increase in renewable energy sources, the iterative incorporation of the new mix can have a significant impact on the resulting outcomes.

4.1 Scenario Integration

The dynamic global energy system model is based on two distinct models, each with disparate assumptions. This results in markedly disparate shares of RES until 2050 across both scenarios. The proportions of each energy source in the global electricity production mix were incorporated into the model. The values pertaining to carbon capture and use/storage (CCUS) were excluded from consideration due to limitations in the available data. The resulting model has a temporal scope from 2020 until 2050, which aligns with the temporal scope of the overall work.

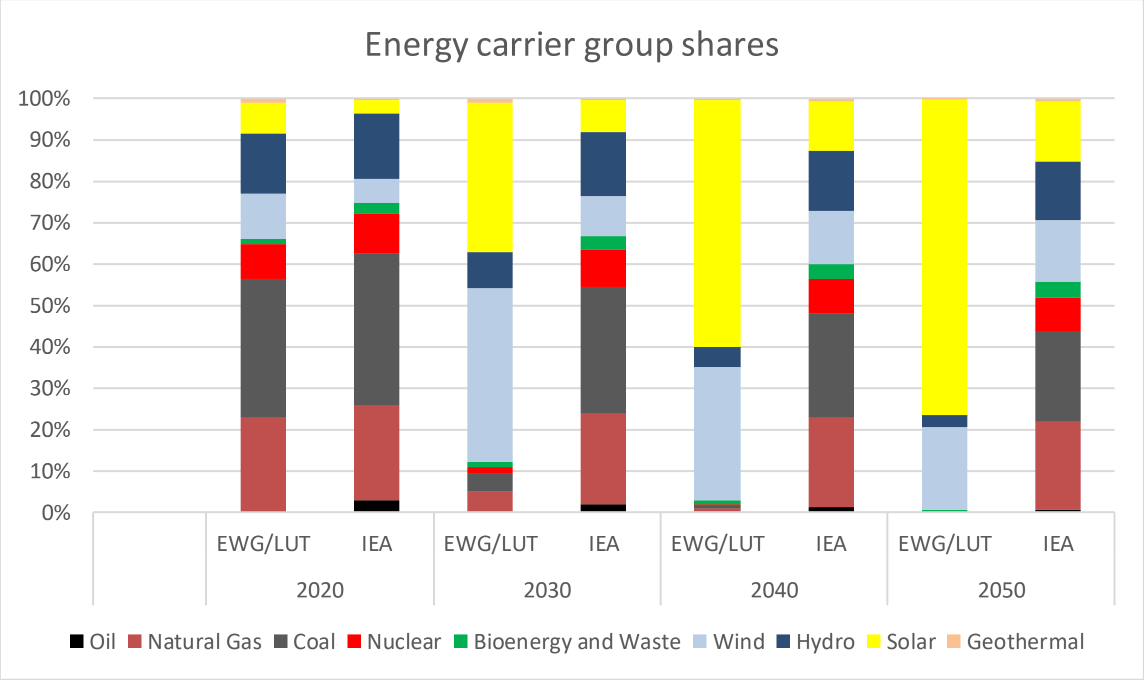

Figure 5: Energy carrier / technology shares integrated into the model for each scenario and year

4.1.1 Business-as-usual Scenario

The World Energy Outlook 2019 from the International Energy Agency (IEA) presents two scenarios for the projected development until 2040. The business-as-usual (BAU) scenario was selected as the reference scenario. The annual generation figures for each energy carrier are presented in Table 5. The scenario represents the development of global energy policy in the absence of any changes to the status quo, with an overall growth in energy demand of 1.4% per year. [131]

Table 5: Adopted global annual production [TWh/a] per energy carrier from IEA (2019)

	2018	2025	2030	2035	2040
COAL	10123	10291	10408	10444	10431
NATURAL GAS	6118	6984	7529	8165	8899
NUCLEAR	2718	2801	3073	3282	3475
OIL	808	724	622	556	490
GEOTHERMAL	90	125	182	248	316
HYDRO	4203	4759	5255	5685	6098
BIOENERGY AND WASTE	636	916	1085	1266	1459
WIND	1266	2413	3327	4330	5275
SOLAR	604	1758	2619	3675	4901

4.1.2 100 % Renewable Scenario

The Lappeenranta University of Technology and the Energy Watch Group (EWG/LUT) published a report entitled Global Energy System Based on 100% Renewable Energy: Power, Heat, Transport, and Desalination Sectors. This report presents a global energy system model that serves as the foundation for the second scenario presented here. Table 6 presents a summary of the annual generation for each energy carrier. The scenario was selected for this study as a 100%-RES scenario in 2050. The objective is to achieve the Paris Agreement goals, and the model was constructed using a linear optimization approach that minimizes the total annual cost while ensuring consistent electricity demand coverage across all subregions worldwide throughout the transition to a 100% renewable energy system. [132]

Table 6: Adopted global annual production [TWh/a] per energy carrier from Ram et al. (2019) [132]

	2020	2030	2040	2050
COAL	9024	2023	445	0
NATURAL GAS	6093	2300	908	43
NUCLEAR	2218	719	365	126
OIL	41	2	0	0
GEOTHERMAL	319	503	465	381
HYDRO	3894	4103	4121	4192
BIOENERGY AND WASTE	352	629	658	580
WIND	2951	19479	27275	27307
SOLAR	1947	16778	50465	104648

4.2 Technological development

It can be reasonably assumed that, between the years 2020 and 2050, not only will the composition of the electricity mix evolve, but also the technological development of electricity-producing technologies and developments at the system level. These developments are modeled with efficiency gains and recycling rates, which both contribute to a change in the potential environmental impact per unit of electricity produced. These assumptions are subject to a considerable degree of uncertainty and are not reflected in the individual PV and wind power plants of the PtX plants in the foreground system.

4.2.1 Wind Power Plant

The wind group is divided into two categories: offshore and onshore wind power generation. The technological advancement of both technologies is incorporated into the model through an adjusted utilization of the wind power plant per unit of energy. The value is calculated using the following formula:

$$\frac{\left(\frac{Cn}{Co}\right)^{0.6}}{1000 * WLH * Cn * LT}$$

WLH: Wind load hours [hr/a]; Cn: New capacity [MW]; Co: Old capacity [MW], LT: Lifetime [a]

The wind load hours are calculated with the capacity factor and the number of hours per year. The implemented capacity factors of offshore and onshore wind power plants are derived from the averaged projections from the remap case of IRENA (2019) [114]. It is assumed that the lifetime of the wind power plants will be 20 years. The mean capacity of offshore wind power plants is calculated using the total projected capacity of offshore wind power and the projected number of turbines, as outlined by IRENA (2016) [133]. The mean capacity of onshore wind power plants is extrapolated using the global mean weight ratings from IRENA (2019) [114]. The existing ecoinvent datasets for the construction of wind power plants with a capacity of 4.5 MW (onshore) and 2 MW (offshore) are utilized as the reference value for the old capacity (Co). The capacity increase and its implied additional requirements are calculated with a scaling factor of 0.6.

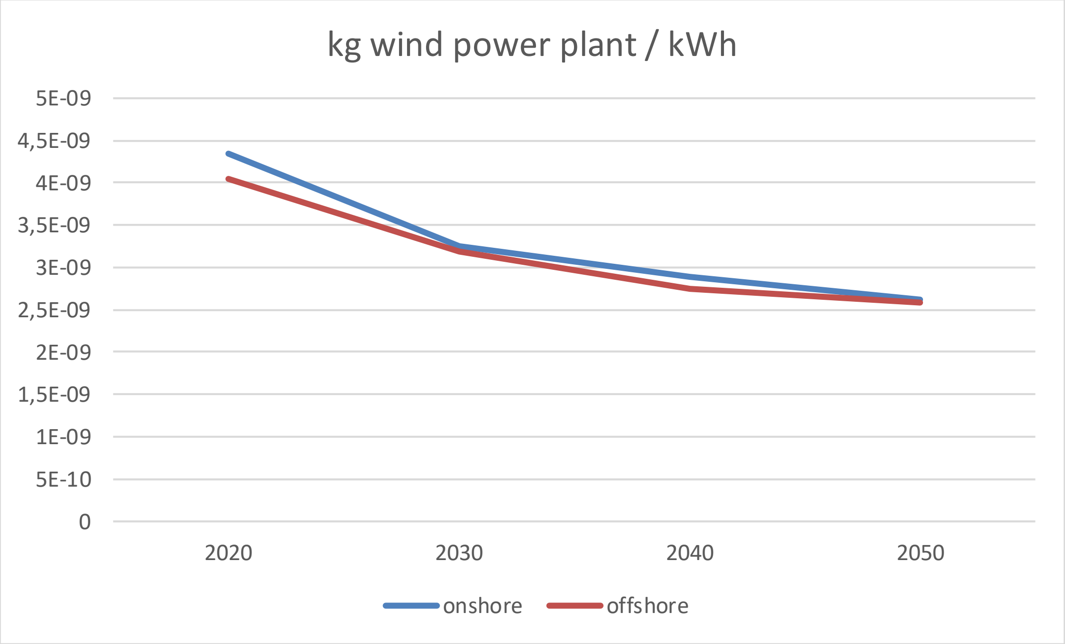

Figure 6: Modelled wind power plant utilization per kWh

Figure 6 depicts the modeled utilization of wind power plants per kWh. As illustrated, the wear and tear of these plants per kWh of electricity produced exhibits a notable decline, from approximately 4E-09 and 4.5E-09 to nearly 2.5E-09. This decline is indicative of a corresponding decrease in the potential environmental impact. This is a simplified assumption, as other factors also influence the lifetime and production of electricity over the lifetime. Nevertheless, this supposition is consistent with the overarching methodology employed in LCA.

4.2.2 Photovoltaic Power Plant

The solar energy sector is divided into two main categories: PV and concentrated solar power (CSP).

The modelling of PV in this study is based on ecoinvent data sets that have been modified. The assessed PV data sets represent a range of technologies and construction types with varying characteristics. The following technologies are considered in this study:

1. Polycrystalline silicon, consisting of small crystals.

2. Monocrystalline silicon, a continuous crystal.

3. Amorphous silicon, which is the non-crystalline form of silicon.

4. Copper indium diselenide technology, which uses copper, indium and selenium instead of conventional silicon.

5. Thin-film PV modules with cadmium telluride.

6. PV modules with silicon ribbon technology.

The only plant with a higher capacity is based on the ecoinvent dataset "electricity production, photovoltaic, 570 kWp open ground installation, multi-Si." Nevertheless, it is assumed that all technologies can be scaled. All technologies that utilize silicon are included, with construction methods categorized as either "integrated" or "panel mounted". Given the limited availability of data, copper indium diselenide panels are only assessed as mounted, and cadmium telluride modules are only assessed as integrated construction.

The modification encompasses both the supply chains and the yields. In order to maintain a global perspective, all supply chains associated with the PV processes have been adjusted to reflect global averages. Furthermore, a global average yield was implemented, which is based on a global average radiation value. It is assumed that the average yield will increase by 18% of the original value in each subsequent decade, in order to reflect the anticipated improvements in the efficiency of future modules. Given the considerable uncertainty surrounding future developments, it is assumed that improvements in efficiency will be uniform across all technologies. It is assumed that the plant lifetime will increase in a linear fashion from 28.5 years in 2020 to 35 years in 2050, with similar increases as those proposed by Pehnt (2006). [134]

4.2.3 Recycling

In light of the prospective evolution of diverse electricity-generating technologies and their prospective environmental consequences, the resources utilized in the construction of these facilities are subjected to additional analysis alongside technological advancement. This approach was also integrated into Pehnt (2006). Given the material content of electricity-producing technologies and the potential for recycling, aluminum and steel are evaluated with increasing recycling ratios. [134]

The production of aluminum is modeled with three distinct input types. The primary aluminum ingot represents the non-recycled share. The term "new scrap" refers to the salvage material generated during the production of aluminum, which is then reintegrated into the production chain. The post-consumer scrap is defined as the portion of a product that is collected for recycling after it has been discarded by the consumer.

The corresponding datasets of the ecoinvent database were modified. The ratio of origins (Europe/Rest of the World) is maintained at a constant value, while the share of the primary and the two recycling pathways is modelled in accordance with the statistics reported by World Aluminium (2017). The proportions for the year 2050 are extrapolated in accordance with the preceding trends. [135]

Steel production is modeled with two distinct input types. The electric arc process represents the stage at which the majority of recycled steel is employed as an input material. The converter process represents the conventional method, which employs primary steel. Once more, the ratio of origins (Europe, Canada-Quebec, Rest of world) is held constant, while the shares of the two production types are modelled according to the reference-demand case of Oda et al. (2013). The recycling ratios are displayed in Figure 7. [136]

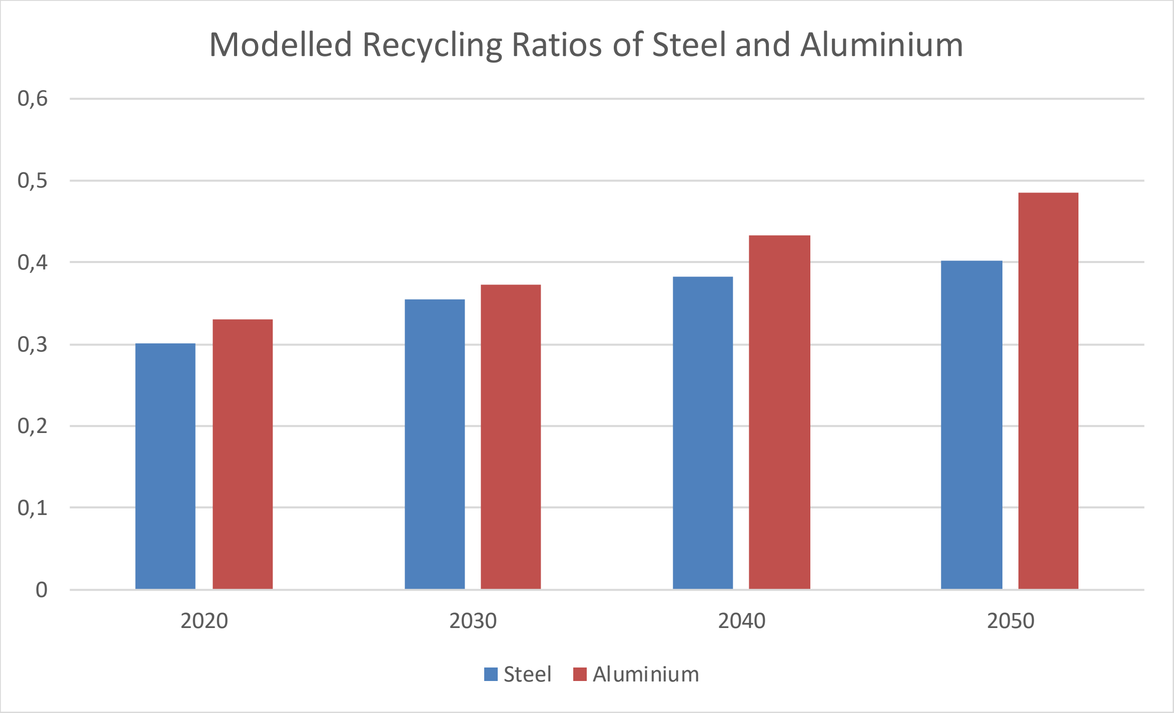

Figure 7: Modelled recycling ratios

4.3 Results

The GWP per kWh was calculated with ReCiPe 2016 (H) for the years 2020, 2030, 2040, and 2050 with three voltage levels within each year and scenario. In the case of all other impact categories, only the years 2020 and 2050 were assessed, with the use of low-voltage electricity.

While the results of the business-as-usual scenario demonstrate a minimal reduction in CO_2 equivalent emissions over a 30-year period, the optimistic scenario exhibits values of approximately 0.02 kg CO_2 eq/kWh, as illustrated in Figure 8. This represents approximately 5% of the potential environmental impact of the BAU 2050 scenario. The greatest reduction occurs between the years 2020 and 2030 in the EWG/LUT scenario.

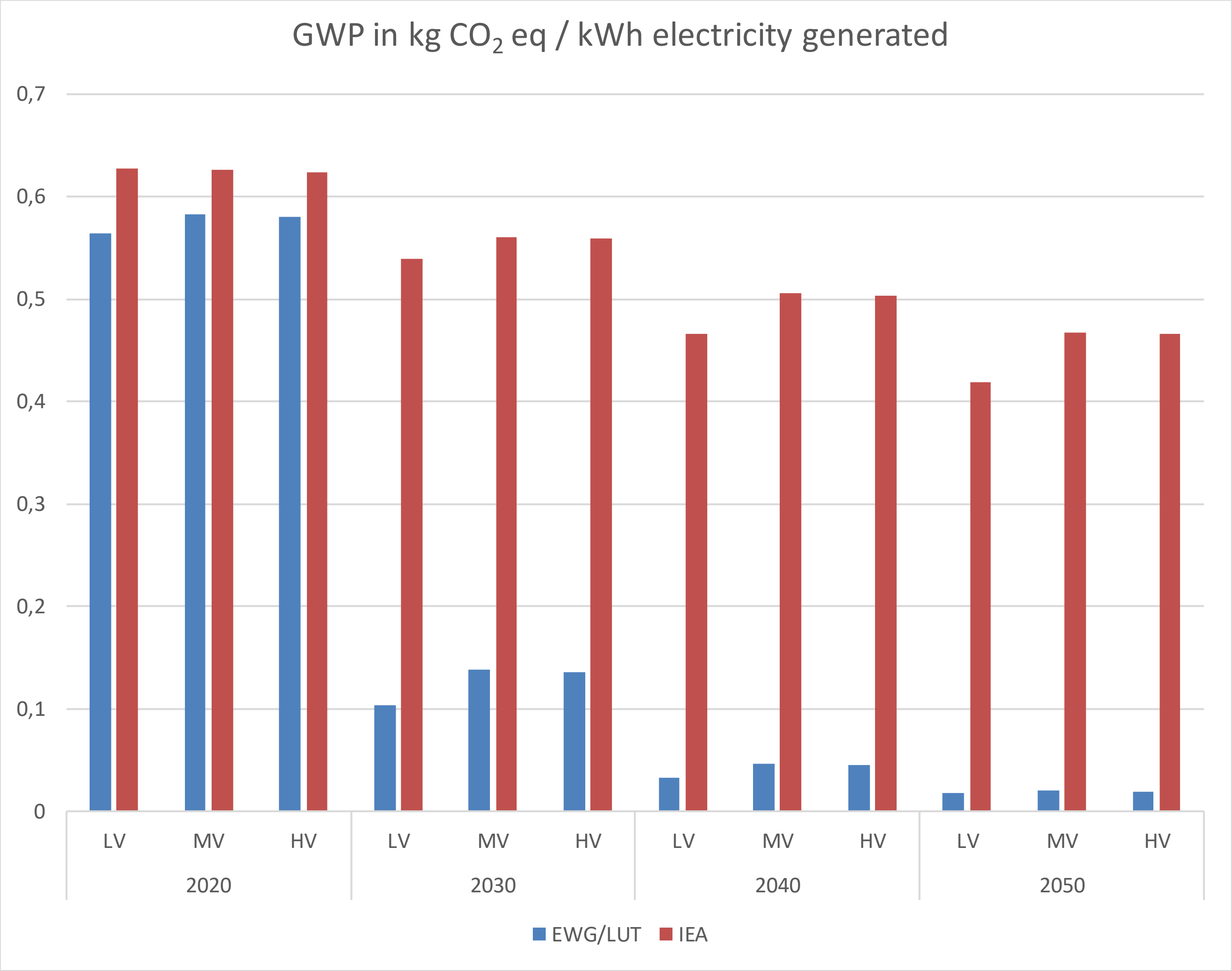

Figure 8: Results of the global energy model: GWP

Figure 9 presents a comparison of the potential environmental impact developments from 2020 to 2050. While the potential impact on terrestrial ecotoxicity and mineral resource scarcity increases from 2020 to 2050, the potential environmental impacts within all other assessed impact categories decrease.

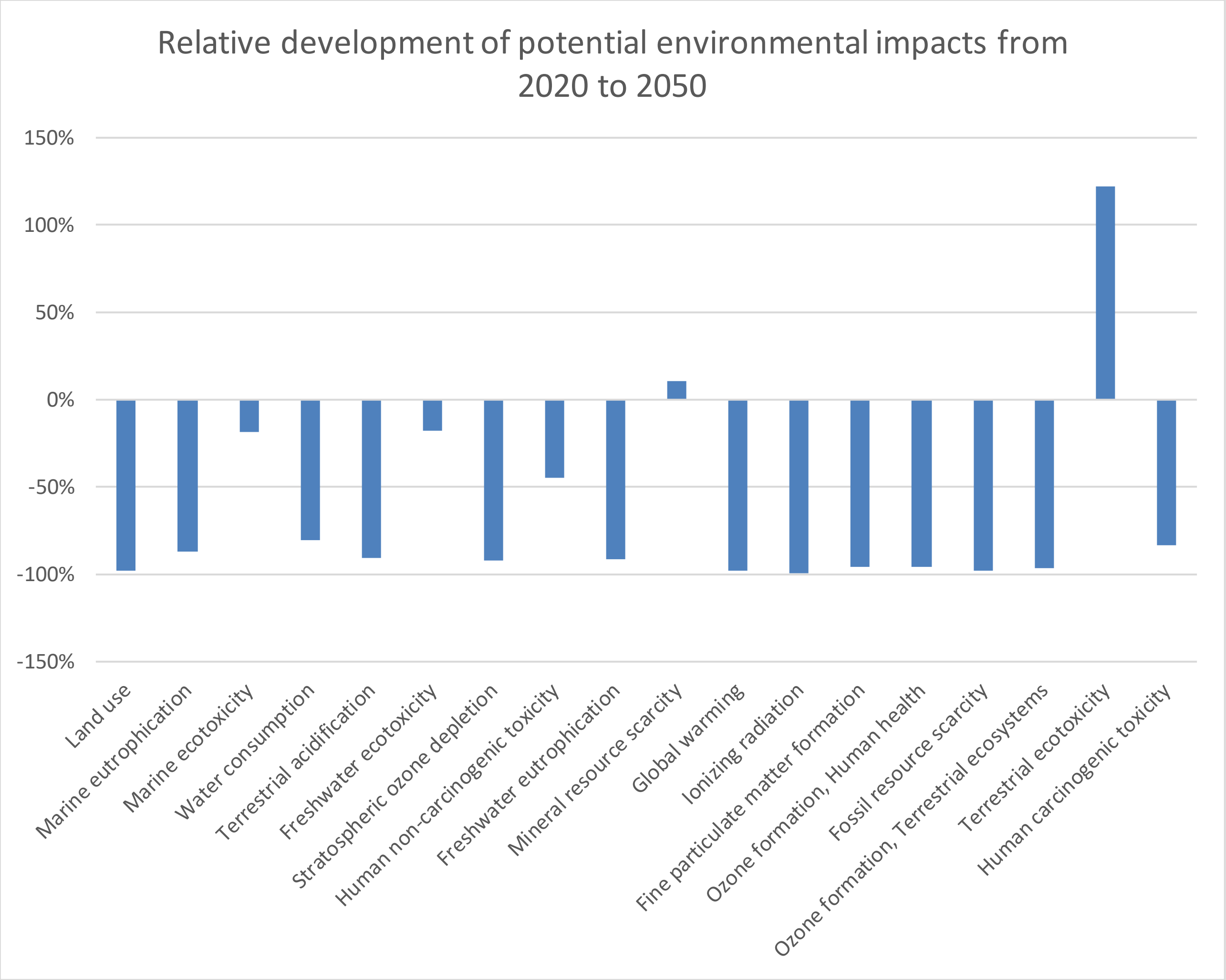

Figure 9: Results analysis of electricity provision within all impact categories

The results demonstrate that it is theoretically feasible to achieve a significant reduction in GWP and a positive trajectory in the majority of other impact categories through an expansion of renewable electricity generation technologies in the coming decades. However, they also illustrate a considerable discrepancy between the BAU and the optimistic scenario. The discrepancy indicates that the expansion of renewable energy capacities on a global scale must be significantly accelerated in the coming years and decades. Another significant feature of this model is its capacity to incorporate the iterative effects of a changing energy system model throughout its entire life cycle within all available impact categories. As illustrated in Figure 11, the majority of impacts are positive, with two negative developments evident across the entire life cycle. In the primary model of this dissertation, only the optimistic scenario is integrated as the background system for the 2050 scenario. The BAU scenario for 2050 is not included in this analysis, as it is largely similar to the 2020 scenario and would yield comparable results with only minor differences in potential environmental impacts.

5. Opportunities and Challenges with the Transition towards Power-to-X-based fuels in the Aviation Sector

The primary model of this dissertation presents country-specific potential environmental impacts and social risks associated with the production of PtX-based fuel across a range of impact categories. The quantitative results for each location are then compared to the fossil- and bio-based benchmark values and evaluated in accordance with the previously described method.

The results of each category are presented and discussed in this section. In the initial phase of this section, the results are presented and analyzed using two distinct types of diagrams. The initial diagram of each indicator is intended to facilitate comparison between the quantitative results of PtX-based fuels and those of fossil- and bio-based fuels. The second diagram of each indicator illustrates the ratio of constellations that achieve at least one of the benchmarks. In the event that such information is available, the primary contributors, potential measures, and activities are described and discussed within each category. In the case of the socio-governmental indicators, the main contributors are not discussed in detail, given the considerable variation observed between countries.

The second part of this section presents a summary of the results, along with an analysis of the main opportunities and risks, and their connection to the contributions within the assessed categories.

5.1 Impact Assessment

The following 17 sub-sections provide an overview of the assessed quantitative and qualitative opportunities and risks associated with a transition to PtX in comparison to fossil- and bio-based fuels. The categories are structured in a manner that is aligned with the SDGs, with the objective of establishing a connection between the identified opportunities and risks and the overarching sustainability concerns. It is not anticipated that any of the SDGs will be achieved through a transition to PtX-based fuels alone. The term "category" is employed in lieu of the actual SDGs, as they are not entirely based on the same indicators.

For each selected indicator, the median and mean values of the PtX configurations are compared to the median and mean values of bio-based fuel production and the median and weighted mean values of fossil-based fuel production for the 2022 scenario and the 2050 scenario. Given that fossil-based fuels are produced on a global scale, the weighted average was calculated on the basis of international supply chains. The bio- and PtX-based fuel production pathways are based on theoretical potentials and thus were not integrated with a weighing factor. The proportion of PtX constellations that achieve at least one of the benchmarks, either the bio-based or the fossil-based benchmark, is included as a result for each assessed indicator for the 2022 scenario and the 2050 scenario. A lower risk or impact than that of one of the benchmarks is regarded as a positive development. It is evident that fossil-based fuels must be replaced on a global scale. Should the social risks or potential environmental impacts of PtX-based fuel production prove to be lower than those associated with fossil-based fuels, this would represent a positive development, offering an opportunity for this transition. If the social risks or potential environmental impacts of the PtX-based fuel production are higher than with fossil-based fuels but lower than with bio-based fuels, this still represents a more sustainable alternative in the context of decarbonization/defossilization. Nevertheless, if the social risk or potential environmental impact is higher than that of fossil-based fuels, this could prove to be a significant challenge during the transition period, even if it is lower than that of bio-based fuels. In the event that neither of the two benchmarks can be reached, the category is regarded as especially critical and requires further detailed examination. Should additional qualitative opportunities or risks emerge within the categories, they are discussed in conjunction with the quantitative results. In the current scenario, 79% of constellations achieve the CO_2 reduction benchmark of 70%. Consequently, 79% of the constellations with the highest technical potential are considered within the categories of the 2022 scenario. In the 2050 scenario, a greater number of constellations are considered, including those with a lower technical potential, which are assessed within the other categories.

This work does not evaluate countries on a single-country level for two reasons: Firstly, it should be noted that social risks are connected to a high level of uncertainty. From a global perspective, the figures remain significant and provide valuable insights. Nevertheless, in order to quantify the specific social risk of a product in a given country, a more detailed assessment would be required, incorporating a greater quantity of primary data drawn from the supply chain and the product's life cycle. Secondly, the entire life cycle is evaluated using the methodologies of S-LCA and LCA. This indicates that a high risk does not necessarily originate from the circumstances within the assessed country, but rather from other stages along the life cycle. It is not the intention of this work to disadvantage any country on the basis of the elevated risk profile reflected in the results. It would be more prudent to address and tackle these risks on a global level, which would facilitate a sustainable transition on a worldwide scale. The country-specific results may be utilized internally to address specific issues by implementing measures that are tailored to the particular circumstances, which could help to mitigate those risks.

Category 1: No Poverty

As illustrated in Figure 10, the assessed pathways exhibit a median risk of unfair salaries within a range of 4.3 to 5.0. Additionally, the mean value of PtX is observed to be higher than that of both the fossil- and the bio-based benchmarks. It can be observed that there are overall more technically relevant constellations that would exhibit a lower risk of unfair salaries with PtX than with fossil- or bio-based fuel, in comparison to constellations with a higher risk under the prevailing circumstances. Figure 11 illustrates that 55% of the assessed constellations would result in a sustainable development with regard to fair salary, whereas the remaining constellations would entail an elevated risk in accordance with the model.

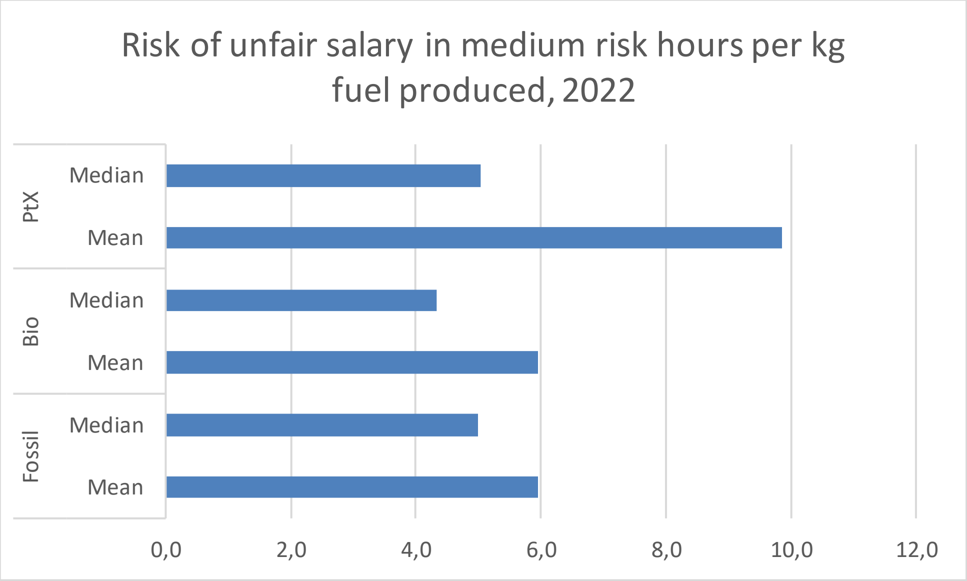

Figure 10: Median and mean results: Fair salary, 2022

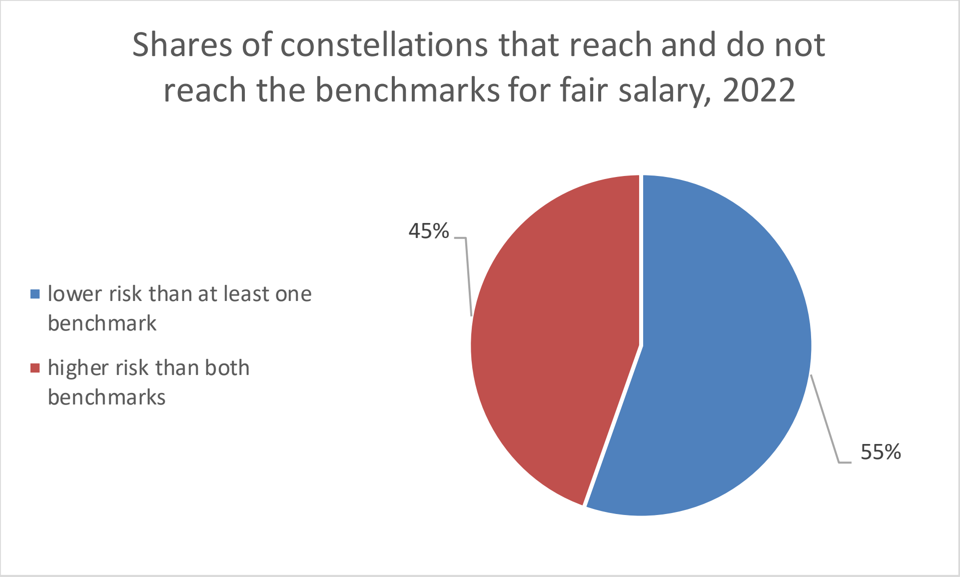

Figure 11: Distribution of constellations: Fair salary, 2022

The mean and median risk of unfair salaries within the PtX value chain is projected to decline by 2050, as illustrated in Figure 12, contingent upon the modeled technological and economic development of PtX and renewable energy technologies. Figure 13 illustrates that the number of constellations exhibiting positive developments with regard to fair salaries is set to increase, reaching a proportion of 69%. In the 2022 scenario, the countries and regions that reach the CO_2 benchmark are those with a higher technical potential. In contrast, the 2050 scenario also includes countries and regions with a lower technical potential. In the 2050 scenario, the median risk of unfair salaries along the value chain is lower than in both reference cases. Nevertheless, the mean value of PtX is greater than that of the two reference technologies.

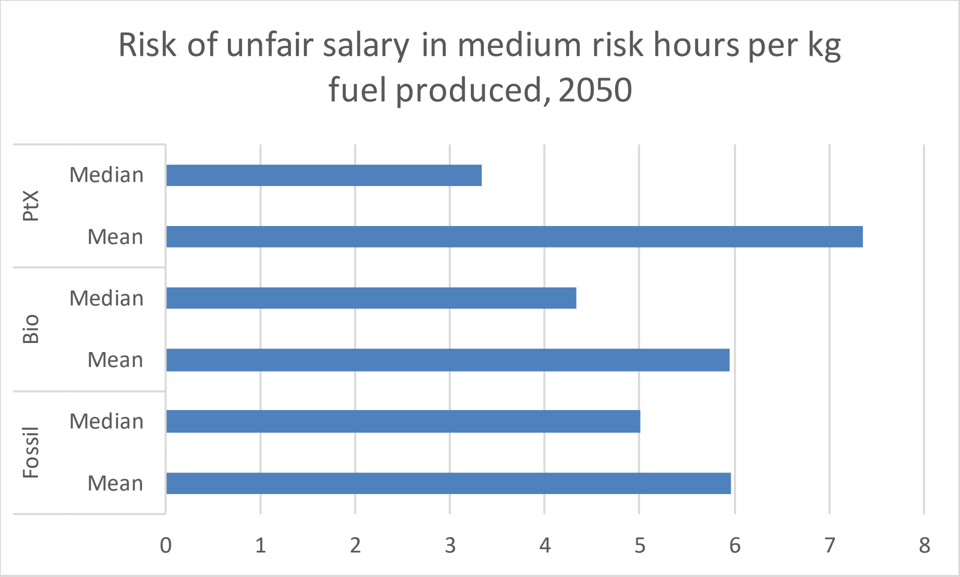

Figure 12: Median and mean results: Fair salary, 2050

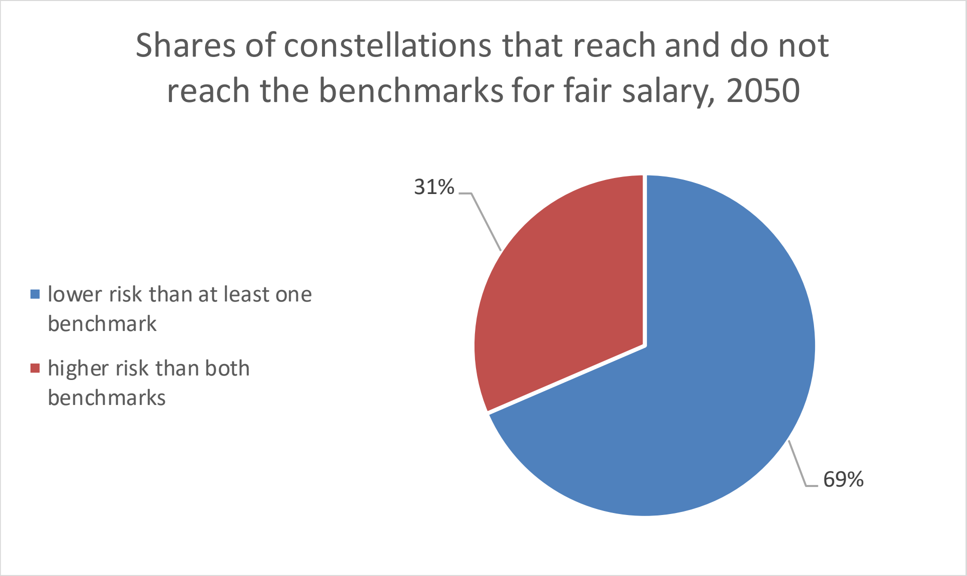

Figure 13: Distribution of constellations: Fair salary, 2050

It is notable that the issue of fair salary along the entire value chain is not considered as critical in this context. This is due to the fact that 55% of the constellations reaching the CO_2 benchmark also reach at least one of the benchmarks for fair salary in the 2022 scenario. Furthermore, even 69% of the constellations reaching the CO_2 benchmark in the 2050 scenario also reach at least one of the benchmarks for fair salary. Nevertheless, a number of constellations are identified as being at high risk, as evidenced by the considerable discrepancy between the mean and median values observed in both scenarios. To facilitate a positive global development, it is recommended that training and capacity development be provided to enable the acquisition of the requisite skills to receive higher salaries. It is also essential to ensure that adequate salaries are paid within the value chains. It is imperative that training programs and collaborative initiatives be devised at the earliest possible stage on a global scale. This will ensure that the requisite skills are imparted to the workforce in a timely manner, enabling them to fill the various roles within the value chain when the demand arises. The loss and creation of jobs with a just transition from fossil-based fuels to PtX-based fuels is a crucial consideration in this regard. Should such a transition occur, a considerable number of jobs in the fossil industry will ultimately become obsolete. However, a transition to renewables and PtX can serve to offset this deficit. It is likely that countries with high potential for renewable energy will derive the greatest benefit in this regard, as opposed to countries with lower potential. In any case, the re-skilling of staff currently employed in the fossil sector, as well as the training of staff for the entire field of green hydrogen and related areas, could ultimately reduce the risk. [124]

Category 2: Zero Hunger

As illustrated in Figure 14, the values for terrestrial acidification are particularly elevated in the context of bio-based fuel production. The results for PtX-based fuels are lower, but still reach values that are almost twice as high as those for fossil-based fuels in the 2022 scenario. Figure 15 illustrates that all of the evaluated configurations achieve at least one benchmark.

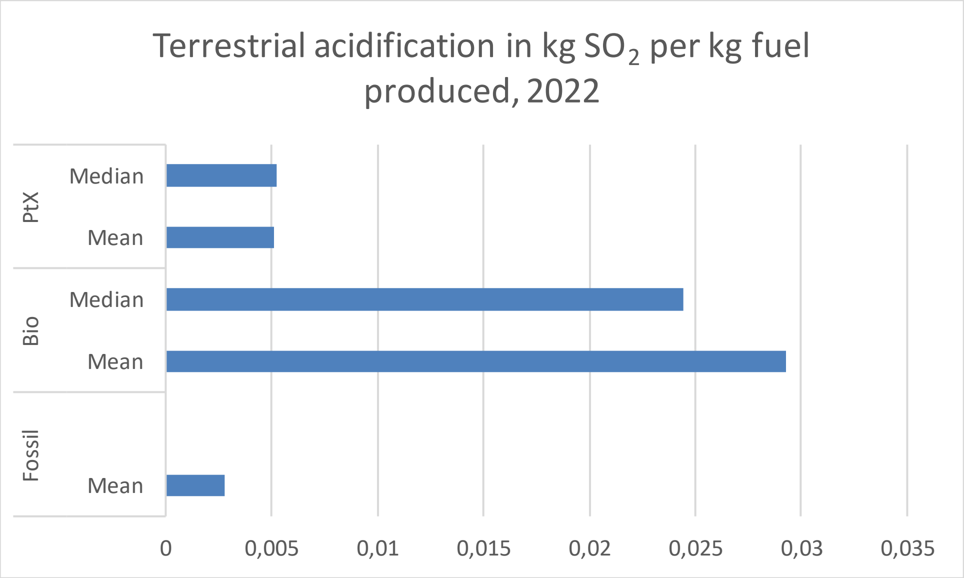

Figure 14: Median and mean results: Terrestrial acidification, 2022

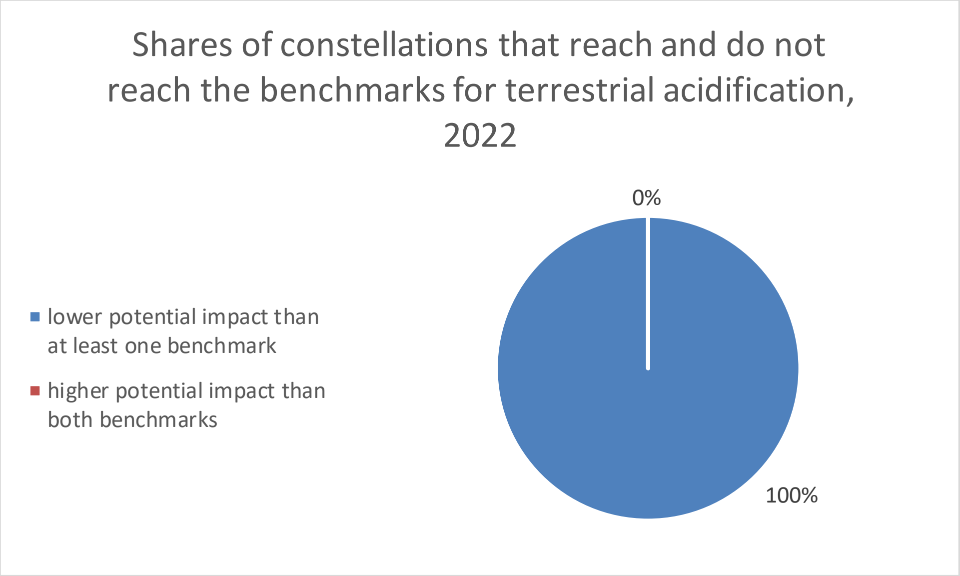

Figure 15: Distribution of constellations: Terrestrial acidification, 2022

As illustrated in Figure 16, the potential environmental impact of both PtX- and bio-based fuels increases in the 2050 scenario. It can be seen that PtX-based fuels would still result in a lower potential environmental impact within this category than bio-based fuels, but also a higher potential environmental impact than fossil-based fuels. As illustrated in Figure 17, all of the assessed constellations are capable of reaching at leaste one benchmark.

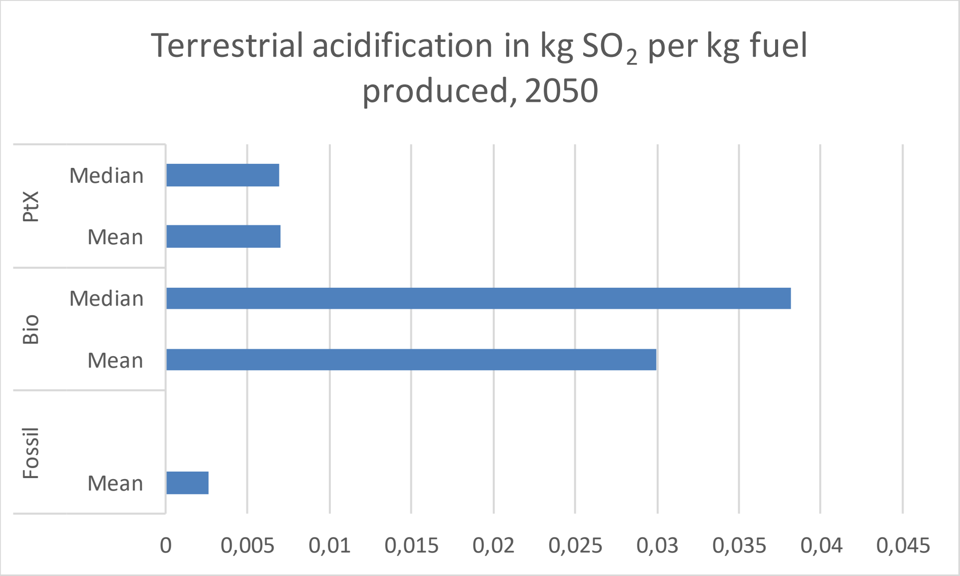

Figure 16: Median and mean results: Terrestrial acidification, 2050

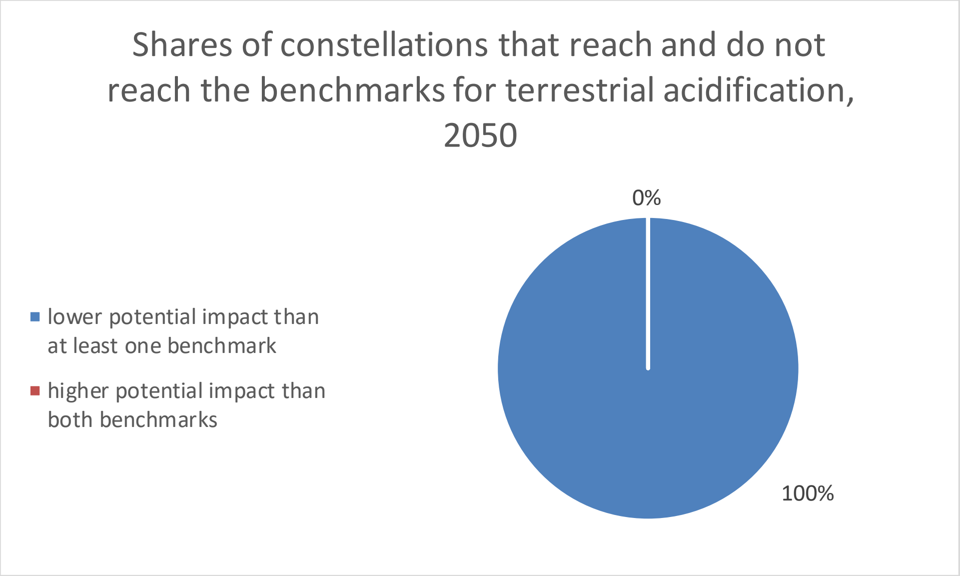

Figure 17: Distribution of constellations: Terrestrial acidification, 2050

In the event that one of the two benchmarks (fossil- or bio-based fuel) is reached, PtX is regarded as a more sustainable alternative in this study. In light of the global climate crisis, it is evident that the fossil-based approach cannot be sustained in the future. Moreover, with the at least in the short-term only other feasible alternative of bio-based fuels for aviation, an advantage to either of the benchmarks is a positive development. Nevertheless, the category should not be overlooked, as the potential impact would be greater than that of current fossil-based fuel production.

As shown in figure 18, offshore and onshore wind power are connected to a lower risk of terrestrial acidification than PV. A higher share of offshore wind power plants can be seen as one example which decreases the potential terrestrial acidification per kWh produced and thereby eventually per kg fuel produced. Offshore wind power is not a viable solution for every location in the world and should not be seen as the main solution to this problem, but rather a mix of different technologies should be considered.

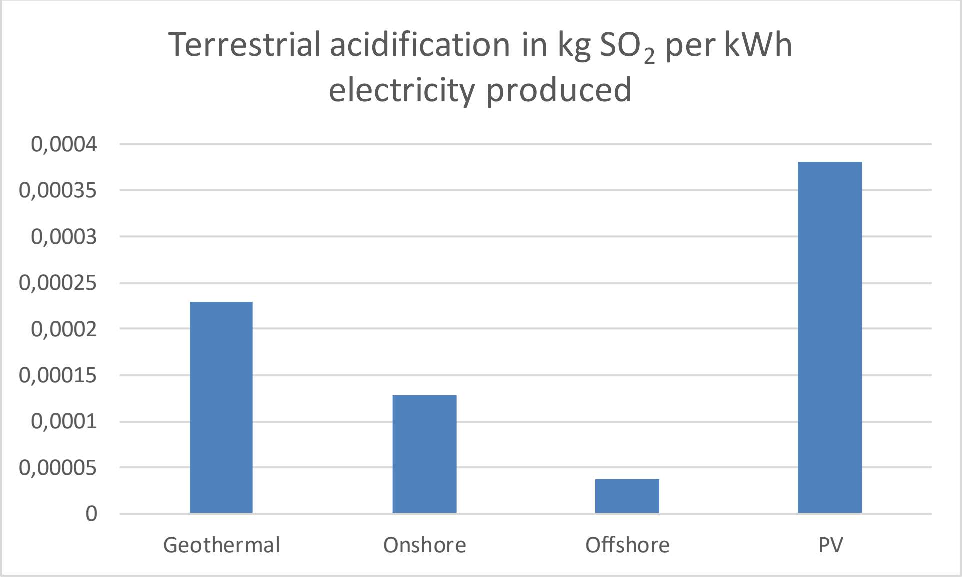

Figure 18: Terrestrial acidification potential of electricity generation from renewable sources

Furthermore, the current geopolitical situation presents an additional opportunity for addressing global hunger, particularly in the context of its impact on the global ammonia supply chain. Ammonia is a vital ingredient in the production of N-based fertilizers, with a significant international trade volume. Recently, a reliance on ammonia imports from a single country has resulted in fertilizer shortages in many regions. PtX offers the potential for ammonia production that is independent of natural gas resources. This is achieved by synthesizing green hydrogen from an electrolyzer with N from an air separation unit, which replaces the existing grey H_2 input within the system. This allows for the production of ammonia at the local level in a greater number of countries, which can contribute to enhanced global food security.

Furthermore, the topic of biogenic carbon sources for PtX is also pertinent within this category. As with the production of bio-based fuels, it is of paramount importance that the carbon is sourced in a sustainable manner that does not compromise food production. It seems probable that biogenic CO_2 will play a significant role in PtX, given that DAC is not yet available on a global industrial scale and industrial point sources are not a sustainable solution in the long term. In this regard, it is important to source CO_2 from sustainable sources, ensuring that there is no negative impact within this category.

Category 3: Good Health and Well-being

While the mean value of the fossil-based fuels is lower than those of both alternatives, the mean and median values of bio-based fuels are the highest. As illustrated in Figure 19, the values of PtX-based fuels are both lower than those of bio-based fuels. As illustrated in Figure 20, the non-carcinogenic human toxicity potential of PtX-based fuels is not a significant concern in the scenario of 2022. However, the potential environmental impact is considerably greater than that of fossil-based fuels.

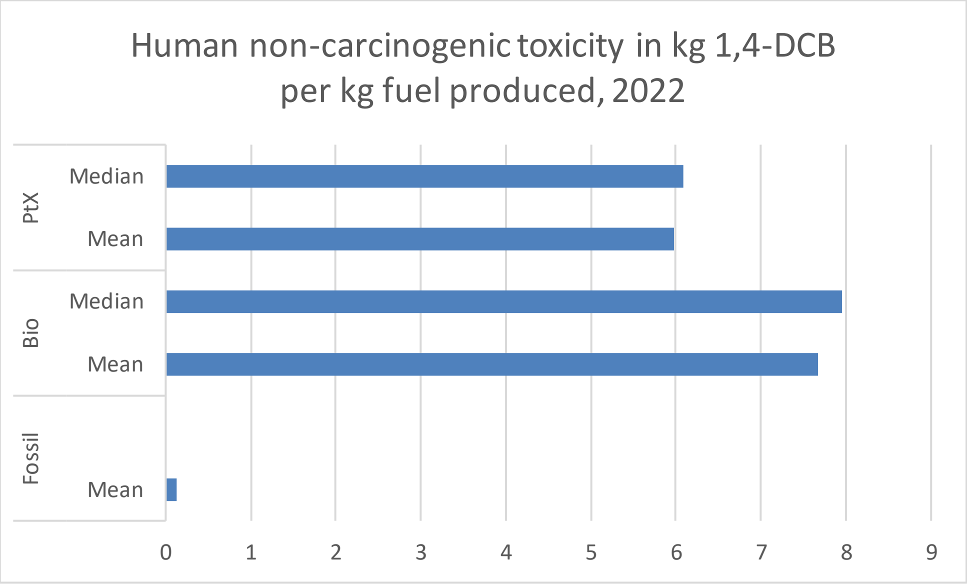

Figure 19: Median and mean results: Human non-carcinogenic toxicity, 2022

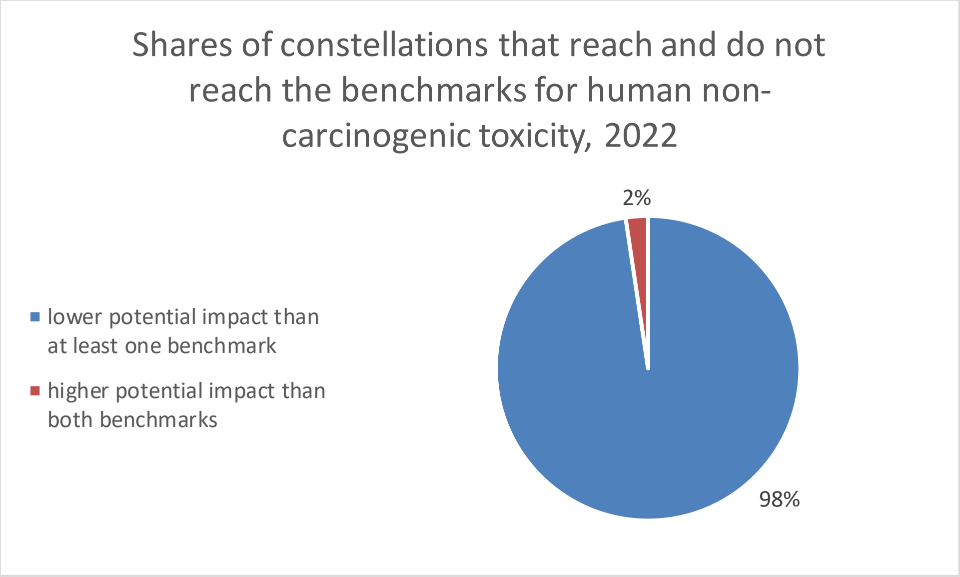

Figure 20: Distribution of constellations: Human non-carcinogenic toxicity, 2022

In the long run, the competitiveness against fossil fuels decreases, as figure 21 shows. The potential human non-carcinogenic toxicity along the life cycle of PtX-based fuels increases from 2022 to 2050. The results of bio-based fuels and PtX-based fuels are on a comparable level in the 2050 scenario, the share of constellations that reach at least one benchmark decreases to 50 %, as depicted in figure 22.

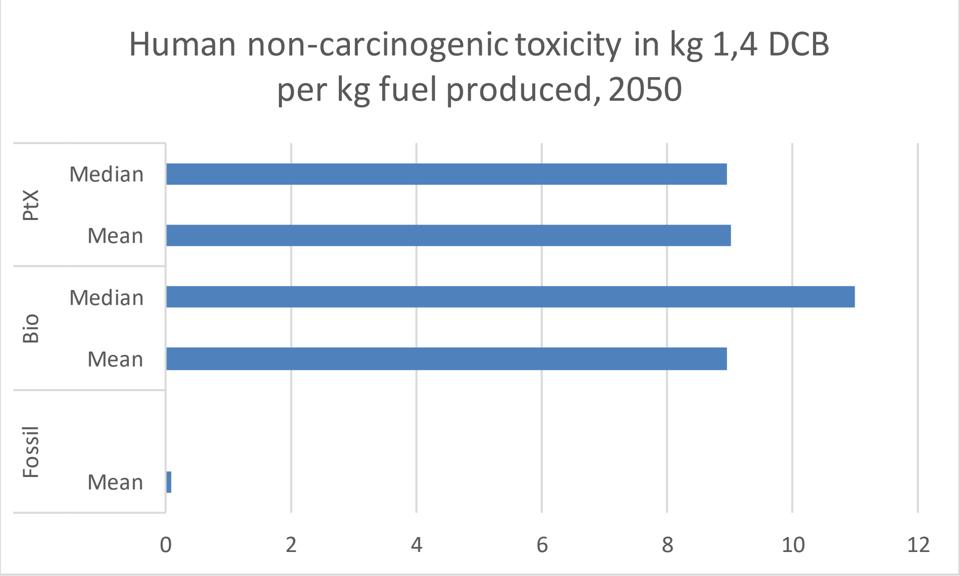

Figure 21: Median and mean results: Human non-carcinogenic toxicity, 2050

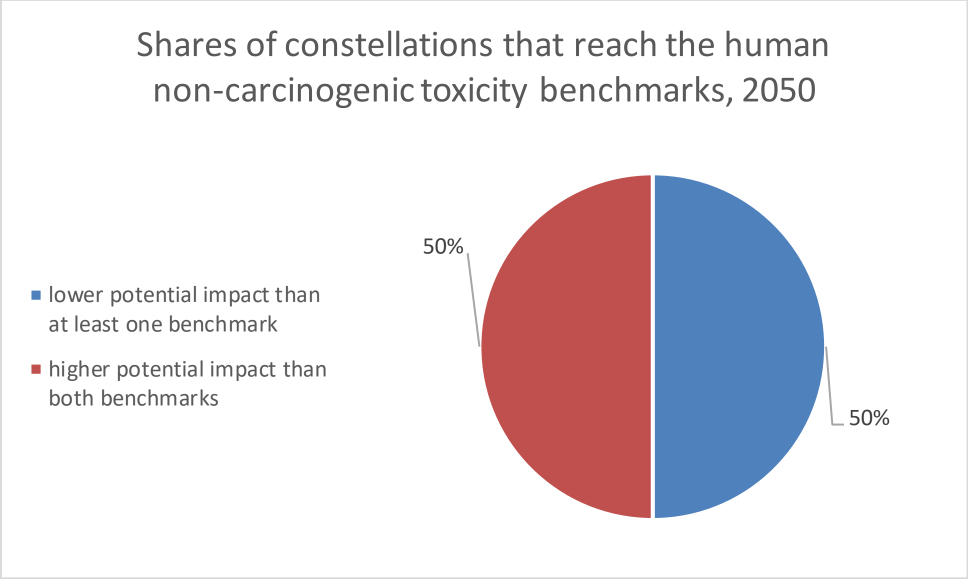

Figure 22: Distribution of constellations: Human non-carcinogenic toxicity, 2050

Figure 23 illustrates that the median and mean values for human carcinogenic toxicity throughout the life cycle are higher for PtX-based fuels than for both alternatives. Although PtX can achieve partial benefits in comparison to the bio-based benchmark for human non-carcinogenic toxicity, no considered constellation can reach the fossil- or bio-based benchmark for carcinogenic toxicity within the current scenario, as illustrated in Figure 24. Accordingly, this represents a critical area of concern, in which no benefits can be achieved in comparison to fossil- or bio-based fuels.

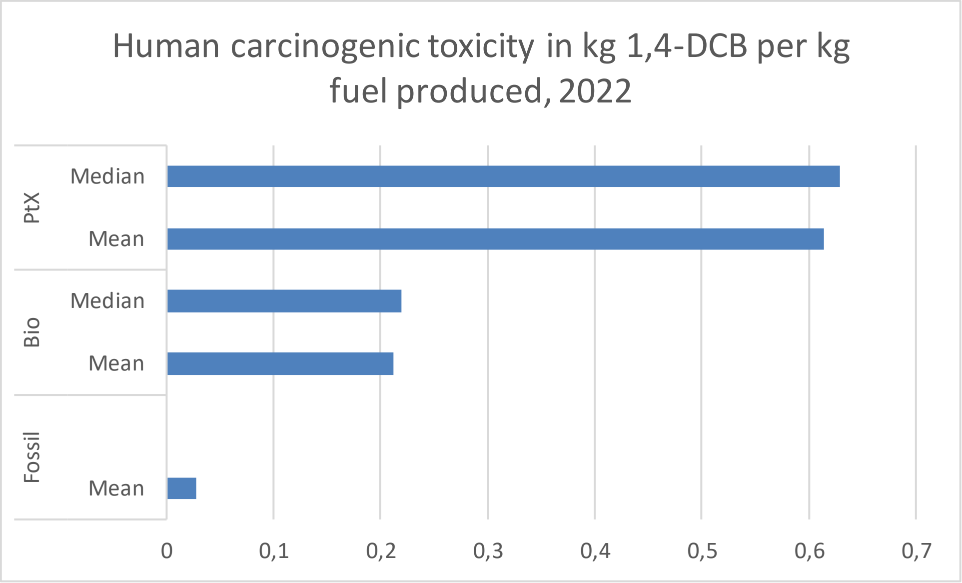

Figure 23: Median and mean results: Human carcinogenic toxicity, 2022

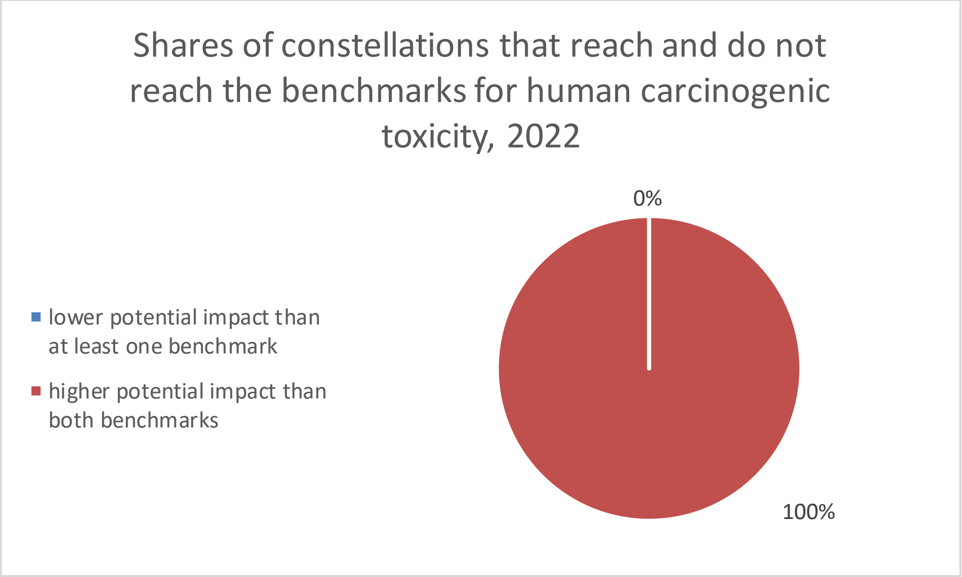

Figure 24: Distribution of constellations: Human carcinogenic toxicity, 2022

In the long-term scenario of 2050, the potential impact through PtX-based fuels is lower than in the current scenario. The results are illustrated in Figure 25. Nevertheless, it is evident from Figure 26 that the PtX route does not offer any advantages over the other alternatives.

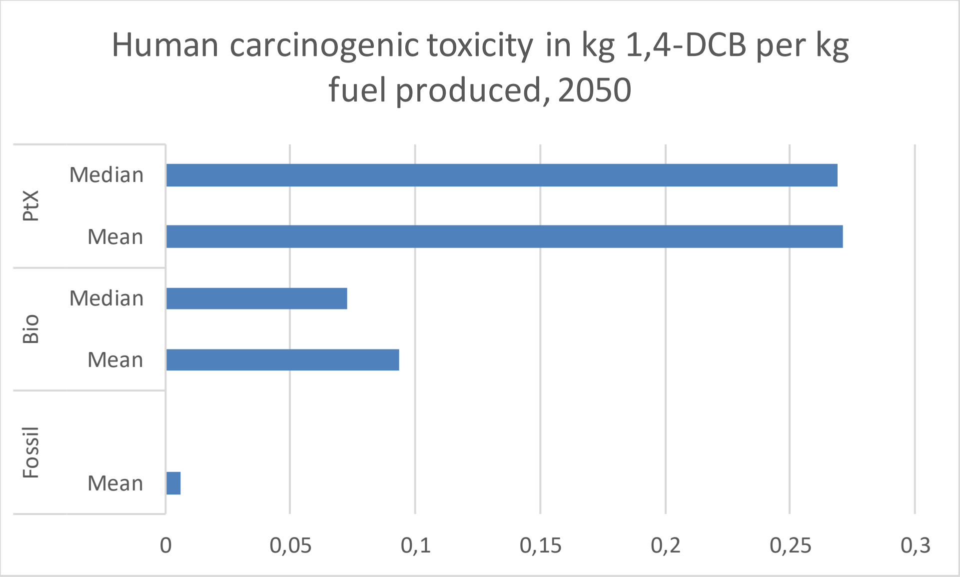

Figure 25: Median and mean results: Human carcinogenic toxicity, 2050

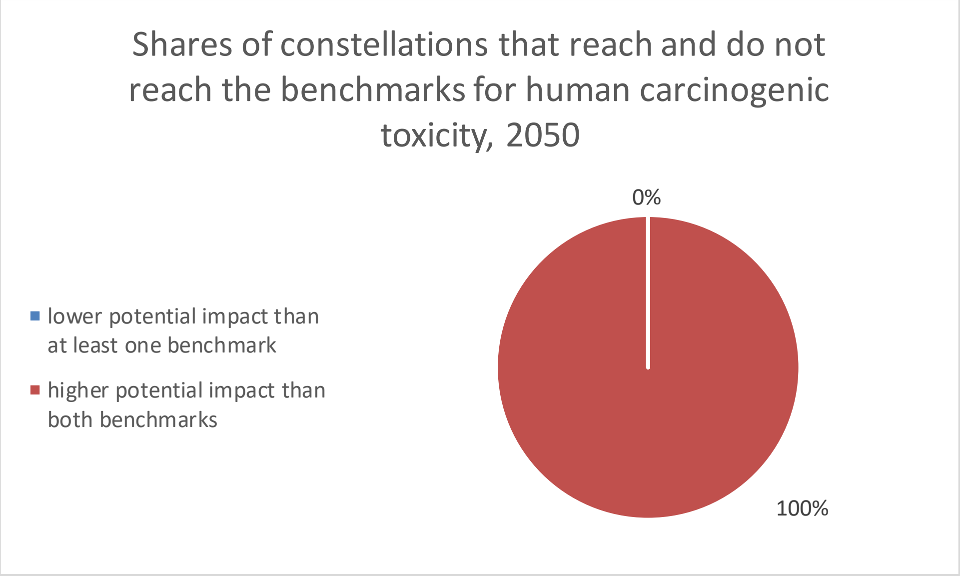

Figure 26: Distribution of constellations: Human carcinogenic toxicity, 2050

Figure 27 shows that the median values of all three assessed pathways are distributed between 0.38 and 0.59 medium risk hours, with the values of PtX-based fuels being the highest ones. At the same time, the mean value of PtX-based fuels is much higher than the other values. As it can be seen in figure 28, 61 % of the constellations reach a positive development for the indicator of health expenditures.

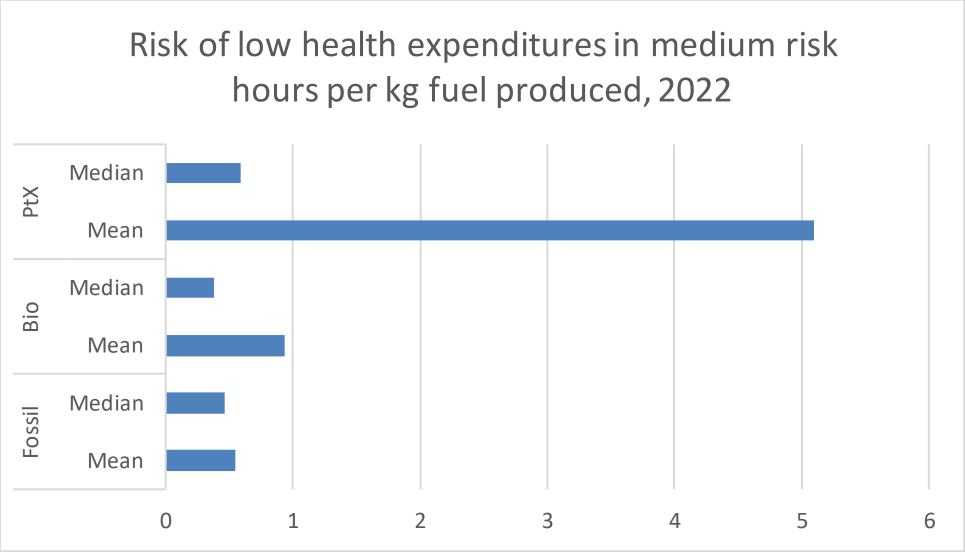

Figure 27: Median and mean results: Health expenditures, 2022

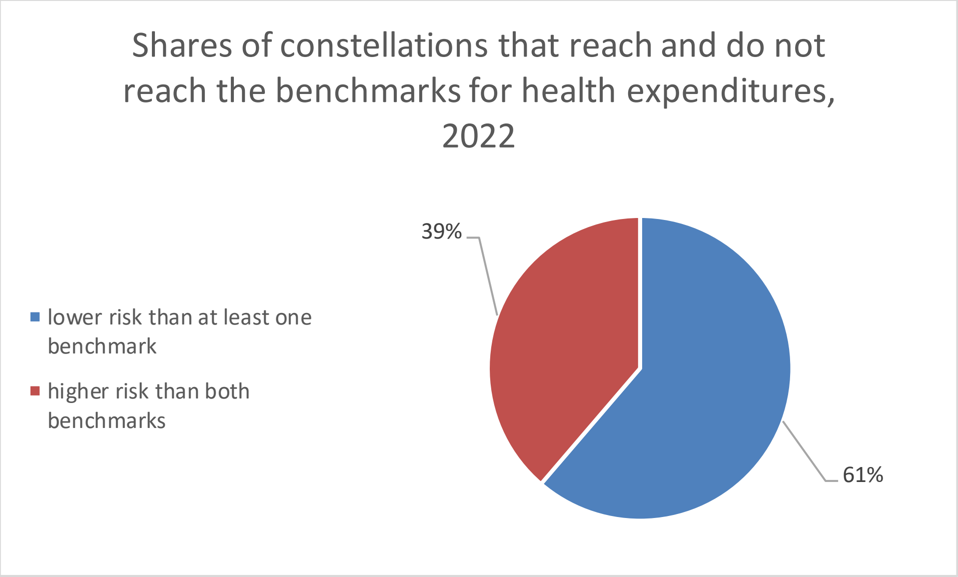

Figure 28: Distribution of constellations: Health expenditures, 2022

With the potential development until 2050, the benefits with regards to health expenditures in the countries increase in comparison to the fossil- and bio-based benchmarks. The share of constellations with a benefit over a benchmark increases to 69 %, as shown in figure 30. As figure 29 shows, the median value of PtX is lower than the median values of both benchmarks, the mean value of PtX also decreases in the 2050 scenario. It should however be noted that this modeled development is only explained by the lower costs and therefore lower amount of risk hours that are connected to PtX, and a higher share of constellations that is considered in the assessment due to the CO_2 benchmark. The 2050 scenario makes the price of the PtX-constellations more comparable to the benchmarks, which then leads to a better comparability of the risks without the high price difference. An actual development in health expenditures is not considered here.

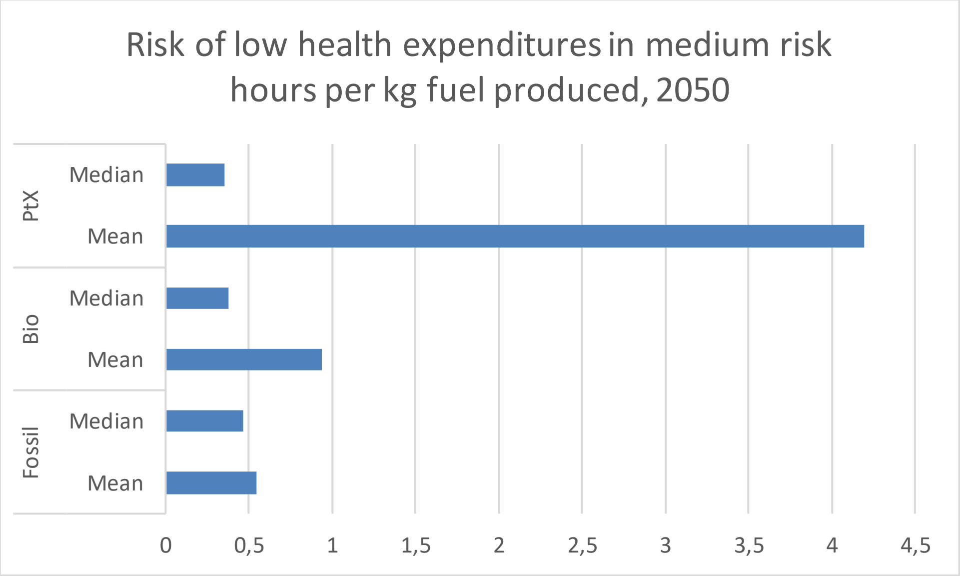

Figure 29: Median and mean results: Health expenditures, 2050

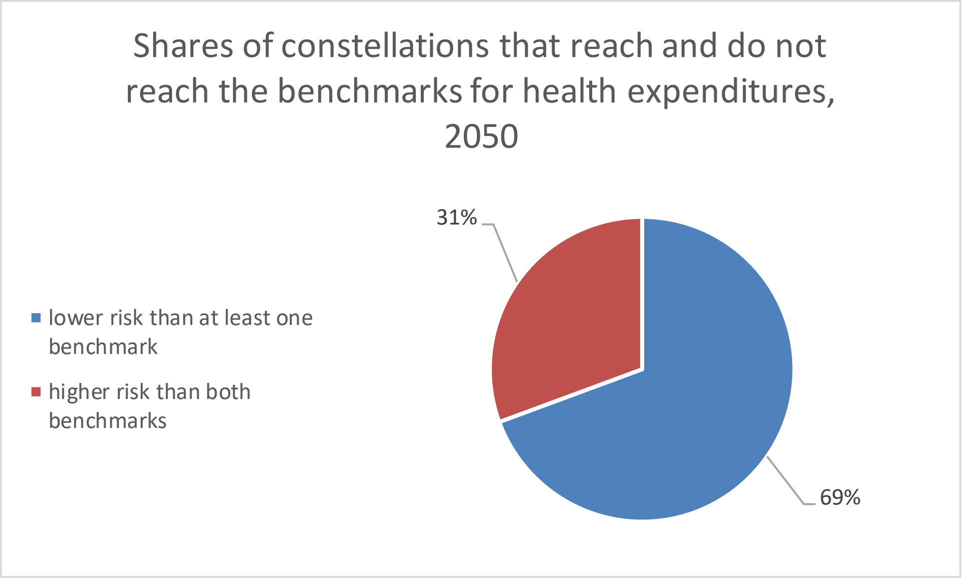

Figure 30: Distribution of constellations: Health expenditures, 2050

While the objective of PtX technologies is to reduce the GWP, which also has an effect on human health in the long run, it is essential to consider the short-term effects when developing PtX value chains. The probability of low health expenditures throughout the life cycle is relatively low in comparison to the reference pathways. However, the mean values are considerably higher in both scenarios, indicating the presence of some constellations with a relatively elevated risk. This should be considered at the country level. A transition to PtX-based fuels has the potential to have adverse effects on human health, particularly in terms of toxicity. In comparison to the provision of fossil-based fuels, the potential environmental impacts associated with PtX value chains (powered by PV and wind power) are more significant. The risk of non-carcinogenic toxicity to humans, primarily associated with the treatment of sulfidic tailings from silver and copper mining throughout the life cycle of PtX-based fuels, is relatively low in the 2022 scenario. However, it becomes a more significant concern in the 2050 scenario. The potential for human carcinogenic toxicity is a significant concern in each constellation and in both scenarios. As illustrated in the annex, the greatest contribution to human carcinogenic toxicity is associated with electric arc furnace slag, which is typically produced during steel manufacturing. Consequently, both impact categories are associated with the provision of the requisite materials throughout the entire life cycle. It is imperative that pathways with a lower impact and other measures be subjected to a thorough assessment. Concurrently, it is imperative to implement safety standards for the handling of materials and monitoring of potential leakages and exposure to toxic substances along the value chain, with the objective of minimizing any potential health risks.

Category 4: Quality Education

As illustrated in Figure 31, the mean risk of low education expenditures throughout the life cycle of PtX-based fuel in this model is more than two times as high as the risk of the benchmarks, while the median risk is situated between the risks of the bio- and the fossil-based fuels. Figure 32 illustrates that a considerable proportion of PtX configurations can attain advantages over bio- and fossil-based fuels in the domain of quality education (77%).

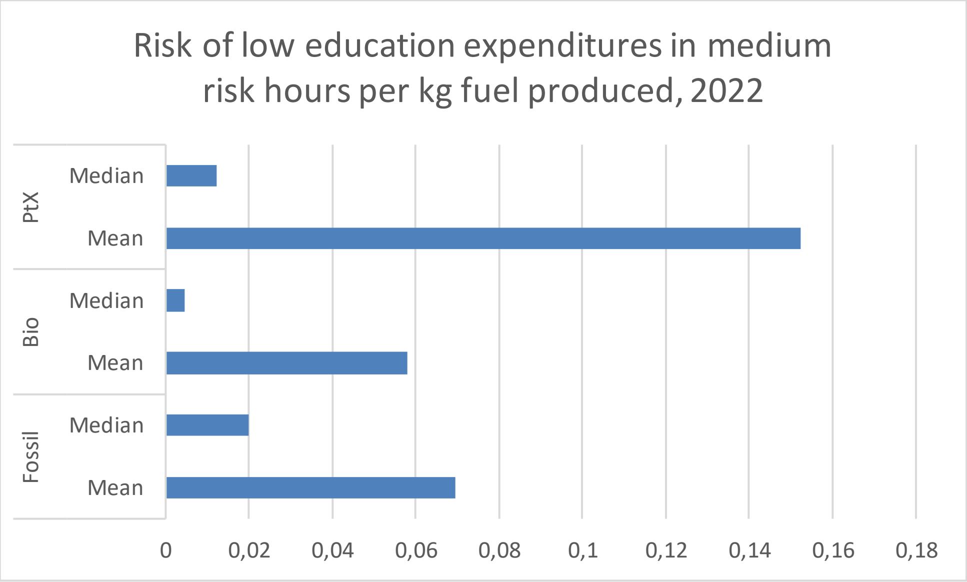

Figure 31: Median and mean results: Expenditures on education, 2022

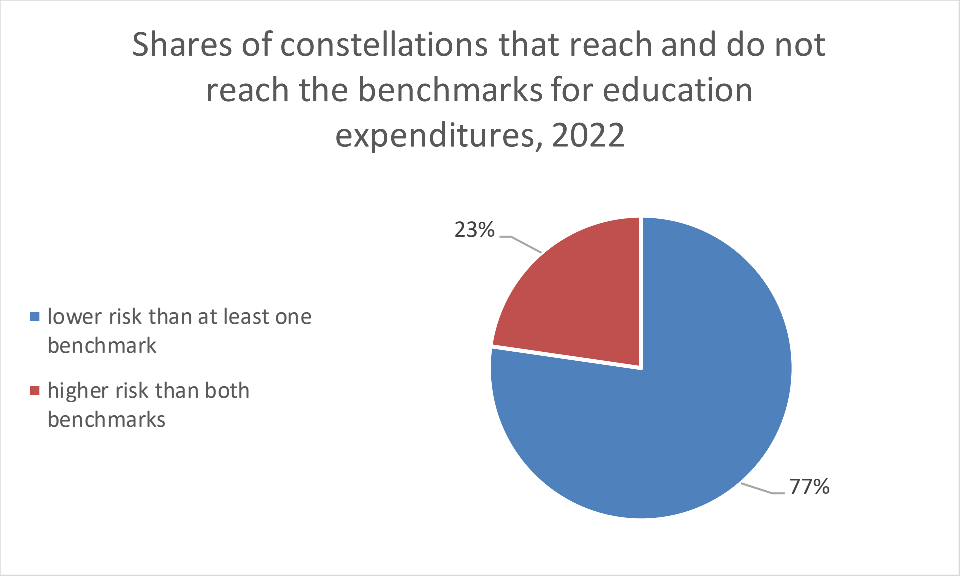

Figure 32: Distribution of constellations: Education expenditures, 2022

Figure 33 illustrates that, under the 2050 scenario, the competitiveness of PtX-based fuels increases in comparison to fossil-based fuels. As illustrated in Figure 34, the proportion of constellations that achieve at least one benchmark rises to 85%. Concurrently, the mean risk value rises and is markedly higher for PtX than for both benchmarks. In contrast, the PtX median value remains relatively constant.

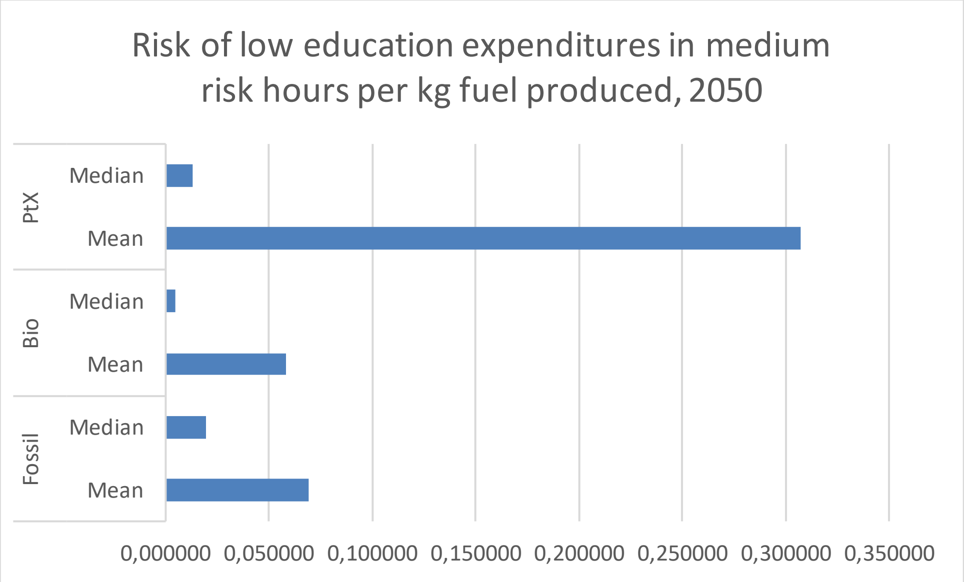

Figure 33: Median and mean results: Education expenditures, 2050

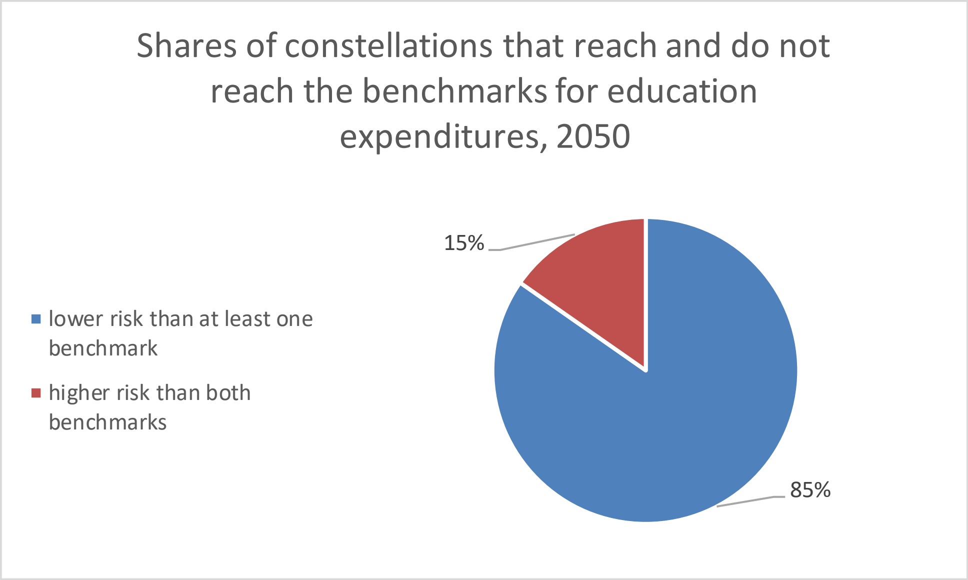

Figure 34: Distribution of constellations: Education expenditures, 2050

The elevated mean values in comparison to the median values indicate the presence of a subset of constellations exhibiting a substantially higher risk profile, while the majority of constellations are associated with a relatively low risk. As the number of considered constellations increases, so too does the proportion of constellations with an elevated risk (2050 scenario). In light of the considerable proportion of constellations that fall within the specified benchmarks, it can be posited that the transition at the global level does not inherently entail a significant degree of risk. However, the elevated risk in a number of countries should not be overlooked. Therefore, it is advised to support that an increased level of education spending and quality is attained when constructing a PtX value chain in countries where the level of education is currently inadequate. As investments may also be directed towards countries with a lower level of education for the development of international PtX value chains, it would be beneficial if education spending was increased accordingly. This presents a valuable opportunity to advance the transport sector in a more sustainable direction while also providing support to countries with lower levels of educational standards.

Category 5: Gender Equality

Figure 35 illustrates that, in comparison to fossil- and bio-based fuels, the PtX median value is higher than with both benchmarks. Furthermore, the mean value is several times higher than the fossil benchmark. Figure 36 illustrates that 56% of the PtX constellations reach at least one of the benchmarks.

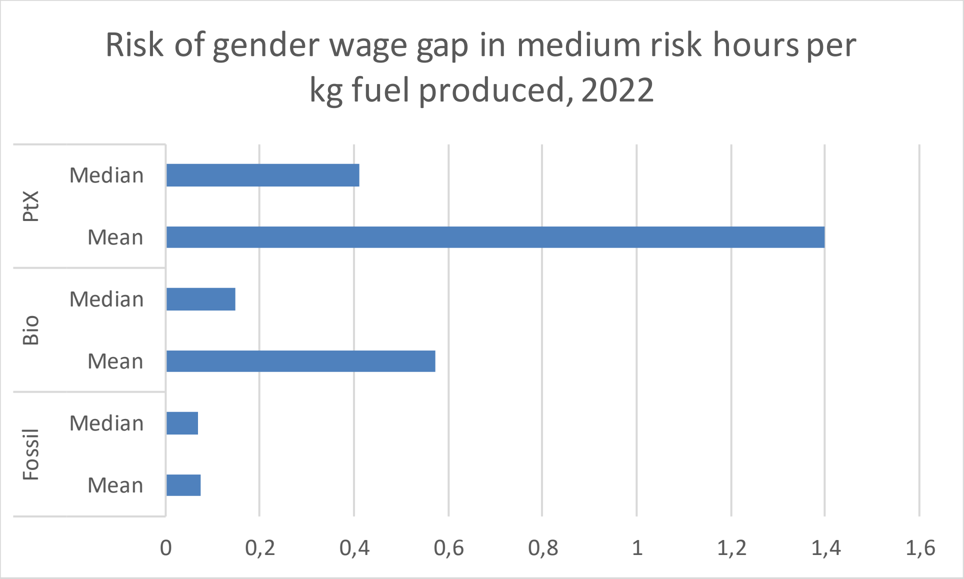

Figure 35: Median and mean results: Gender wage gap, 2022

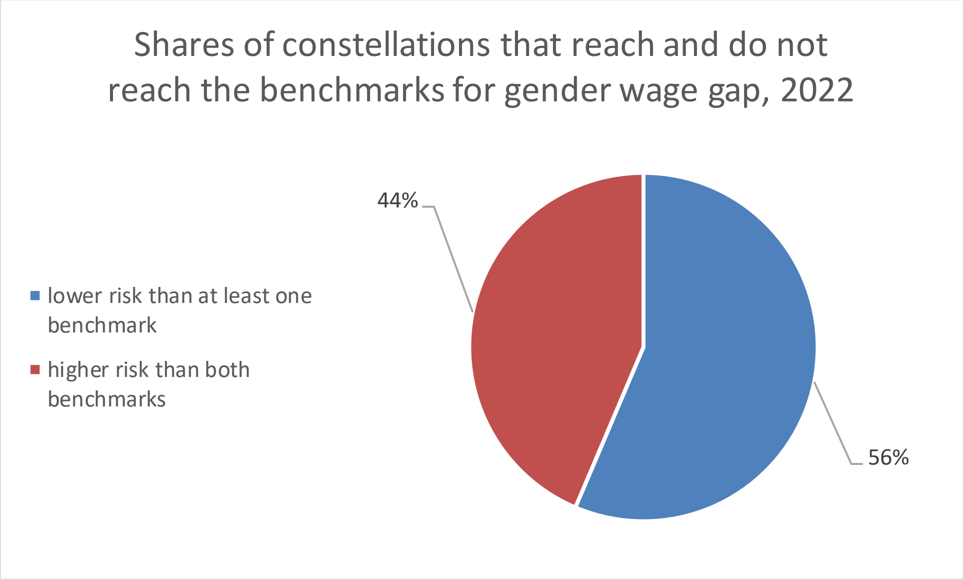

Figure 36: Distribution of constellations: Gender wage gap, 2022

In the 2050 scenario, the median and mean risk of PtX-based fuels are observed to decrease. Nevertheless, the values remain higher than those observed for fossil- and bio-based fuels, as illustrated in Figure 37. Figure 38 nevertheless indicates that the proportion of constellations that achieve either of the benchmarks increases to 69%.

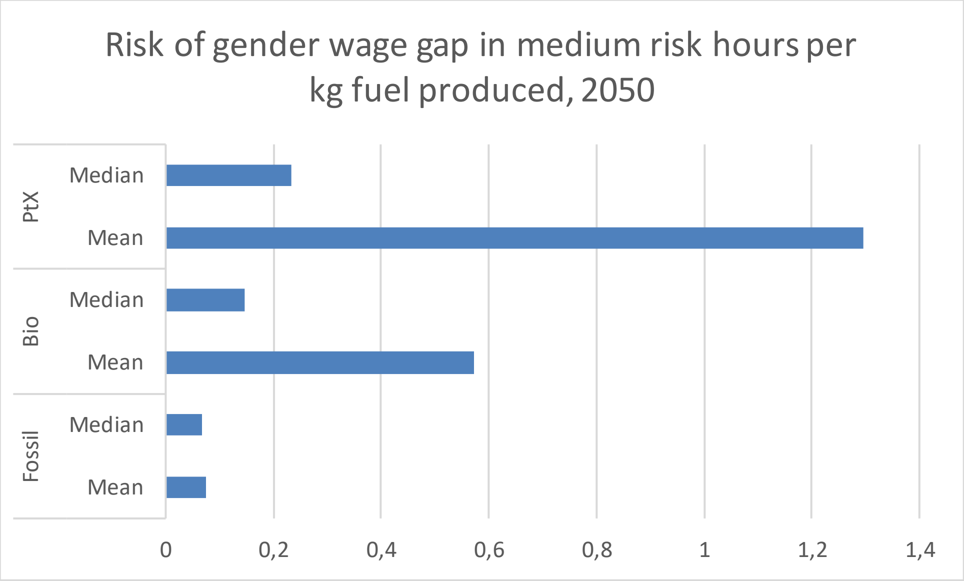

Figure 37: Median and mean results: Gender wage gap, 2050

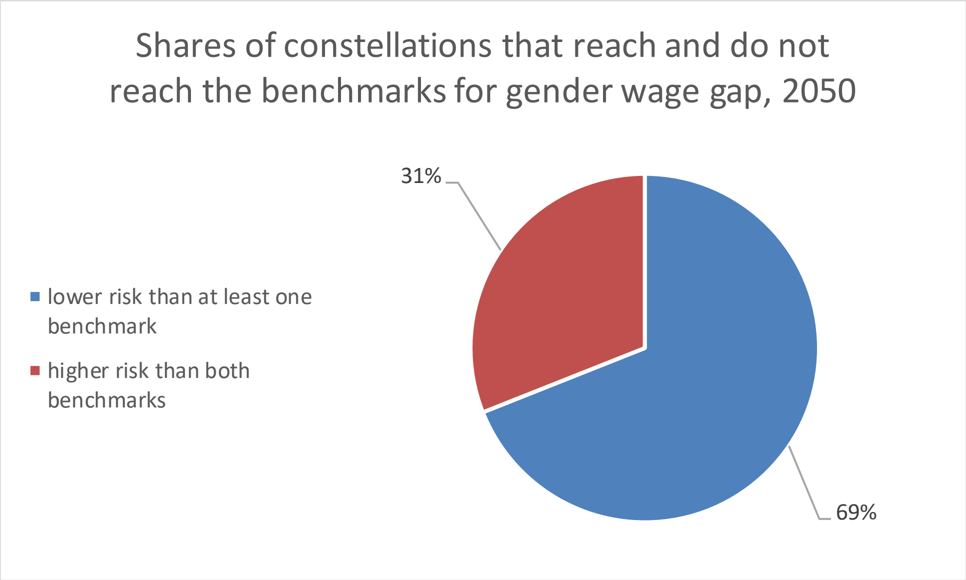

Figure 38: Distribution of constellations: Gender wage gap, 2050

Initiatives such as Women in Green Hydrogen (WiGH) facilitate and endorse the advancement of women in this domain, which, among other strategies, could potentially contribute to an enhancement in gender equality. Ultimately, each stakeholder in the value chain must address the issue and ensure that remuneration and opportunities are equalized through a variety of measures. In an article published by UN Women, five strategies for fostering gender equality and sustainability were outlined. The authors identify several key measures for a positive development, including the empowerment of female smallholders, investments in care, support for women's leadership, funding of women's organizations, and protection of women's health. In order to achieve this positive development, they are calling for social and policy reforms. The German Feminist Development Policy, developed by the Federal Ministry for Economic Cooperation and Development (BMZ), advocates for gender-transformative approaches that address the underlying causes of the problem rather than merely addressing the symptoms. These approaches seek to reshape male-dominated structures. This objective will be achieved by ensuring that women are represented in greater numbers in decision-making processes, that they have better access to resources, and that their rights are ensured. [138], [139]

Category 6: Clean Water and Sanitation

As illustrated in Figure 39, the mean values of all production pathways are considerably higher than the respective median values. At the same time, the median and mean values for PtX exceed those of the two benchmarks. Nevertheless, a total of 67% of the constellations are capable of attaining a benefit over at least one of the benchmarks, as illustrated in Figure 40.

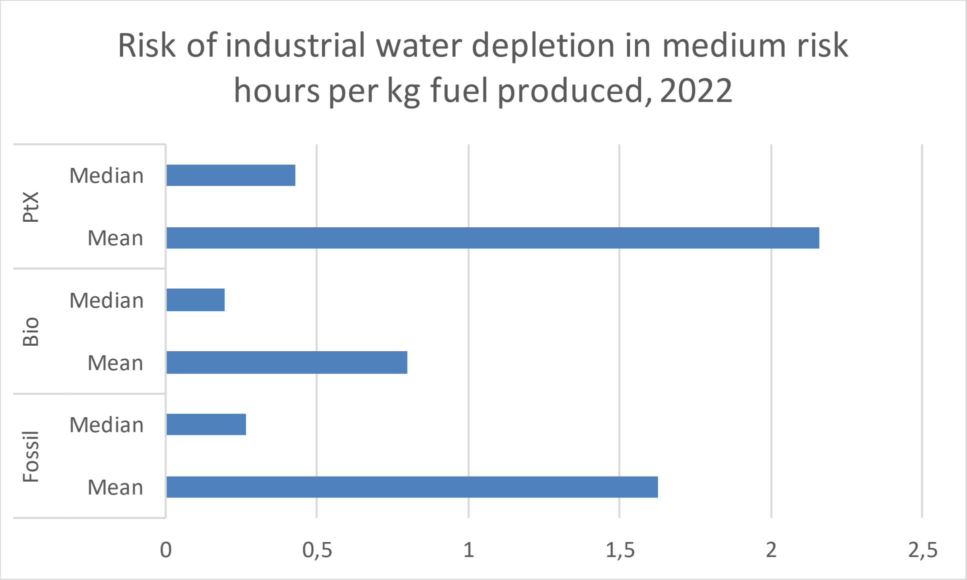

Figure 39: Median and mean results: Industrial water depletion, 2022

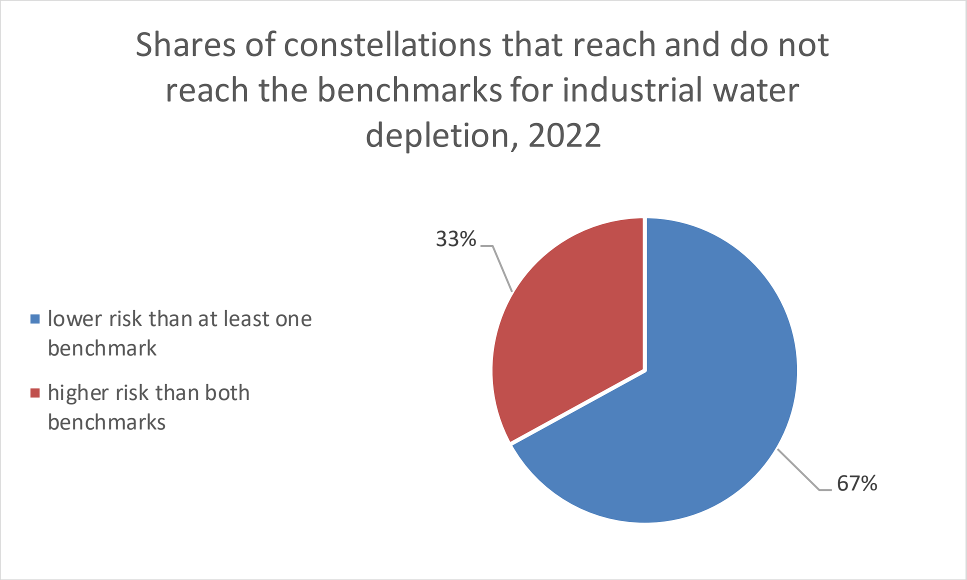

Figure 40: Distribution of constellations: Industrial water depletion, 2022

As illustrated in the results of the 2050 scenario in Figure 41, the median value of PtX is observed to decline below the values of both benchmarks. However, the mean value remains higher than the mean values of both benchmarks. Figure 42 illustrates that the 79% of assessed constellations exhibit a lower risk of industrial water depletion than that indicated by the benchmarks.

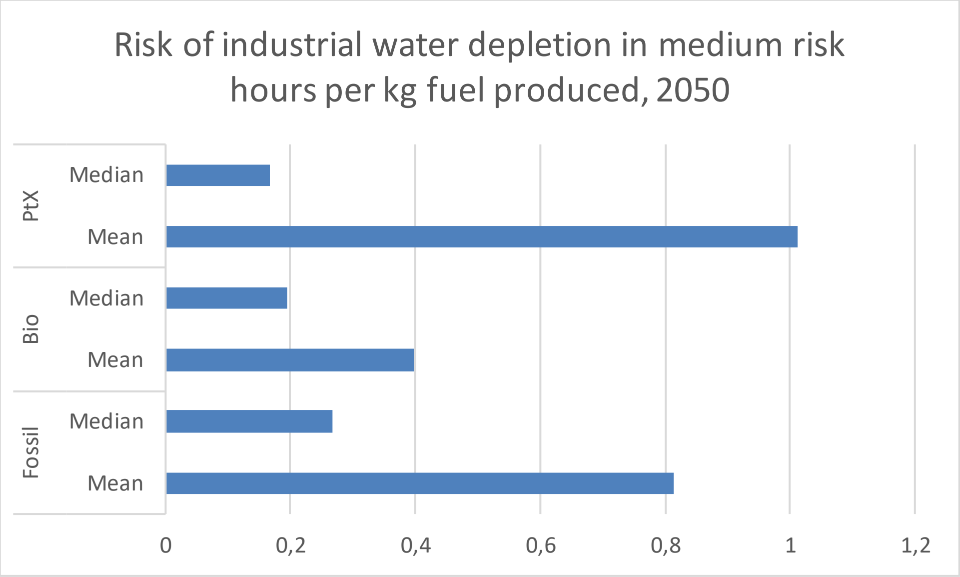

Figure 41: Median and mean results: Industrial water depletion, 2050

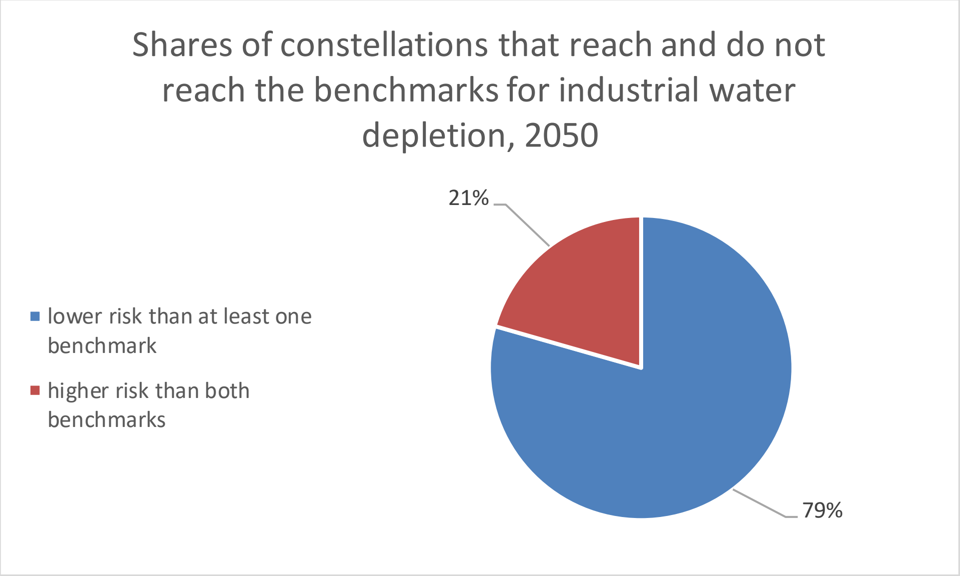

Figure 42: Distribution of constellations: Industrial water depletion, 2050

Figure 43 illustrates that the water consumption is significantly lower than that associated with the production of bio-based fuels. However, in comparison to fossil-based fuels, the life cycle of PtX-based fuel production is associated with a higher level of water consumption. As illustrated in Figure 44, all the examined PtX constellations meet at least one benchmark.

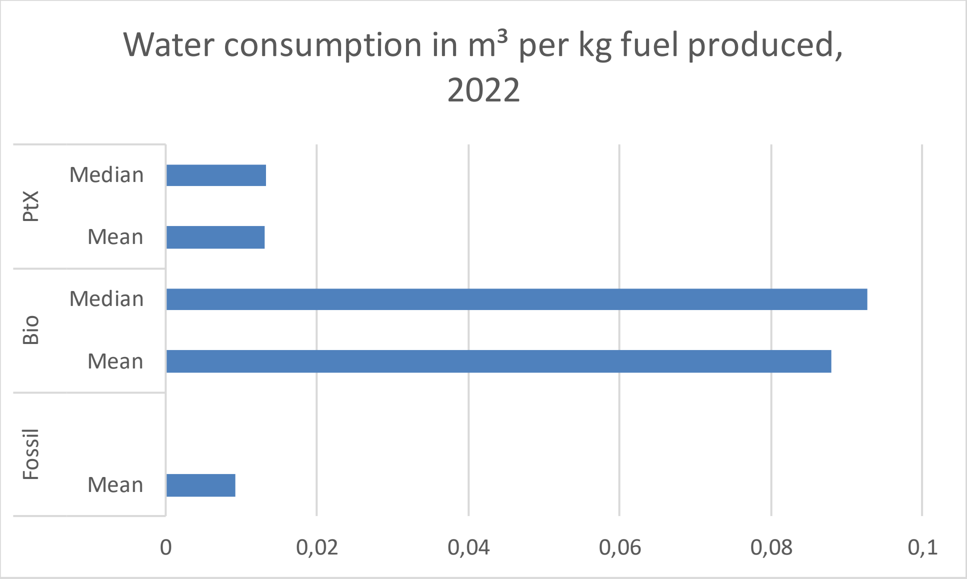

Figure 43: Median and mean results: Water consumption, 2022

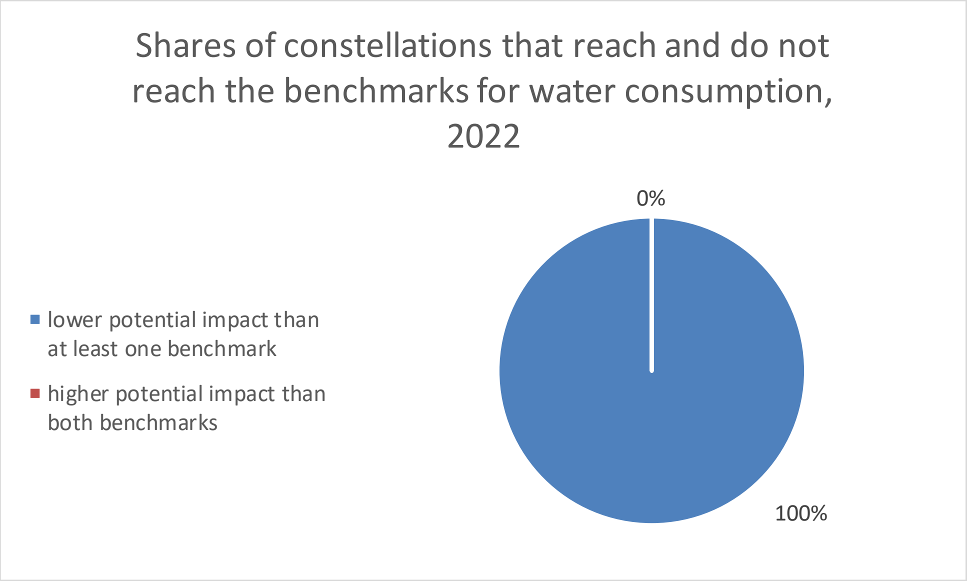

Figure 44: Distribution of constellations: Water consumption, 2022

As illustrated in Figure 45, the projected water consumption associated with the production of PtX-based fuels in the 2050 scenario would remain lower than that of bio-based fuels, but would exceed the water consumption associated with the production of fossil-based fuels. As illustrated in Figure 46, all of the examined constellations achieve a net benefit over one benchmark in the 2050 scenario as well.

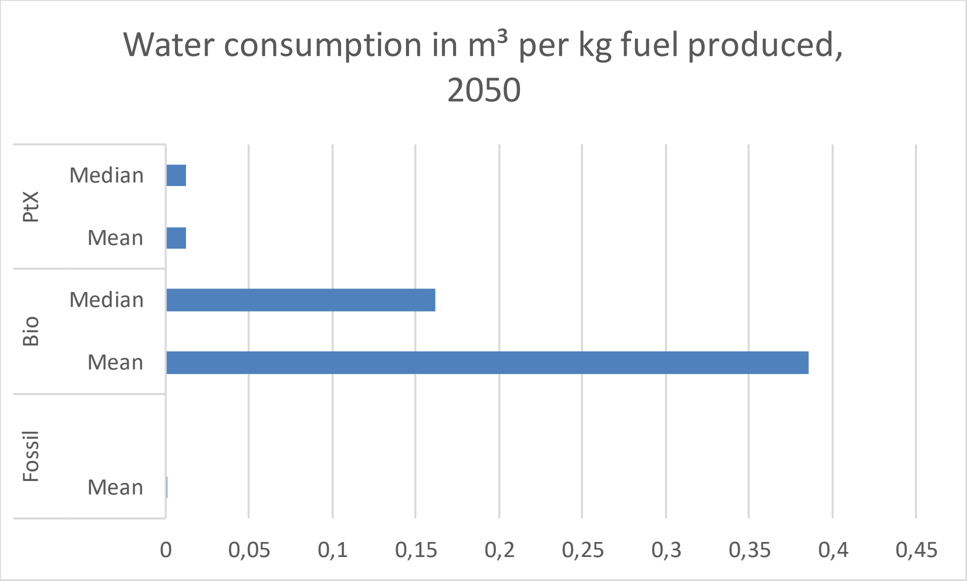

Figure 45: Median and mean results: Water consumption, 2050

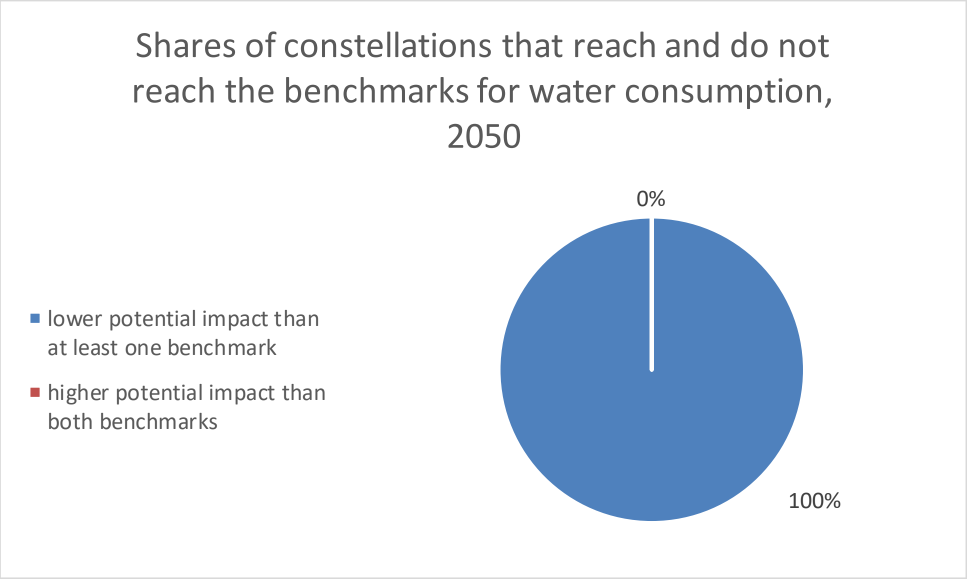

Figure 46: Distribution of constellations: Water consumption, 2050

In light of the pressing necessity for a transition away from fossil-based fuels, the risk of water scarcity is likely to become an increasingly critical concern in the future. In consideration of the current alternatives, it is evident that PtX-based fuels offer a distinct advantage over bio-based fuels in this regard. The water demand for PtX-based fuels is higher than that for the production of fossil kerosene, but substantially lower than for bio-based fuels, as also evidenced by a study conducted by the German Environment Agency. [140]

Nevertheless, a considerable number of countries with high potential for PtX are also countries with a relatively high risk of water scarcity or countries in which industry already utilizes a considerable amount of the available water. Despite the reduced risk in comparison to bio-based fuels, this will constitute an additional challenge to be addressed in the context of a transition to PtX. It is imperative that this heightened risk be addressed, and there are methods by which the risk can be mitigated with PtX.

One potential avenue for reducing the risk is the desalination of sea water for use in the PtX process, while simultaneously supplying the local population with additional drinking water. The additional costs would be relatively modest in comparison to the remainder of the PtX process. Nevertheless, the brine (as a waste product) must be processed in a sustainable manner and not released back into the environment without prior treatment, in order to prevent any negative impact on the surrounding ecosystem. The treatment of the brine can be a costly process; however, it can be linked to the recovery of minerals, which can lead to a more economically viable implementation and a benefit regarding the scarcity of mineral resources. A variety of technologies can be employed to recover resources from the brine and to manage the brine in a more environmentally friendly manner, including solar ponds, membrane distillation, membrane distillation crystallization, pressure retarded osmosis, electrodialysis, reverse electrodialysis, microbial desalination cells, and adsorption. These technologies differ in terms of their efficiency, maintenance requirements, costs, and the resources that can be extracted by them, as described in Panagopoulos et al. (2019) and Mavukkandy et al. (2019). [141], [142]

In a circular approach, as proposed by Thiel et al. (2017), sodium hydroxide is recovered from the desalination brine and subsequently employed in the desalination process for pretreatment of the seawater. Moreover, hydrochloric acid can be obtained and utilized for the cleaning of the plant or for other chemical production processes. [143]

As indicated in the dena study on the water consumption of power fuels, two additional possibilities exist for reducing water stress by PtX: the utilization of water from DAC, which is a byproduct of CO_2 extraction, and the integration of alernative technologies, such as the utilisation of electrolysers, which are capable of utilising low-grade and saline water, thereby avoiding any direct competition with drinking water availability. Both approaches are not yet available on an industrial scale and require further research and development. Nevertheless, they can be regarded as supplementary measures. [144]

Category 7: Affordable and clean Energy

Figure 47 illustrates that the land use for PtX-based fuels is significantly lower than for bio-based fuels. As illustrated in Figure 48, all of the examined configurations meet at least one benchmark. Concurrently, the values associated with the production of PtX-based fuels exceed those of fossil fuels.

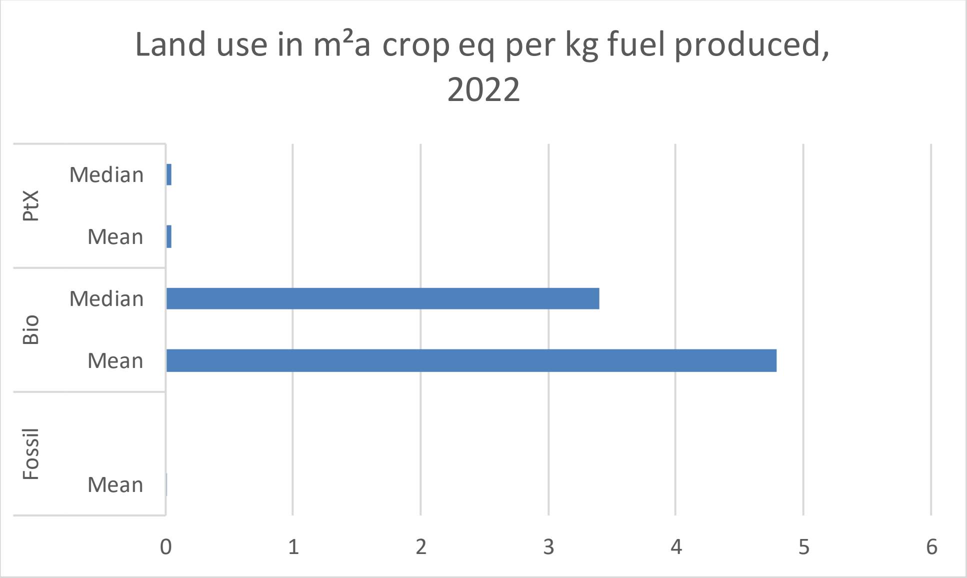

Figure 47: Median and mean results: Land use, 2022

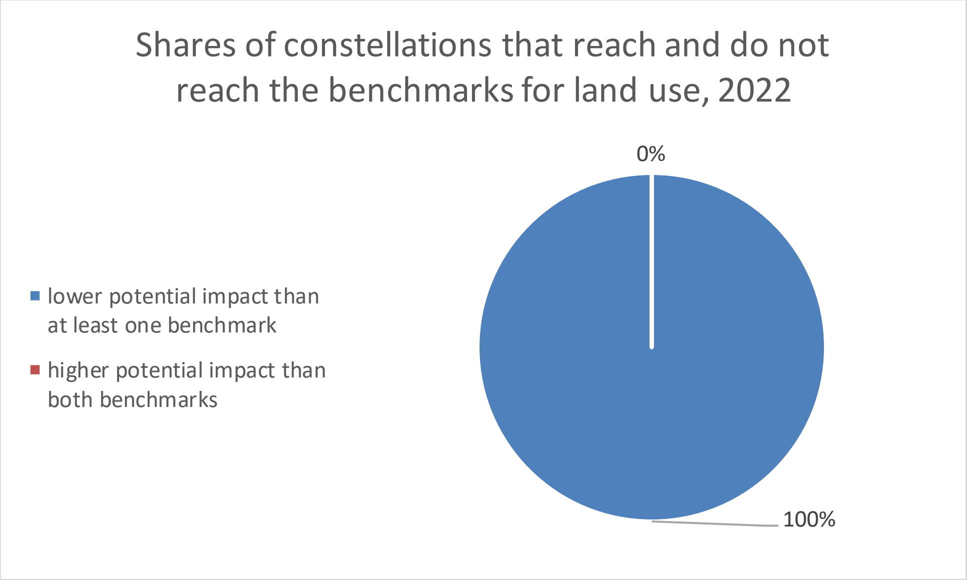

Figure 48: Distribution of constellations: Land use, 2022

In the 2050 scenario, the potential land use for bio-based fuel production remains significantly higher than that for both fossil- and PtX-based fuel production, as illustrated in Figure 49. It can be observed that all constellations that are capable of reaching the CO_2 benchmark are also able to reach at least one benchmark with regard to land use, as illustrated in Figure 50.

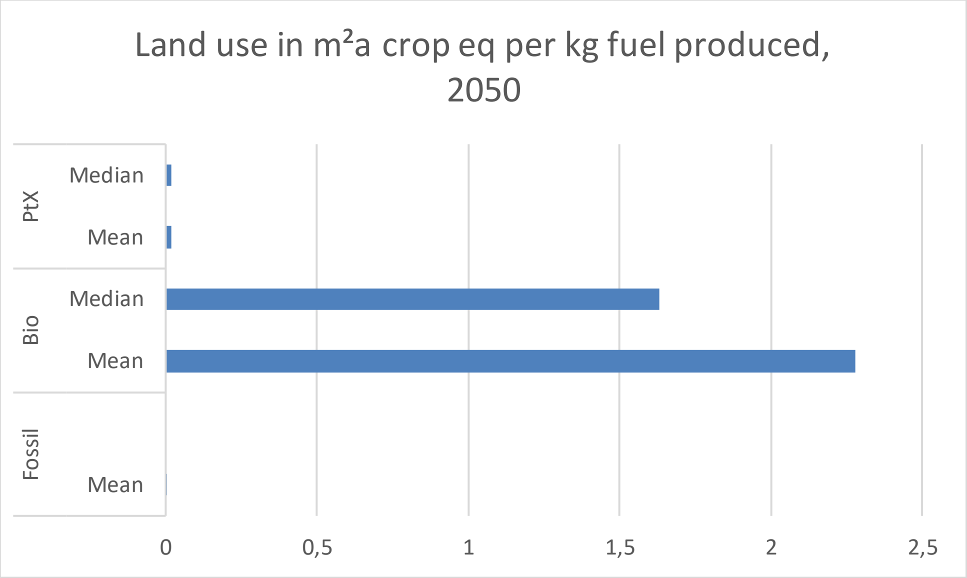

Figure 49: Median and mean results: Land use, 2050

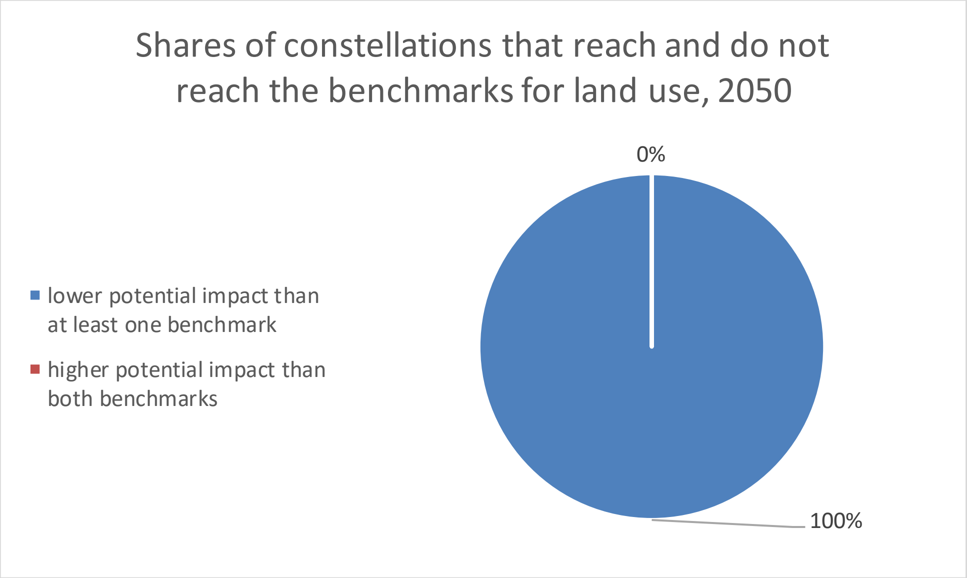

Figure 50: Distribution of constellations: Land use, 2050

As with water consumption, the issue of land use may emerge as a further challenge to be addressed in the transition away from fossil fuels. While the risk is lower than with biofuels, the additional land required for this transition may present a significant challenge. It is imperative to guarantee that the expansion of renewable energy sources to meet domestic electricity demand is not impeded in the interest of developing RES capacities for PtX. In light of the considerable price elasticity of electricity generation for PtX, there is a risk that high-potential areas will frequently be utilized for PtX. It seems inevitable that there will be an increase in land use, given the lack of viable alternatives and the necessity of RES capacities for the grid and for PtX. Consequently, it is essential to simultaneously expand both capacities. It is also imperative to encourage and develop effective land use strategies, as well as assess the potential for offshore solutions. For example, the Fraunhofer Institute for Solar Energy Systems (ISE) is engaged in several research projects exploring the integration of electricity generation into agricultural areas, with the objective of simultaneously utilizing the land for multiple purposes. As reported by REN21 (2022), six countries have already enacted policies supporting the integration of PV into agriculture. [145], [146]

Category 8: Decent Work and economic Growth.

Figure 51 illustrates that the median and mean risk values of child labor throughout the life cycle are higher for the production of PtX-based fuels than for both bio- and fossil-based fuel production. The issue of child labor is contingent upon the geographical location and value chain in question. Consequently, the results are also influenced by the fact that a greater number of countries are considered in the context of PtX than in the case of the alternatives. Consequently, a significant number of high-risk areas must be evaluated throughout the entire life cycle. The mean value for the risk of PtX is higher than all other values. As illustrated in Figure 52, only 49% of the constellations achieve a positive outcome with respect to at least one of the benchmarks, which renders this category particularly critical.

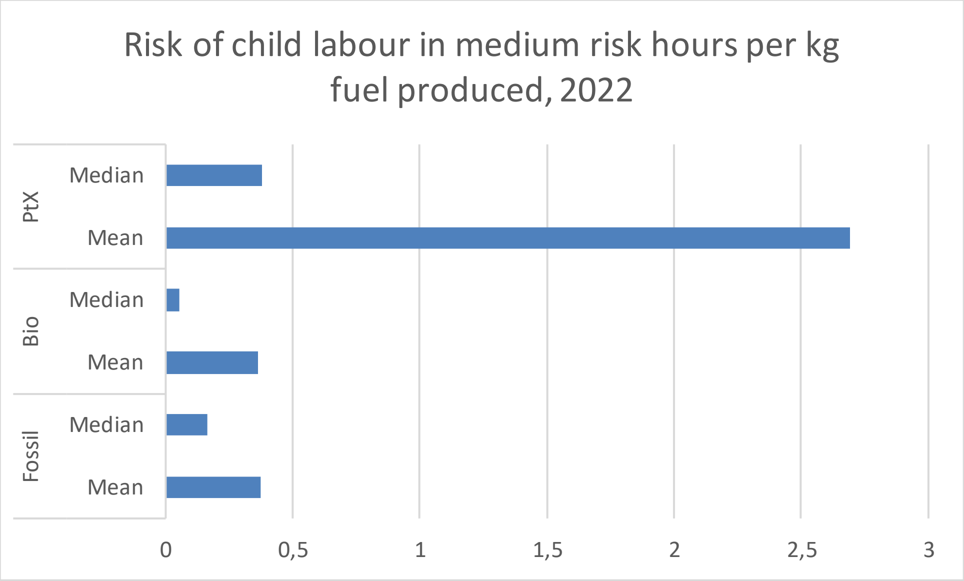

Figure 51: Median and mean results: Child labor, 2022

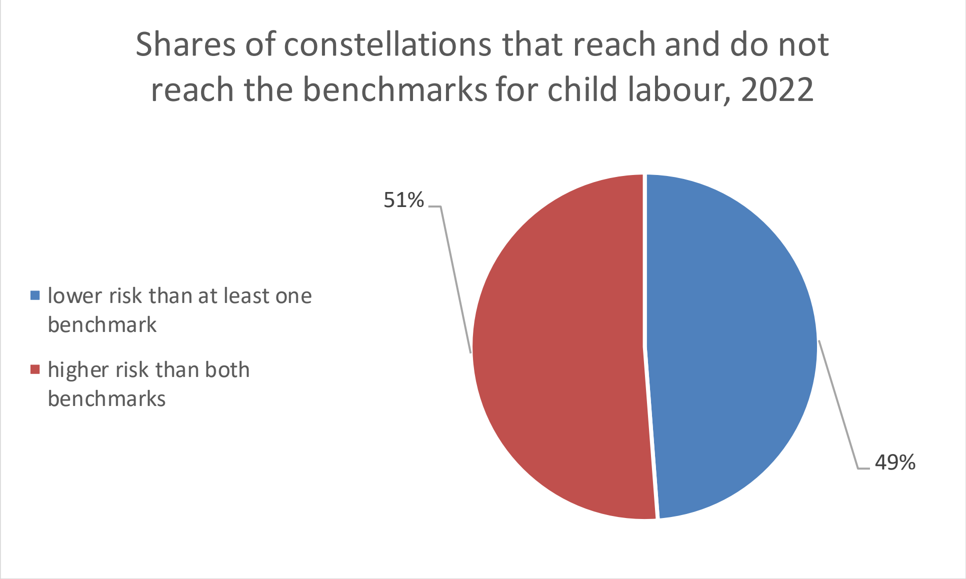

Figure 52: Distribution of constellations: Child labor, 2022

In the scenario projected for 2050, the median and mean values for PtX would remain higher than those for both benchmarks, as illustrated in Figure 53. Figure 54 illustrates that the proportion of constellations that demonstrate a positive outcome in relation to either of the benchmarks increases to 57%. This suggests that, on average, an advantage could be achieved by 2050. Nevertheless, the results also indicate that numerous regions and areas would continue to face significant challenges in this regard, underscoring the necessity for comprehensive monitoring along the entire value chain.

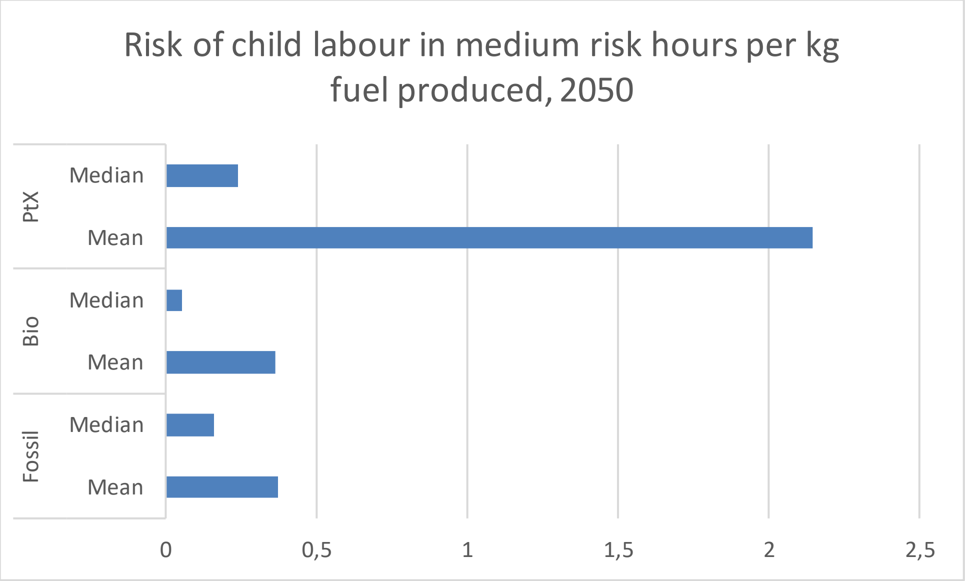

Figure 53: Median and mean results: Child labor, 2050

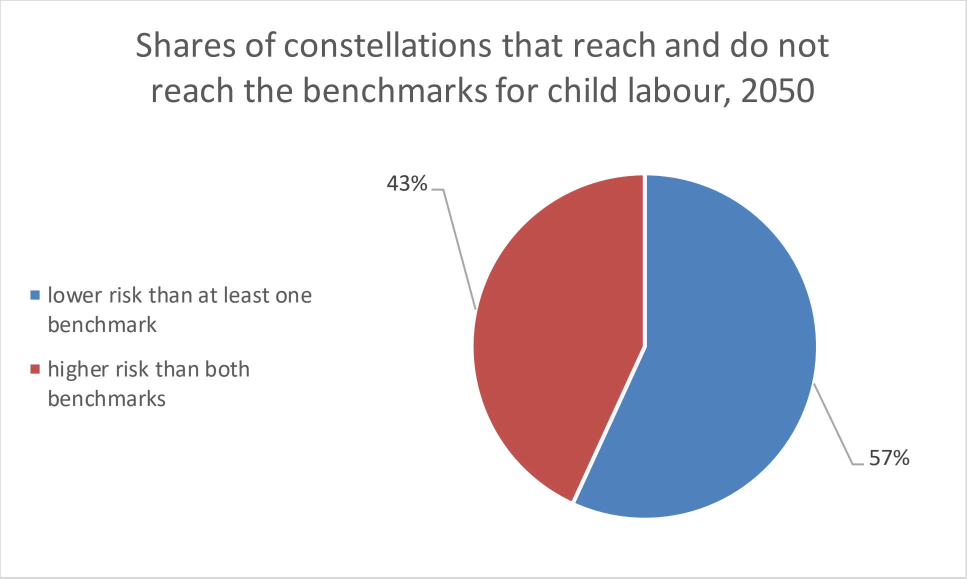

Figure 54: Distribution of constellations: Child labor, 2050

Given the possibility that some regions may be subject to a heightened risk of child labor relative to bio-based and fossil-based fuels, more research is required. It is of particular significance to address this subject matter throughout the entirety of the value chain, commencing with the extraction of the requisite resources for the various technologies, including those pertaining to electricity generation, and extending beyond the mere operation of a single facility. Typically, this involves the responsibility of multiple parties along the value chain. It is imperative that monitoring schemes and certifications be implemented to guarantee that children are not exploited in the production of fuels. Concurrently, the fundamental issue must be confronted. It is imperative that the conditions and structures that give rise to child labor be addressed and restructured in a manner that is transformative and ensures the well-being of children.

Category 9: Industry, Innovation and Infrastructure

As illustrated in Figure 55, the production of fossil-based fuels is connected to the highest potential environmental impact with regard to fossil resource scarcity, followed by bio-based fuel production. In contrast, PtX-based fuel production is associated with the lowest potential impact. Figure 56 illustrates that the PtX constellations have the potential to reach either of the benchmarks, with 100% representation. This implies that all PtX constellations that are technically viable have the capacity to reduce the reliance on and utilization of fossil resources throughout the value chains, showing an advantage over bio-based fuels as well.

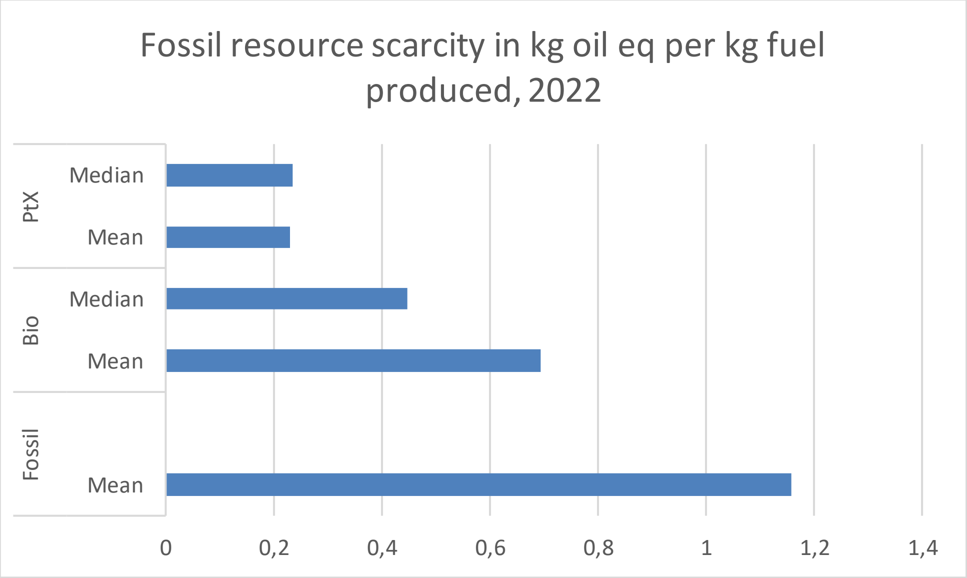

Figure 55: Median and mean results: Fossil resource scarcity, 2022

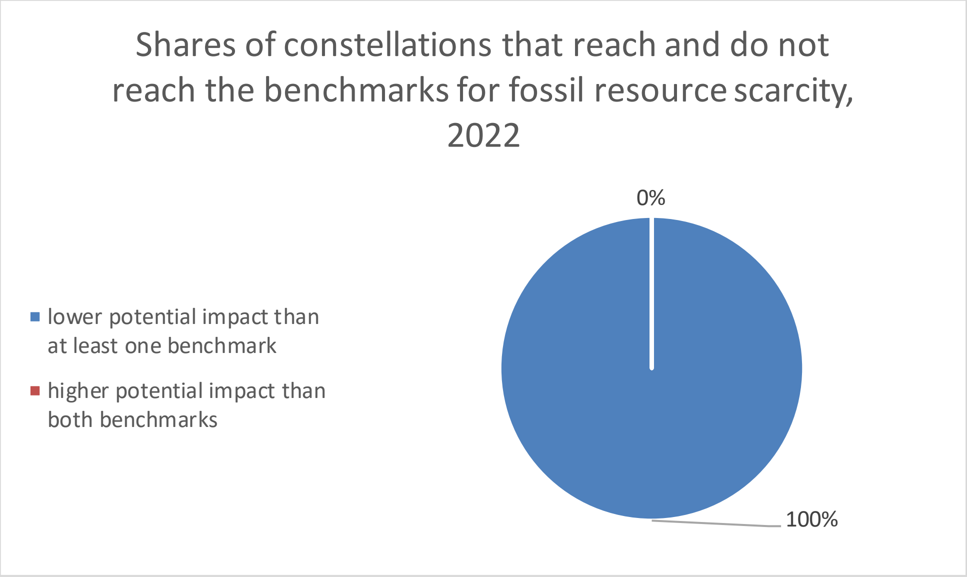

Figure 56: Distribution of constellations: Fossil resource scarcity, 2022

In the 2050 scenario, the values for both bio- and PtX-based fuel production decrease further, as illustrated in Figure 57. The sequence of the results for all pathways remains unaltered. As illustrated in Figure 58, the PtX constellations achieve the benchmarks with 100% in the 2050 scenario.

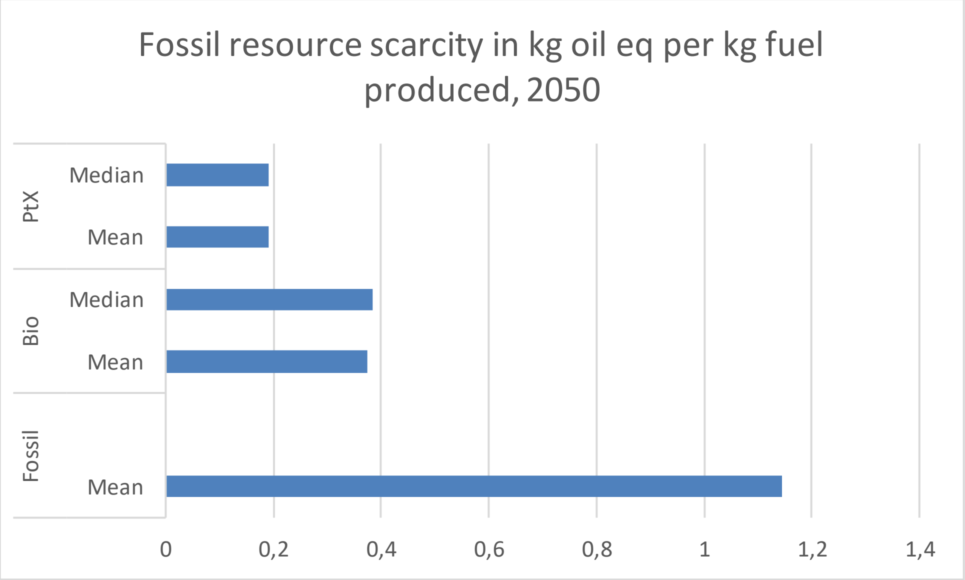

Figure 57: Median and mean results: Fossil resource scarcity, 2050

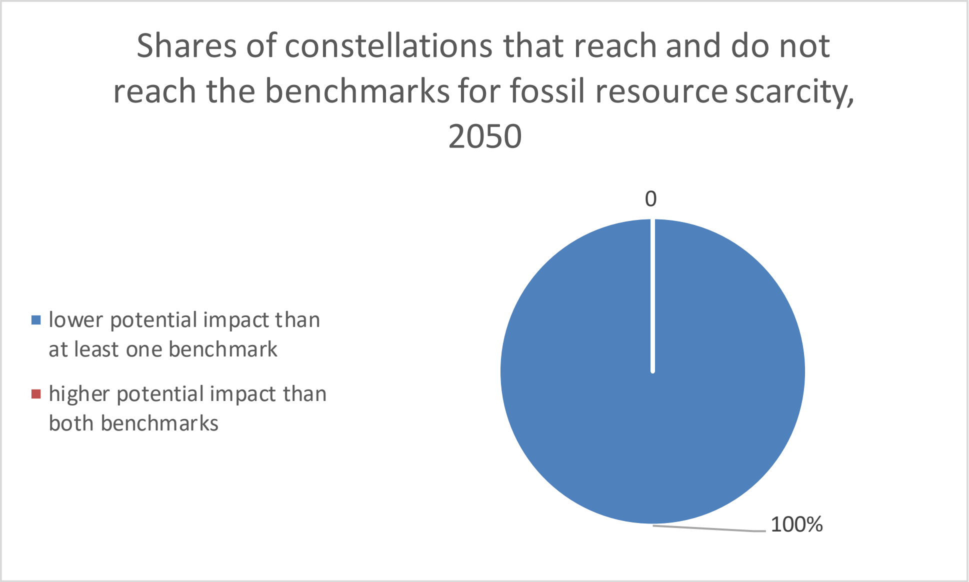

Figure 58: Distribution of constellations: Fossil resource scarcity, 2050

A transition from fossil-based fuels to PtX-based fuels would result in a reduction in fossil resource scarcity. In comparison to bio-based fuels, the results also demonstrate a distinct advantage. While this category seems unproblematic and the benefits are readily apparent, the issue of fossil resources remains a concern within this context: The utilization of fossil carbon sources for the synthesis of hydrocarbons through PtX. The PtX constellations modelled here rely on DAC as a source of renewable CO_2 from the atmosphere. The process results in a reduction in atmospheric CO_2 concentration. Upon combustion of the fuel, the net increase in atmospheric CO_2 is equal to the amount adsorbed and incorporated into the product prior to combustion. While the carbon cycle is relatively short and renewable in this scenario, the requisite technology is not yet ready for deployment on a global scale. Consequently, industrial point sources are frequently contemplated, particularly in sectors where the likelihood of avoiding fossil CO_2 emissions in the near future is low (e.g., cement production). A topic of considerable debate is whether the use of biogenic CO_2 or CO_2 provided by DAC is sufficient to make PtX fuel sustainable, or whether, in the short to medium term, fossil CO_2 sources could be used for sustainable PtX products. The primary rationale for this assertion is that they are currently widely accessible, cost-effective, and would necessitate less energy for extraction in comparison to DAC. Nevertheless, the utilization of fossil CO_2 for PtX may potentially give rise to a fossil lock-in effect. The infrastructure for the provision of CO_2 from industrial point sources would be constructed, transforming this emission into a valuable commodity rather than an undesired byproduct. This would render the emission of this CO_2 a desired activity. Such a scenario could result in the prolongation of fossil-based energy provision and other processes that would otherwise have been terminated.

Category 10: Reduced Inequalities

As illustrated in Figure 59, the median and mean risk values for PtX-based fuel production are higher than those of both benchmarks. In particular, the mean value is higher than the mean values of fossil- and bio-based fuels. As illustrated in Figures 60 and 61, 61% of the evaluated configurations demonstrate a benefit over the established benchmarks.

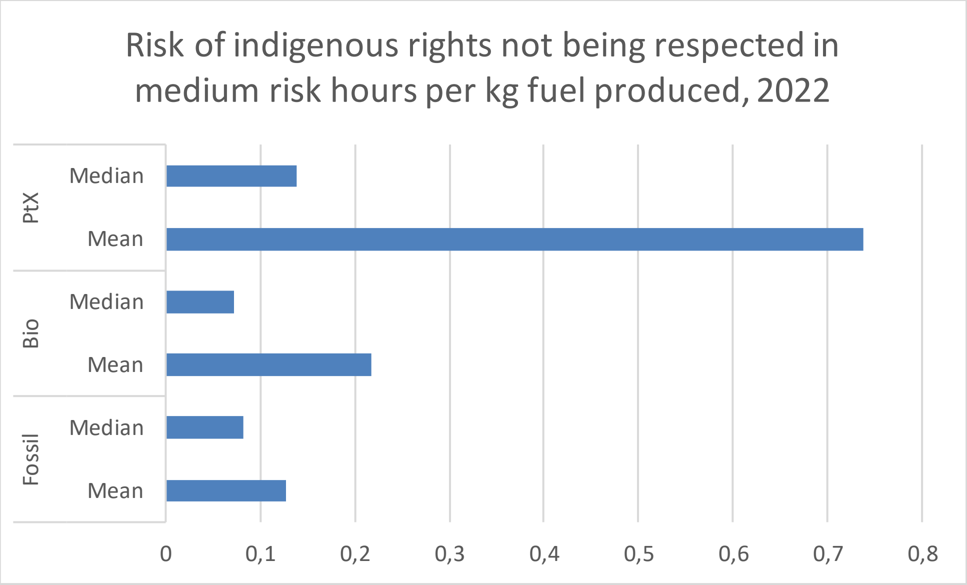

Figure 59: Median and mean results: Indigenous rights, 2022

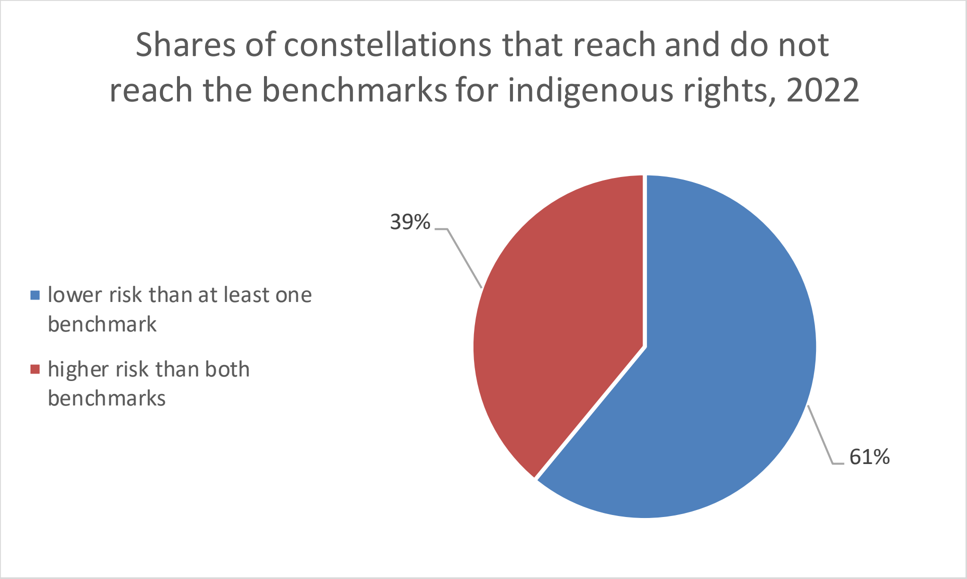

Figure 60: Distribution of constellations: Indigenous rights, 2022

The median risk for all three pathways is comparatively higher than the median values, when the modeled developments until 2050 are considered. This is illustrated in Figure 61. As illustrated in Figure 62, 68% of the evaluated constellations have the potential to achieve a positive development within this category by 2050.

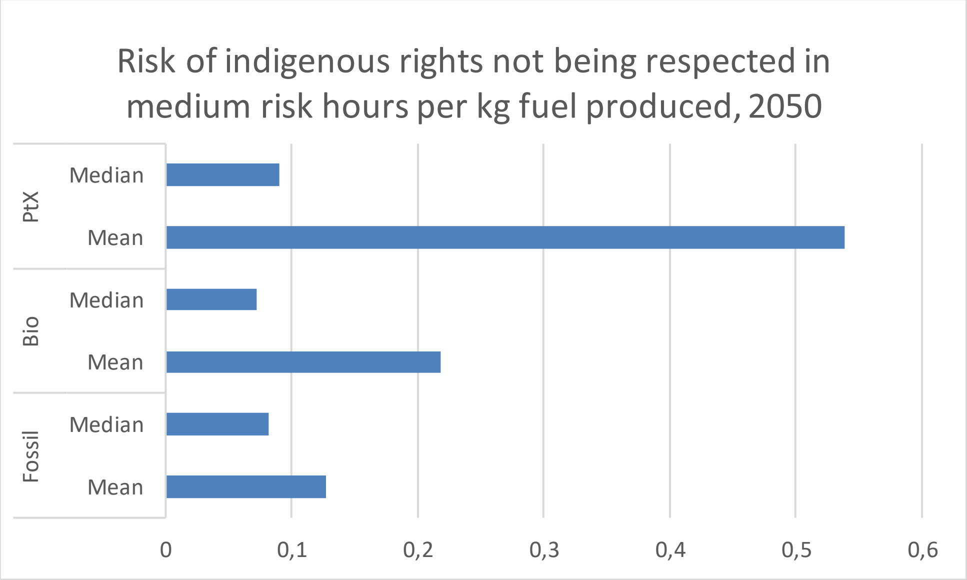

Figure 61: Median and mean results: Indigenous rights, 2050

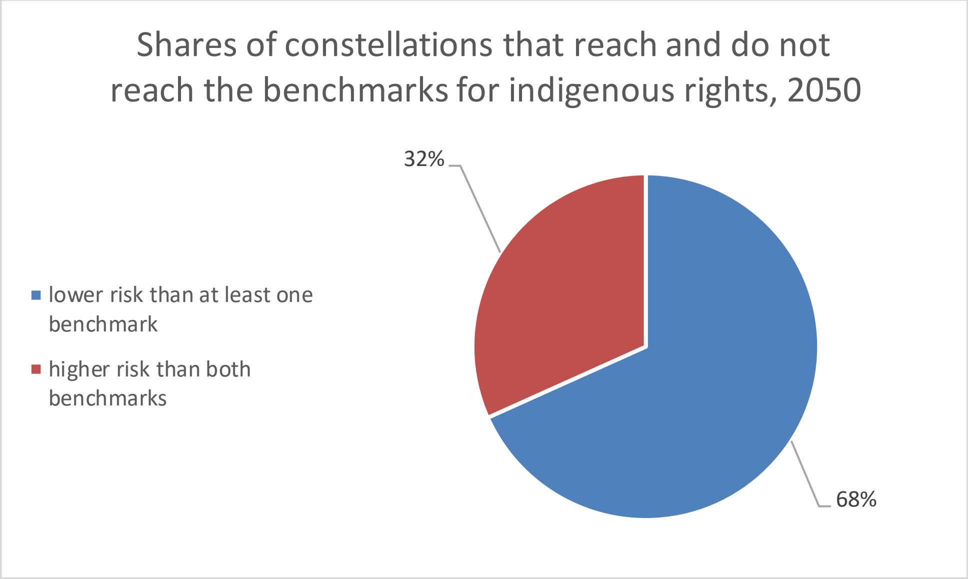

Figure 62: Distribution of constellations: Indigenous rights, 2050

It is often the case that indigenous rights are not given due consideration when discussions are held regarding the transition to alternative fuels. Nevertheless, as evidenced by the results presented here, it is a topic worthy of further consideration.

The construction of new capacities for renewable electricity generation and other PtX processes may pose a risk to the living area and conditions of indigenous peoples. Similarly, the expansion of biomass production or fossil resource extraction carries an inherent risk, whether the fuels in question are fossil- or bio-based.

The relatively high mean values indicate that there are some countries or regions with a high risk and many with a relatively low risk. It would therefore be advantageous to assess this topic at the national or local level, given the specific risks present in different regions. In any case, the involvement of the local population is an essential aspect of a just transition and should be a fundamental element of any new project.

Category 11: Sustainable Cities and Communities

As the results in Figure 63 show, the potential formation of particulate matter along the fuel production life cycle reaches the lowest values for fossil-based fuels, the highest values for bio-based fuels, while the production of PtX-based fuels reaches values in between the other two pathways. It is important to note that the combustion of the fuel is not considered here. All evaluated PtX-based fuel production constellations can achieve an advantage over a benchmark in this category, as shown in Figure 64.

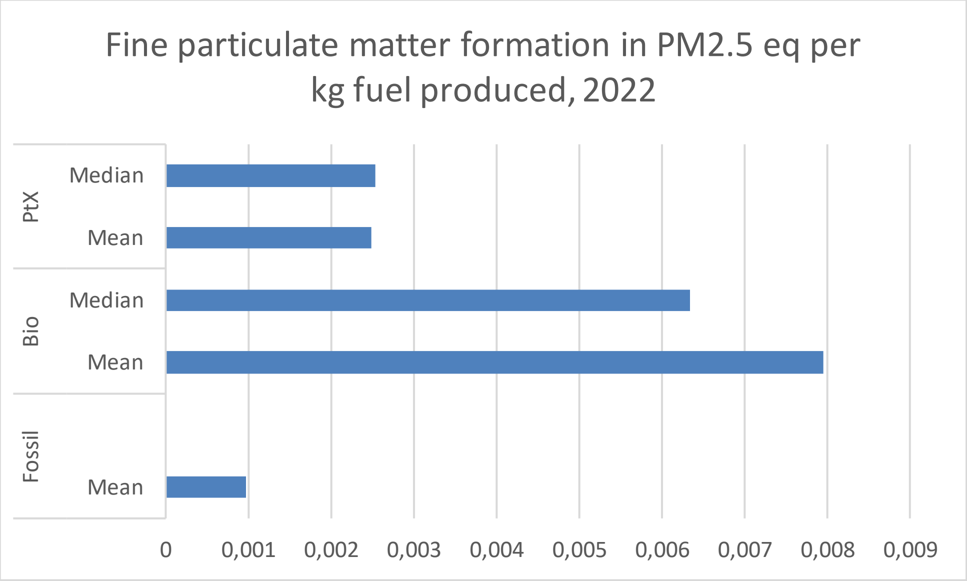

Figure 63: Median and mean results: Fine particulate matter formation, 2022

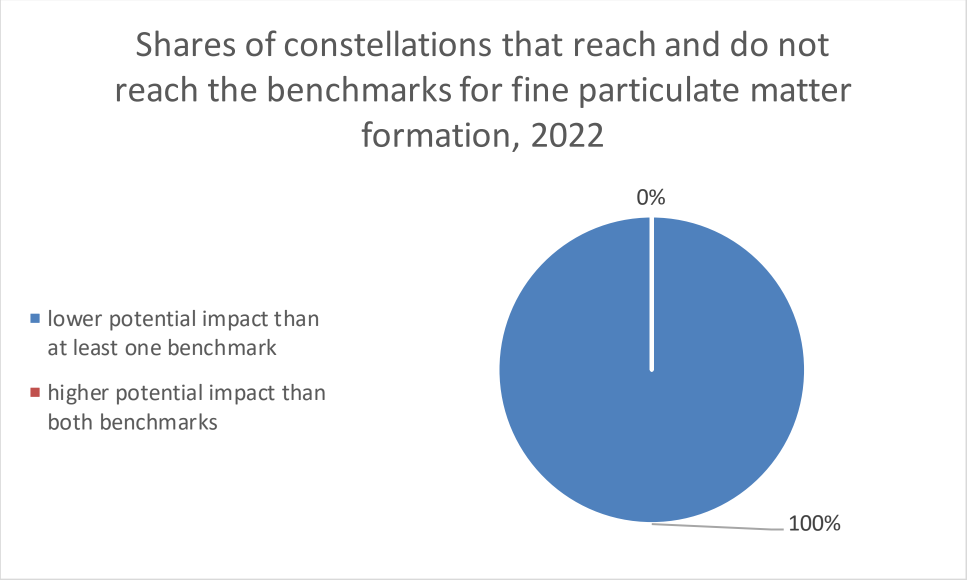

Figure 64: Distribution of constellations: Fine particulate matter formation, 2022

As shown in Figure 65, the potential environmental impacts of PtX-based fuel production in the 2050 scenario would also be lower than those of bio-based fuel production and higher than those of fossil-based fuel production. Figure 66 shows that there is an advantage over at least one benchmark in all constellations considered.

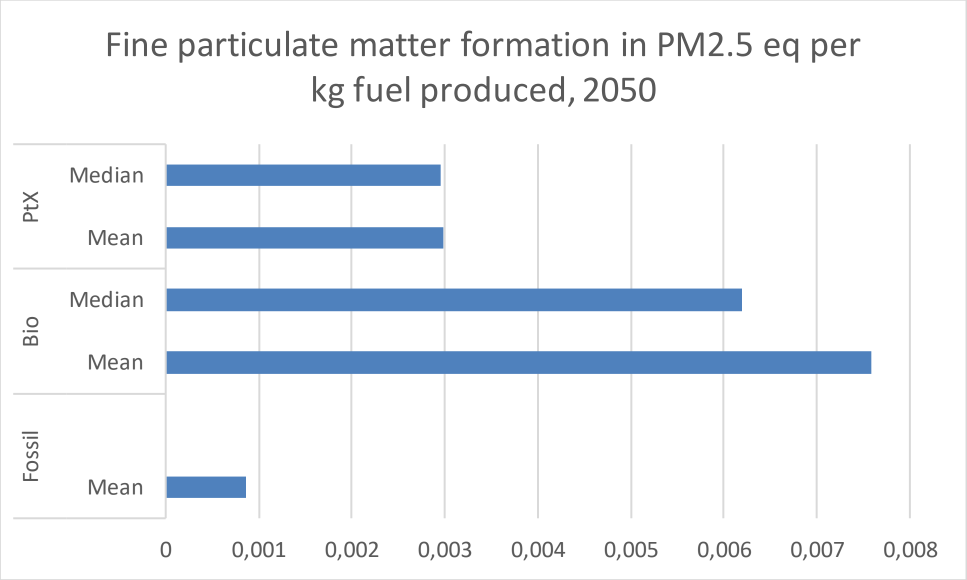

Figure 65: Median and mean results: Fine particulate matter formation, 2050

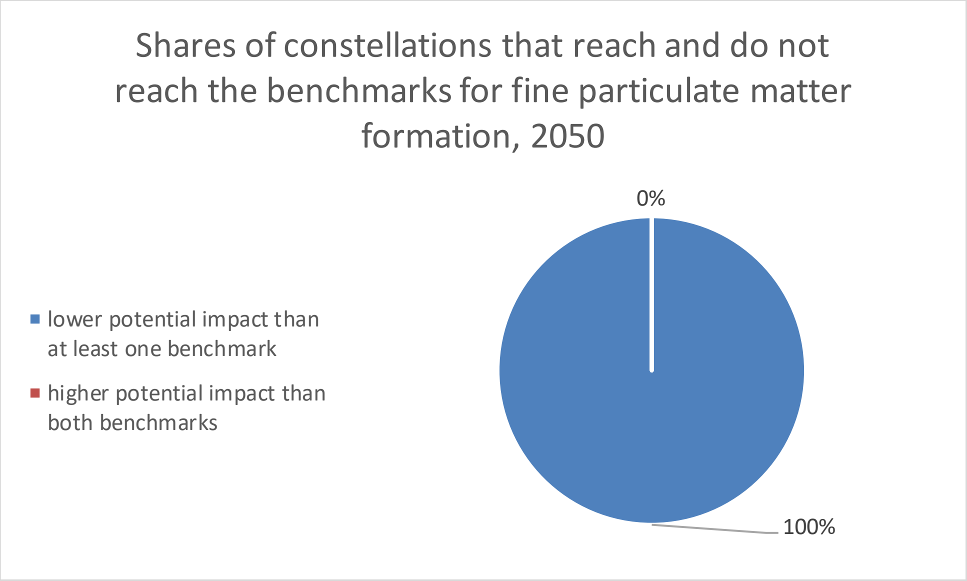

Figure 66: Distribution of constellations: Fine particulate matter formation, 2050

The energy source for PtX plays an important role within this category. Therefore, the choice of technology and the amount of FLH influence the potential environmental impact. Figure 67 shows that there are large differences in the potential PM formation values along the different renewable energy technologies. Similar to Figure 18, this result should not be interpreted as a call for the exclusive use of offshore wind as an energy source for PtX. It is intended to highlight the importance of the energy source and the importance of diversification.

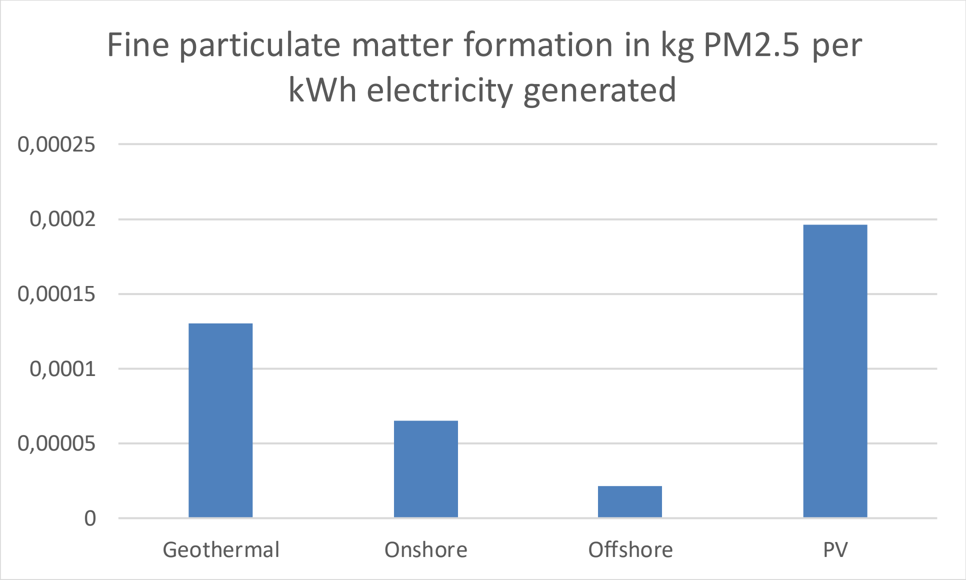

Figure 67: Fine particulate matter formation potential of electricity generation from renewable sources

The scope of this model ends with the provision of the fuel, which is not the main contributing life cycle phase for this indicator. The results of Aurell et al. (2017) show an average emission of 0.129 kg PM2.5 per kg of jet fuel burned. Therefore, fuel production plays a minor role within this category. According to the German Federal Environmental Agency, the formation of particulate matter when burning PtX-based fuels is lower than when burning fossil-based fuels. [147], [148]

Category 12: Responsible Consumption and Production

As shown in Figure 68, the production of PtX-based fuels is associated with the highest values in the mineral resource scarcity category. The benchmark technologies show lower values, especially the fossil-based fuel production. Overall, none of the evaluated PtX constellations can achieve an advantage over bio- or fossil-based fuels, as shown in Figure 69.

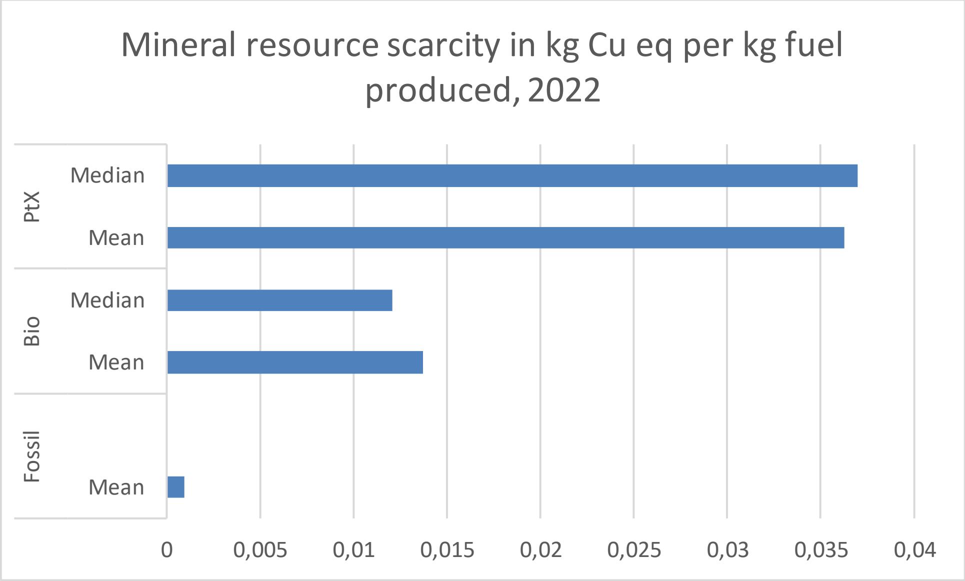

Figure 68: Median and mean results: Mineral resource scarcity, 2022

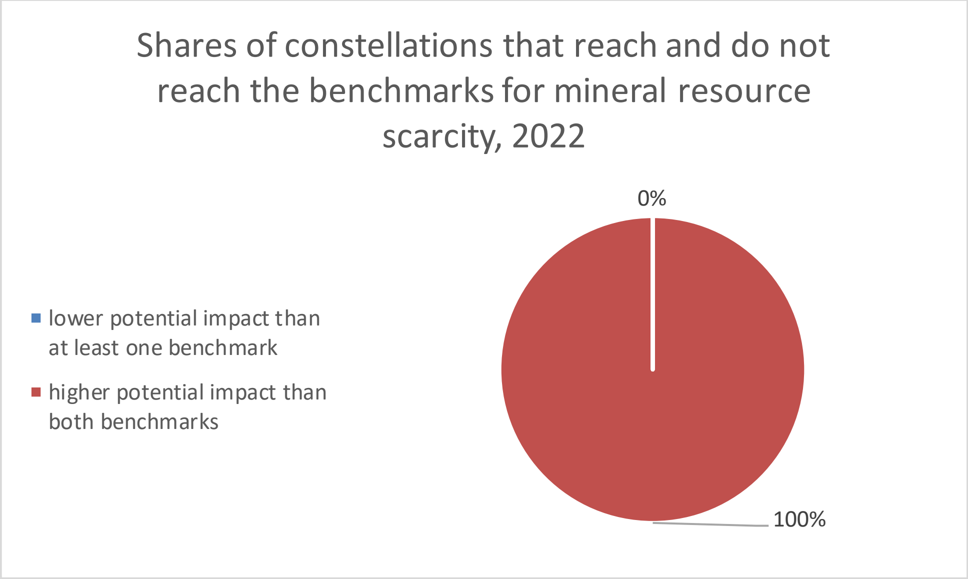

Figure 69: Distribution of constellations: Mineral resource scarcity, 2022

With the technological development of the 2050 scenario, there would still be no advantage in mineral resource scarcity over fossil or bio-based fuels with any of the PtX constellations, as Figure 71 shows.

While the impact of PtX-based fuel production is higher than that of bio-based fuels, it is still evident that both alternative fuels would have a much higher potential impact on mineral resource scarcity than conventional fossil-based fuels, as seen in Figure 70.

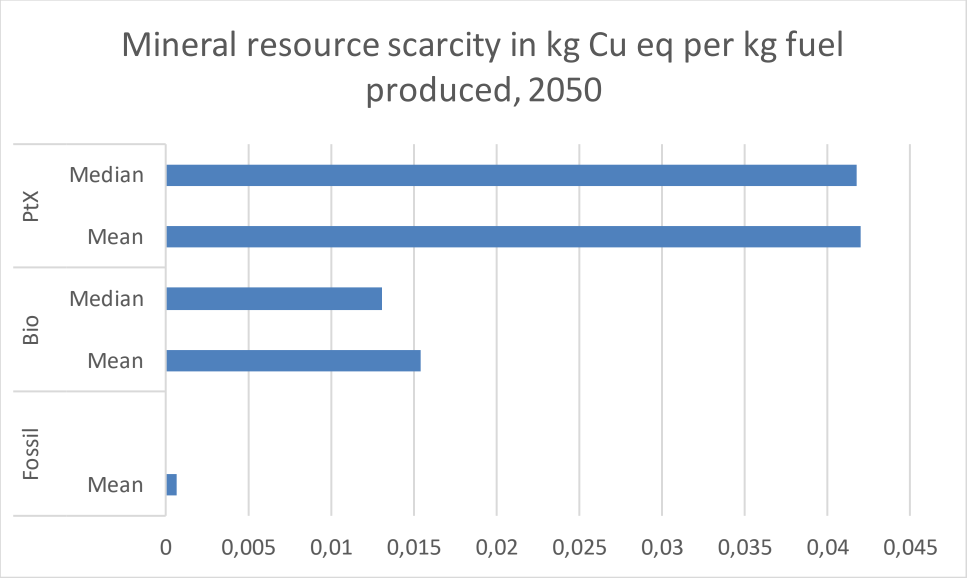

Figure 70: Median and mean results: Mineral resource scarcity, 2050

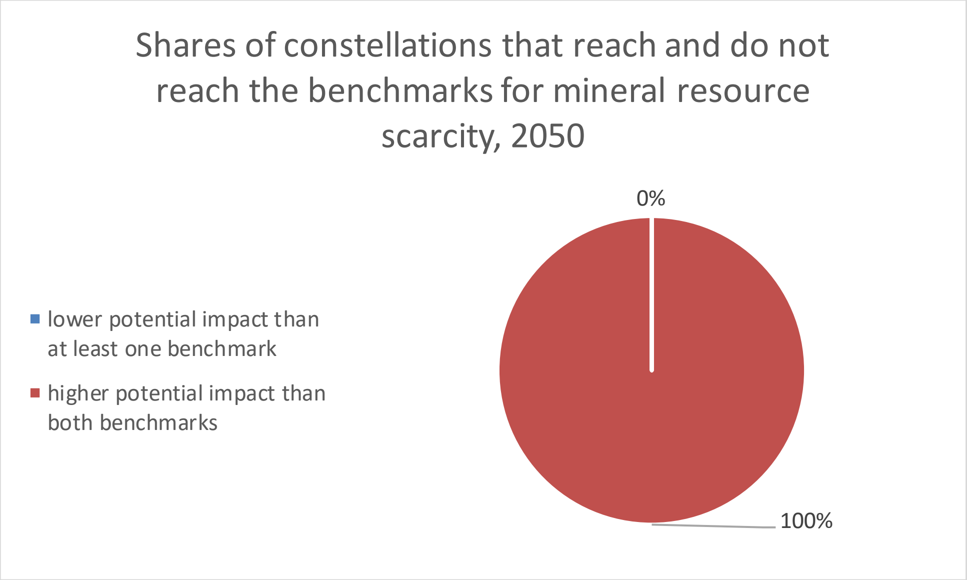

Figure 71: Distribution of constellations: Mineral resource scarcity, 2050

While the scarcity of fossil resources is a great opportunity for PtX, the scarcity of mineral resources is a great challenge. In order to manage scarcity, efficient use of materials must be promoted. One way to address this challenge is to reduce the use of mineral resources required for the various PtX processes. This must be ensured throughout the value chain to minimize the potential environmental impact of mineral resource scarcity. This could include optimization of catalyst surface area or thinner coating layers. Another example would be a mix of electrolyser technologies, as the different types of electrolyzers are constructed with different materials. In addition, the lifetime of the equipment and its efficiency should be improved, resulting in more output per kg of material used. In addition, the end of life of the equipment must be taken into account: Recycling of used materials must be ensured, monitored and encouraged. The recyclability of equipment must be considered at the design stage of the technologies. The processes for recovering the materials must be analyzed and planned as early as possible. [55]

Water desalination also plays a role in this aspect. The Mineral Recovery Enhanced Desalination (MRED) process, for example, recovers minerals in brackish water before it is desalinated. In this way, minerals are recovered and desalination feed water recovery is optimized. [149]

Category 13: Climate Action

The results in this section are shown only with the amounts of constellations that meet the CO_2 benchmark within the two scenarios, as this is the only calculation method used for the GWP indicator. The CO_2 benchmark is calculated with a 70% reduction from the fossil benchmark of 94 g CO_2eq/MJ introduced in Section 3.2.1. Figure 72 shows that a share of 79% can reach this value in the current scenario.

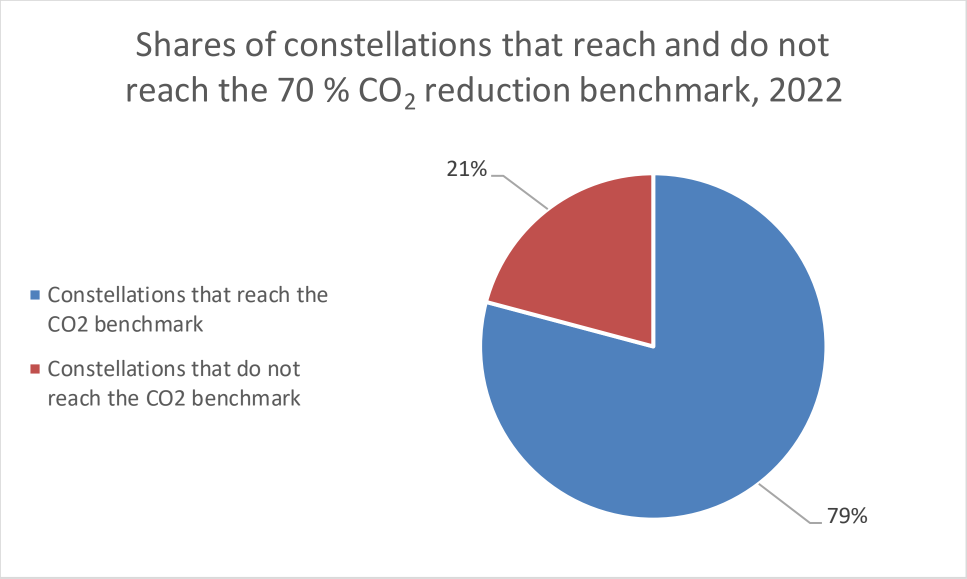

Figure 72: Distribution of constellations: Global Warming Potential, 2022

With the developments modeled until 2050, taking into account a "greener" grid mix and technological development for the production of the plants, a share of 91% would reach the benchmark, as shown in Figure 73.

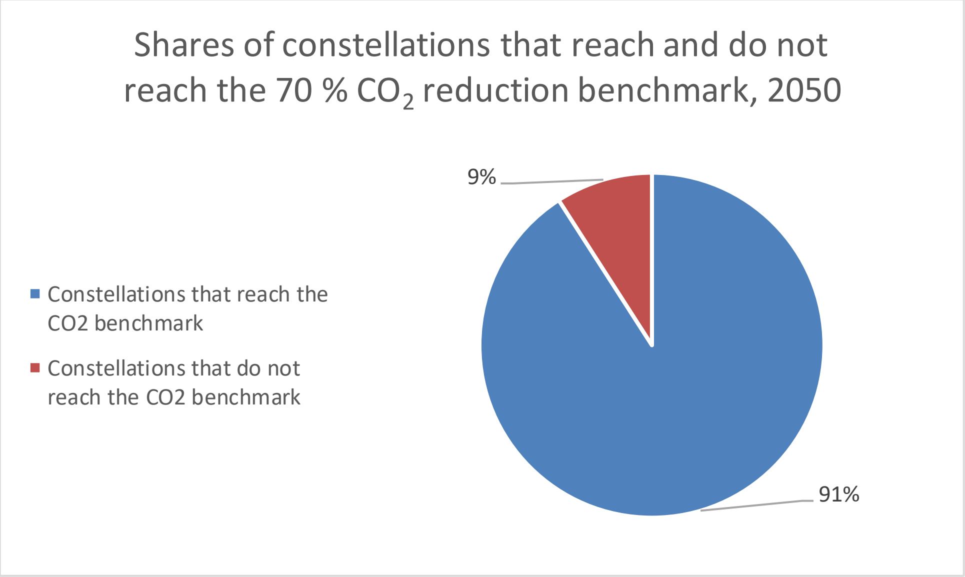

Figure 73: Distribution of constellations: Global Warming Potential, 2050

The key message of this section is that PtX must go hand in hand with the decarbonization of the energy sector. More renewable energy and less fossil energy must be used in the electricity mix, which reduces the carbon footprint of all production processes along the value chain. This will reduce the specific carbon footprint of the wind and PV power plants, as well as the other processes, and thus the carbon footprint of PtX-based fuels. With the current relatively high share of fossil-based energy in the global grid mix, PtX-based fuels do not meet this benchmark in all locations. Therefore, it is important to consider a high amount of FLH when determining the energy source for the PtX plant. The amount of FLH modeled here is based on country averages, which means that there are typically areas in each country that offer higher amounts and therefore more favorable conditions. A high level of FLH offsets the relatively high carbon footprint of solar PV in particular with the current global grid mix. With a higher share of renewables in the global grid mix, the amount of FLH becomes less critical for this aspect, but remains still relevant in general, especially from a cost perspective.

PtX is energy intensive and has several sustainability risks. More efficient and sustainable technologies or measures are available for many applications in the context of climate protection. The focus should be on hard-to-abate sectors where there is either no current alternative to liquid fuels (e.g. aviation or shipping) or where the molecular structures of hydrocarbons or ammonia are required and the economy depends on them (e.g. chemical industry or fertilizer production). Only in combination with the other steps can climate protection be implemented in a sustainable way.

Category 14: Life below Water

As shown in Figure 74, the potential environmental impact of PtX-based fuel production on marine eutrophication is lower than that of bio-based fuel production and higher than that of fossil-based fuel production. Figure 75 shows that all constellations meet at least one of the benchmarks.

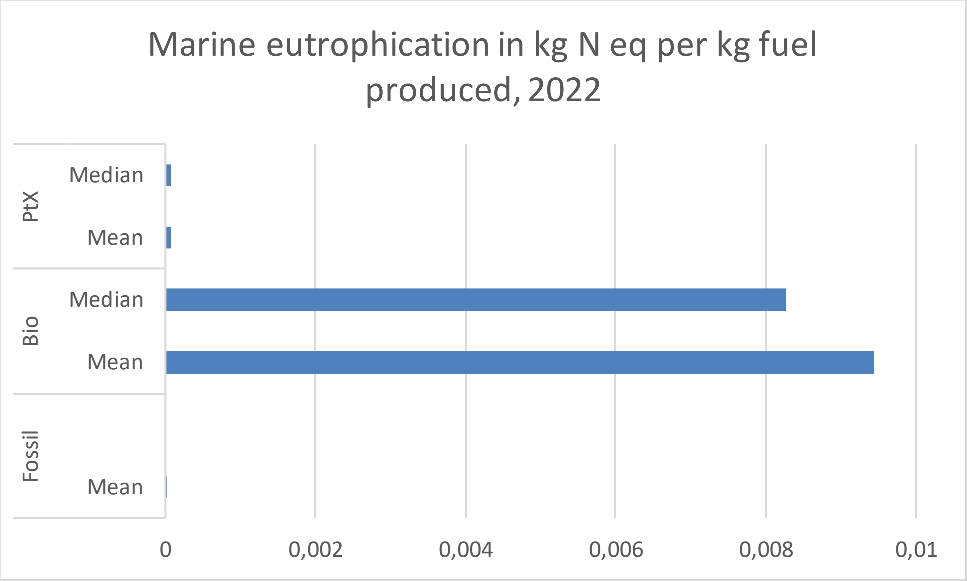

Figure 74: Median and mean results: Marine eutrophication, 2022

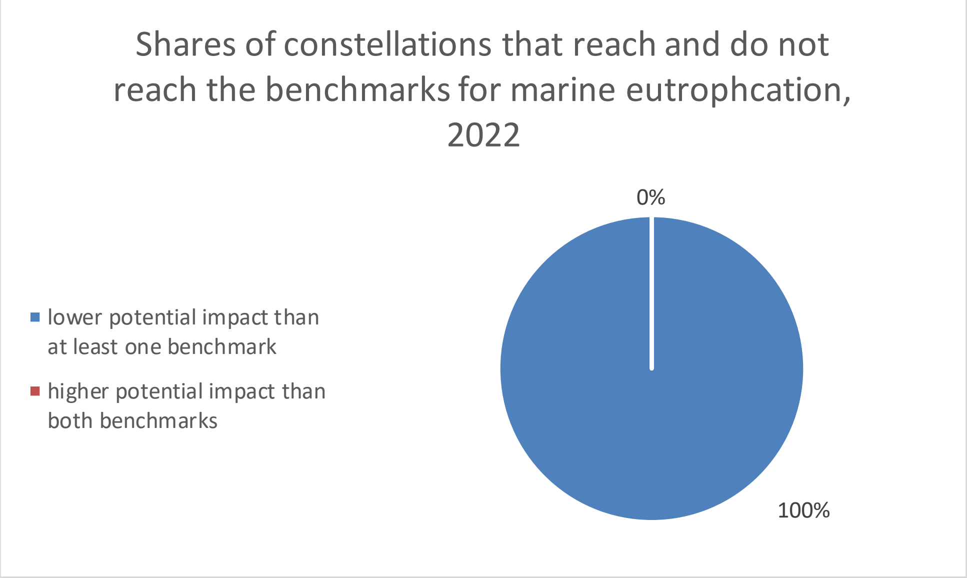

Figure 75: Distribution of constellations: Marine eutrophication, 2022

As shown in Figure 76, the potential environmental impacts on marine eutrophication from PtX-based fuel production are lower than those from bio-based fuel production even in the 2050 scenario, but still higher than those from fossil-based fuel production. As shown in Figure 77, each of the modeled PtX constellations that reaches the CO_2 benchmark in 2050 can achieve a benefit within this category.

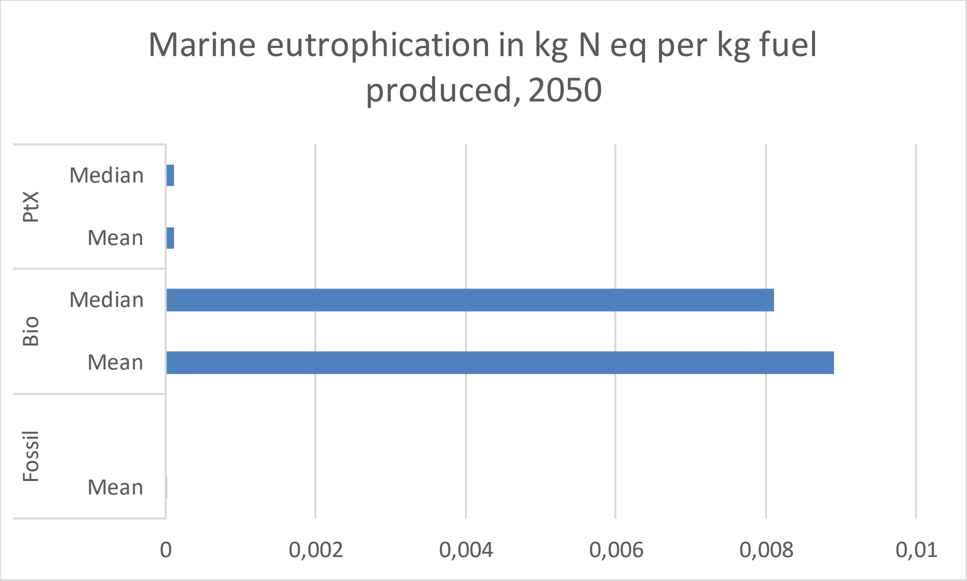

Figure 76: Median and mean results: Marine eutrophication, 2050

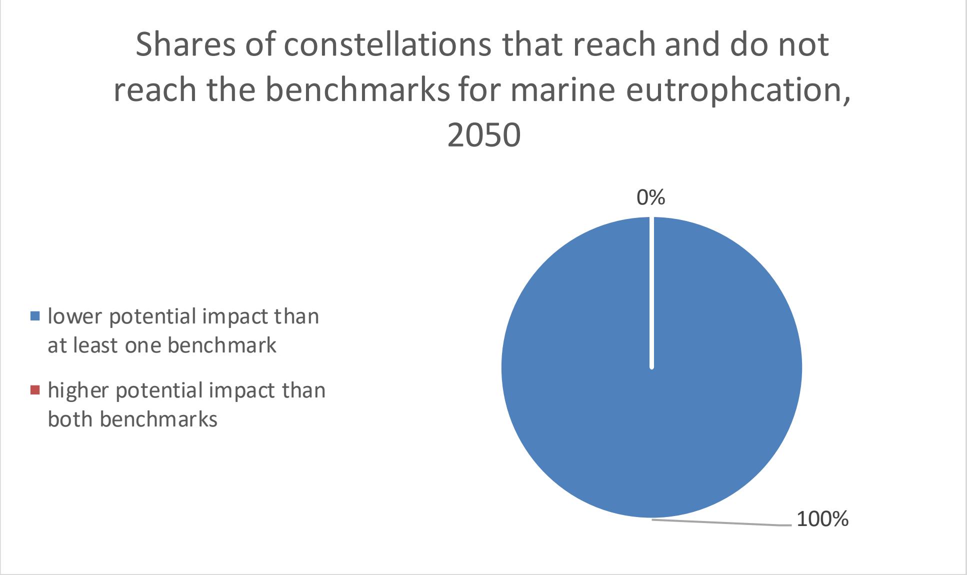

Figure 77: Distribution of constellations: Marine eutrophication, 2050

Compared to the alternative of bio-based fuels, this category is not critical. While the potential impacts are higher than for fossil-based fuels, the risk is much lower than for bio-based fuels. Marine eutrophication is mainly driven by agriculture, in particular by the use of N- and phosphorus-based fertilizers. From a purely technological perspective, the use of DAC as a carbon source for PtX does not need to be linked to the use of agricultural resources, except for land use. However, due to the rather low TRL of DAC and the sustainability issues associated with industrial point sources, biogenic CO_2 sources are an important avenue to consider. Biogenic CO_2 can be produced with lower costs and energy requirements than DAC and is already more available from a technological point of view, but at the same time depends on regional availability. However, in order not to increase the risk of increased marine eutrophication or other associated risks, the focus of biogenic CO_2 sources should be on residues only. Biomass will still be needed in many areas, and the residues can be used as a sustainable carbon source, but biomass production should not be dedicated to producing CO_2 as its main output.

Category 15: Life on Land

As shown in Figure 78, the potential environmental impacts within the terrestrial ecotoxicity category are higher for PtX and bio-based fuels than for fossil-based fuels. Both alternative fuels have a much higher potential environmental impact than their fossil-based counterpart. Within this category, the PtX-based fuel is associated with a higher potential environmental impact than the bio-based fuel. Figure 79 shows that the share of constellations that achieve a benefit against at least one benchmark is 12%.

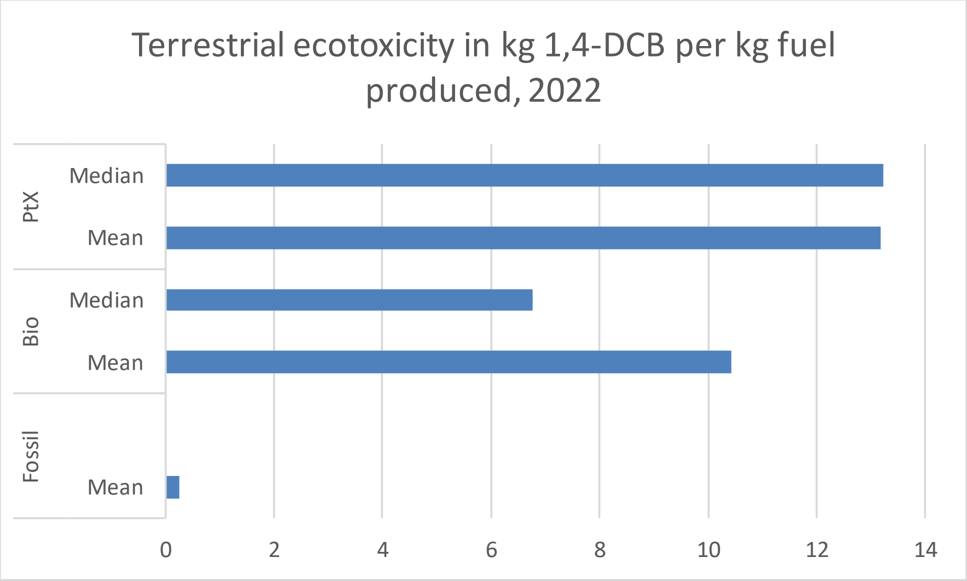

Figure 78: Median and mean results: Terrestrial ecotoxicity, 2022

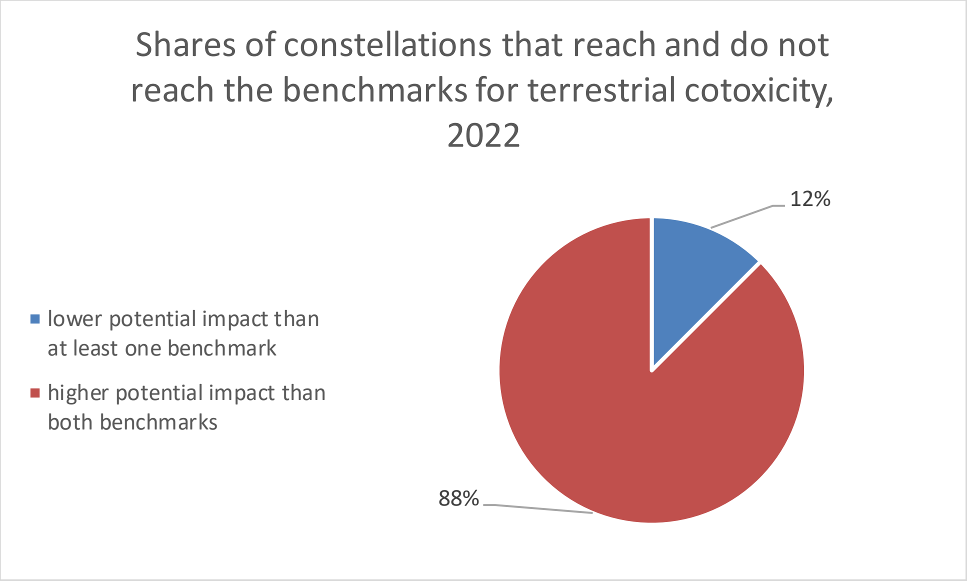

Figure 79: Distribution of constellations: Terrestrial ecotoxicity, 2022

With the modeled development until 2050, Figure 80 shows that the highest values would still be associated with PtX-based fuels, followed by bio-based fuels. The number of constellations reaching a benchmark decreases to 9% as shown in Figure 81.

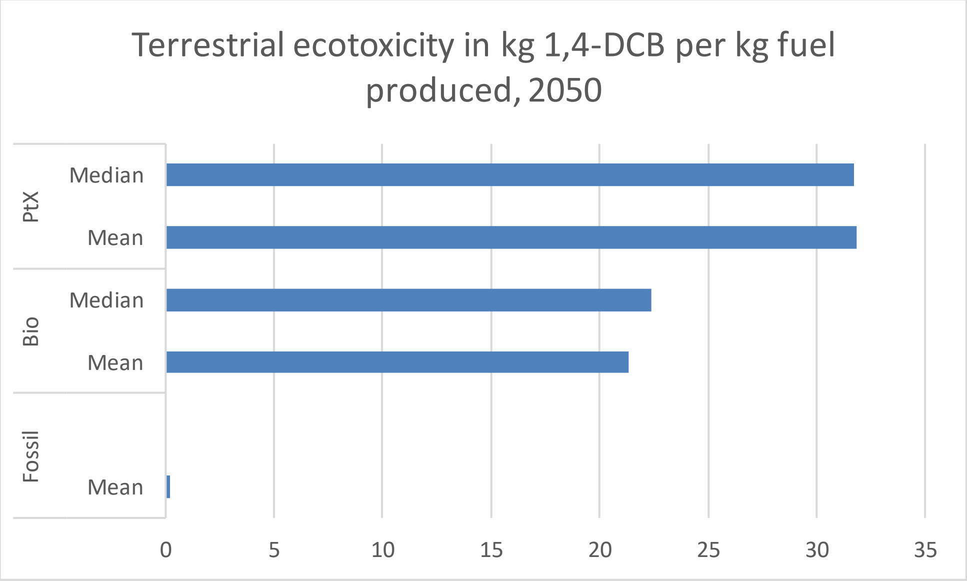

Figure 80: Median and mean results: Terrestrial ecotoxicity, 2050

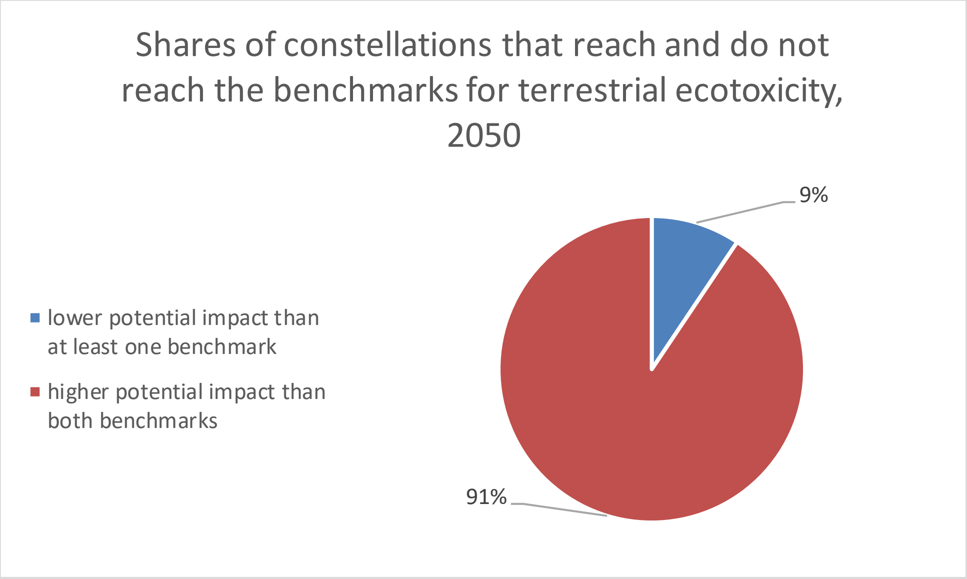

Figure 81: Distribution of constellations: Terrestrial ecotoxicity, 2050

The terrestrial ecotoxicity of the PtX processes is mainly caused by copper, ferronickel and silver, which are used in several processes along the value chain. As the share of RES in the global electricity mix increases, this category becomes more critical. As shown in Figure 82, PV in particular has a relatively high potential environmental impact on terrestrial ecotoxicity among the different RES, while offshore and onshore wind and geothermal have a lower potential impact. It is therefore important to diversify the energy source and aim for a high level of FLH to reduce the overall potential environmental impact of PtX fuel production.

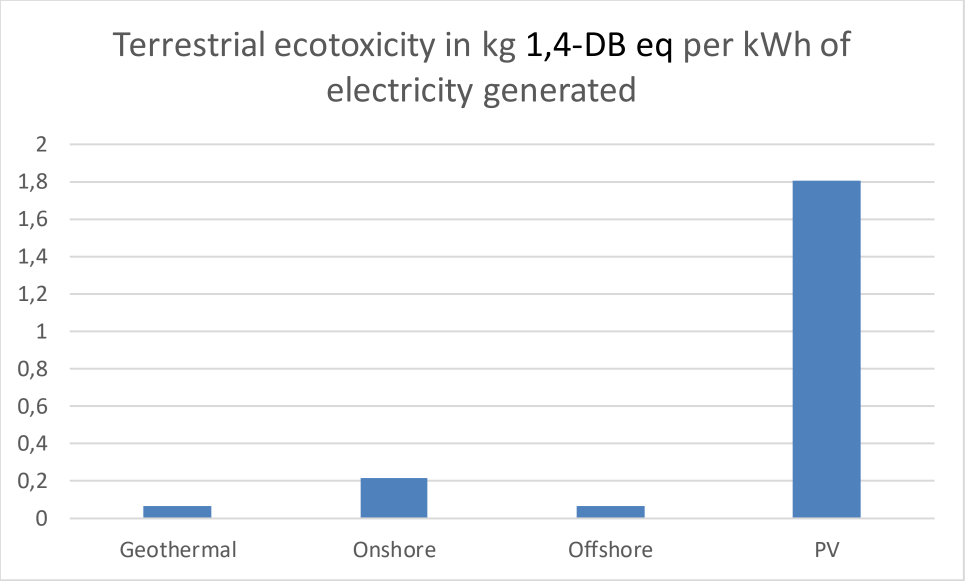

Figure 82: Terrestrial ecotoxicity potential of electricity generation from renewable sources

Category 16: Peace, Justice and strong Institutions

As shown in Figure 83, the mean scores for fossil and bio-based fuel production are higher than those for PtX-based fuel production when it comes to the risk of active involvement in corruption and bribery. However, the median scores for PtX-based fuels are higher than those for the other pathways. It can also be seen that all the means are higher than the medians. Figure 84 shows that 71% of the constellations considered can achieve a benefit within this category.

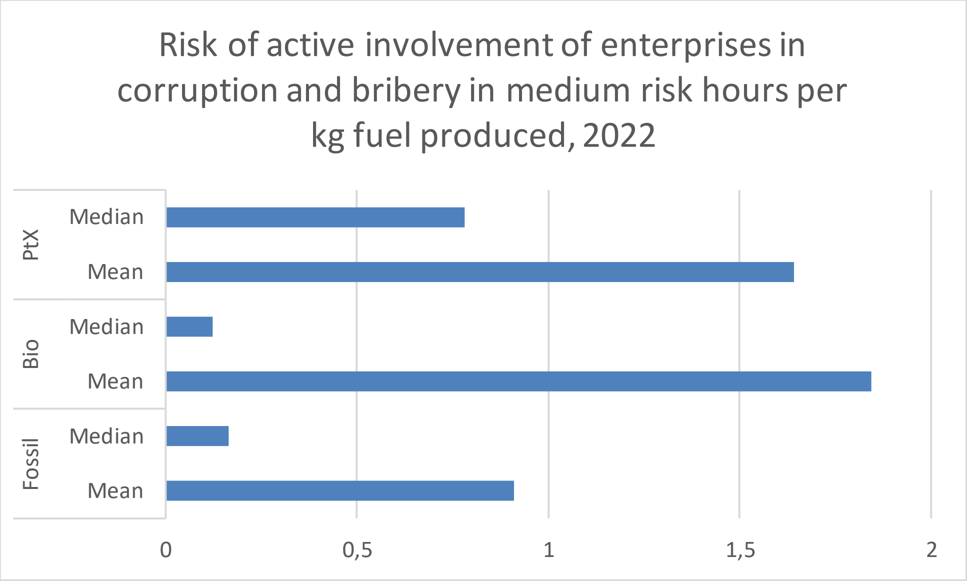

Figure 83: Median and mean results: Active involvement of enterprises in corruption and bribery, 2022

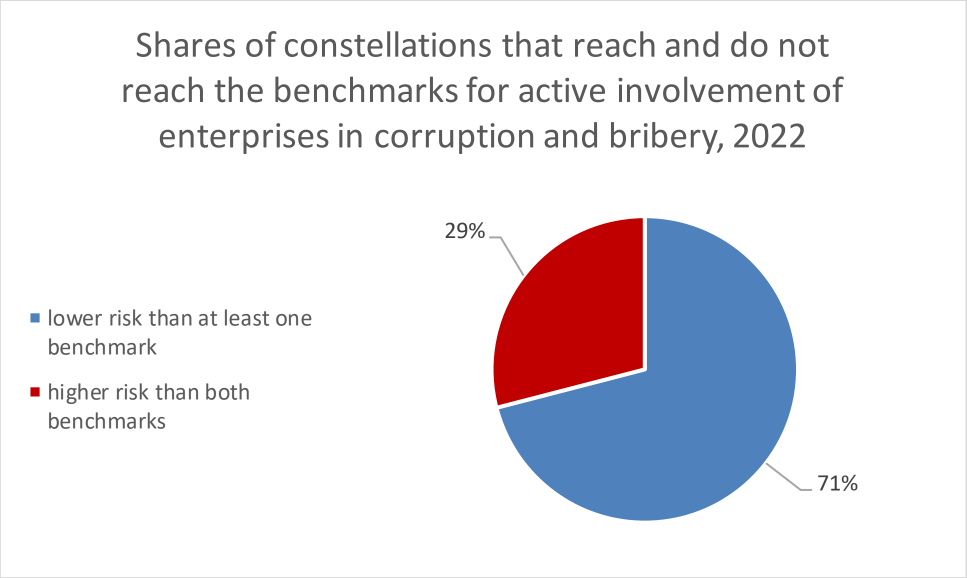

Figure 84: Distribution of constellations: Active involvement of enterprises in corruption and bribery, 2022

In the 2050 scenario, the mean value of PtX-based fuel production would remain at the lowest level of the compared alternatives, the median at the highest level, as shown in Figure 85. The higher mean values compared to the median values are similar to the 2022 scenario. As Figure 86 shows, 86% of the constellations can achieve a benefit.

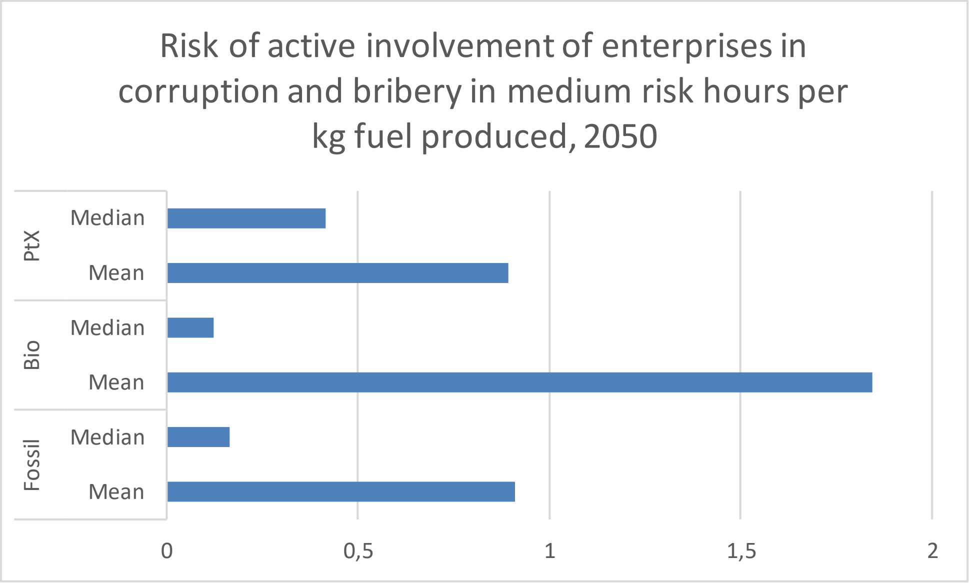

Figure 85: Median and mean results: Active involvement of enterprises in corruption and bribery, 2050

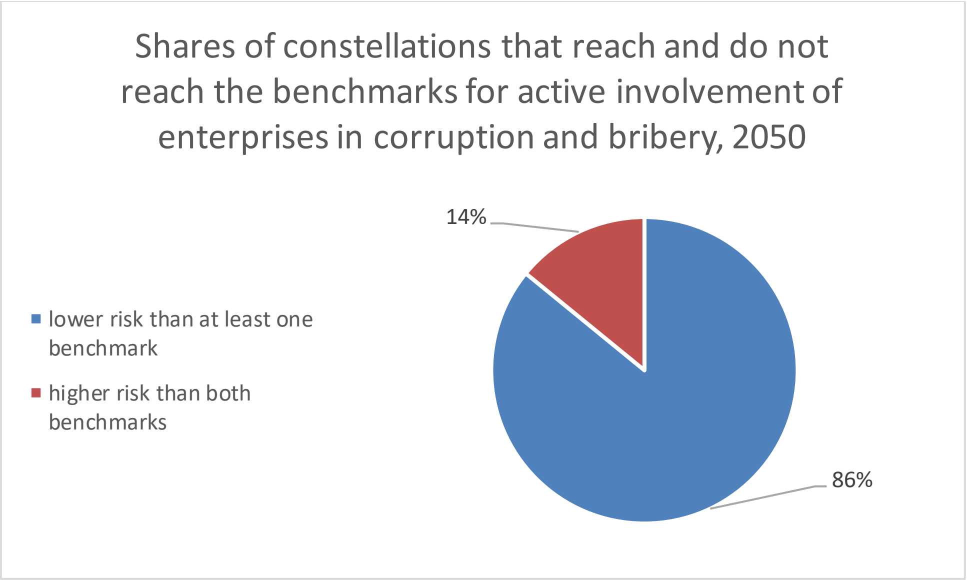

Figure 86: Distribution of constellations: Active involvement of enterprises in corruption and bribery, 2050

In terms of conflict risk, the mean value for PtX-based fuel production is higher than the mean value for fossil and bio-based fuel production, as shown in Figure 87. In particular, for PtX and fossil-based fuel production, the means are significantly higher than the medians. As shown in Figure 88, 79% of the constellations achieve an advantage over one of the benchmarks.

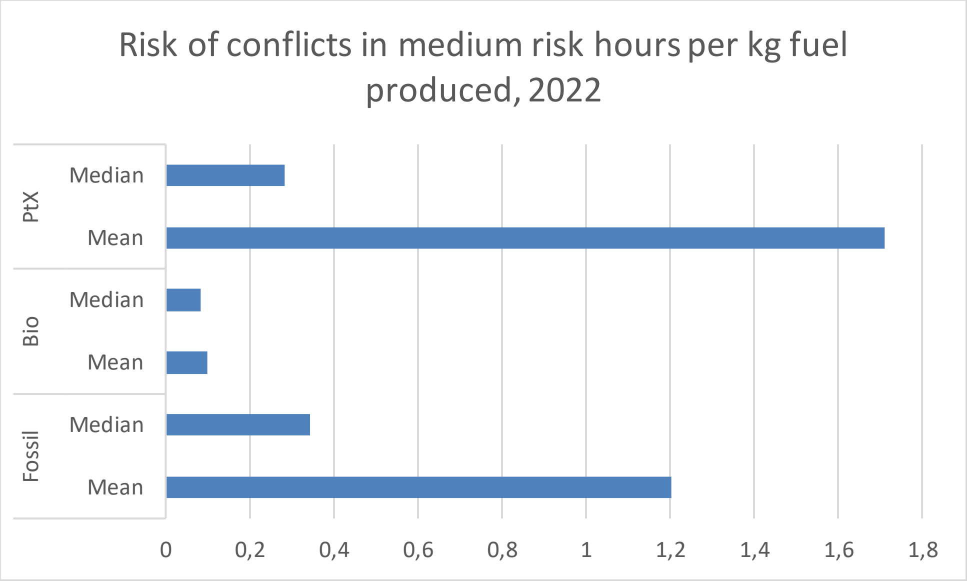

Figure 87: Median and mean results: Risk of conflicts, 2022

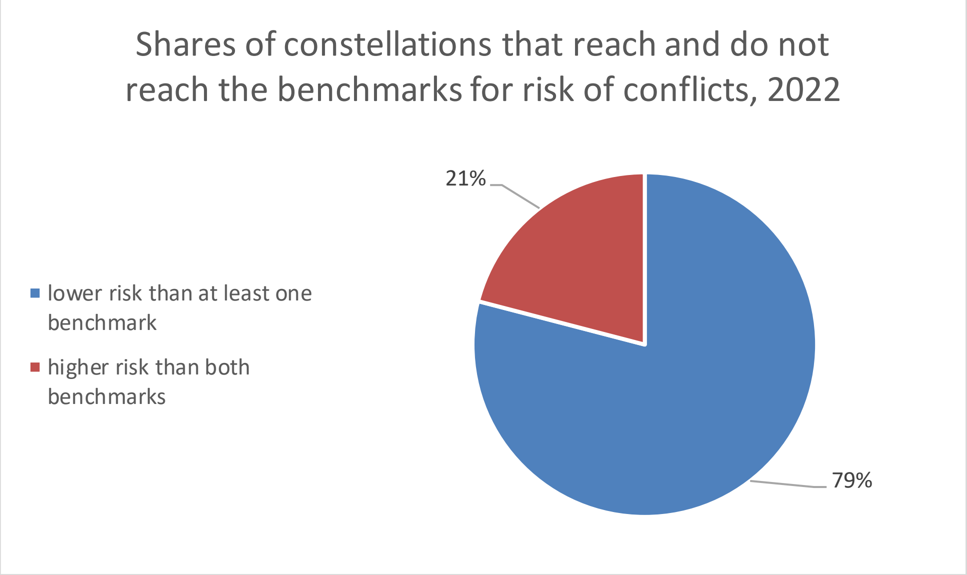

Figure 88: Distribution of constellations: Risk of conflicts, 2022

The median value for the risk of conflicts within the 2050 scenario drops to a lower level for PtX-based fuel production than for fossil-based fuel production, as shown in Figure 89. Both values remain higher than for bio-based fuels in the 2050 scenario. Figure 90 shows that 84% of the constellations are associated with a benefit over at least one benchmark.

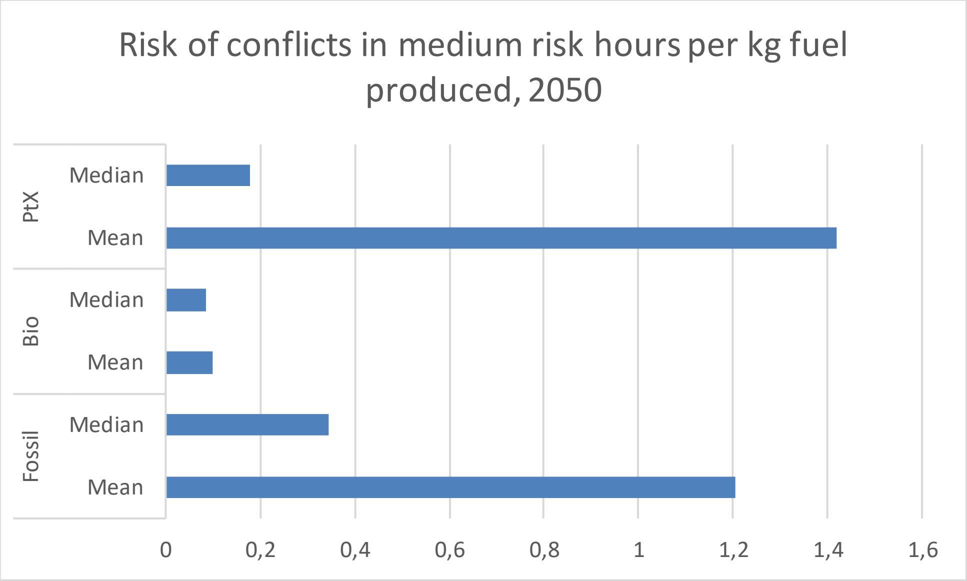

Figure 89: Median and mean results: Risk of conflicts, 2050

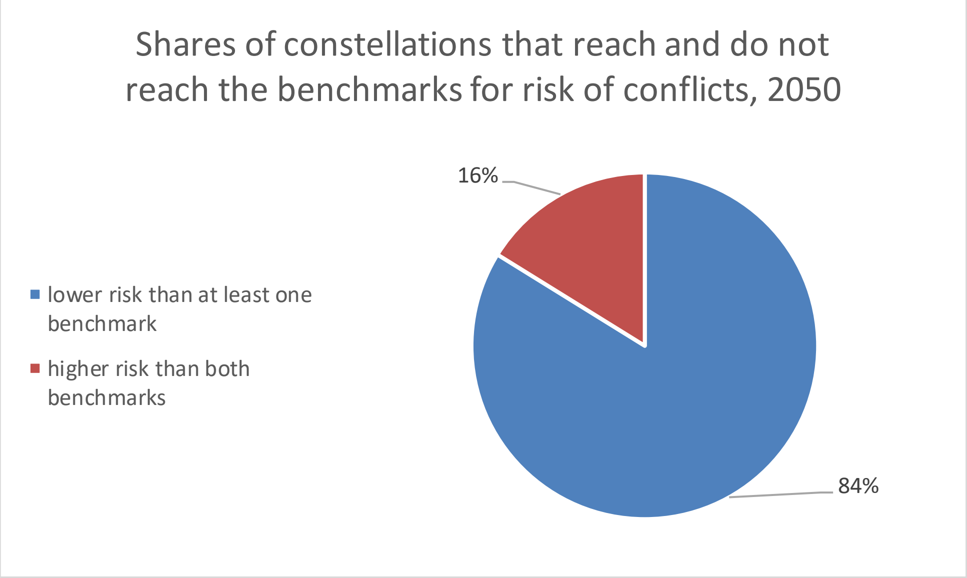

Figure 90: Distribution of constellations: Risk of conflicts, 2050

As already mentioned in Section 3.2.2, large-scale energy projects are often associated with the risk of corruption and bribery. Although the number of PtX constellations with a lower risk of corruption and bribery than fossil or bio-based pathways is high, there are also constellations with a much higher risk. As the PtX constellations cover countries and regions all over the world, both low and high risk areas for corruption are included.

Especially in countries and regions with a high risk of corruption and bribery, measures for increased transparency and participation would have to be ensured. This could be supported by a mandatory demonstration of anti-corruption measures throughout the life cycle of projects. Accessible information on companies and individuals involved, financial flows, and stakeholder involvement would be beneficial in combating corruption and bribery in these projects.

At the same time, the risk of conflict can be linked to dependencies, resource availability and power imbalances. One opportunity associated with the transition to PtX-based fuels is potential independence. If countries are able to produce their own fuels, the power of certain countries over others will be reduced, which could affect the risk of conflict. The transition to PtX-based fuels could reshape the global energy market.

Category 17: Partnership for the Goals

As shown in the other 16 categories, PtX is not sustainable by default. Global cooperation is needed to ensure a sustainable transition on a global scale. At the same time, there are risks involved in working with other countries, as discussed in category 16. Corruption and bribery, as well as the risk of conflict, are significant and need to be addressed and overcome. Especially when considering international PtX value chains, where the end or intermediate products are to be traded internationally, the sustainability of the partnership has to be ensured.

As seen in the initial case of Desertec, there have been plans for international cooperation in renewable energy in the past, but without focusing on local needs. When it comes to developing international PtX value chains, local socio-economic needs and expectations, technical and environmental conditions, and government policies may be different from those expected by partner countries. The local context needs to be included in the planning process, which is also an opportunity to increase the acceptance and sound implementation of the technology. In order to better understand the local context, dialogue formats and partnerships with local institutions could be implemented, where all these aspects are discussed and aligned in a way that leads to sustainable development at both global and local levels.

When we talk about the techno-ecological dimension, we are talking about the choice of sources for water, carbon, land and energy, which have been discussed in the other categories. The additional water desalination for more available drinking water, a more reliable electricity supply through an improved grid, a carbon source that does not lead to the locking-in of fossil-based industries in the country. At the same time, the end of the value chain, the demand for the products, is equally important.

Production costs are higher, and transportation infrastructure may be unavailable or very expensive to export PtX-based fuels from where they are produced. One approach to this problem is to export only the CO_2 reduction of the fuel through a book-and-claim approach with certificates. This means that the additional production costs are paid by the customer regardless of the location and use of the actual PtX-based fuel, so the fuel does not need to be transported. This can facilitate and encourage the production of PtX-based fuels in many countries, as the higher costs are covered and the CO_2 emissions are reduced in any case. In the long run, however, the fossil-based fuel should be replaced everywhere. [150]

Capacity development activities are an activity that can support a sustainable and just transition by strengthening the local level of knowledge and participation, which should then lead to a socially and environmentally sustainable transition for local stakeholders. For capacity development partnerships, it is important to identify the benefits and expectations for each partner. At the same time, the expectations should be in line with the strengths of each partner, so that the cooperation system benefits from an orientation towards strengths. With different levels of power and different interests among the cooperation partners, there should always be room to address increasing conflict potential and thus find common solutions. [151]

5.2 Main Opportunities and Challenges

As can be seen in Figure 91, a very high proportion of constellations that reach the CO_2 benchmark can also achieve advantages over at least one benchmark in most of the techno-ecologically relevant indicators assessed. PtX-based fuels are associated with positive development against at least one benchmark for the indicators of terrestrial acidification, water consumption, land use, fossil resource scarcity, particulate matter formation, and marine eutrophication. The most critical risks from a techno-ecological perspective in the short and long term are mineral resource scarcity (responsible consumption and production category) and human carcinogenic toxicity (health and well-being category). For both indicators, no constellation achieves an advantage over the benchmark technologies, neither in the 2022 scenario nor in the 2050 scenario. Terrestrial ecotoxicity (life on land category) can only reach values of 12 and 9%, representing another critical challenge within the techno-ecological dimension. Human non-carcinogenic toxicity (health and well-being category) is not critical in the short term but becomes more critical by 2050. All critical categories depend on the resource extraction and processing of materials used for the processes along the value chain, and even very high FLH do not result in an advantage for PtX-based fuel production over the benchmark technologies.

The results of the social indicators are more spread out, which can be explained by the fact that the governmental and social conditions in each country are different. Child labor is the only socio-governmental indicator with a share below 50%, making it a less sustainable alternative in 2022. However, it can be seen that sustainable development can be achieved in all categories by 2050, i.e. at least 50% of the PtX constellations could achieve at least one benchmark and thus a positive development in all socio-governmental categories

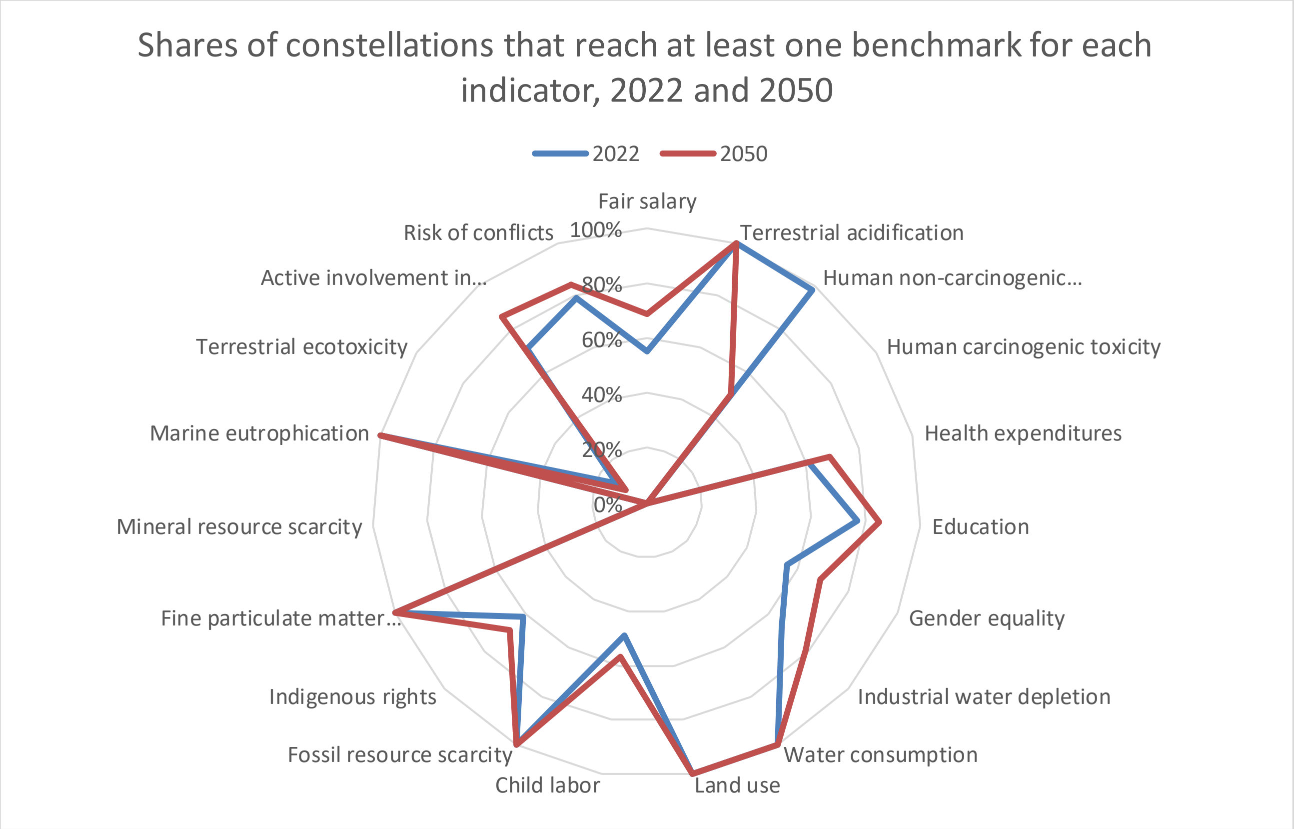

Figure 91: Shares of constellations that reach at least one benchmark (all indicators)

As Figure 92 shows, fewer constellations can achieve a positive development against both benchmark technologies. Within the techno-ecological dimension, only the indicator fossil resource scarcity shows significant benefits against both benchmarks. In the socio-economic dimension, there are still many opportunities. More than 50% of the benefits against both benchmarks by 2050 can be achieved with the indicators Indigenous Rights, Child Labor, Industrial Water Depletion, Education Expenditures, Health Expenditures, Active Involvement in Corruption and Bribery, and Fair Salary. These categories show a high opportunity for sustainable development with PtX-based fuels in the long run. The risk of conflict and gender equality categories become more critical when compared to both benchmarks rather than just one.

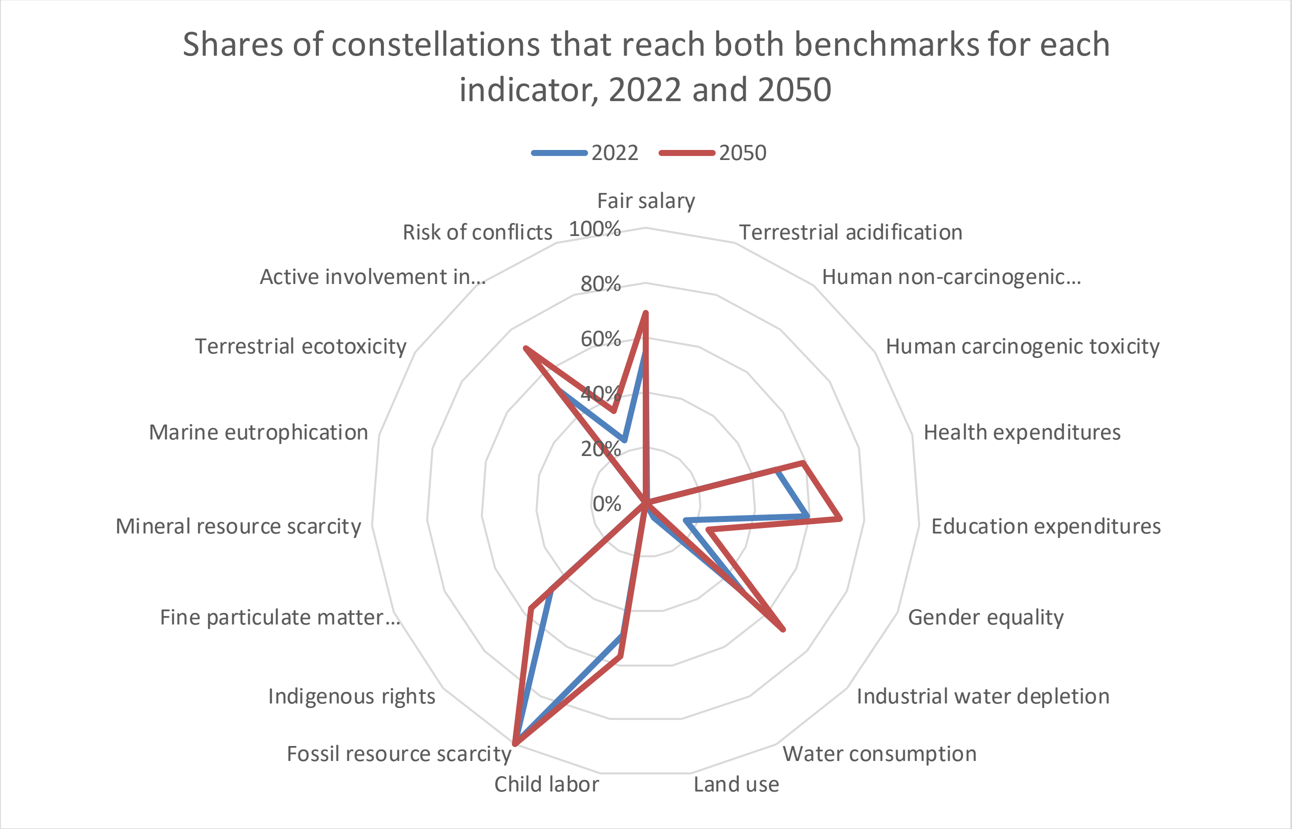

Figure 92: Shares of constellations that reach both benchmarks (all indicators)

Figures 91 and 92 show that there are many opportunities to improve the sustainability of fuel production with PtX-based fuels, especially when considering benefits against at least one of the benchmarks. The difference between the results in Figures 91 and 92 shows the importance of comparing new technologies not only with the status quo (fossil fuels), but also with the remaining alternatives. There are opportunities and risks associated with all three paths, and none of them is the solution to all sustainability issues. As the transition from a fossil-based economy is inevitable, the additional challenges associated with this transition need to be assessed and addressed.

Approaches and measures from a techno-ecological and a socio-political perspective to address these challenges are summarized in the following subsections. The approaches presented are based on the literature in the respective field or on commonly discussed approaches in the context of green H_2 and PtX. The approaches presented are not exhaustive and could be complemented and improved by other measures. It is therefore important to understand the source of the problems so that further countermeasures can be developed in the future. Another key aspect in reducing the potential impact and risk of the categories presented is to reduce fuel consumption in the first place by sufficiency.

5.2.1 Techno-ecological Perspective

The approaches within the techno-ecological sphere are summarized and categorized into potential fields of intervention.

Global Warming Potential

As GWP reduction is the main objective, several essential aspects of GWP reduction by PtX are discussed here - two important aspects are renewability and additionality of electricity from renewable sources. If fossil-based energy is used to power PtX processes (especially the electrolyzers), the lifecycle CO_2 emissions are much higher than with fossil-based fuels. It is therefore important to ensure that only renewable energy is used throughout the process. Furthermore, the capacity for this renewable energy should be additional. At the same time, it is inevitable that the share of renewable energy in the grid mix will increase. The higher the share of renewables in the global grid mix, the lower the carbon footprint of all upstream processes along the value chain and the final product. This can be seen in the share of constellations currently meeting the CO_2 benchmark and the share meeting the benchmark in the 2050 scenario. At the same time, the energy sector needs to be decarbonized, while PtX is implemented for those sectors where it is not yet possible to use electricity from RES more efficiently.

The third important parameter is the amount of FLH for electricity generation. The higher the amount of FLH, the lower the specific GWP of the generated electricity and therefore of the PtX fuel. Therefore, the right technologies should be chosen for each site. One way to achieve a high utilization rate of the remaining parts of the PtX plant (everything downstream of the electricity generation itself), which then reduces the specific GWP of the PtX process, is to combine PV and wind power plants in a hybrid approach. Although there is some overlap, the total amount of FLH is greatly increased.

The carbon part of the synthetic hydrocarbons is another important aspect of the GWP along the life cycle. It is not specifically shown in the result as the other carbon sources are not part of the model, but it is still an important aspect to mention. In contrast to the industrial sources, DAC and biomass initially lead to a reduced CO_2 concentration in the atmosphere, and to a net zero value when the CO_2 is later released again. CCU from industrial sources delays the emission and eventually leads to a higher atmospheric CO_2 concentration and GWP, and still requires fossil fuels as feedstock, except for process-related CO_2 emissions such as in cement production. In order not to increase the CO_2 concentration in the atmosphere for a longer period of time, a closed carbon cycle must be achieved. The shorter the cycle, the shorter the duration of CO_2 in the atmosphere, which should be the goal. DAC achieves the shortest cycle because it initially reduces the concentration. The uptake of CO_2 by biomass takes several years. The cycle with fossil CO_2 is the longest and should be avoided if possible. Apart from the possible emission of fossil CO_2 with CCU, the use of industrial point sources could also lead to a longer lifetime of fossil-based processes and industries. This makes the emission of CO_2 a desirable outcome, as it is seen as a necessary resource. This dependence on and prolongation of fossil-based industry is often referred to as "carbon lock-in" or "fossil lock-in". CCU from (fossil) industrial sources would attach a positive value to fossil CO_2 emissions and the associated infrastructure, thus hindering the global defossilization process.

Material Sourcing, Processing and Disposal

The use of raw materials for the PtX processes and renewable energy technologies along the value chain must be minimized to avoid scarcity and other negative impacts from extraction, processing, transportation and disposal. As shown in the results, the extraction and processing of various materials leaves a critical potential environmental footprint in several categories. In order to use them in the most efficient way, it is also important not to rely on a single technology (e.g. type of electrolyzer or electricity generation technology), but to analyze and diversify different pathways. A mix of technologies and research into new technologies and pathways in this area can help to avoid dependence on a few materials.

Once the material is identified, it should be used in a sustainable way. Therefore, the material demand for the different processes should be reduced as much as possible without compromising the function and lifetime of the process, as the lifetime of the process also determines the amount of material used. Therefore, the aim should be to extend the lifetime of the technologies. In addition, at the end of the life of the technologies, the materials should be efficiently recycled and reused. Circular approaches should be promoted and implemented along the entire value chain. The example of using the brine from water desalination plants instead of discharging it into the water with negative impacts shows the importance of analyzing the potential of circular approaches.

Land Use

Especially the additional power generation from renewable sources and the DAC technology require large areas of land. While land use is still lower than for bio-based fuels, sustainable land use must be ensured. Land should be used efficiently and sustainably, such as with a hybrid approach of agriculture and PV power plants. Offshore installations may also be a solution in some areas. The expansion of RES for national grids must not be blocked by the construction of RES for PtX. There may be competition between the two, especially in areas that would allow a high number of FLH. Both expansions will be necessary, and available land with the right conditions may be scarce. If a country already has a high share of RES in its electricity mix, the risk of competition is lower.

Water Use

The availability of water for the local population should always be a priority before considering the use of water for fuel production. While many of the areas with high potential for RES are also areas with a high risk of water scarcity, combined approaches should be considered. Increased capacity for water desalination, which could then provide water to the population, and the PtX process are potential solutions. However, this does not guarantee the elimination of water scarcity in general. In the case of landlocked countries, other sustainable sources of water must be considered.

5.2.2 Socio-governmental Perspective

Approaches within the socio-governmental sphere are summarized and categorized into potential areas of intervention.

Employment along the Value Chain

Employment is linked to many of the indicators assessed and therefore needs to be addressed comprehensively and carefully. The loss of jobs in the fossil industry due to the phase-out of fossil fuels should be addressed. However, as noted by the IEA (2022), many of the job skills are compatible with those that will be required for H_2 production in the future. It is important to facilitate a just transition by providing the necessary training, retraining and job opportunities. As conditions differ from country to country, this transition needs to be developed in dialogue with affected stakeholders, such as trade unions, employers, civil society and policy makers, and should be coordinated across different ministries, as energy, employment and education are affected. Within the same area, gender equality and fair wages should be addressed. As the results and the IEA report show, the risk of gender inequality is high not only in the fossil industry, but also in the renewable energy sector. While there are positive developments in the innovative part of the industry, more action is needed in this area. Policy frameworks for improved hiring practices and initiatives within the industry should be developed to achieve a positive development for gender equality. Similarly, fair wages in general should be ensured along the entire value chain, as this indicator also reaches a critical value in many constellations in the results. This can be addressed in a similar way by policy frameworks and initiatives/trade unions. [152]

The risk of child labor is usually higher in the upstream part of the value chain, i.e. in resource extraction. Because there are many intermediaries and companies involved, child labor is difficult to monitor. The OECD report on Due Diligence Challenges and Opportunities in Sourcing Cobalt and Copper from the Democratic Republic of Congo provides some considerations on how to monitor this issue. In the downstream part of the value chain, fine refiners are usually actors with exclusive contracts and financing relationships, which gives them the leverage to demand due diligence in the upstream part. However, each actor in the downstream part of the value chain should also ensure audits and control mechanisms for this issue. [153]

Corruption and Bribery

Corruption and bribery can be relevant throughout the life cycle of a project. Resource extraction is often affected by this topic, although it is less commonly addressed than child labor and hazardous working conditions. One initiative that addresses corruption in this area is the Extractive Industries Transparency Initiative (EITI). EITI has developed a standard that is already being implemented in 57 countries around the world (EITI, 2022). It is implemented by local multi-stakeholder groups at the national level, ensuring that the required data is published by the respective groups. It covers data requirements at several stages, starting with contracts and licenses, through production and revenue collection, to revenue allocation and social and economic expenditures. Good governance can be addressed through international initiatives to ensure transparency. Further down the PtX value chain, specific agreements such as the Open Solar Contract (IRENA and TWI, 2019), which already includes anti-bribery and anti-corruption provisions, can be used. In this way, it is already contractually established and guaranteed that corruption will be addressed. Even if such an agreement does not completely prevent corruption and bribery, it is an important step towards a legal obligation that should be combined with a high level of transparency. [153]–[156]

Dialogs, Partnerships, Conflicts and Capacity Development

The rights of indigenous peoples and any local populations in areas where PtX-based fuels could be produced need to be considered at an early stage. Stakeholder dialogues, in which local people are heard and their concerns addressed, must be included in the early stages of new projects. It must be ensured that their land is not taken illegally for new projects. A policy framework should be implemented to ensure this dialogue and protection of rights. This framework could create an obligation to integrate these dialogues into new PtX production plant projects.

As there is a high potential for international partnerships and cooperation in the field of PtX, it is very likely that countries with different interests and different levels of technical and other capacities will form partnerships or cooperate in capacity building activities. There is a potential for conflict, as the transition from fossil to PtX-based fuels could rearrange the entire international energy market and power balance. The potential to produce fuels would no longer depend on the availability of fossil resources, but other parameters would become relevant. This could allow countries to become major energy exporters, even if they haven't been in the past, and vice versa. As demand for fossil fuels declines, this could have a destabilizing effect on countries that currently depend on exports of these fuels. A transition to a green export narrative by producing and exporting green H_2 and PtX based products could at least reduce this risk. In any case, it is important to integrate the conflict potential into project development, with strategies to address it or with alternative plans. Recent geopolitical circumstances have shown that dependence on one country for energy imports can lead to a global energy crisis. PtX can help achieve a higher level of energy independence, although partnerships are still essential.

Spending on both education and health is low in many of the countries/regions assessed. An indirect link of both categories to the value chains of fuel production can be drawn by considering the education required for the jobs and good health conditions for a productive workforce. In terms of education, the IEA (2022) reports that energy companies face challenges in finding employees with the necessary education in science, technology, engineering and mathematics, as well as in project management and other technical positions. However, education and health cover many more aspects and should not be focused only on ensuring the availability of personnel for fuel production. According to fDi Markets (2022), the current global development of green H_2 and PtX will lead to a high increase in foreign direct investment (FDI). Some of this money could be used to increase spending on health and education in general. However, according to the OECD (2002), levels of general education and health are often prerequisites for attracting FDI. These prerequisites may not be as relevant for investors in the PtX sector, where the focus is usually on achieving a high level of FLH and low LCOE. In this case, FDI can be used to support in-country development, but should not be the only strategy. Other activities dedicated to human capacity development should be the basis for improving the situation. Capacity development activities are an important tool to implement all the measures discussed at the global level. With awareness and understanding of the issues, the proposed measures can be implemented in a sustainable manner. [157], [158], [152]

Compliance and Certification

In addition to strengthening the capacity and awareness of all partners, various measures should be taken to control and monitor compliance and sustainability along the value chain.

Different actors along the value chain are affected by different monitoring requirements. In particular, child labor is highly relevant at the point of extraction of the required resources (it still needs to be considered along the entire value chain), other categories such as fair wages, corruption and gender equality are distributed along the entire value chain, and others such as the exclusive use of renewable energy and carbon would be more relevant at the site of the PtX plant itself.

Due to the fact that many different stages are relevant and should be controlled in terms of sustainability, several schemes are necessary. The techno-ecological measures can be controlled at the site with certification measures and audits that certify the sustainable production of PtX-based fuels (and other products). The further up the value chain the measures are located, the more difficult it is to monitor and certify the sustainability aspects. However, it would still be necessary to ensure all of the above to contribute to sustainable development.

With certification, customers would also become more relevant actors. And with airlines using sustainably produced PtX-based fuels, the price of flying would probably rise. The willingness to pay more for flights could become very relevant to ensure that sustainability concerns can be addressed. In order to better understand the need, global awareness campaigns with a high level of transparency along the value chain would be helpful. In addition, current subsidies for fossil-based kerosene could be transferred to PtX-based fuels to reduce the economic impact.

6. Limitations

The model of this work is subject to a high degree of uncertainty and limitations. It is a generic model to assess opportunities and risks at an aggregated, global level. It is not intended to provide an in-depth analysis of a specific site or technology, but rather to provide an overview of critical sustainability issues around the world. With this overview of global sustainability issues, countermeasures can be developed and integrated at an early stage. For a more specific assessment of specific projects and regions within countries, more specific data would be required, including existing infrastructure, water availability, and social conditions. The model of this work is based on the simplified assumption that the same PtX process can be implemented in any country without considering additional infrastructure or transportation requirements. The modeled process is connected to either an onshore wind or PV power plant with a country-specific FLH, while the electrolyzer load is harmonized with the amount of FLH of the respective energy source. Storage facilities for H_2, electricity or other material/energy flows are not considered in the model.

The cost of electricity generation is solely determined by the chosen technology and the FLH. The amount of FLH is assessed on an average level per country, so there are always less and more favorable conditions in each country. As the amount of FLH is a very important parameter in this model, it is part of the sensitivity analysis. Both lower and higher amounts are evaluated.

Cost differences due to labor, logistics and infrastructure costs at the local level are not taken into account. At the same time, no consideration is given to the development of socio-economic aspects. The only evolution of these indicators within the 2050 scenario is the evolution of the process and the price of LCOE, and therefore the lower number of worker hours per kg of fuel produced. Although positive and negative developments within the different categories can be expected globally, the integration of country-specific developments for each assessed country/region is not foreseeable and cannot be assessed within the scope of this work. The S-LCA datasets are too complex to be analyzed in the context of potential developments in each country.

With the latest energy crisis, the price of fossil fuels has risen sharply. The price of fossil oil has been changed to a higher price to account for this development. However, it may decrease again or increase even further. Due to the uncertainty of future developments, the costs of the fossil-based benchmark are therefore included in the sensitivity analysis, which analyzes positive and negative price developments and their impact on the results.

Another source of uncertainty is the 2050 scenario, which is based on the very optimistic assumption that the share of renewables in the global energy mix will increase to almost 100%. Although policies are in place at the global level to achieve this goal, the actual achievement is uncertain, as are the technological and economic developments in this scenario.

The modeled PtX process is based on a set of specific technologies that could be replaced by alternatives. In particular, the choice of electrolyser technology could change the results, mainly due to different materials required for the construction and a difference in energy efficiency. A different type of CO_2 capture technology and synthesis process would also affect the results of the model. In particular, the CO_2 sources could also have stronger effects on the efficiency of the CO_2-emitting process, the additional release of fossil CO_2, and longer-term effects - especially for industrial point sources and the inherent fossil lock-in effect in the long term.

7. Sensitivity Analysis

Fossil-bassed feedstock price

As fossil feedstock prices have recently changed significantly, both a 100% increase and a 50% decrease were implemented for the sensitivity analysis. The results of the increased oil price scenarios for 2022 and 2050 in Figure 94 show that PtX-based fuels achieve a higher level of benefit in several categories.

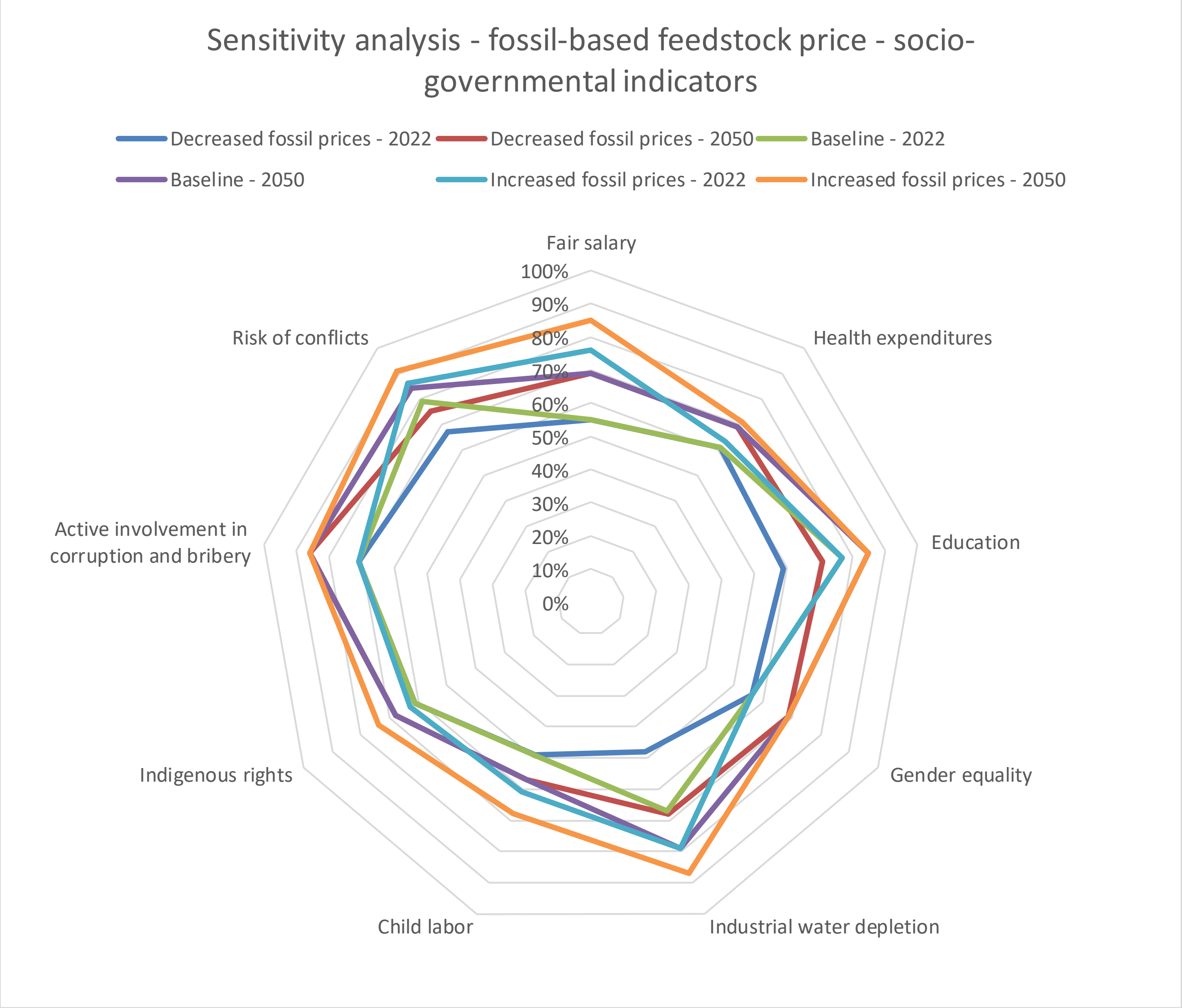

Figure 93: Results of the sensitivity analysis of oil prices: Impacts on socio-governmental results

Full Load Hours

The amount of FLH is another key parameter of the model and therefore part of the sensitivity analysis due to its influence on costs and therefore on social impacts as well as on potential environmental impacts. An increase to 200% and a decrease to 50% were evaluated. As Figure 95 shows, in some cases a higher level of FLH (200%) leads to a decrease in benefits, for example for the indicator of active involvement in corruption and bribery. In other cases, the higher amount of FLH leads to benefits, for example for the indicator of industrial water depletion.

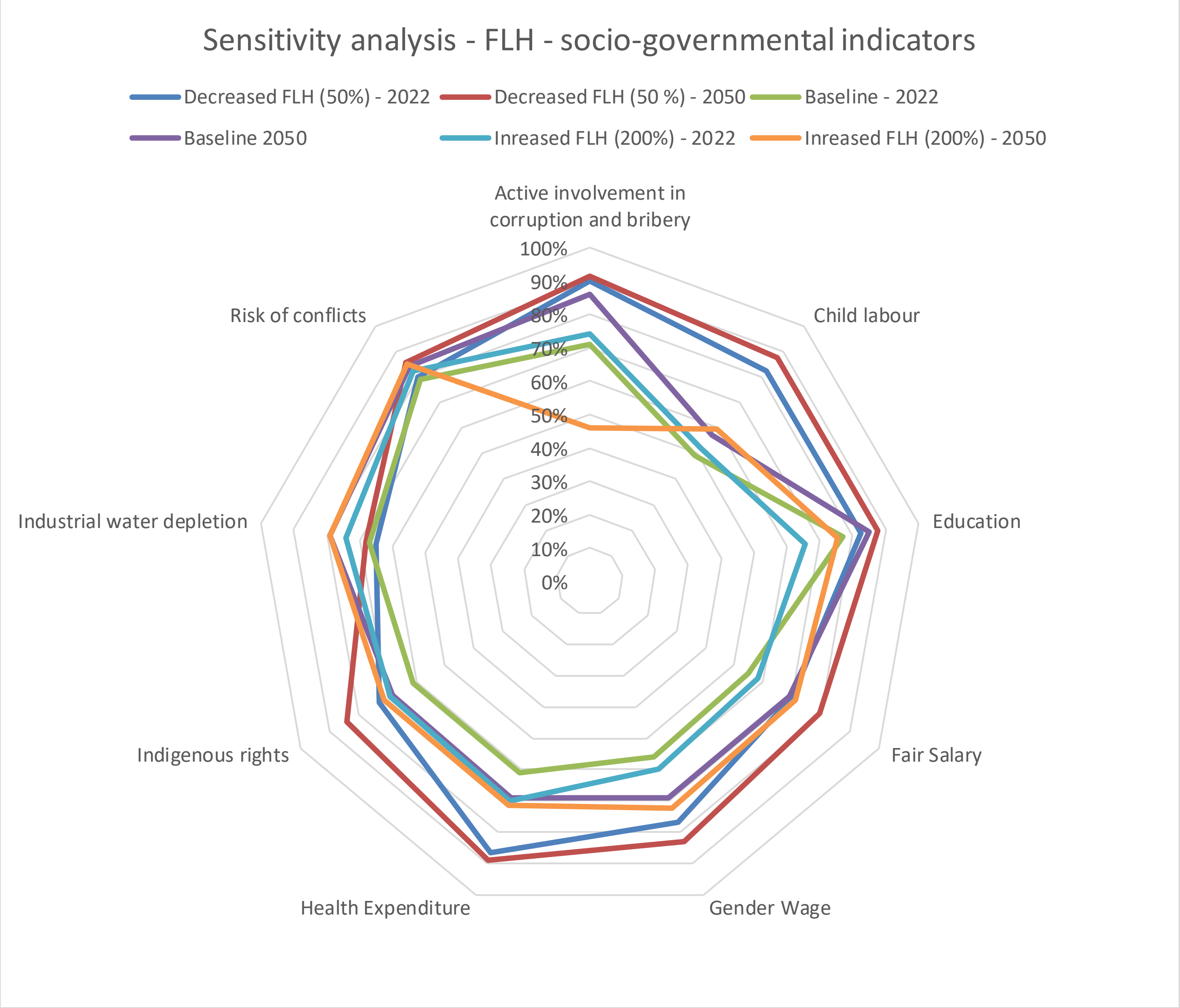

Figure 94: Sensitivity analysis: Full load hours – Influence on socio-governmental indicators

The reason for a partial decrease in the potential benefits with a higher amount of FLH is that a higher amount of FLH also reduces the GWP of the PtX fuel production, thus qualifying more constellations to meet the CO_2 benchmark. With more constellations reaching the CO_2 benchmark, more constellations (and thus countries) are considered in the assessment, some of which are associated with higher social risks. Thus, the absolute number of constellations that reach the benchmarks increases with a higher amount of FLH, but the relative number of constellations with an advantage in certain categories may decrease due to more assessed constellations.

The results of the sensitivity analysis of the environmental categories are very different from those of the social categories. Most of the categories assessed give a very clear result as to whether a benefit can be achieved, and the amount of FLH does not change this distinction in most cases. The exceptions are human non-carcinogenic toxicity and terrestrial ecotoxicity.

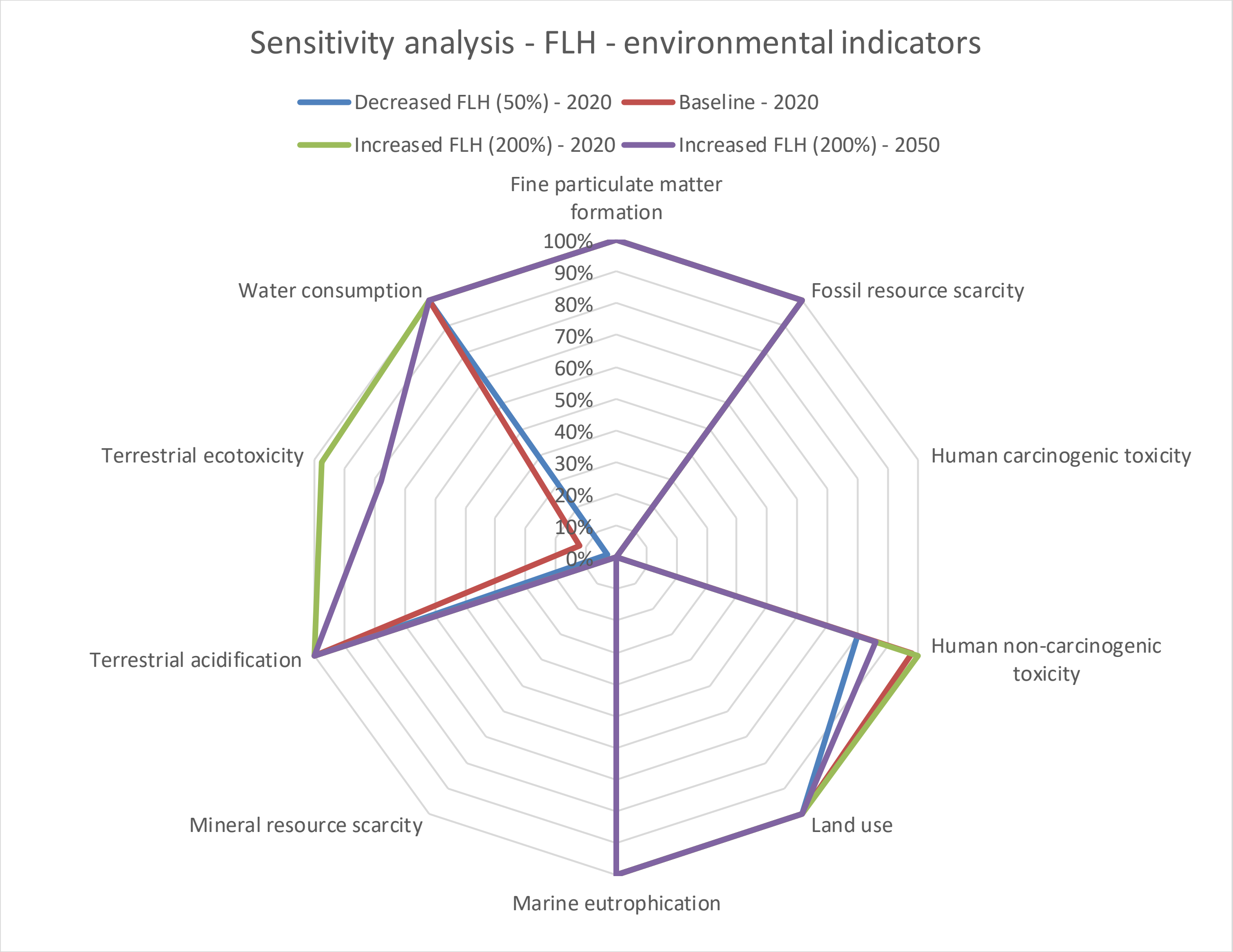

Figure 95: Sensitivity analysis: Full load hours – Influence on environmental indicators

It can be seen that there are certain environmental aspects that will be critical at any location at any level of achievable FLH. The most critical areas, mineral resource scarcity, human toxicity, and terrestrial ecotoxicity, should be specifically addressed with additional measures. Otherwise, they could become an additional problem that did not exist to this extent with fossil-based fuels and would not exist to this extent with bio-based fuels.

8. Conclusions and Outlook

The results show that PtX and PtX-based fuels are not sustainable by default, but with the right applications and measures, a positive contribution to sustainability can be achieved in many areas. Several risks and opportunities have been identified and assessed in this work, and others may emerge in the future. Linking the impact categories to the SDGs was intended to cover the currently most pressing sustainability issues. In combination with the dynamic global energy system model of 2050, the impacts of sector coupling in a decarbonized future on the assessed processes were identified. As can be seen from the results, it is important to consider these coupling effects and not to analyze each sector separately. At the same time, the global scope was intended to ensure that certain social risks were not overlooked due to their lower incidence or relevance in specific regions. This broad thematic and geographic coverage was an important step in identifying and analyzing opportunities and risks. This type of early-stage sustainability assessment can identify and address potential risks before they become difficult to manage. However, a sustainability assessment, along with any actions and recommendations based on it, are merely the first steps toward achieving a higher level of sustainability. These findings and measures will need to be adapted, supplemented and operationalized for implementation at the extraction, production and project levels during the next stages of development.

To answer the first part of the research question, the main opportunities and risks of the transition are summarized in the following paragraph:

Mineral resource scarcity, human carcinogenic toxicity and terrestrial ecotoxicity were identified as the main environmental risks, plus human non-carcinogenic toxicity also becoming critical in the long term. Although the results were slightly below the benchmark, child labor was identified as the main social risk along the value chain in the short term. On the other hand, the results also show many opportunities for sustainable development: Terrestrial acidification, water consumption, land use, fossil resource scarcity, particulate matter formation, and marine eutrophication. Each of these indicators represents an opportunity for sustainable development when measured against one of the two techno-ecological benchmarks. The societal opportunities are broader, as more sustainable development can be observed in all categories assessed by 2050. When measured against both benchmarks together, the indicators Indigenous Rights, Child Labor, Industrial Water Depletion, Education Expenditures, Health Expenditures, Active Involvement in Corruption and Bribery, and Fair Salary still show a positive development with PtX-based fuels, at least by 2050.

In order to answer the second part of the research question, the areas of potential intervention must be distinguished: The areas of potential intervention are distributed across the different stages of the life cycle and value chain. If they are not addressed and managed properly, the negative impacts on sustainability could even outweigh the benefits. The most obvious requirement for contributing to sustainability is that the electricity for the PtX plant must come from RES. If this is not the case, no climate change benefits can be achieved. However, the RES capacities for PtX should be implemented in addition to the existing ones, while the RES capacities for the national grids also need to be expanded. As demonstrated in the 2050 scenario, a global electricity mix with a higher share of RES affects the entire value chain. While ensuring that the energy source for PtX is renewable and additional, the other sustainability measures need to be addressed and implemented in parallel. The sensitivity analysis also shows that a high share of RES is very beneficial and reduces many risks and impacts along the life cycle as well as the specific costs. Some of the sustainability concerns and measures are relevant at the technology or plant design level, others at the raw material sourcing level, at the PtX plant operation level, or at the decommissioning level. Certification and monitoring are essential at many stages of the value chain, the right policies and regulations need to be in place, and those responsible for implementing the measures need to be identified and incentivized to do so. The example of gender-transformative approaches, as pursued by the BMZ's Feminist Development Policy, could also be applied to the other socio-political categories. The conventional structures and policies that currently lead to negative sustainability aspects must be addressed and restructured. At the same time, the complexity of the process steps, their resource requirements, and their implications at the international level are quite high compared to the fossil fuel economy. This makes sustainability monitoring both more difficult and more necessary. Since many of the social and environmental risks occur at different stages of the life cycle and therefore in different parts of the world, a high degree of international cooperation is required.

There are many aspects of international cooperation that need to be considered. As new partnerships and international supply chains are established, the global energy market and related geopolitical landscape are changing. It is therefore important to engage in international dialogues, develop strategies and form partnerships. Three main approaches can be distinguished: Either countries are more import-oriented, more export-oriented, or more self-sufficient. Importing or exporting does not have to be limited to pure green H_2, but can also include PtX-based fuels, chemicals, steel or other products based on green H_2. This provides an opportunity to diversify economies and not limit trade to the fuel. With all these potential applications, processes and industries involved, technology transfer and R&D play an important role in the transition. Establishing best practices, more sustainable and efficient production methods will support the sustainable transition. When considering international trade in PtX-based products, new infrastructure will also be required. There are already considerations and international discussions about new pipeline and shipping routes for PtX.

This work is focused on the aviation sector, assessing the opportunities and risks of PtX-based fuels as a substitute for fossil or bio-based jet fuel. The opportunity to transform the aviation sector into a more sustainable one after the COVID-19 pandemic could lead to a significant reduction in global greenhouse gas emissions if the fuel is gradually replaced by PtX-based fuels. In the EU, an SAF quota of 2% by 2025 and 70% by 2050 is being implemented. However, aviation is only one potential application for green H_2, as the shipping, chemical and steel industries also currently lack alternatives. Typically, either the molecular structure of hydrocarbons (or other chemicals) is needed as a feedstock for the processes and products of our global economy, or the energy content and density is needed in a form that can be transported and used in our engines. As with jet fuel, it is important to compare the sustainability opportunities and risks with the status quo and other alternatives, if any.

The results and sensitivity analysis show that a high level of benefits can be achieved in both environmental and social categories. However, some risks remain high, and some may even increase in the future. International cooperation, transformative approaches to address the roots of socio-economic risks, research and development, resource efficiency and sufficiency are key steps towards a higher level of sustainability. In any case, the transition to green H2-based synthetic fuels improves aviation's GWP and positively impacts other sustainability indicators. The critical issues can be addressed through combined efforts and dedicated measures.

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Annex

The following tables show the upstream contributors (with at least 1 % contribution) of the main process steps of the PtX-based fuel production for each assessed LCA indicator within both scenarios. The contributions within the overall system are not displayed, as they are different for each assessed amount of FLH.

1. Fine Particulate Matter Formation

PV 2022

electricity production, lignite | electricity, high voltage | Cutoff, U - ID	8 %
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	6 %
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	4 %
electricity production, lignite | electricity, high voltage | Cutoff, U - US-MRO	2 %
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RoW	2 %
electricity production, lignite | electricity, high voltage | Cutoff, U - TR	2 %
electricity production, lignite | electricity, high voltage | Cutoff, U - US-SERC	2 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	2 %
coking | coke | Cutoff, U - RoW	2 %
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	2 %
electricity production, lignite | electricity, high voltage | Cutoff, U - US-TRE	2 %
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	2 %
electricity production, lignite | electricity, high voltage | Cutoff, U - US-WECC	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SD	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - RoW	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CL	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-JS	1 %
transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff, U - GLO	1 %
blasting | blasting | Cutoff, U - RoW	1 %
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RER	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - IN-UP	1 %
platinum group metal mine operation, ore with high palladium content | copper, cathode | Cutoff, U - RU	1 %

electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SX	1 %

PV 2050

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	5 %
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RoW	5 %
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	5 %
copper production, primary | copper | Cutoff, U - RAS	4 %
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	4 %
coking | coke | Cutoff, U - RoW	3 %
copper production, primary | copper | Cutoff, U - RoW	3 %
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	3 %
electricity production, lignite | electricity, high voltage | Cutoff, U - ID	3 %
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	2 %
copper production, primary | copper | Cutoff, U - RLA	2 %
anaerobic digestion of manure | biogas | Cutoff, U - RoW	2 %
sinter production, iron | sinter, iron | Cutoff, U - GLO	2 %
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	2 %
copper production, primary | copper | Cutoff, U - RNA	2 %
blasting | blasting | Cutoff, U - RoW	2 %
silicon production, metallurgical grade | silicon, metallurgical grade | Cutoff, U - RoW	1 %
magnesium production, pidgeon process | magnesium | Cutoff, U - CN	1 %
copper production, primary | copper | Cutoff, U - AU	1 %
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	1 %
silicon carbide production | silicon carbide | Cutoff, U - RoW	1 %
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	1 %
iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	1 %
ceramic tile production | ceramic tile | Cutoff, U - RoW	1 %
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RER	1 %

Wind 2022

platinum group metal mine operation, ore with high palladium content | copper, cathode | Cutoff, U - RU	7%
coking | coke | Cutoff, U - RoW	5%
electricity production, lignite | electricity, high voltage | Cutoff, U - ID	5%
blasting | blasting | Cutoff, U - RoW	4%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	4%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CL	4%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	4%
transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff, U - GLO	2%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	2%
blasting | blasting | Cutoff, U - RER	2%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	2%
clinker production | clinker | Cutoff, U - RoW	2%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-MRO	1%
treatment of waste polyvinylchloride, open burning | waste polyvinylchloride | Cutoff, U - GLO	1%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	1%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RoW	1%
iron sinter production | iron sinter | Cutoff, U - RoW	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CN	1%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	1%
molybdenite mine operation | copper concentrate, sulfide ore | Cutoff, U - GLO	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-SERC	1%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	1%

Wind 2050

copper production, primary | copper | Cutoff, U - RAS	11%
copper production, primary | copper | Cutoff, U - RoW	8%
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	8%
copper production, primary | copper | Cutoff, U - RLA	7%
coking | coke | Cutoff, U - RoW	5%

copper production, primary | copper | Cutoff, U - RNA	5%
copper production, primary | copper | Cutoff, U - AU	4%
sinter production, iron | sinter, iron | Cutoff, U - GLO	4%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	3%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	3%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	3%
nickel mine operation, sulfidic ore | copper | Cutoff, U - GLO	3%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	3%
blasting | blasting | Cutoff, U - RoW	2%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	2%
iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	2%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	2%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RNA	2%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	1%
blasting | blasting | Cutoff, U - RER	1%
treatment of waste polyvinylchloride, open burning | waste polyvinylchloride | Cutoff, U - GLO	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RLA	1%
clinker production | clinker | Cutoff, U - RoW	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%

SOEC 2022

platinum group metal mine operation, ore with high palladium content | nickel, class 1 | Cutoff, U - RU	14 %
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	11 %
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	8%
electricity production, lignite | electricity, high voltage | Cutoff, U - ID	5%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	4%
ferronickel production | ferronickel | Cutoff, U - GLO	3%
smelting and refining of nickel concentrate, 16% Ni | nickel, class 1 | Cutoff, U - GLO	3%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-MRO	2%
electricity production, lignite | electricity, high voltage | Cutoff, U - TR	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-SERC	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CL	1%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	1%
platinum group metal mine operation, ore with high palladium content | copper, cathode | Cutoff, U - RU	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-TRE	1%
coking | coke | Cutoff, U - RoW	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-WECC	1%
blasting | blasting | Cutoff, U - RoW	1%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	1%
heat and power co-generation, lignite | electricity, high voltage | Cutoff, U - RU	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%

SOEC 2050

platinum group metal mine operation, ore with high palladium content | nickel, 99.5% | Cutoff, U - RU	23%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	14%
nickel mine operation, sulfidic ore | nickel, 99.5% | Cutoff, U - GLO	11%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	10%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	3%
copper production, primary | copper | Cutoff, U - RAS	3%
coking | coke | Cutoff, U - RoW	2%
copper production, primary | copper | Cutoff, U - RoW	2%
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	2%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	2%
copper production, primary | copper | Cutoff, U - RLA	2%
sinter production, iron | sinter, iron | Cutoff, U - GLO	1%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	1%
copper production, primary | copper | Cutoff, U - RNA	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%

DAC 2022

ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	15%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	9%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	7%
coking | coke | Cutoff, U - RoW	4%
ferronickel production | ferronickel | Cutoff, U - GLO	4%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	3%
electricity production, lignite | electricity, high voltage | Cutoff, U - ID	3%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	2%
transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff, U - GLO	2%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2%
sour gas, burned in gas turbine | sour gas, burned in gas turbine | Cutoff, U - RoW	1%
iron sinter production | iron sinter | Cutoff, U - RER	1%
clinker production | clinker | Cutoff, U - CH	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%

DAC 2050

ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	18%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	10%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	8%

coking | coke | Cutoff, U - RoW	6%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	5%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	5%
sinter production, iron | sinter, iron | Cutoff, U - GLO	4%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	3%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	3%
iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	3%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2%
sour gas, burned in gas turbine | sour gas, burned in gas turbine | Cutoff, U - RoW	1%
clinker production | clinker | Cutoff, U - CH	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%
copper production, primary | copper | Cutoff, U - RAS	1%

Chemical Factory, organics 2022

electricity production, lignite | electricity, high voltage | Cutoff, U - ID	7%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	6%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	6%
platinum group metal mine operation, ore with high palladium content | copper, cathode | Cutoff, U - RU	5%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	4%
blasting | blasting | Cutoff, U - RoW	3%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CL	3%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-MRO	2%
blasting | blasting | Cutoff, U - RER	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - TR	1%
ferronickel production | ferronickel | Cutoff, U - GLO	1%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-SERC	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-TRE	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - US-WECC	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	1%
coking | coke | Cutoff, U - RoW	1%

Chemical factory, organics 2050

copper production, primary | copper | Cutoff, U - RAS	11%
copper production, primary | copper | Cutoff, U - RoW	8%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	8%
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	7%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	7%
copper production, primary | copper | Cutoff, U - RLA	6%
copper production, primary | copper | Cutoff, U - RNA	4%
copper production, primary | copper | Cutoff, U - AU	3%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	3%
nickel mine operation, sulfidic ore | copper | Cutoff, U - GLO	2%
blasting | blasting | Cutoff, U - RoW	2%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2%
coking | coke | Cutoff, U - RoW	2%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	2%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	2%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RNA	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	1%
blasting | blasting | Cutoff, U - RER	1%
sinter production, iron | sinter, iron | Cutoff, U - GLO	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RLA	1%

2. Fossil Resource Scarcity

PV 2022

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	22%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	6%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	5%
ethylene production, average | ethylene, average | Cutoff, U - RoW	5%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	5%
petroleum production, onshore | petroleum | Cutoff, U - RME	4%
natural gas production | natural gas, high pressure | Cutoff, U - RU	4%
lignite mine operation | lignite | Cutoff, U - RoW	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	3%
natural gas production | natural gas, high pressure | Cutoff, U - US	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	3%
natural gas production | natural gas, high pressure | Cutoff, U - RoW	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	3%
natural gas production, unprocessed, at extraction | natural gas, unprocessed, at extraction | Cutoff, U - GLO	3%
lignite mine operation | lignite | Cutoff, U - RER	3%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	2%
petroleum production, onshore | petroleum | Cutoff, U - RU	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	2%

petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	2%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - RoW	1%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - US	1%
hard coal mine operation, open cast, dragline | hard coal, run-of-mine | Cutoff, U - ZA	1%

PV 2050

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	20%
ethylene production, average | ethylene, average | Cutoff, U - RoW	10%
natural gas production | natural gas, high pressure | Cutoff, U - RU	8%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	6%
petroleum production, onshore | petroleum | Cutoff, U - RME	6%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	5%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	3%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	3%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	3%
petroleum production, onshore | petroleum | Cutoff, U - RU	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	2%
natural gas production | natural gas, high pressure | Cutoff, U - RoW	2%
natural gas production, unprocessed, at extraction | natural gas, unprocessed, at extraction | Cutoff, U - GLO	2%
ethylene production, average | ethylene, average | Cutoff, U - RER	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	2%
lignite mine operation | lignite | Cutoff, U - RoW	1%
natural gas production | natural gas, high pressure | Cutoff, U - US	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RU	1%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	1%

Wind 2022

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	15%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	8%
petroleum production, onshore | petroleum | Cutoff, U - RME	8%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	7%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	5%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	4%
petroleum production, onshore | petroleum | Cutoff, U - RU	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	3%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	3%
natural gas production | natural gas, high pressure | Cutoff, U - RU	3%
lignite mine operation | lignite | Cutoff, U - RoW	3%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	2%

natural gas production | natural gas, high pressure | Cutoff, U - US	2%
natural gas production | natural gas, high pressure | Cutoff, U - RoW	2%
natural gas production, unprocessed, at extraction | natural gas, unprocessed, at extraction | Cutoff, U - GLO	2%
ethylene production, average | ethylene, average | Cutoff, U - RoW	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RU	1%
lignite mine operation | lignite | Cutoff, U - RER	1%
petroleum production, onshore | petroleum | Cutoff, U - RoW	1%

Wind 2050

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	14%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	11%
petroleum production, onshore | petroleum | Cutoff, U - RME	10%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	10%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	6%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	5%
petroleum production, onshore | petroleum | Cutoff, U - RU	5%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	3%
natural gas production | natural gas, high pressure | Cutoff, U - RU	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	3%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RU	2%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	1%
petroleum production, onshore | petroleum | Cutoff, U - RoW	1%
petroleum production, onshore | petroleum | Cutoff, U - RAF	1%
polyethylene production, high density, granulate | polyethylene, high density, granulate | Cutoff, U - RoW	1%

SOEC 2022

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	19%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	7%
petroleum production, onshore | petroleum | Cutoff, U - RME	7%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	6%
natural gas production | natural gas, high pressure | Cutoff, U - RU	5%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	4%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	4%
lignite mine operation | lignite | Cutoff, U - RoW	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	3%
petroleum production, onshore | petroleum | Cutoff, U - RU	3%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	3%
natural gas production | natural gas, high pressure | Cutoff, U - US	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	3%
natural gas production | natural gas, high pressure | Cutoff, U - RoW	2%

natural gas production, unprocessed, at extraction | natural gas, unprocessed, at extraction | Cutoff, U - GLO	2%
lignite mine operation | lignite | Cutoff, U - RER	2%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - RoW	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RU	1%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - US	1%
hard coal mine operation, open cast, dragline | hard coal, run-of-mine | Cutoff, U - ZA	1%

SOEC 2050

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	15%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	13%
petroleum production, onshore | petroleum | Cutoff, U - RME	12%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	6%
natural gas production | natural gas, high pressure | Cutoff, U - RU	6%
petroleum production, onshore | petroleum | Cutoff, U - RU	5%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	5%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	3%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RU	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	2%
petroleum production, onshore | petroleum | Cutoff, U - RoW	2%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	1%
petroleum production, onshore | petroleum | Cutoff, U - RAF	1%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - NL	1%

DAC 2022

polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	24%
natural gas production | natural gas, high pressure | Cutoff, U - RU	10%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	7%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	7%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	6%
natural gas production | natural gas, high pressure | Cutoff, U - RoW	3%
natural gas production, unprocessed, at extraction | natural gas, unprocessed, at extraction | Cutoff, U - GLO	3%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	3%
natural gas production | natural gas, high pressure | Cutoff, U - US	3%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	3%
petroleum production, onshore | petroleum | Cutoff, U - RME	3%
lignite mine operation | lignite | Cutoff, U - RER	2%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - RoW	2%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	2%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - NL	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	1%

petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - Europe, without Russia and Turkey	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RU	1%
petroleum production, onshore | petroleum | Cutoff, U - RU	1%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - US	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	1%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - GB	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	1%

DAC 2050

polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	27%
natural gas production | natural gas, high pressure | Cutoff, U - RU	9%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	8%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	7%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	7%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	3%
petroleum production, onshore | petroleum | Cutoff, U - RME	3%
natural gas production | natural gas, high pressure | Cutoff, U - RoW	3%
natural gas production, unprocessed, at extraction | natural gas, unprocessed, at extraction | Cutoff, U - GLO	3%
natural gas production | natural gas, high pressure | Cutoff, U - US	3%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	2%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - NL	2%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - RoW	2%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	1%
petroleum production, onshore | petroleum | Cutoff, U - RU	1%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	1%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - GB	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	1%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - US	1%

Chemical Factory, organics 2022

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	22%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	7%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	5%
petroleum production, onshore | petroleum | Cutoff, U - RME	5%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	5%
lignite mine operation | lignite | Cutoff, U - RoW	4%
natural gas production | natural gas, high pressure | Cutoff, U - RU	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	3%
natural gas production | natural gas, high pressure | Cutoff, U - US	3%
natural gas production | natural gas, high pressure | Cutoff, U - RoW	3%

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	3%
lignite mine operation | lignite | Cutoff, U - RER	3%
natural gas production, unprocessed, at extraction | natural gas, unprocessed, at extraction | Cutoff, U - GLO	3%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	2%
petroleum production, onshore | petroleum | Cutoff, U - RU	2%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	2%
ethylene production, average | ethylene, average | Cutoff, U - RoW	2%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - RoW	2%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - US	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RU	1%
hard coal mine operation, open cast, dragline | hard coal, run-of-mine | Cutoff, U - ZA	1%
hard coal mine operation, underground | hard coal, run-of-mine | Cutoff, U - ZA	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - Europe, without Russia and Turkey	1%

Chemical factory, organics 2050

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	19%
petroleum and gas production, on-shore | petroleum | Cutoff, U - RoW	10%
petroleum production, onshore | petroleum | Cutoff, U - RME	9%
natural gas production | natural gas, high pressure | Cutoff, U - RU	6%
petroleum and gas production, off-shore | petroleum | Cutoff, U - RoW	5%
petroleum production, onshore | petroleum | Cutoff, U - RU	4%
hard coal mine operation | hard coal, run-of-mine | Cutoff, U - IN	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - AU	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RoW	3%
natural gas production | natural gas, high pressure | Cutoff, U - DZ	3%
petroleum and gas production, off-shore | natural gas, high pressure | Cutoff, U - NO	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - ID	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RU	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - RNA	2%
natural gas production | natural gas, high pressure | Cutoff, U - RoW	2%
natural gas production, unprocessed, at extraction | natural gas, unprocessed, at extraction | Cutoff, U - GLO	2%
polyethylene production, high density, granulate | polyethylene, high density, granulate | Cutoff, U - RoW	1%
natural gas production | natural gas, high pressure | Cutoff, U - US	1%
petroleum production, onshore | petroleum | Cutoff, U - RoW	1%
polyethylene production, low density, granulate | polyethylene, low density, granulate | Cutoff, U - RoW	1%
petroleum and gas production, on-shore | natural gas, high pressure | Cutoff, U - RoW	1%

3. Global Warming Potential

PV 2022

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	6%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	4%

electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	2 %
electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, U - RoW	2 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-JS	2 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SD	2 %
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RoW	2 %
electricity production, lignite | electricity, high voltage | Cutoff, U - DE	2 %
pig iron production | pig iron | Cutoff, U - RoW	2 %
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SX	1 %
ethylene production, average | ethylene, average | Cutoff, U - RoW	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-HE	1 %
silicon production, metallurgical grade | silicon, metallurgical grade | Cutoff, U - RoW	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-HB	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - RoW	1 %
heat and power co-generation, natural gas, conventional power plant, 100MW electrical | heat, district or industrial, natural gas | Cutoff, U - RU	1 %
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-ZJ	1 %

PV 2050

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	6 %
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	5 %
pig iron production | pig iron | Cutoff, U - GLO	5 %
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RoW	5 %
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	3 %
silicon production, metallurgical grade | silicon, metallurgical grade | Cutoff, U - RoW	3 %
ethylene production, average | ethylene, average | Cutoff, U - RoW	3 %
heat and power co-generation, natural gas, conventional power plant, 100MW electrical | heat, district or industrial, natural gas | Cutoff, U - RU	2 %
heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	2 %
electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, U - RoW	2 %

silicon carbide production | silicon carbide | Cutoff, U - RoW	2%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	2%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	2%
sinter production, iron | sinter, iron | Cutoff, U - GLO	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-JS	1%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SD	1%
heat and power co-generation, natural gas, conventional power plant, 100MW electrical | heat, district or industrial, natural gas | Cutoff, U - RoW	1%

Wind 2022

clinker production | clinker | Cutoff, U - RoW	9%
pig iron production | pig iron | Cutoff, U - RoW	8%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	5%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	4%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	3%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	3%
iron sinter production | iron sinter | Cutoff, U - RoW	2%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	2%
clinker production | clinker | Cutoff, U - Europe without Switzerland	2%
clinker production | clinker | Cutoff, U - US	1%
pig iron production | pig iron | Cutoff, U - RER	1%
quicklime production, in pieces, loose | quicklime, in pieces, loose | Cutoff, U - RoW	1%
clinker production | clinker | Cutoff, U - IN	1%

Wind 2050

pig iron production | pig iron | Cutoff, U - GLO	19%
clinker production | clinker | Cutoff, U - RoW	14%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	8%
sinter production, iron | sinter, iron | Cutoff, U - GLO	5%

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	4%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	4%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	4%
quicklime production, in pieces, loose | quicklime, in pieces, loose | Cutoff, U - RoW	3%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	2%
coking | coke | Cutoff, U - RoW	2%
clinker production | clinker | Cutoff, U - Europe without Switzerland	2%
heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	1%
transport, freight, light commercial vehicle | transport, freight, light commercial vehicle | Cutoff, U - RoW	1%
transport, freight, lorry 16-32 metric ton, EURO3 | transport, freight, lorry 16-32 metric ton, EURO3 | Cutoff, U - RoW	1%

SOEC 2022

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	11%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	5%
clinker production | clinker | Cutoff, U - RoW	2%
heat production, natural gas, at industrial furnace low-NOx >100kW | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	2%
pig iron production | pig iron | Cutoff, U - RoW	2%
heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	2%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	2%
transport, passenger car, large size, diesel, EURO 5 | transport, passenger car, large size, diesel, EURO 5 | Cutoff, U - RoW	1%
electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, U - RoW	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-JS	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SD	1%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	1%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	1%

SOEC 2050

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	21%
pig iron production | pig iron | Cutoff, U - GLO	8%
clinker production | clinker | Cutoff, U - RoW	7%
heat production, natural gas, at industrial furnace low-NOx >100kW | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	4%
clinker production | clinker | Cutoff, U - CH	3%
heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	3%
transport, passenger car, large size, diesel, EURO 5 | transport, passenger car, large size, diesel, EURO 5 | Cutoff, U - RoW	2%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	2%
sinter production, iron | sinter, iron | Cutoff, U - GLO	2%

diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2%
heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	2%
heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	2%
quicklime production, in pieces, loose | quicklime, in pieces, loose | Cutoff, U - RoW	1%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	1%

DAC 2022

polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	14%
trichloromethane production | trichloromethane | Cutoff, U - RER	9%
treatment of spent solvent mixture, hazardous waste incineration, with energy recovery | spent solvent mixture | Cutoff, U - CH	5%
treatment of spent solvent mixture, hazardous waste incineration | spent solvent mixture | Cutoff, U - CH	5%
clinker production | clinker | Cutoff, U - CH	5%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	4%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	4%
pig iron production | pig iron | Cutoff, U - RER	4%
heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	3%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	2%
iron sinter production | iron sinter | Cutoff, U - RER	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - DE	1%

DAC 2050

polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	17%
trichloromethane production | trichloromethane | Cutoff, U - RER	11%
treatment of spent solvent mixture, hazardous waste incineration | spent solvent mixture | Cutoff, U - CH	11%
pig iron production | pig iron | Cutoff, U - GLO	7%
clinker production | clinker | Cutoff, U - CH	6%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	5%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	5%
heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	4%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	2%
sinter production, iron | sinter, iron | Cutoff, U - GLO	2%
ammonia production, steam reforming, liquid | ammonia, liquid | Cutoff, U - RER	1%

Chemical Factory, organics 2022

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	7%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	5%

clay brick production | clay brick | Cutoff, U - RoW	3%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	2%
clinker production | clinker | Cutoff, U - RoW	2%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2%
electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, U - RoW	2%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-JS	2%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SD	1%
pig iron production | pig iron | Cutoff, U - RoW	1%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SX	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-HE	1%
electricity production, lignite | electricity, high voltage | Cutoff, U - DE	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - US-RFC	1%

Chemical factory, organics 2050

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	16%
pig iron production | pig iron | Cutoff, U - GLO	7%
clay brick production | clay brick | Cutoff, U - RoW	6%
clinker production | clinker | Cutoff, U - RoW	5%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	5%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	3%
clay brick production | clay brick | Cutoff, U - RER	2%
sinter production, iron | sinter, iron | Cutoff, U - GLO	2%
clinker production | clinker | Cutoff, U - CH	2%
heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland	2%
quicklime production, in pieces, loose | quicklime, in pieces, loose | Cutoff, U - RoW	1%
heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	1%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	1%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	1%
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	1%
heat and power co-generation, natural gas, conventional power plant, 100MW electrical | heat, district or industrial, natural gas | Cutoff, U - RU	1%

4. Human carcinogenic toxicity

PV 2022

treatment of electric arc furnace slag, residual material landfill | electric arc furnace slag | Cutoff, U - RoW	59%
treatment of redmud from bauxite digestion, residual material landfill | redmud from bauxite digestion | Cutoff, U - RoW	16%
treatment of basic oxygen furnace slag, residual material landfill | basic oxygen furnace slag | Cutoff, U - GLO	4%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	4%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	3%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	3%
treatment of hard coal ash, residual material landfill | hard coal ash | Cutoff, U - RoW	2%
treatment of electric arc furnace dust, residual material landfill | electric arc furnace dust | Cutoff, U - RoW	2%

PV 2050

treatment of redmud from bauxite digestion, residual material landfill | redmud from bauxite digestion | Cutoff, U - RoW	30%
treatment of slag, unalloyed electric arc furnace steel, residual material landfill | slag, unalloyed electric arc furnace steel | Cutoff, U - RoW	25%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	10%
treatment of basic oxygen furnace waste, residual material landfill | basic oxygen furnace waste | Cutoff, U - RoW	9%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	9%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	3%
treatment of dust, unalloyed electric arc furnace steel, residual material landfill | dust, unalloyed electric arc furnace steel | Cutoff, U - RoW	2%
treatment of hard coal ash, residual material landfill | hard coal ash | Cutoff, U - RoW	2%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	2%
treatment of residue from Na-dichromate production, residual material landfill | residue from Na-dichromate production | Cutoff, U - RoW	1%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	1%

Wind 2022

treatment of electric arc furnace slag, residual material landfill | electric arc furnace slag | Cutoff, U - RoW	83%
treatment of basic oxygen furnace slag, residual material landfill | basic oxygen furnace slag | Cutoff, U - GLO	5%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	2%
treatment of copper slag, residual material landfill | copper slag | Cutoff, U - GLO	2%
treatment of electric arc furnace dust, residual material landfill | electric arc furnace dust | Cutoff, U - RoW	2%

Wind 2050

treatment of slag, unalloyed electric arc furnace steel, residual material landfill | slag, unalloyed electric arc furnace steel | Cutoff, U - RoW	50%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	18%
treatment of basic oxygen furnace waste, residual material landfill | basic oxygen furnace waste | Cutoff, U - RoW	13%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	6%

treatment of dust, unalloyed electric arc furnace steel, residual material landfill | dust, unalloyed electric arc furnace steel | Cutoff, U - RoW	2%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	2%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	2%

SOEC 2022

treatment of electric arc furnace slag, residual material landfill | electric arc furnace slag | Cutoff, U - RoW	84%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	4%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	2%
treatment of electric arc furnace dust, residual material landfill | electric arc furnace dust | Cutoff, U - RoW	2%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	1%
treatment of basic oxygen furnace slag, residual material landfill | basic oxygen furnace slag | Cutoff, U - GLO	1%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	1%

SOEC 2050

treatment of slag, unalloyed electric arc furnace steel, residual material landfill | slag, unalloyed electric arc furnace steel | Cutoff, U - RoW	42%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	14%
treatment of dust, alloyed electric arc furnace steel, residual material landfill | dust, alloyed electric arc furnace steel | Cutoff, U - RoW	12%
treatment of basic oxygen furnace waste, residual material landfill | basic oxygen furnace waste | Cutoff, U - RoW	7%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	6%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	6%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	2%
treatment of residue from Na-dichromate production, residual material landfill | residue from Na-dichromate production | Cutoff, U - RoW	2%
treatment of nickel smelter slag, residual material landfill | nickel smelter slag | Cutoff, U - RoW	2%
treatment of redmud from bauxite digestion, residual material landfill | redmud from bauxite digestion | Cutoff, U - RoW	2%
treatment of dust, unalloyed electric arc furnace steel, residual material landfill | dust, unalloyed electric arc furnace steel | Cutoff, U - RoW	1%

DAC 2022

treatment of electric arc furnace slag, residual material landfill | electric arc furnace slag | Cutoff, U - RoW	81%
treatment of basic oxygen furnace slag, residual material landfill | basic oxygen furnace slag | Cutoff, U - GLO	5%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	3%
treatment of redmud from bauxite digestion, residual material landfill | redmud from bauxite digestion | Cutoff, U - RoW	2%
trichloromethane production | trichloromethane | Cutoff, U - RER	2%
treatment of electric arc furnace dust, residual material landfill | electric arc furnace dust | Cutoff, U - RoW	1%

DAC 2050

treatment of slag, unalloyed electric arc furnace steel, residual material landfill | slag, unalloyed electric arc furnace steel | Cutoff, U - RoW	39%

treatment of basic oxygen furnace waste, residual material landfill | basic oxygen furnace waste | Cutoff, U - RoW	13%
treatment of dust, alloyed electric arc furnace steel, residual material landfill | dust, alloyed electric arc furnace steel | Cutoff, U - RoW	12%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	10%
trichloromethane production | trichloromethane | Cutoff, U - RER	7%
treatment of redmud from bauxite digestion, residual material landfill | redmud from bauxite digestion | Cutoff, U - RoW	4%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	2%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	2%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	2%
treatment of average incineration residue, residual material landfill | average incineration residue | Cutoff, U - RoW	1%
treatment of nickel smelter slag, residual material landfill | nickel smelter slag | Cutoff, U - RoW	1%
treatment of dust, unalloyed electric arc furnace steel, residual material landfill | dust, unalloyed electric arc furnace steel | Cutoff, U - RoW	1%
chloromethyl methyl ether production | chloromethyl methyl ether | Cutoff, U - RER	1%

Chemical Factory, organics 2022

treatment of electric arc furnace slag, residual material landfill | electric arc furnace slag | Cutoff, U - RoW	78%
treatment of redmud from bauxite digestion, residual material landfill | redmud from bauxite digestion | Cutoff, U - RoW	4%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	2%
treatment of copper slag, residual material landfill | copper slag | Cutoff, U - GLO	2%
treatment of basic oxygen furnace slag, residual material landfill | basic oxygen furnace slag | Cutoff, U - GLO	2%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	2%
treatment of electric arc furnace dust, residual material landfill | electric arc furnace dust | Cutoff, U - RoW	2%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	1%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	1%

Chemical factory, organics 2050

treatment of slag, unalloyed electric arc furnace steel, residual material landfill | slag, unalloyed electric arc furnace steel | Cutoff, U - RoW	33%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	25%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	8%
treatment of basic oxygen furnace waste, residual material landfill | basic oxygen furnace waste | Cutoff, U - RoW	7%
treatment of redmud from bauxite digestion, residual material landfill | redmud from bauxite digestion | Cutoff, U - RoW	6%
treatment of dust, alloyed electric arc furnace steel, residual material landfill | dust, alloyed electric arc furnace steel | Cutoff, U - RoW	6%
treatment of sludge from steel rolling, residual material landfill | sludge from steel rolling | Cutoff, U - RoW	4%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	2%
treatment of dust, unalloyed electric arc furnace steel, residual material landfill | dust, unalloyed electric arc furnace steel | Cutoff, U - RoW	2%
treatment of nickel smelter slag, residual material landfill | nickel smelter slag | Cutoff, U - RoW	1%

5. Human non-carcinogenic toxicity

PV 2022

treatment of sulfidic tailings, from silver mine operation, tailings impoundment | sulfidic tailings, from silver mine operation | Cutoff, U - MX	13%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CL	11%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RoW	8%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	8%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	7%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	6%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - PE	4%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CN	4%
treatment of sulfidic tailings, from silver mine operation, tailings impoundment | sulfidic tailings, from silver mine operation | Cutoff, U - AU	3%
treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | sulfidic tailings, from zinc-lead mine operation | Cutoff, U - CN	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CA	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - US	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - AU	2%
treatment of sulfidic tailings, from silver mine operation, tailings impoundment | sulfidic tailings, from silver mine operation | Cutoff, U - US	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RU	2%
treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | sulfidic tailings, from zinc-lead mine operation | Cutoff, U - RoW	2%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RER	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ID	1%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ZM	1%
treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | sulfidic tailings, from zinc-lead mine operation | Cutoff, U - AU	1%

PV 2050

treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	77%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	7%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	2%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RER	1%
primary zinc production from concentrate | zinc | Cutoff, U - RoW	1%
copper production, primary | copper | Cutoff, U - RAS	1%
copper production, primary | copper | Cutoff, U - RoW	1%
copper production, primary | copper | Cutoff, U - RLA	1%

Wind 2022

treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CL	22%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RoW	16%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - PE	8%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CN	7%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CA	5%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - US	5%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - AU	5%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RU	4%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ID	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ZM	2%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	2%
treatment of sulfidic tailings, from gold mine operation, tailings impoundment | sulfidic tailings, from gold mine operation | Cutoff, U - AU	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - KZ	2%
treatment of sulfidic tailings, from gold mine operation, tailings impoundment | sulfidic tailings, from gold mine operation | Cutoff, U - US	1%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	1%

Wind 2050

treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	90%
copper production, primary | copper | Cutoff, U - RAS	2%
copper production, primary | copper | Cutoff, U - RoW	2%
copper production, primary | copper | Cutoff, U - RLA	1%

SOEC 2022

treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CL	16%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RoW	12%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	8%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - PE	6%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	6%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CN	5%
ferronickel production | ferronickel | Cutoff, U - GLO	4%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CA	4%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - US	4%

treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - AU	4%
treatment of sulfidic tailings, from nickel mine operation, tailings impoundment | sulfidic tailings, from nickel mine operation | Cutoff, U - RoW	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RU	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ID	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ZM	2%
treatment of sulfidic tailings, generic, tailings impoundment | sulfidic tailings, generic | Cutoff, U - GLO	2%
treatment of sulfidic tailings, from nickel mine operation, tailings impoundment | sulfidic tailings, from nickel mine operation | Cutoff, U - CA	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - KZ	1%
treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | sulfidic tailings, from zinc-lead mine operation | Cutoff, U - CN	1%
treatment of hard coal ash, municipal incineration with fly ash extraction | hard coal ash | Cutoff, U - CH	1%

SOEC 2050

treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	83%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	3%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	3%
copper production, primary | copper | Cutoff, U - RAS	2%
copper production, primary | copper | Cutoff, U - RoW	1%
copper production, primary | copper | Cutoff, U - RLA	1%

DAC 2022

trichloromethane production | trichloromethane | Cutoff, U - RER	15%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CL	12%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	9%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RoW	8%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	7%
ferronickel production | ferronickel | Cutoff, U - GLO	5%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - PE	4%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CN	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CA	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - US	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - AU	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RU	2%
treatment of basic oxygen furnace slag, residual material landfill | basic oxygen furnace slag | Cutoff, U - GLO	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ID	2%

treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ZM	1%
treatment of coal slurry, impoundment | coal slurry | Cutoff, U - GLO	1%

DAC 2050

treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	60%
trichloromethane production | trichloromethane | Cutoff, U - RER	14%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	5%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	5%

Chemical Factory, organics 2022

treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CL	19%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RoW	14%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - PE	7%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CN	6%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CA	5%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - US	4%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - AU	4%
treatment of sulfidic tailings, from gold mine operation, tailings impoundment | sulfidic tailings, from gold mine operation | Cutoff, U - AU	4%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RU	3%
treatment of sulfidic tailings, from gold mine operation, tailings impoundment | sulfidic tailings, from gold mine operation | Cutoff, U - US	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ID	3%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	3%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - ZM	2%
treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | sulfidic tailings, from zinc-lead mine operation | Cutoff, U - CN	2%
treatment of sulfidic tailings, from silver mine operation, tailings impoundment | sulfidic tailings, from silver mine operation | Cutoff, U - MX	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - KZ	1%
treatment of sulfidic tailings, from gold mine operation, tailings impoundment | sulfidic tailings, from gold mine operation | Cutoff, U - CN	1%
treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | sulfidic tailings, from zinc-lead mine operation | Cutoff, U - RoW	1%

Chemical factory, organics 2050

treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	91%
copper production, primary | copper | Cutoff, U - RAS	2%
copper production, primary | copper | Cutoff, U - RoW	1%

copper production, primary | copper | Cutoff, U - RLA	1%

6. Marine Eutrophication

PV 2022

treatment of wastewater from PV cell production, capacity 5E9l/year | wastewater from PV cell production | Cutoff, U - RoW	35%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	14%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	14%
multi-Si wafer production | multi-Si wafer | Cutoff, U - RoW	13%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	4%
uranium production, in yellowcake, in-situ leaching | uranium, in yellowcake | Cutoff, U - GLO	1%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	1%
treatment of dross from Al electrolysis, residual material landfill | dross from Al electrolysis | Cutoff, U - RoW	1%
treatment of sludge from pulp and paper production, sanitary landfill | sludge from pulp and paper production | Cutoff, U - RoW	1%
treatment of waste plastic, mixture, unsanitary landfill, wet infiltration class (500mm) | waste plastic, mixture | Cutoff, U - GLO	1%

PV 2050

treatment of wastewater from PV cell production, capacity 5E9l/year | wastewater from PV cell production | Cutoff, U - RoW	42%
multi-Si wafer production | multi-Si wafer | Cutoff, U - RoW	15%
treatment of dross from Al electrolysis, residual material landfill | dross from Al electrolysis | Cutoff, U - RoW	14%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	6%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	6%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	2%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	2%
treatment of waste plastic, mixture, unsanitary landfill, wet infiltration class (500mm) | waste plastic, mixture | Cutoff, U - GLO	1%
multi-Si wafer production | multi-Si wafer | Cutoff, U - RER	1%

Wind 2022

nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	20%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	19%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	16%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	10%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	10%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CL	2%

treatment of waste plastic, mixture, unsanitary landfill, wet infiltration class (500mm) | waste plastic, mixture | Cutoff, U - GLO	1%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RoW	1%
soybean production | soybean | Cutoff, U - RoW	1%
uranium production, in yellowcake, in-situ leaching | uranium, in yellowcake | Cutoff, U - GLO	1%

Wind 2050

treatment of dross from Al electrolysis, residual material landfill | dross from Al electrolysis | Cutoff, U - RoW	49%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	19%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	12%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	6%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	6%

SOEC 2022

rare earth element mine operation and beneficiation, ion adsorption clays | rare earth carbonate concentrate | Cutoff, U - CN	50%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	12%
rare earth element mine operation and beneficiation, ion adsorption clays | rare earth carbonate concentrate | Cutoff, U - RoW	11%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	10%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	5%
uranium production, in yellowcake, in-situ leaching | uranium, in yellowcake | Cutoff, U - GLO	1%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland	1%

SOEC 2050

treatment of dross from Al electrolysis, residual material landfill | dross from Al electrolysis | Cutoff, U - RoW	45%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	20%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	18%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	2%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	1%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	1%

DAC 2022

trimethylamine production | trimethylamine | Cutoff, U - RER	65%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	8%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	8%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	7%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland	2%

treatment of spent solvent mixture, hazardous waste incineration, with energy recovery | spent solvent mixture | Cutoff, U - CH	1%
treatment of spent solvent mixture, hazardous waste incineration | spent solvent mixture | Cutoff, U - CH	1%
uranium production, in yellowcake, in-situ leaching | uranium, in yellowcake | Cutoff, U - GLO	1%

DAC 2050

trimethylamine production | trimethylamine | Cutoff, U - RER	77%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	7%
treatment of dross from Al electrolysis, residual material landfill | dross from Al electrolysis | Cutoff, U - RoW	4%
treatment of spent solvent mixture, hazardous waste incineration | spent solvent mixture | Cutoff, U - CH	3%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	2%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	1%

Chemical Factory, organics 2022

treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	26%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	26%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	14%
uranium production, in yellowcake, in-situ leaching | uranium, in yellowcake | Cutoff, U - GLO	3%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - CL	2%
treatment of sulfidic tailings, from copper mine operation, tailings impoundment | sulfidic tailings, from copper mine operation | Cutoff, U - RoW	2%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland	1%
treatment of waste wood, untreated, unsanitary landfill, wet infiltration class (500mm) | waste wood, untreated | Cutoff, U - GLO	1%
treatment of dross from Al electrolysis, residual material landfill | dross from Al electrolysis | Cutoff, U - RoW	1%

Chemical factory, organics 2050

treatment of dross from Al electrolysis, residual material landfill | dross from Al electrolysis | Cutoff, U - RoW	58%
treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	26%
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	6%
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	1%

7. Mineral Resource Scarcity

PV 2022

bauxite mine operation | bauxite | Cutoff, U - GLO	25%
silver-gold mine operation with refinery | silver | Cutoff, U - RoW	20%
iron ore mine operation and beneficiation | iron ore concentrate | Cutoff, U - RoW	9%

ferronickel production | ferronickel | Cutoff, U - GLO	7%
iron ore mine operation, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	6%
copper production, cathode, solvent extraction and electrowinning process | copper, cathode | Cutoff, U - GLO	5%
zinc mine operation | zinc concentrate | Cutoff, U - GLO	4%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	4%
iron ore mine operation, 63% Fe | iron ore, crude ore, 63% Fe | Cutoff, U - IN	3%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	3%
molybdenite mine operation | copper concentrate, sulfide ore | Cutoff, U - GLO	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CN	1%

PV 2050

iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	24%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	14%
silver-gold mine operation with refinery | silver | Cutoff, U - RoW	13%
gold-silver-zinc-lead-copper mine operation and refining | silver | Cutoff, U - RoW	6%
zinc-lead mine operation | zinc concentrate | Cutoff, U - GLO	5%
gold-silver-zinc-lead-copper mine operation and refining | copper | Cutoff, U - RoW	5%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	5%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	4%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RLA	4%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RNA	3%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RER	2%
copper production, solvent-extraction electro-winning | copper, from solvent-extraction electro-winning | Cutoff, U - GLO	2%
molybdenite mine operation | molybdenite | Cutoff, U - GLO	1%
iron mine operation and iron ore beneficiation to 65% Fe | iron ore, beneficiated, 65% Fe | Cutoff, U - CA-QC	1%
nickel mine operation, sulfidic ore | copper | Cutoff, U - GLO	1%

Wind 2022

iron ore mine operation and beneficiation | iron ore concentrate | Cutoff, U - RoW	15%
copper production, cathode, solvent extraction and electrowinning process | copper, cathode | Cutoff, U - GLO	11%
iron ore mine operation, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	10%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	8%
ferronickel production | ferronickel | Cutoff, U - GLO	8%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	7%
iron ore mine operation, 63% Fe | iron ore, crude ore, 63% Fe | Cutoff, U - IN	5%
molybdenite mine operation | copper concentrate, sulfide ore | Cutoff, U - GLO	3%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CN	2%
cobalt production | copper concentrate, sulfide ore | Cutoff, U - GLO	2%
cobalt production | copper, anode | Cutoff, U - GLO	2%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - AU	2%
gold mine operation and gold production, unrefined | gold, unrefined | Cutoff, U - RoW	2%

clay pit operation | clay | Cutoff, U - RoW	2%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RU	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CA	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - US	1%
silver-gold mine operation with refinery | gold | Cutoff, U - RoW	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - ID	1%
zinc mine operation | copper concentrate, sulfide ore | Cutoff, U - GLO	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - ZM	1%

Wind 2050

iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	30%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	14%
gold-silver-zinc-lead-copper mine operation and refining | copper | Cutoff, U - RoW	9%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	8%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	7%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RLA	6%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RNA	4%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RER	4%
copper production, solvent-extraction electro-winning | copper, from solvent-extraction electro-winning | Cutoff, U - GLO	3%
nickel mine operation, sulfidic ore | copper | Cutoff, U - GLO	2%
molybdenite mine operation | molybdenite | Cutoff, U - GLO	2%
gold production | gold | Cutoff, U - RoW	1%
iron mine operation and iron ore beneficiation to 65% Fe | iron ore, beneficiated, 65% Fe | Cutoff, U - CA-QC	1%
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	1%
clay pit operation | clay | Cutoff, U - CH	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - AU	1%

SOEC 2022

ferronickel production | ferronickel | Cutoff, U - GLO	51%
cobalt production | nickel, class 1 | Cutoff, U - GLO	6%
rare earth element mine operation and beneficiation, ion adsorption clays | rare earth carbonate concentrate | Cutoff, U - CN	5%
nickel mine operation and benefication to nickel concentrate, 16% Ni | nickel concentrate, 16% Ni | Cutoff, U - CA-QC	4%
iron ore mine operation and beneficiation | iron ore concentrate | Cutoff, U - RoW	4%
chromite ore concentrate production | chromite ore concentrate | Cutoff, U - GLO	3%
iron ore mine operation, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	2%
cobalt production | cobalt | Cutoff, U - GLO	2%
copper production, cathode, solvent extraction and electrowinning process | copper, cathode | Cutoff, U - GLO	2%
platinum group metal mine operation, ore with high palladium content | nickel, class 1 | Cutoff, U - RU	2%
nickel mine operation and benefication to nickel concentrate, 7% Ni | nickel concentrate, 7% Ni | Cutoff, U - CN	2%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	2%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	1%

cobalt production | ferronickel | Cutoff, U - GLO	1%
rare earth element mine operation and beneficiation, ion adsorption clays | rare earth carbonate concentrate | Cutoff, U - RoW	1%
iron ore mine operation, 63% Fe | iron ore, crude ore, 63% Fe | Cutoff, U - IN	1%

SOEC 2050

ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	58%
iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	11%
nickel mine operation, sulfidic ore | nickel, 99.5% | Cutoff, U - GLO	7%
chromite ore concentrate production | chromite ore concentrate | Cutoff, U - GLO	3%
platinum group metal mine operation, ore with high palladium content | nickel, 99.5% | Cutoff, U - RU	3%
gold-silver-zinc-lead-copper mine operation and refining | copper | Cutoff, U - RoW	2%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	2%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	2%
cobalt production | cobalt | Cutoff, U - GLO	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RLA	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RNA	1%

DAC 2022

ferronickel production | ferronickel | Cutoff, U - GLO	57%
iron ore mine operation and beneficiation | iron ore concentrate | Cutoff, U - RoW	12%
iron ore mine operation, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	8%
bauxite mine operation | bauxite | Cutoff, U - GLO	4%
iron ore mine operation, 63% Fe | iron ore, crude ore, 63% Fe | Cutoff, U - IN	3%
chromite ore concentrate production | chromite ore concentrate | Cutoff, U - GLO	3%
cobalt production | ferronickel | Cutoff, U - GLO	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	1%

DAC 2050

ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	61%
iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	26%
chromite ore concentrate production | chromite ore concentrate | Cutoff, U - GLO	3%
iron mine operation and iron ore beneficiation to 65% Fe | iron ore, beneficiated, 65% Fe | Cutoff, U - CA-QC	1%
molybdenite mine operation | molybdenite | Cutoff, U - GLO	1%

Chemical Factory, organics 2022

ferronickel production | ferronickel | Cutoff, U - GLO	30%
copper production, cathode, solvent extraction and electrowinning process | copper, cathode | Cutoff, U - GLO	8%
clay pit operation | clay | Cutoff, U - RoW	6%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	6%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	5%

bauxite mine operation | bauxite | Cutoff, U - GLO	5%
gold mine operation and gold production, unrefined | gold, unrefined | Cutoff, U - RoW	3%
iron ore mine operation and beneficiation | iron ore concentrate | Cutoff, U - RoW	3%
molybdenite mine operation | copper concentrate, sulfide ore | Cutoff, U - GLO	2%
silver-gold mine operation with refinery | gold | Cutoff, U - RoW	2%
clay pit operation | clay | Cutoff, U - CH	2%
iron ore mine operation, 63% Fe | iron ore, crude ore, 63% Fe | Cutoff, U - IN	2%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CN	2%
iron ore mine operation, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	2%
zinc mine operation | zinc concentrate | Cutoff, U - GLO	2%
cobalt production | copper concentrate, sulfide ore | Cutoff, U - GLO	2%
chromite ore concentrate production | chromite ore concentrate | Cutoff, U - GLO	2%
cobalt production | copper, anode | Cutoff, U - GLO	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - AU	1%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RU	1%

Chemical factory, organics 2050

ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	30%
iron mine operation, crude ore, 46% Fe | iron ore, crude ore, 46% Fe | Cutoff, U - GLO	9%
gold-silver-zinc-lead-copper mine operation and refining | copper | Cutoff, U - RoW	7%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	7%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	6%
clay pit operation | clay | Cutoff, U - RoW	6%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RLA	5%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RNA	4%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RER	3%
gold production | gold | Cutoff, U - RoW	3%
zinc-lead mine operation | zinc concentrate | Cutoff, U - GLO	3%
clay pit operation | clay | Cutoff, U - CH	2%
copper production, solvent-extraction electro-winning | copper, from solvent-extraction electro-winning | Cutoff, U - GLO	2%
chromite ore concentrate production | chromite ore concentrate | Cutoff, U - GLO	2%
nickel mine operation, sulfidic ore | copper | Cutoff, U - GLO	1%

8. Terrestrial Acidification

PV 2022

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	6%
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RoW	3%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	3%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	3%

blasting | blasting | Cutoff, U - RoW	3 %
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	2 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - RoW	2 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	2 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SD	2 %
transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff, U - GLO	2 %
platinum group metal mine operation, ore with high palladium content | copper, cathode | Cutoff, U - RU	2 %
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RER	2 %
zinc coating, coils | zinc coat, coils | Cutoff, U - RoW	2 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-JS	2 %
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	2 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SX	1 %
silicon production, metallurgical grade | silicon, metallurgical grade | Cutoff, U - RoW	1 %
transport, freight, sea, container ship | transport, freight, sea, container ship | Cutoff, U - GLO	1 %
electricity production, oil | electricity, high voltage | Cutoff, U - RoW	1 %
blasting | blasting | Cutoff, U - RER	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-ZJ	1 %
silicon carbide production | silicon carbide | Cutoff, U - RoW	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-HB	1 %
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-HE	1 %

PV 2050

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	6 %
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RoW	6 %
anaerobic digestion of manure | biogas | Cutoff, U - RoW	6 %
copper production, primary | copper | Cutoff, U - RAS	5 %
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	5 %
copper production, primary | copper | Cutoff, U - RoW	4 %
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	4 %

copper production, primary | copper | Cutoff, U - RLA	3%
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	3%
blasting | blasting | Cutoff, U - RoW	3%
zinc coating, coils | zinc coat, coils | Cutoff, U - RoW	2%
copper production, primary | copper | Cutoff, U - RNA	2%
silicon production, metallurgical grade | silicon, metallurgical grade | Cutoff, U - RoW	2%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
copper production, primary | copper | Cutoff, U - AU	2%
sinter production, iron | sinter, iron | Cutoff, U - GLO	2%
silicon carbide production | silicon carbide | Cutoff, U - RoW	1%
blasting | blasting | Cutoff, U - RER	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%
nickel mine operation, sulfidic ore | copper | Cutoff, U - GLO	1%
flat glass production, uncoated | flat glass, uncoated | Cutoff, U - RER	1%
zinc coating, coils | zinc coat, coils | Cutoff, U - RER	1%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	1%

Wind 2022

platinum group metal mine operation, ore with high palladium content | copper, cathode | Cutoff, U - RU	12%
blasting | blasting | Cutoff, U - RoW	9%
blasting | blasting | Cutoff, U - RER	4%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	4%
transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff, U - GLO	4%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	4%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	3%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RoW	2%
clinker production | clinker | Cutoff, U - RoW	2%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	2%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CN	2%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	2%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	2%
coking | coke | Cutoff, U - RoW	2%
iron sinter production | iron sinter | Cutoff, U - RoW	2%

Wind 2050

copper production, primary | copper | Cutoff, U - RAS	16%
copper production, primary | copper | Cutoff, U - RoW	11%
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	11%
copper production, primary | copper | Cutoff, U - RLA	9%
copper production, primary | copper | Cutoff, U - RNA	6%
copper production, primary | copper | Cutoff, U - AU	5%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	4%
blasting | blasting | Cutoff, U - RoW	4%
nickel mine operation, sulfidic ore | copper | Cutoff, U - GLO	3%
sinter production, iron | sinter, iron | Cutoff, U - GLO	3%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	3%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	2%
blasting | blasting | Cutoff, U - RER	2%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2%
anaerobic digestion of manure | biogas | Cutoff, U - RoW	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%
clinker production | clinker | Cutoff, U - RoW	1%
coking | coke | Cutoff, U - RoW	1%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	1%

SOEC 2022

platinum group metal mine operation, ore with high palladium content | nickel, class 1 | Cutoff, U - RU	24%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	12%
smelting and refining of nickel concentrate, 16% Ni | nickel, class 1 | Cutoff, U - GLO	4%
blasting | blasting | Cutoff, U - RoW	2%
platinum group metal mine operation, ore with high palladium content | copper, cathode | Cutoff, U - RU	2%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	2%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	2%
transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff, U - GLO	1%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	1%
blasting | blasting | Cutoff, U - RER	1%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	1%
electricity production, oil | electricity, high voltage | Cutoff, U - RoW	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	1%

SOEC 2050

platinum group metal mine operation, ore with high palladium content | nickel, 99.5% | Cutoff, U - RU	32%
nickel mine operation, sulfidic ore | nickel, 99.5% | Cutoff, U - GLO	14%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	12%
copper production, primary | copper | Cutoff, U - RAS	4%
copper production, primary | copper | Cutoff, U - RoW	3%
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	3%
copper production, primary | copper | Cutoff, U - RLA	2%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	2%
anaerobic digestion of manure | biogas | Cutoff, U - RoW	2%
blasting | blasting | Cutoff, U - RoW	2%
copper production, primary | copper | Cutoff, U - RNA	2%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%
sinter production, iron | sinter, iron | Cutoff, U - GLO	1%
copper production, primary | copper | Cutoff, U - AU	1%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	1%

DAC 2022

polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	14%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	11%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	4%
transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff, U - GLO	3%
sour gas, burned in gas turbine | sour gas, burned in gas turbine | Cutoff, U - RoW	2%
blasting | blasting | Cutoff, U - RoW	2%
clinker production | clinker | Cutoff, U - CH	2%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	2%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	1%
coking | coke | Cutoff, U - RoW	1%
tube insulation production, elastomere | tube insulation, elastomere | Cutoff, U - DE	1%
iron sinter production | iron sinter | Cutoff, U - RER	1%
trimethylamine production | trimethylamine | Cutoff, U - RER	1%
blasting | blasting | Cutoff, U - RER	1%
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	1%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	1%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	1%

DAC 2050

polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	16%

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	12%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	7%
sinter production, iron | sinter, iron | Cutoff, U - GLO	5%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	5%
anaerobic digestion of manure | biogas | Cutoff, U - RoW	4%
sour gas, burned in gas turbine | sour gas, burned in gas turbine | Cutoff, U - RoW	2%
clinker production | clinker | Cutoff, U - CH	2%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	2%
coking | coke | Cutoff, U - RoW	2%
copper production, primary | copper | Cutoff, U - RAS	2%
blasting | blasting | Cutoff, U - RoW	2%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
tube insulation production, elastomere | tube insulation, elastomere | Cutoff, U - DE	1%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	1%
trimethylamine production | trimethylamine | Cutoff, U - RER	1%
copper production, primary | copper | Cutoff, U - RoW	1%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	1%
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	1%
copper production, primary | copper | Cutoff, U - RLA	1%

Chemical factory, organics 2022

heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	9%
platinum group metal mine operation, ore with high palladium content | copper, cathode | Cutoff, U - RU	8%
blasting | blasting | Cutoff, U - RoW	7%
blasting | blasting | Cutoff, U - RER	3%
electricity production, hard coal, conventional | electricity, high voltage | Cutoff, U - ZA	3%
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RoW	2%
transport, freight, sea, bulk carrier for dry goods | transport, freight, sea, bulk carrier for dry goods | Cutoff, U - GLO	2%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CN	2%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-NM	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - RoW	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-SD	1%
treatment of waste natural gas, sour, burned in production flare | waste natural gas, sour | Cutoff, U - GLO	1%
zinc coating, coils | zinc coat, coils | Cutoff, U - RoW	1%

electricity production, oil | electricity, high voltage | Cutoff, U - RoW	1%
electricity production, hard coal | electricity, high voltage | Cutoff, U - CN-JS	1%
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	1%

Chemical factory, organics 2050

copper production, primary | copper | Cutoff, U - RAS	14%
copper production, primary | copper | Cutoff, U - RoW	10%
platinum group metal mine operation, ore with high palladium content | copper | Cutoff, U - RU	10%
copper production, primary | copper | Cutoff, U - RLA	8%
heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | Cutoff, U - RoW	8%
copper production, primary | copper | Cutoff, U - RNA	6%
copper production, primary | copper | Cutoff, U - AU	5%
blasting | blasting | Cutoff, U - RoW	4%
nickel mine operation, sulfidic ore | copper | Cutoff, U - GLO	3%
anaerobic digestion of manure | biogas | Cutoff, U - RoW	3%
transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO	2%
blasting | blasting | Cutoff, U - RER	2%
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	1%
sinter production, iron | sinter, iron | Cutoff, U - GLO	1%
zinc coating, coils | zinc coat, coils | Cutoff, U - RoW	1%

9. Terrestrial ecotoxicity

PV 2022

photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	74%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RER	16%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RoW	1%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CN	1%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	
Silver	99%

PV 2050

photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	60%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RER	13%
copper production, primary | copper | Cutoff, U - RAS	7%
copper production, primary | copper | Cutoff, U - RoW	6%
copper production, primary | copper | Cutoff, U - RLA	6%
primary zinc production from concentrate | zinc | Cutoff, U - RoW	2%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	1%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	
Silver	99%

Wind 2022

smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RoW	20%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CN	18%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RoW	8%
treatment of copper scrap by electrolytic refining | copper, cathode | Cutoff, U - RoW	7%
ferronickel production | ferronickel | Cutoff, U - GLO	7%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CL	5%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - JP	4%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RER	3%
treatment of copper cake | copper, cathode | Cutoff, U - GLO	3%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - IN	3%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RU	2%
cast iron production | cast iron | Cutoff, U - RoW	2%
printed wiring board production, for surface mounting, Pb free surface | printed wiring board, for surface mounting, Pb free surface | Cutoff, U - GLO	2%
zinc mine operation | copper concentrate, sulfide ore | Cutoff, U - GLO	2%
treatment of copper scrap by electrolytic refining | copper, cathode | Cutoff, U - RER	2%

Wind 2050

copper production, primary | copper | Cutoff, U - RAS	29%
copper production, primary | copper | Cutoff, U - RoW	27%
copper production, primary | copper | Cutoff, U - RLA	25%
copper production, primary | copper | Cutoff, U - AU	4%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	3%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RoW	3%
copper production, primary | copper | Cutoff, U - RNA	1%
copper production, primary | copper | Cutoff, U - RER	1%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RER	1%

SOEC 2022

ferronickel production | ferronickel | Cutoff, U - GLO	41%
nickel mine operation and benefication to nickel concentrate, 7% Ni | nickel concentrate, 7% Ni | Cutoff, U - CN	22%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RoW	4%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CN	3%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RoW	3%
cobalt production | nickel, class 1 | Cutoff, U - GLO	3%
heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	3%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	2%
treatment of copper scrap by electrolytic refining | copper, cathode | Cutoff, U - RoW	1%
treatment of brake wear emissions, passenger car | brake wear emissions, passenger car | Cutoff, U - RoW	1%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RER	1%

cast iron production | cast iron | Cutoff, U - RoW	1%

SOEC 2050

ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	27%
copper production, primary | copper | Cutoff, U - RAS	17%
copper production, primary | copper | Cutoff, U - RoW	16%
copper production, primary | copper | Cutoff, U - RLA	15%
nickel mine operation, sulfidic ore | nickel, 99.5% | Cutoff, U - GLO	4%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RoW	3%
copper production, primary | copper | Cutoff, U - AU	2%
heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Cutoff, U - Europe without Switzerland	2%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	2%
treatment of brake wear emissions, passenger car | brake wear emissions, passenger car | Cutoff, U - RoW	1%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RER	1%

DAC 2022

ferronickel production | ferronickel | Cutoff, U - GLO	60%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RoW	7%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RoW	4%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CN	4%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	3%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RER	3%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CL	1%

DAC 2050

ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	47%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RoW	9%
copper production, primary | copper | Cutoff, U - RAS	8%
copper production, primary | copper | Cutoff, U - RoW	8%
copper production, primary | copper | Cutoff, U - RLA	7%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RER	4%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	3%
steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - RER	2%
steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	1%
copper production, primary | copper | Cutoff, U - AU	1%

Chemical Factory, organics 2022

ferronickel production | ferronickel | Cutoff, U - GLO	22%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RoW	15%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CN	13%

treatment of copper scrap by electrolytic refining | copper, cathode | Cutoff, U - RoW	5%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RoW	4%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - CL	4%
printed wiring board production, for surface mounting, Pb free surface | printed wiring board, for surface mounting, Pb free surface | Cutoff, U - GLO	3%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - JP	3%
zinc mine operation | zinc concentrate | Cutoff, U - GLO	3%
treatment of copper cake | copper, cathode | Cutoff, U - GLO	2%
brazing solder production, cadmium free | brazing solder, cadmium free | Cutoff, U - RoW	2%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - IN	2%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RER	2%
smelting of copper concentrate, sulfide ore | copper, anode | Cutoff, U - RU	2%
printed wiring board production, for surface mounting, Pb containing surface | printed wiring board, for surface mounting, Pb containing surface | Cutoff, U - GLO	1%
zinc mine operation | copper concentrate, sulfide ore | Cutoff, U - GLO	1%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	1%
treatment of copper scrap by electrolytic refining | copper, cathode | Cutoff, U - RER	1%

Chemical factory, organics 2050

copper production, primary | copper | Cutoff, U - RAS	27%
copper production, primary | copper | Cutoff, U - RoW	25%
copper production, primary | copper | Cutoff, U - RLA	23%
ferronickel production, 25% Ni | ferronickel, 25% Ni | Cutoff, U - GLO	6%
copper production, primary | copper | Cutoff, U - AU	4%
primary zinc production from concentrate | zinc | Cutoff, U - RoW	3%
treatment of brake wear emissions, lorry | brake wear emissions, lorry | Cutoff, U - RoW	2%
copper production, primary | copper | Cutoff, U - RNA	1%
copper production, primary | copper | Cutoff, U - RER	1%

10. Water Consumption

PV 2022

silicon production, multi-Si, casted | silicon, multi-Si, casted | Cutoff, U - RoW	22%
silicon production, electronics grade | silicon, electronics grade | Cutoff, U - RoW	18%
silicon production, electronics grade | silicon, electronics grade | Cutoff, U - DE	18%
silicon production, electronics grade | silicon, solar grade | Cutoff, U - RoW	4%
silicon production, electronics grade | silicon, solar grade | Cutoff, U - DE	4%

photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	4%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - NO	2%
water production, decarbonised | water, decarbonised | Cutoff, U - CN	2%
silicon production, multi-Si, casted | silicon, multi-Si, casted | Cutoff, U - RER	2%
water production, completely softened | water, completely softened | Cutoff, U - RoW	1%
water production, decarbonised | water, decarbonised | Cutoff, U - RoW	1%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	-1%
treatment of wastewater from PV cell production, capacity 5E9l/year | wastewater from PV cell production | Cutoff, U - RoW	-2%

PV 2050

silicon production, multi-Si, casted | silicon, multi-Si, casted | Cutoff, U - RoW	24%
silicon production, electronics grade | silicon, electronics grade | Cutoff, U - RoW	20%
silicon production, electronics grade | silicon, electronics grade | Cutoff, U - DE	20%
silicon production, electronics grade | silicon, solar grade | Cutoff, U - RoW	5%
silicon production, electronics grade | silicon, solar grade | Cutoff, U - DE	5%
photovoltaic cell production, multi-Si wafer | photovoltaic cell, multi-Si wafer | Cutoff, U - RoW	5%
water production and supply, decarbonised | water, decarbonised, at user | Cutoff, U - RoW	3%
silicon production, multi-Si, casted | silicon, multi-Si, casted | Cutoff, U - RER	2%
water production and supply, decarbonised | water, decarbonised, at user | Cutoff, U - RER	1%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U | Global - GLO	1%
treatment of wastewater from PV cell production, capacity 5E9l/year | wastewater from PV cell production | Cutoff, U - RoW	-2%

Wind 2022

nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	10%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - RoW	9%
steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	8%
iron pellet production | iron pellet | Cutoff, U - IN	7%
gravel and sand quarry operation | gravel, round | Cutoff, U - RoW	6%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	5%
hot rolling, steel | hot rolling, steel | Cutoff, U - RoW	4%
steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - IN	3%
steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RoW	3%
gravel and sand quarry operation | gravel, round | Cutoff, U - CH	3%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	3%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	3%
hot rolling, steel | hot rolling, steel | Cutoff, U - Europe without Austria	3%
air separation, cryogenic | oxygen, liquid | Cutoff, U - RoW	2%
gravel and sand quarry operation | sand | Cutoff, U - RoW	2%
water production, decarbonised | water, decarbonised | Cutoff, U - RoW	2%
tap water production, conventional treatment | tap water | Cutoff, U - RoW	2%
water production, decarbonised | water, decarbonised | Cutoff, U - CN	2%
water production, decarbonised | water, decarbonised | Cutoff, U - US	2%

hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	1%
sheet rolling, steel | sheet rolling, steel | Cutoff, U - RoW	1%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - PE	1%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - NO	1%
treatment of wastewater from pig iron production, capacity 5E9l/year | wastewater from pig iron production | Cutoff, U - RoW	-1%
treatment of wastewater, unpolluted, capacity 5E9l/year | wastewater, unpolluted | Cutoff, U - RoW	-2%
market for tap water | tap water | Cutoff, U - RoW	-2%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland	-2%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	-14%

Wind 2050

gravel and sand quarry operation | gravel, round | Cutoff, U - RoW	14%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	13%
gravel and sand quarry operation | sand | Cutoff, U - RoW	7%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RER	7%
hot rolling, steel | hot rolling, steel | Cutoff, U - RoW	5%
steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RoW	4%
hot rolling, steel | hot rolling, steel | Cutoff, U - RER	4%
air separation, cryogenic | oxygen, liquid | Cutoff, U - RoW	3%
steel production, converter, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	3%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	2%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U | Global - GLO	2%
polyvinylchloride production, suspension polymerisation | polyvinylchloride, suspension polymerised | Cutoff, U - RoW	2%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U | Global - GLO	1%
sheet rolling, steel | sheet rolling, steel | Cutoff, U - RoW	1%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U | Global - GLO	1%
tap water production, conventional treatment | tap water | Cutoff, U - RoW	1%
water production and supply, decarbonised | water, decarbonised, at user | Cutoff, U - RoW	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	1%
petroleum refinery operation | diesel | Cutoff, U - RoW	1%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	1%

SOEC 2022

electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - RoW	28%
water production, decarbonised | water, decarbonised | Cutoff, U - CN	4%
water production, decarbonised | water, decarbonised | Cutoff, U - RoW	3%
gravel and sand quarry operation | gravel, round | Cutoff, U - RoW	3%
water production, decarbonised | water, decarbonised | Cutoff, U - US	3%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - NO	2%
steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	2%

gravel and sand quarry operation | gravel, round | Cutoff, U - CH	2%
sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, U - RoW	2%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U - BR-Southern grid	2%
iron pellet production | iron pellet | Cutoff, U - IN	2%
heat and power co-generation, hard coal | electricity, high voltage | Cutoff, U - PL	2%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	2%
heat and power co-generation, hard coal | electricity, high voltage | Cutoff, U - RoW	2%
electricity production, nuclear, pressure water reactor, heavy water moderated | electricity, high voltage | Cutoff, U - RoW	2%
hot rolling, steel | hot rolling, steel | Cutoff, U - RoW	1%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - PE	1%
steel production, electric, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - RoW	1%
tap water production, conventional treatment | tap water | Cutoff, U - RoW	1%
electricity production, nuclear, pressure water reactor, heavy water moderated | electricity, high voltage | Cutoff, U - CA-ON	1%
heat and power co-generation, hard coal | electricity, high voltage | Cutoff, U - RU	1%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U - CA-QC	1%
water production, decarbonised | water, decarbonised | Cutoff, U - IN	1%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U - BR-Northern grid	1%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland	-2%
market for tap water | tap water | Cutoff, U - RoW	-2%
treatment of wastewater, unpolluted, capacity 5E9l/year | wastewater, unpolluted | Cutoff, U - RoW	-2%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	-7%

SOEC 2050

gravel and sand quarry operation | gravel, round | Cutoff, U - RoW	9%
gravel and sand quarry operation | sand | Cutoff, U - RoW	6%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U | Global - GLO	5%
sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, U - RoW	4%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	4%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U | Global - GLO	4%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U | Global - GLO	4%
hot rolling, steel | hot rolling, steel | Cutoff, U - RoW	3%
air separation, cryogenic | oxygen, liquid | Cutoff, U - RoW	3%
gravel and sand quarry operation | gravel, round | Cutoff, U - CH	3%
water production and supply, decarbonised | water, decarbonised, at user | Cutoff, U - RoW	2%
sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, U - RER	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	2%
hot rolling, steel | hot rolling, steel | Cutoff, U - RER	2%
petroleum refinery operation | diesel | Cutoff, U - RoW	2%
steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RoW	2%
tap water production, conventional treatment | tap water | Cutoff, U - RoW	2%
nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Cutoff, U - RoW	1%
steel production, converter, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	1%

silicon production, electronics grade | silicon, electronics grade | Cutoff, U - DE	1%
silicon production, electronics grade | silicon, electronics grade | Cutoff, U - RoW	1%
treatment of wastewater, unpolluted, capacity 5E9l/year | wastewater, unpolluted | Cutoff, U - RoW	-3%

DAC 2022

polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	17%
water production, deionised | water, deionised | Cutoff, U - CH	9%
gravel and sand quarry operation | gravel, round | Cutoff, U - CH	7%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - CH	6%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	5%
gravel and sand quarry operation | sand | Cutoff, U - CH	4%
steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	3%
chlor-alkali electrolysis, membrane cell | chlorine, gaseous | Cutoff, U - RER	3%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - RoW	3%
chloromethyl methyl ether production | chloromethyl methyl ether | Cutoff, U - RER	3%
iron pellet production | iron pellet | Cutoff, U - IN	3%
steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RER	3%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - NO	3%
trimethylamine production | trimethylamine | Cutoff, U - RER	2%
ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | Cutoff, U - RER w/o RU	2%
chlor-alkali electrolysis, diaphragm cell | chlorine, gaseous | Cutoff, U - RER	2%
heat and power co-generation, hard coal | electricity, high voltage | Cutoff, U - PL	2%
water production, decarbonised | water, decarbonised | Cutoff, U - RoW	2%
hot rolling, steel | hot rolling, steel | Cutoff, U - Europe without Austria	2%
ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | Cutoff, U - RU	2%
methanol production | methanol | Cutoff, U - GLO	2%
steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - IN	1%
sodium chloride production, powder | sodium chloride, powder | Cutoff, U - RoW	1%
water production, decarbonised | water, decarbonised | Cutoff, U - CN	1%
treatment of wastewater, unpolluted, capacity 5E9l/year | wastewater, unpolluted | Cutoff, U - RoW	-1%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - Europe without Switzerland	-1%
anionic resin production | anionic resin | Cutoff, U - CH	-6%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	-6%

DAC 2050

polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RoW	21%
gravel and sand quarry operation | gravel, round | Cutoff, U - CH	9%
polystyrene production, general purpose | polystyrene, general purpose | Cutoff, U - RER	6%
tap water production, underground water without treatment | tap water | Cutoff, U - CH	5%
gravel and sand quarry operation | sand | Cutoff, U - RoW	5%
tap water production, direct filtration treatment | tap water | Cutoff, U - CH	4%
ammonia production, steam reforming, liquid | ammonia, liquid | Cutoff, U - RER	4%
chlor-alkali electrolysis, membrane cell | chlorine, gaseous | Cutoff, U - RER	4%
steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RER	3%

chloromethyl methyl ether production | chloromethyl methyl ether | Cutoff, U - RER	3%
trimethylamine production | trimethylamine | Cutoff, U - RER	2%
chlor-alkali electrolysis, diaphragm cell | chlorine, gaseous | Cutoff, U - RER	2%
hot rolling, steel | hot rolling, steel | Cutoff, U - RER	2%
tap water production, conventional treatment | tap water | Cutoff, U - CH	2%
tap water production, conventional with biological treatment | tap water | Cutoff, U - CH	2%
methanol production | methanol | Cutoff, U - GLO	2%
sodium chloride production, powder | sodium chloride, powder | Cutoff, U - RoW	2%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U | Global - GLO	2%
water production and supply, decarbonised | water, decarbonised, at user | Cutoff, U - RoW	1%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U | Global - GLO	1%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U | Global - GLO	1%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	1%
chlor-alkali electrolysis, mercury cell | chlorine, gaseous | Cutoff, U - RER	1%
air separation, cryogenic | oxygen, liquid | Cutoff, U - RER	1%
steel production, converter, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	1%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	-1%
treatment of wastewater, unpolluted, capacity 5E9l/year | wastewater, unpolluted | Cutoff, U - RoW	-1%
anionic resin production | anionic resin | Cutoff, U - CH	-7%

Chemical Factory, organics 2022

electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - RoW	10%
steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	5%
water production, decarbonised | water, decarbonised | Cutoff, U - CN	4%
water production, decarbonised | water, decarbonised | Cutoff, U - RoW	4%
chemical factory construction | chemical factory | Cutoff, U - RoW	4%
iron pellet production | iron pellet | Cutoff, U - IN	4%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - NO	4%
hot rolling, steel | hot rolling, steel | Cutoff, U - RoW	3%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	3%
water production, decarbonised | water, decarbonised | Cutoff, U - US	3%
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	3%
heat and power co-generation, hard coal | electricity, high voltage | Cutoff, U - PL	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	2%
tap water production, conventional treatment | tap water | Cutoff, U - RoW	2%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U - CA-QC	2%
steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - IN	2%
chemical factory construction | chemical factory | Cutoff, U - RER	2%
gravel and sand quarry operation | gravel, round | Cutoff, U - RoW	2%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U - BR-Southern grid	2%
heat and power co-generation, hard coal | electricity, high voltage | Cutoff, U - RoW	2%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - PE	2%
hot rolling, steel | hot rolling, steel | Cutoff, U - Europe without Austria	1%
electricity production, nuclear, pressure water reactor, heavy water moderated | electricity, high voltage | Cutoff, U - CA-ON	1%
water production, decarbonised | water, decarbonised | Cutoff, U - IN	1%

gravel and sand quarry operation | gravel, round | Cutoff, U - CH	1%
air separation, cryogenic | oxygen, liquid | Cutoff, U - RoW	1%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U - RoW	1%
treatment of wastewater, unpolluted, capacity 5E9l/year | wastewater, unpolluted | Cutoff, U - RoW	-3%
market for tap water | tap water | Cutoff, U - RoW	-3%
treatment of wastewater, average, capacity 1E9l/year | wastewater, average | Cutoff, U - RoW	-9%

Chemical factory, organics 2050

chemical factory construction | chemical factory | Cutoff, U - RoW	7%
hot rolling, steel | hot rolling, steel | Cutoff, U - RoW	5%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U | Global - GLO	5%
gravel and sand quarry operation | gravel, round | Cutoff, U - RoW	4%
electricity production, hydro, reservoir, tropical region | electricity, high voltage | Cutoff, U | Global - GLO	4%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U | Global - GLO	4%
gravel and sand quarry operation | sand | Cutoff, U - RoW	4%
chemical factory construction | chemical factory | Cutoff, U - RER	3%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RAS	3%
water production and supply, decarbonised | water, decarbonised, at user | Cutoff, U - RoW	3%
hot rolling, steel | hot rolling, steel | Cutoff, U - RER	3%
air separation, cryogenic | oxygen, liquid | Cutoff, U - RoW	2%
steel production, converter, low-alloyed | steel, low-alloyed | Cutoff, U - RoW	2%
tap water production, conventional treatment | tap water | Cutoff, U - RoW	2%
polyvinylchloride production, suspension polymerisation | polyvinylchloride, suspension polymerised | Cutoff, U - RoW	2%
aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Cutoff, U - CN	2%
electricity production, hydro, reservoir, alpine region | electricity, high voltage | Cutoff, U - NO	2%
ferrochromium production, high-carbon, 68% Cr | ferrochromium, high-carbon, 68% Cr | Cutoff, U - GLO	2%
hard coal mine operation and hard coal preparation | hard coal | Cutoff, U - CN	2%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	2%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U - RoW	1%
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U - IS	1%
primary zinc production from concentrate | zinc | Cutoff, U - RoW	1%
water production and supply, decarbonised | water, decarbonised, at user | Cutoff, U - RER	1%
copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RNA	1%
gravel and sand quarry operation | gravel, round | Cutoff, U - CH	1%
steel production, converter, unalloyed | steel, unalloyed | Cutoff, U - RoW	1%
wafer production, fabricated, for integrated circuit | wafer, fabricated, for integrated circuit | Cutoff, U - GLO	-1%
treatment of wastewater from wafer fabrication, capacity 1.1E10l/year | wastewater from wafer fabrication | Cutoff, U - RoW	-1%
treatment of wastewater, unpolluted, capacity 5E9l/year | wastewater, unpolluted | Cutoff, U - RoW	-2%